Geometric Patterns and Microstructures in the study of Material Defects and Composites

Silvio Fanzon

supervised by

Mariapia Palombaro

University of Sussex

Department of Mathematics

Presentation Plan

1. **Geometric Patterns of Dislocations**

2. **Microstructures in Composites**

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   - Dislocations

2. **Microstructures in Composites**

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   - Semi-coherent interfaces (Chapter 3)

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   - Proof of the main theorem

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   - Semi-coherent interfaces
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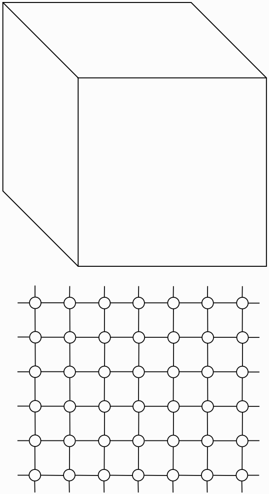
2. **Microgeometries in Composites**
   - Critical lower integrability
   - Convex integration
   - Proof of our main result

Edge dislocations

Dislocations: topological defects in the otherwise periodic structure of a crystal.



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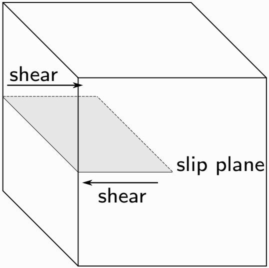

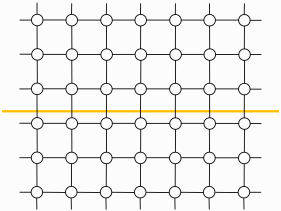

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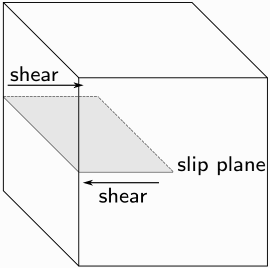

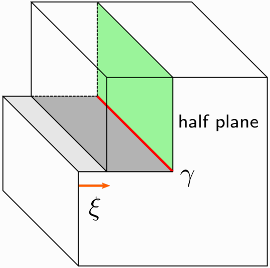

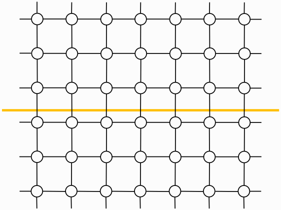

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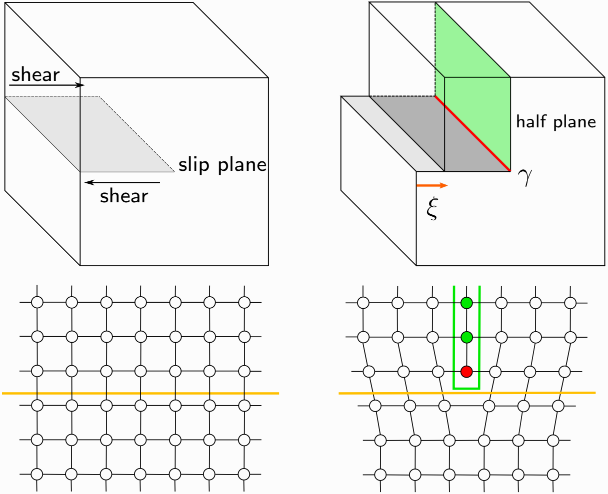

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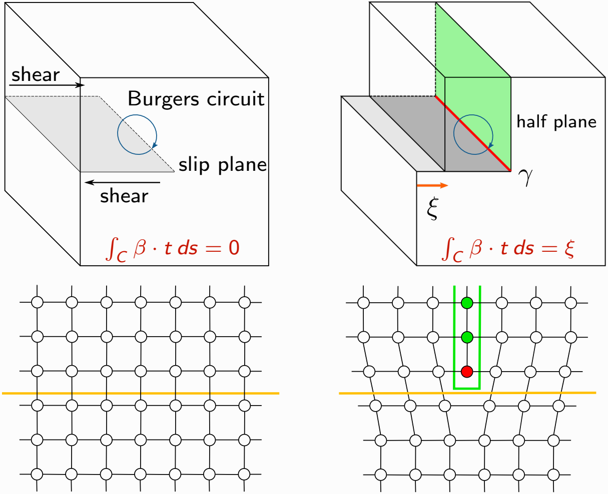

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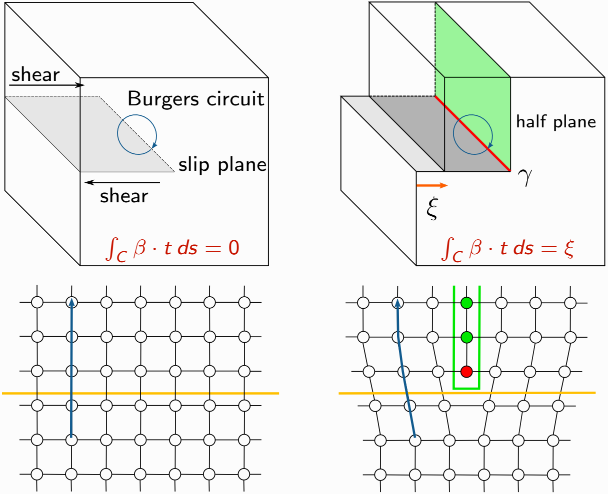

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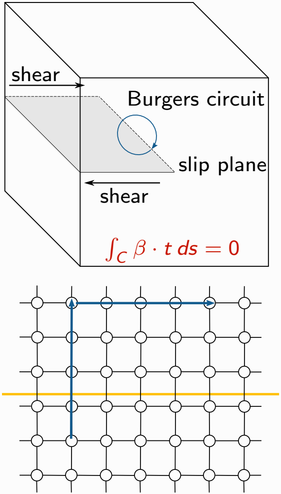

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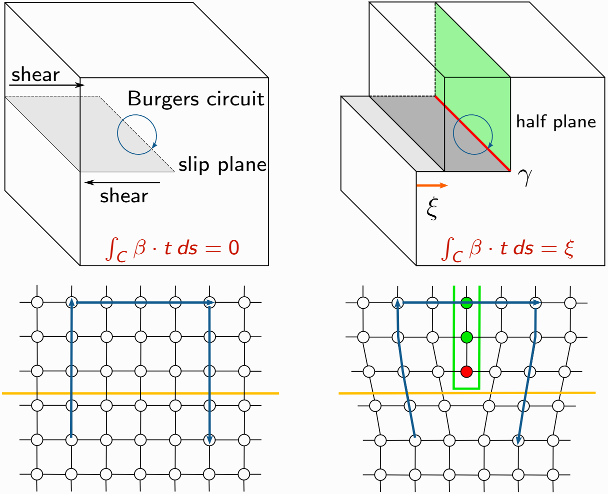

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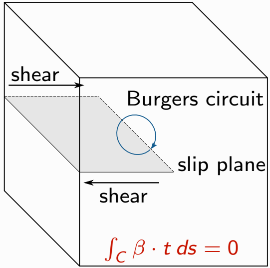

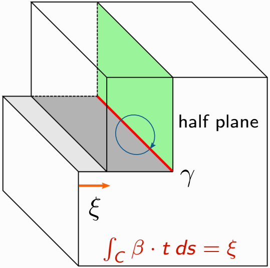

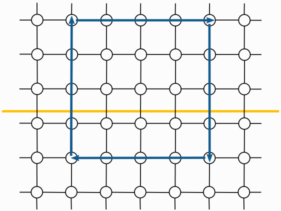

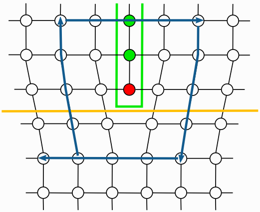

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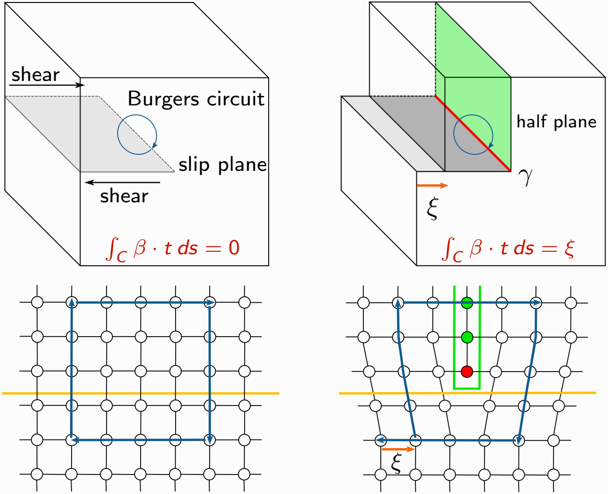

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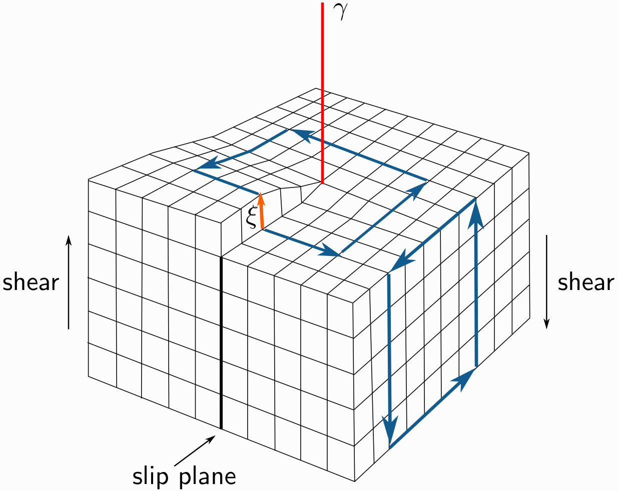

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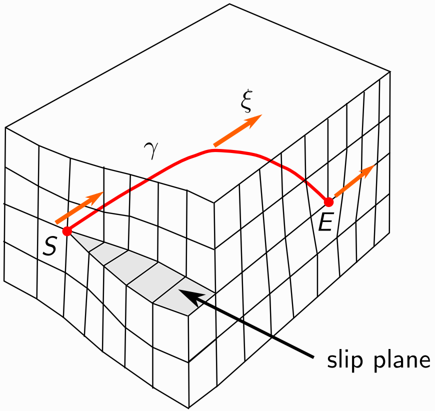
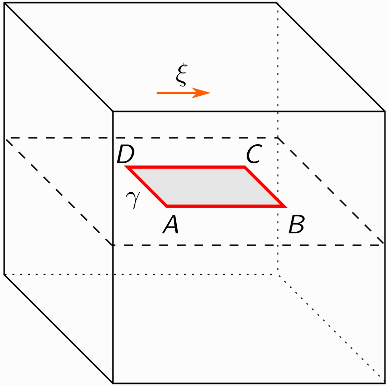
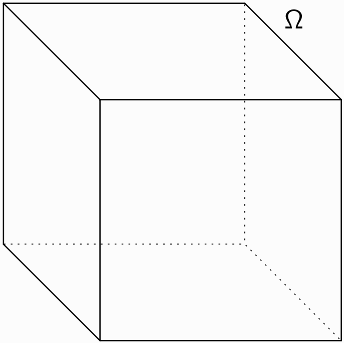




Nonlinear Elasticity

Reference configuration: $\Omega \subset \mathbb{R}^3$ open bounded



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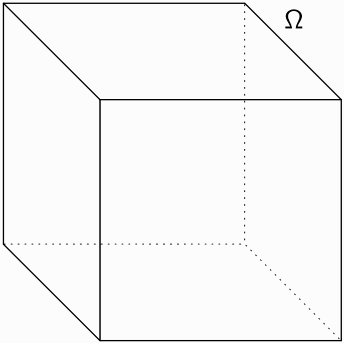

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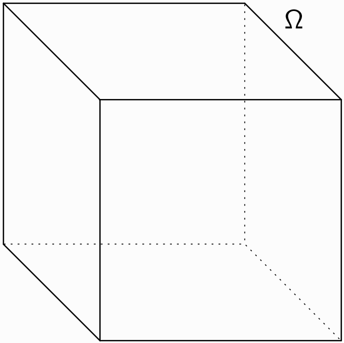

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Energy: associated to a deformation strain β

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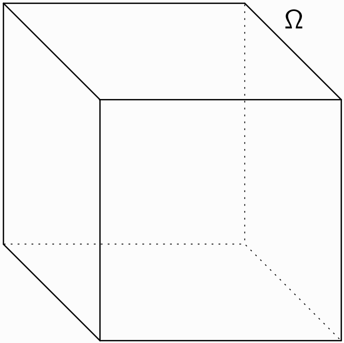

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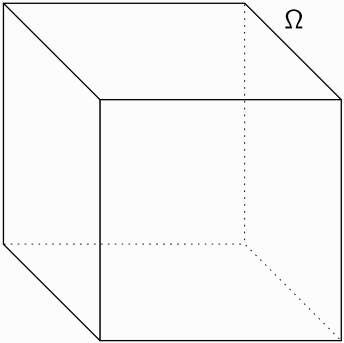

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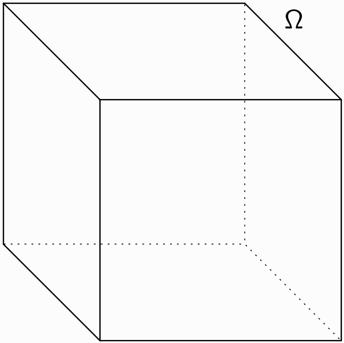

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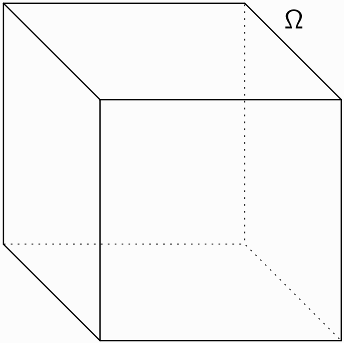

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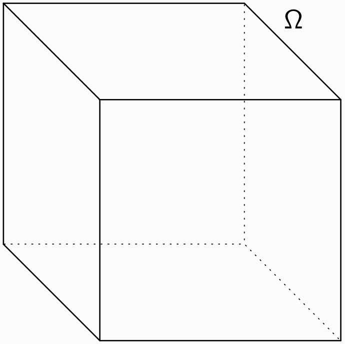
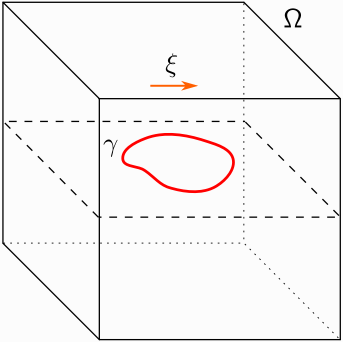


Semi-discrete model for dislocations

Dislocation lines: Lipschitz curves $\gamma \subset \Omega$ such that $\Omega \setminus \gamma$ is not simply connected



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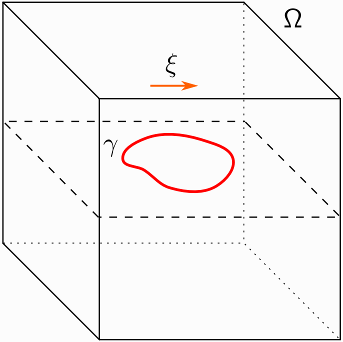

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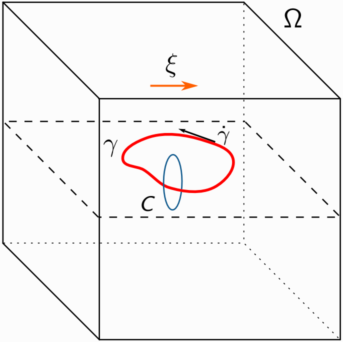
Strain generating (γ, ξ): map $\beta \colon \Omega \to \mathbb{M}^{3\times 3}$ s.t.

$$\mathrm{Curl}\, \beta = -\xi \otimes \dot\gamma\, \mathcal{H}^1 \llcorner \gamma \iff \int_C \beta \cdot t \, d\mathcal{H}^1 = \xi \,.$$



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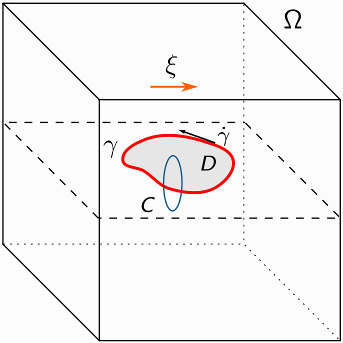


Geometric interpretation: if D encloses γ, there exists a deformation $v \in SBV(\Omega; \mathbb{R}^3)$ s.t.

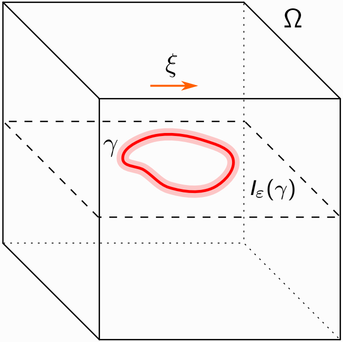
$$Dv = \nabla v \, dx + \xi \otimes n \, \mathcal{H}^2 \llcorner D \,, \quad \beta = \nabla v \,.$$

v has constant jump ξ across the slip region D.

Strains are not L^2

Let β generate (γ, ξ). Consider $\varepsilon > 0$ and

$$I_\varepsilon(\gamma) := \{x \in \mathbb{R}^3 : \ \mathrm{dist}(x, \gamma) < \varepsilon\} .$$



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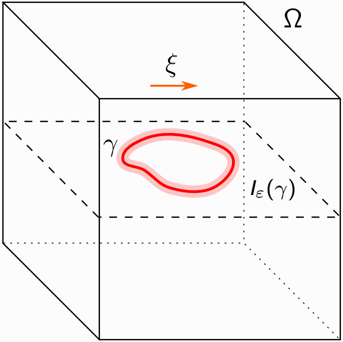

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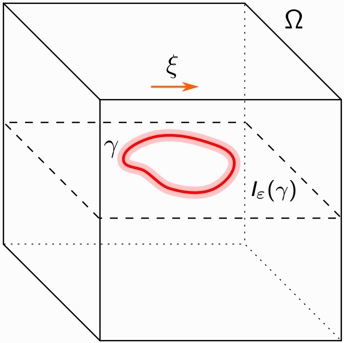
Proof: let $\sigma > \varepsilon$ and $L := \mathrm{length}(\gamma)$



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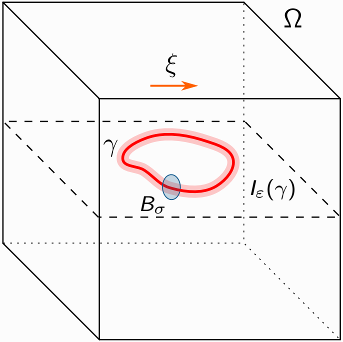

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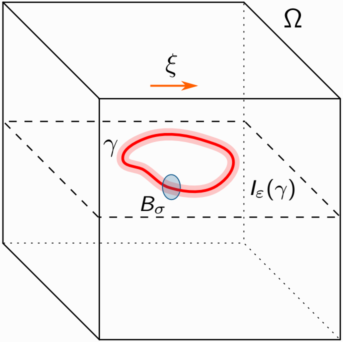

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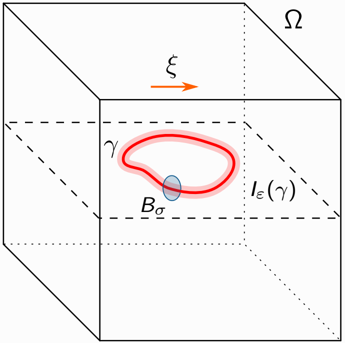
$$= L \frac{|\xi|^2}{2\pi} \log \frac{\sigma}{\varepsilon} \to \infty \ \text{ as } \ \varepsilon \to 0$$



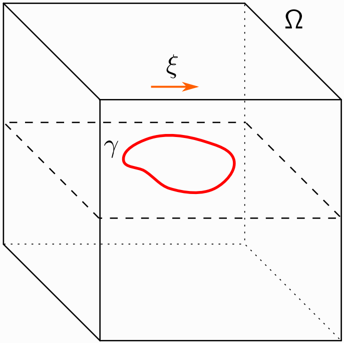
Regularise the problem

Energy Truncation. Fix $p \in (1,2)$ and assume

$$W(F) \sim \operatorname{dist}(F, SO(3))^2 \wedge (|F|^p + 1)\,.$$

Strains are maps $\beta \in L^2(\Omega; \mathbb{M}^{3\times 3})$ such that

$$\operatorname{Curl} \beta = -\xi \otimes \dot\gamma\, \mathcal{H}^1 \llcorner \gamma\,.$$



Regularise the problem

Energy Truncation. Fix $p \in (1,2)$ and assume

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Core Radius Approach. Assume

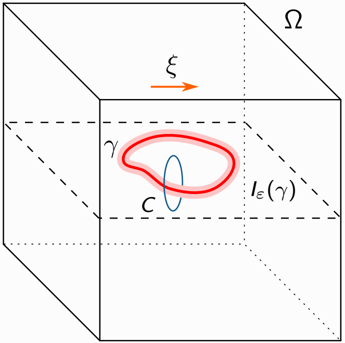
$$W(F) \sim \mathrm{dist}(F, SO(3))^2\,.$$

Let $\varepsilon > 0$ ($\propto$ atomic distance) and consider

$$\Omega_\varepsilon(\gamma) := \Omega \setminus I_\varepsilon(\gamma)\,.$$

Strains are maps $\beta \in L^2(\Omega_\varepsilon(\gamma); \mathbb{M}^{3\times 3})$ such that

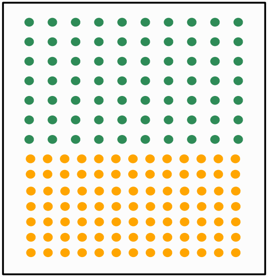
$$\mathrm{Curl}\,\beta \llcorner \Omega_\varepsilon(\gamma) = 0\,, \quad \int_C \beta \cdot t\, d\mathcal{H}^1 = \xi\,.$$



Presentation Plan

Semi-coherent interfaces

Two different crystalline materials joined at a flat interface:



Λ^+

Λ^-

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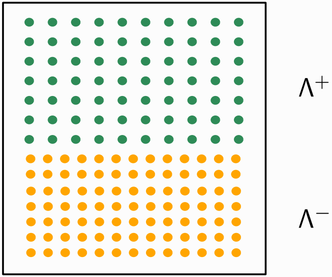

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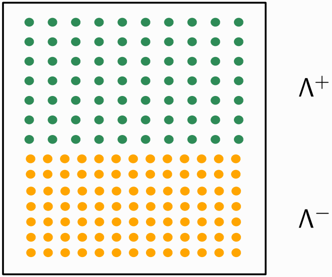

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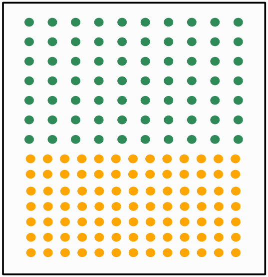

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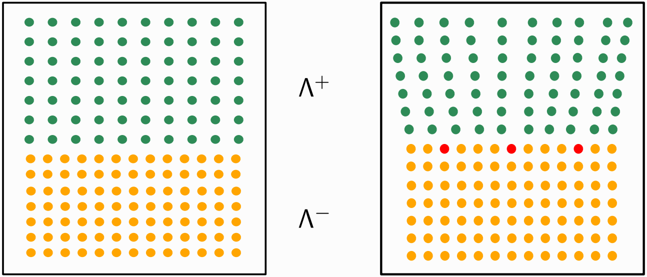
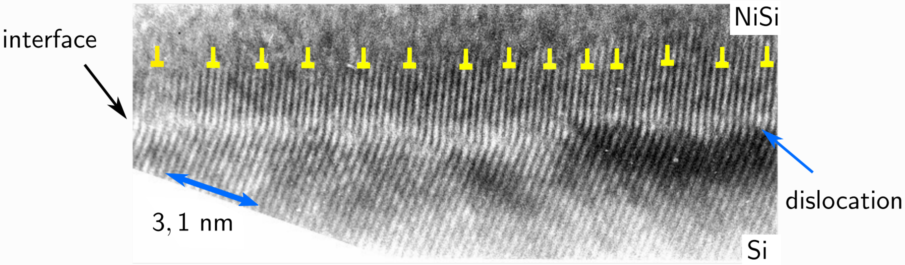
Equilibrium: Λ^+ has lower density than $\Lambda^- \implies$ **edge dislocations** at interface.



Network of dislocations

Experimentally observed phenomena:



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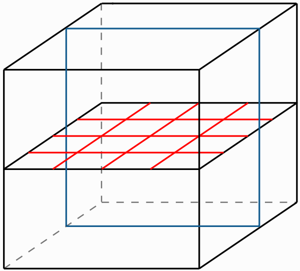

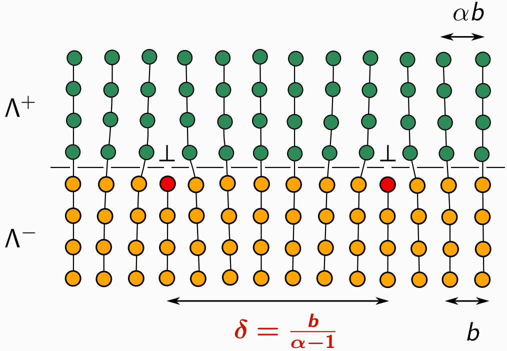

D.A. Porter, K.E. Easterling. *Phase transformations in metals and alloys.* CRC Press (2009)

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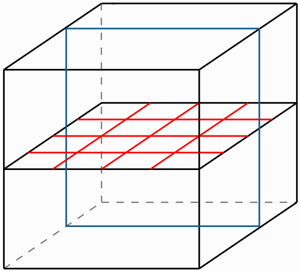

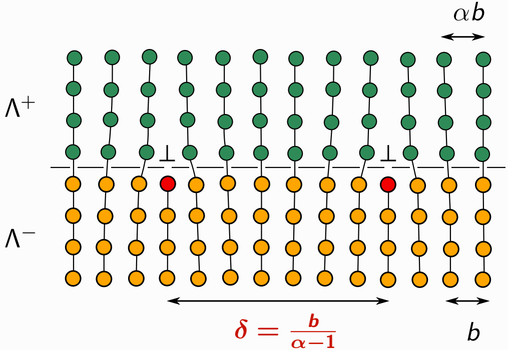

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- analysis of a **semi-discrete model** where dislocations are line defects,

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- derive the simplified (dislocation density) **continuum model**.

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Semi-discrete line defect model

Reference configuration: $\Omega_r := \Omega_r^- \cup S_r \cup \Omega_r^+, \ r > 0,$

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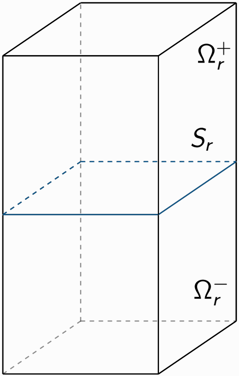

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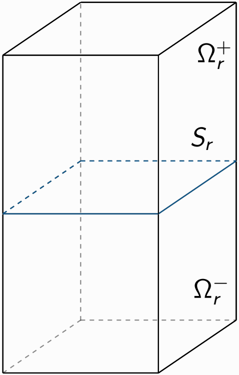

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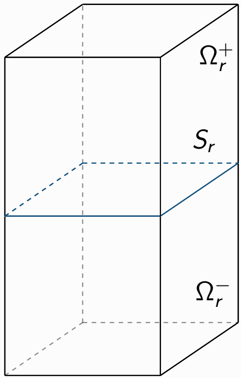

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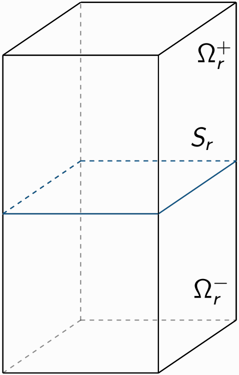

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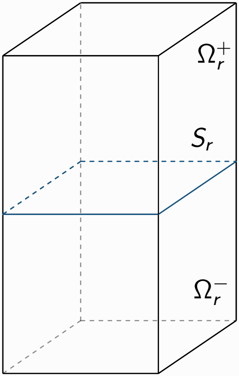

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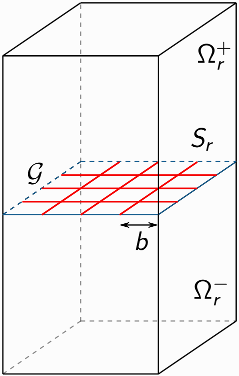

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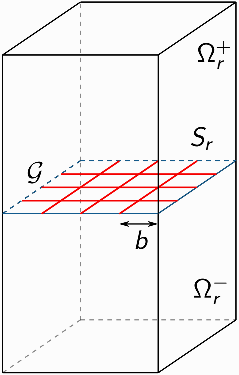

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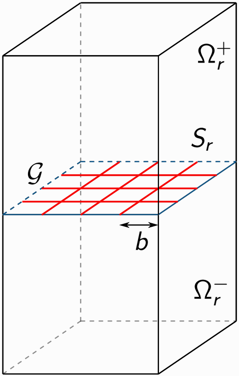

Admissible strains: for a dislocation (Γ, B) are the maps $\beta \in AS(\Gamma, B)$, such that $\beta \in L^p(\Omega_r; \mathbb{M}^{3\times 3})$ and

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Müller, Palombaro. Calculus of Variations and Partial Differential Equations (2008, 2013).

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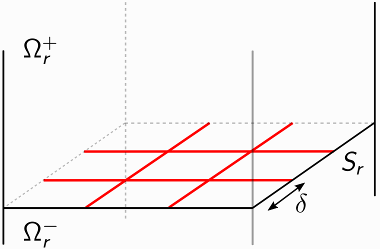

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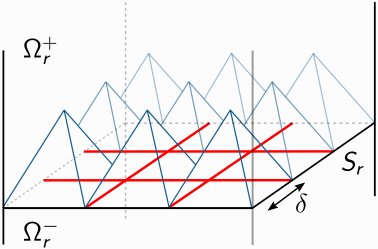

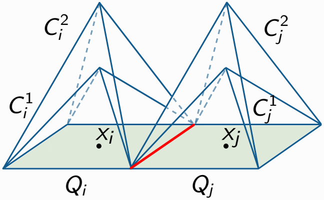

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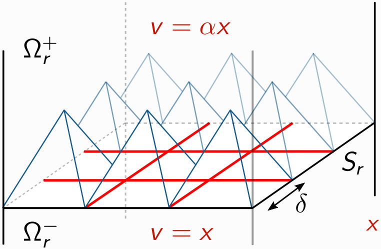

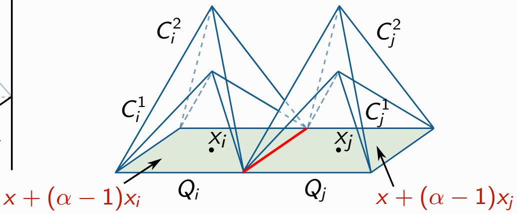

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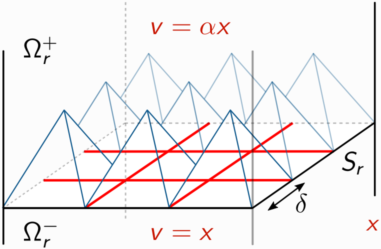

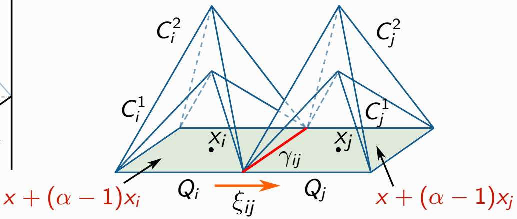

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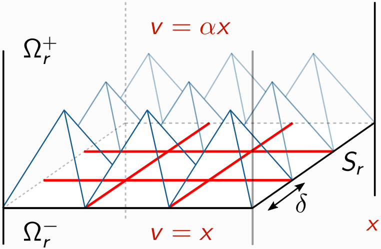
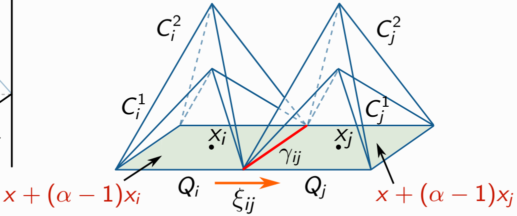
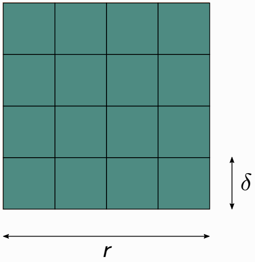
Energy: in each pyramid is $c = c(\alpha, b, p) \implies E_{\alpha,r} \leq c \dfrac{r^2}{\delta^2}$ (as $W(\alpha I) = 0$).





Remarks on the semi-discrete model

Deformed configuration: $v(S_R)$ with v from the upper bound construction



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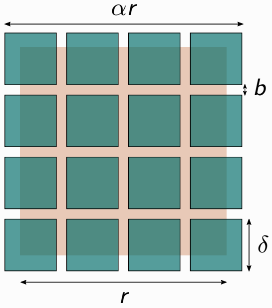

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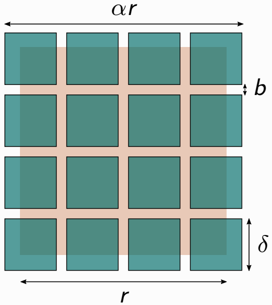

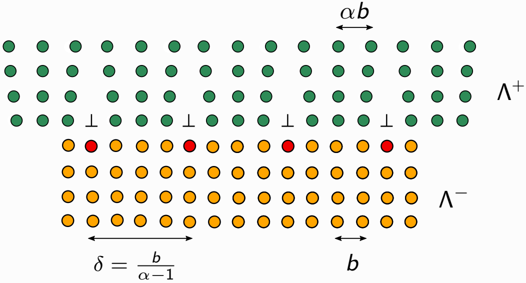

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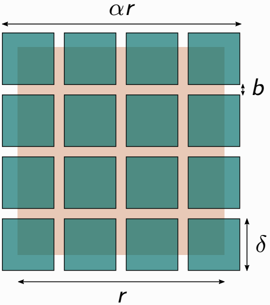

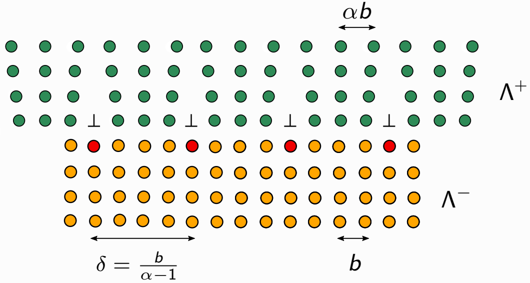

Limitations of the considered model:

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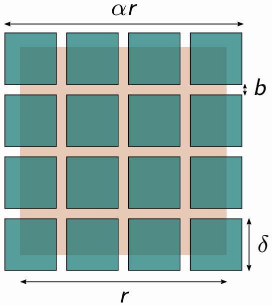

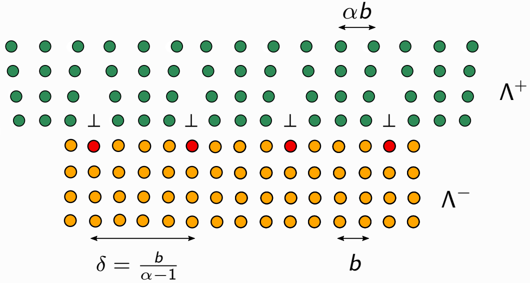

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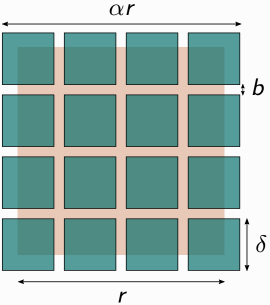

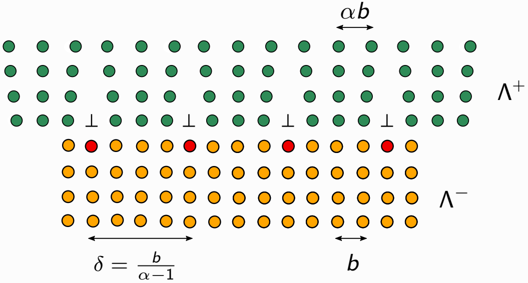

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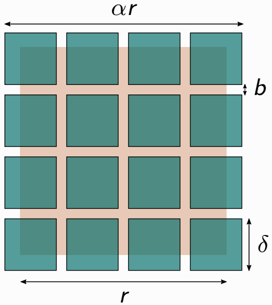

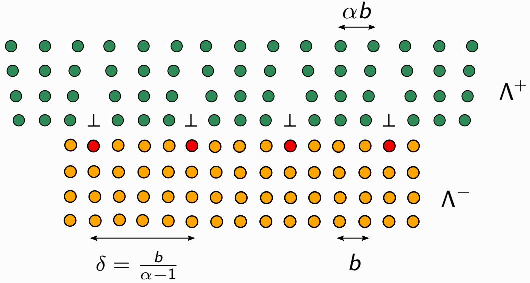

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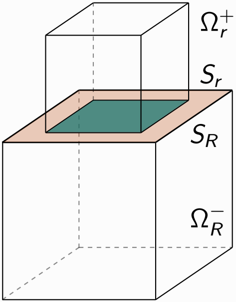
What we do now:

- take a smaller overlayer and enforce match at the interface,
- introduce a simplified continuum (dislocation density) model to better describe true minimisers.

Heuristic for the continuum model



Reference configuration: $\Omega_{R,r} := \Omega_R^- \cup S_r \cup \Omega_r^+$, with $r := \theta R,\ \theta \in [\alpha^{-1}, 1]$

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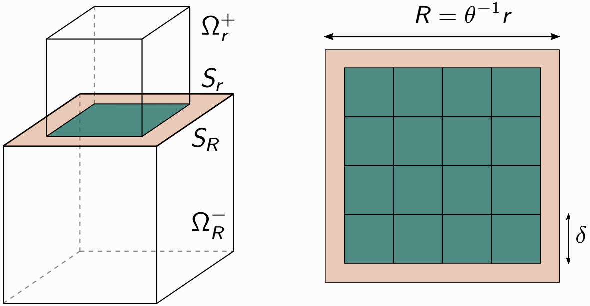

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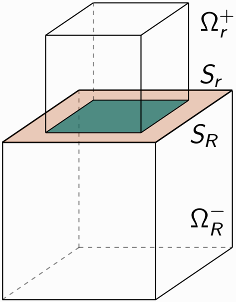

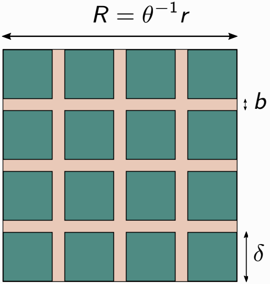

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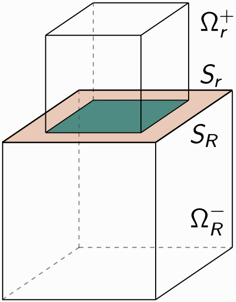

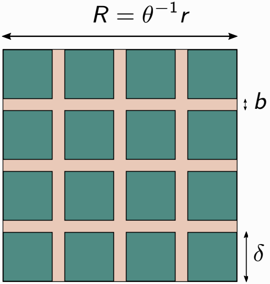

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$$L = 2R\frac{r}{\delta} = \frac{2r^2}{b}(\theta^{-2} - \theta^{-1}) \overset{(\theta^{-1}\approx 1)}{\approx} \frac{r^2}{b}(\theta^{-2} - 1) = \frac{1}{b}(R^2 - r^2) = \frac{1}{b}\,\text{Area Gap}$$

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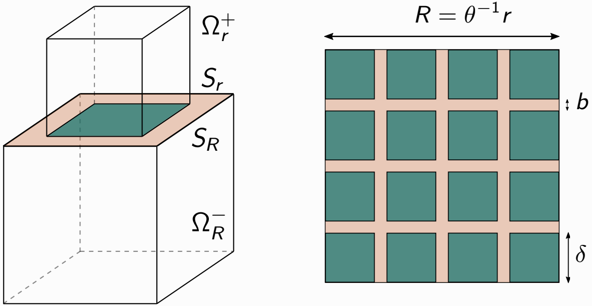

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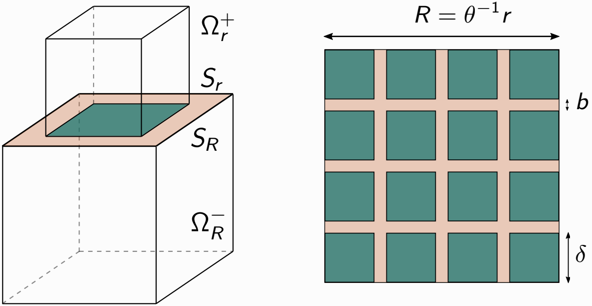

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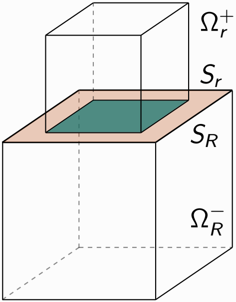

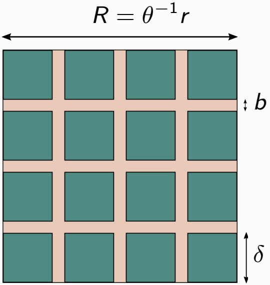

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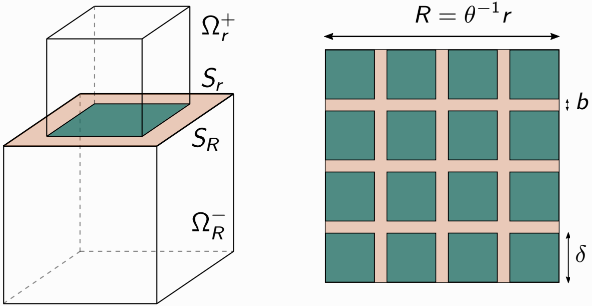

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Hypothesis: Dislocation Energy $\propto$ Dislocation Length. Then optimise over θ.

Continuum model

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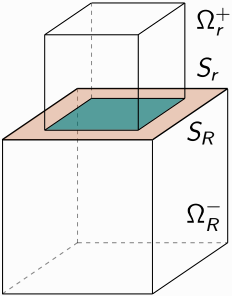

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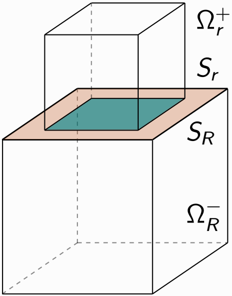
$\implies v(S_r) = S_R$ (interface match)



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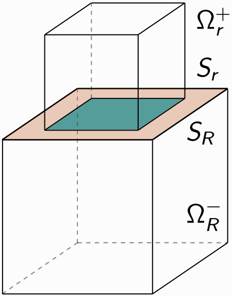

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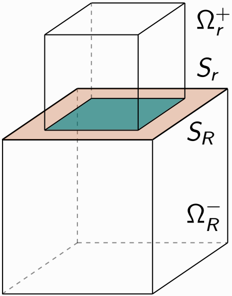

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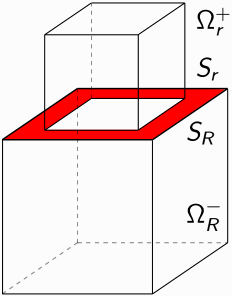

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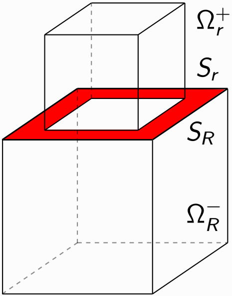

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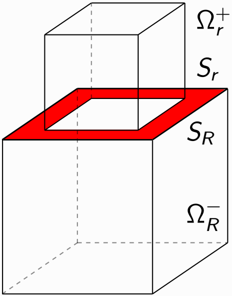

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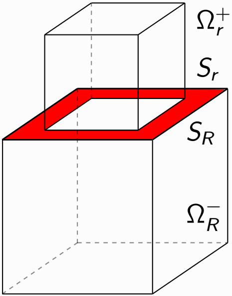

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Energy competition:

- $\theta = 1 \implies$ no dislocation energy

Continuum model

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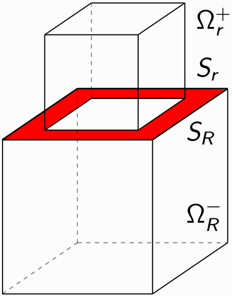

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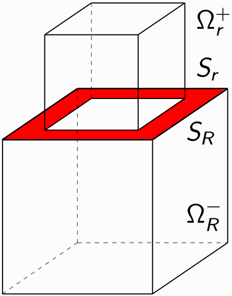
Continuum model



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- $\theta = 1 \implies$ no dislocation energy
- $\theta = \alpha^{-1} \implies$ no elastic energy $\qquad (v := \alpha x, \; W(\alpha I) = 0)$
- $\theta \in (\alpha^{-1}, 1) \implies$ both present

Asymptotic for $E^{tot}_{\alpha,R}$

Let $\theta_R \in [\alpha^{-1}, 1]$ be a minimiser for $E^{tot}_{\alpha,R}$ and define

$$\mathcal{E}^{el}(R) := \frac{\sigma^2}{\alpha^3 C^{el}}\, R\,, \qquad \mathcal{E}^{pl}(R) := \sigma R^2 \left(1 - \frac{1}{\alpha^2}\right) - 2\frac{\sigma^2}{\alpha^3 C^{el}}\, R\,.$$

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Theorem (F., Palombaro, Ponsiglione '15)

As $R \to +\infty$ we have

$$E^{el}_{\alpha,R}(\theta_R) = \mathcal{E}^{el}(R) + O(R) \,, \qquad E^{pl}_{R}(\theta_R) = \mathcal{E}^{pl}(R) + O(R) \,,$$

and therefore

$$E^{tot}_{\alpha,R} = \mathcal{E}^{el}(R) + \mathcal{E}^{pl}(R) + o(R).$$

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Idea of the Proof

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$$E^{el}_{\alpha,R}(\theta) = R^3\theta^3\, E^{el}_{\alpha,1}(\theta)$$

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Step 4. Write the elastic energy as a polynomial

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where $k^{el}_R := C^{el} + \varepsilon_R > 0$ and $k^{el}_R \to C^{el}$.

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Step 5. The total energy computed along θ_R is equal to

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Step 8. Since $\theta_R - \theta^m_R \to 0$, by using (1.1), minimality, and computing $P_{R,k}(\theta^m_R)$, we have the thesis

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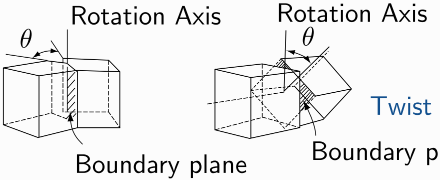
- Grain boundaries, the misfit between the crystal lattices are described by rotations rather than dilations.
  Read, Shockley (1950) - Hirth, Carnahan (1992)

Tilt boundary



Twist boundary

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- Optimal geometry for the dislocation net (square vs hexagonal)
  Koslowski, Ortiz (2004)

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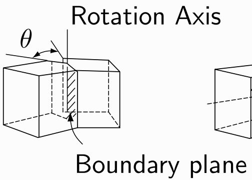

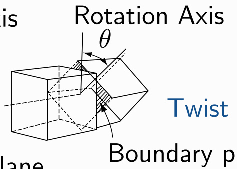

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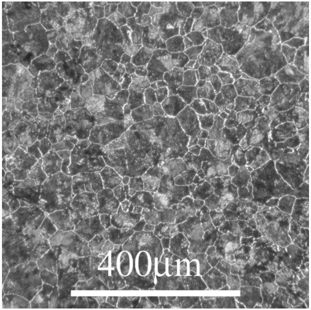
Presentation Plan

1. **Geometric Patterns of Dislocations**
   - Dislocations
   - Semi-coherent interfaces
   - Linearised polycrystals
2. **Microgeometries in Composites**
   - Critical lower integrability
   - Convex integration
   - Proof of our main result

Polycrystals

Polycrystal: formed by many grains, having the **same** lattice structure, mutually rotated $\implies$ interface misfit at **grain boundaries**.



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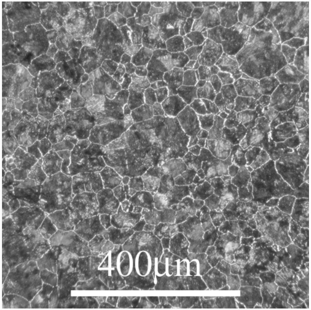
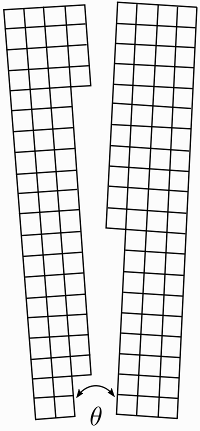


Goal: obtain polycrystalline structures as minimisers of some energy functional.

F., Palombaro, Ponsiglione. *Linearised Polycrystals from a 2D System of Edge Dislocations.* Preprint (2017)

Tilt grain boundaries

Tilt boundary: small angle rotation θ between grains



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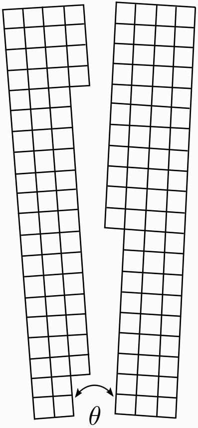
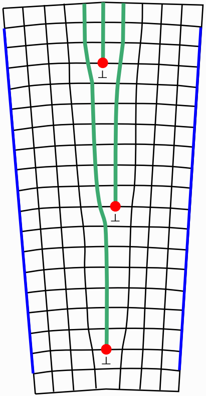
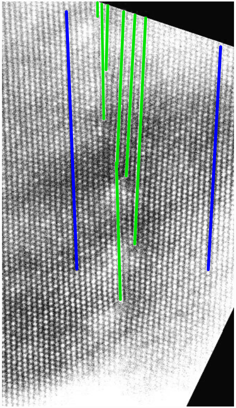
Tilt boundary: small angle rotation θ between grains $\implies$ **edge dislocations**.







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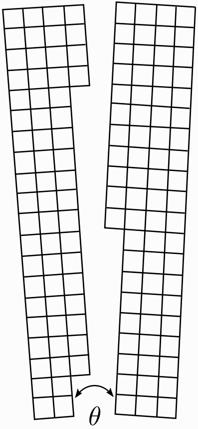

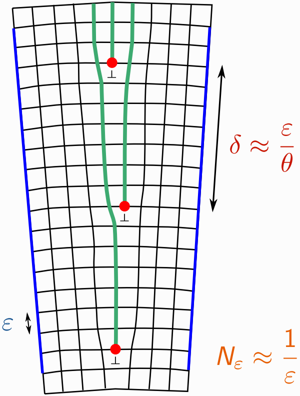

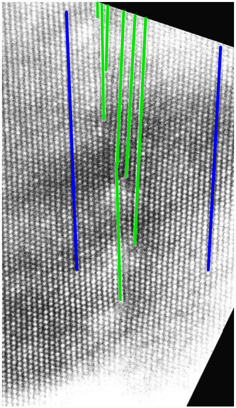

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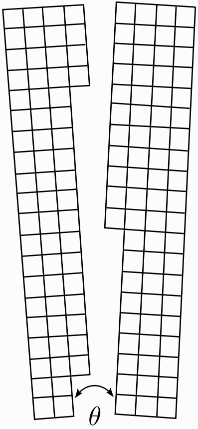

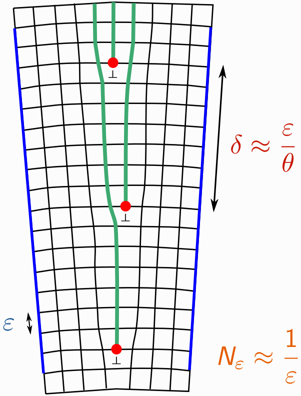

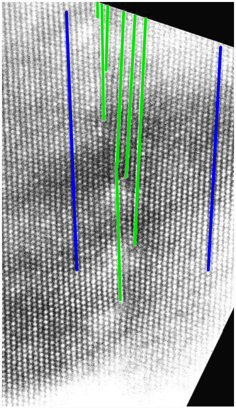

Porter, Easterling. CRC Press (2009) - Gottstein. Springer (2013)

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Setting: consider a 2D system of N_ε edge dislocations, where $\varepsilon > 0$ is the lattice spacing and

$$N_\varepsilon \to +\infty \quad \text{as} \quad \varepsilon \to 0 \,.$$

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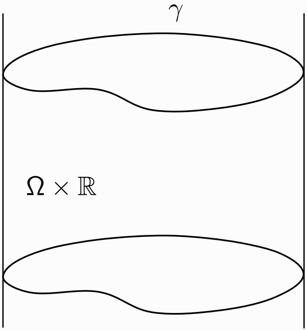
Linearised polycrystals: our energy regime will imply

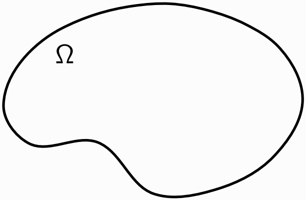
$$N_\varepsilon \ll \frac{1}{\varepsilon}$$

$\Longrightarrow$ we have less dislocations than tilt grain boundaries. However we still obtain polycrystalline minimisers, but with grains rotated by an infinitesimal angle $\theta \approx 0$.

Setting (linearised planar elasticity)

Reference configuration: $\Omega \subset \mathbb{R}^2$ open bounded.





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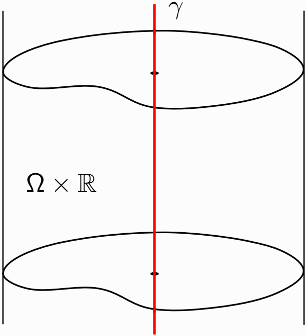

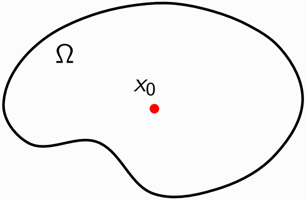

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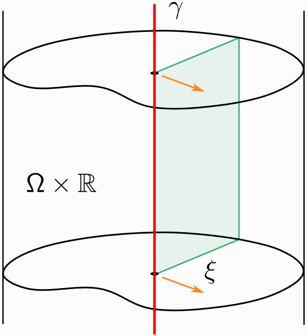

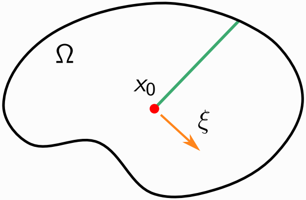

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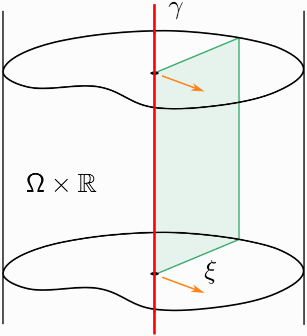
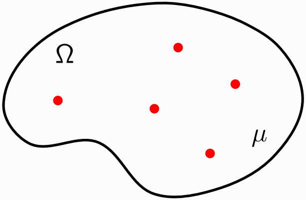
$$\mu := \sum_{i=1}^{N} \xi_i \, \delta_{x_i} , \quad \xi_i \in \mathcal{S} .$$





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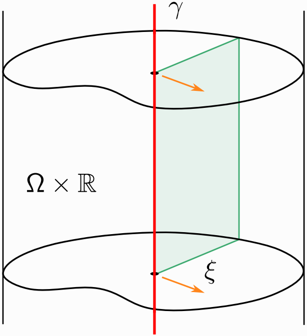

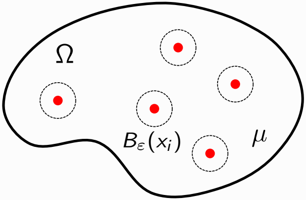

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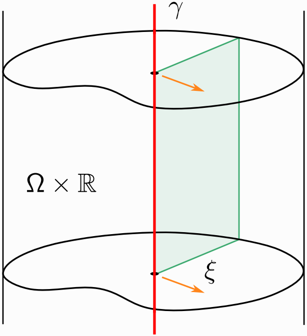

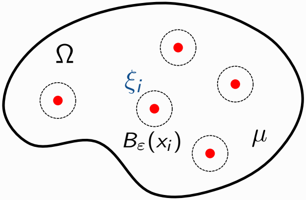

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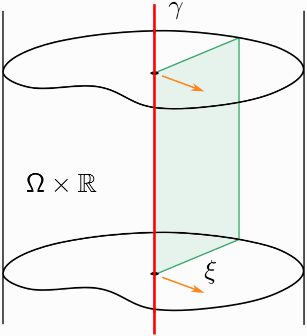

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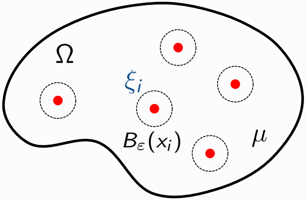

Linearised Energy: $\mathbb{C}F : F \sim |F^{\mathrm{sym}}|^2$, then

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Self-energy of a single dislocation core

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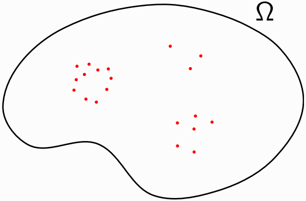

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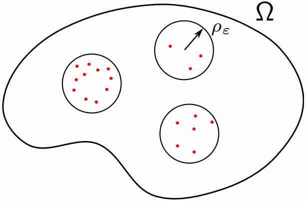

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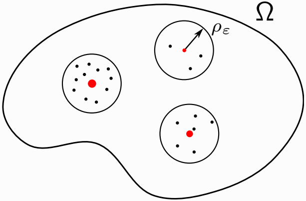

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with $\mathbb{S} := \mathrm{Span}_{\mathbb{Z}} \, \mathcal{S}$ set of multiple Burgers vectors, and

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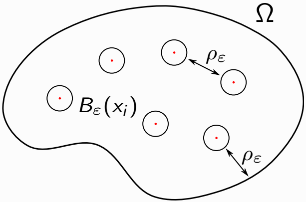

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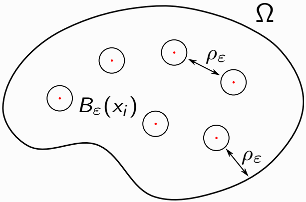

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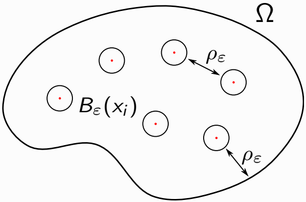

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Energy scaling: each dislocation accounts for $|\log \varepsilon| \implies$ relevant scaling is

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Define $\varphi \colon \mathbb{R}^2 \to [0, \infty)$ as the relaxation of ψ (splitting multiple dislocations)

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Adding boundary conditions

Dirichlet type BC: at level $\varepsilon > 0$ fix a boundary condition $g_\varepsilon \colon \Omega \to \mathbb{M}^{2\times 2}$ s.t.

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Minimising $\mathcal{F}_{\mathrm{BC}}$ with piecewise constant BC

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with $m_k < m_{k+1}$ and $\{U_k\}_{k=1}^M$ Caccioppoli partition of Ω.

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Polycrystals as energy minimisers

Theorem (F., Palombaro, Ponsiglione '17)

Given a piecewise constant boundary condition g_A, there exists a piecewise constant minimiser of $\mathcal{F}_{\mathrm{BC}}(\mu, 0, A)$

$$A = \sum_{k=1}^{M} A_k \chi_{E_k} \, ,$$

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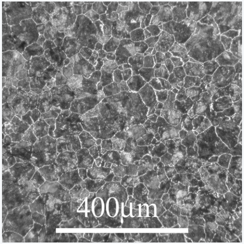

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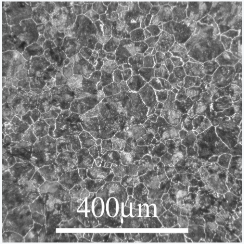

Open Question: Are all minimisers piecewise constant? Uniqueness?

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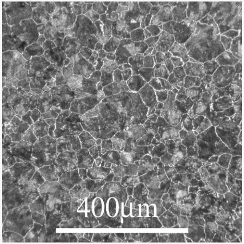

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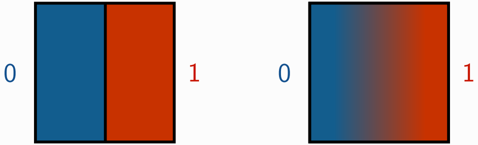
Essential: that the boundary condition is piecewise affine on the whole $\partial\Omega$.



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Proof: let $\tilde{u}$ be a minimiser for (1.3). By anisotropic Coarea Formula

$$\int_\Omega \varphi\left(\frac{dD\tilde{u}}{d|D\tilde{u}|}\right)\, d|D\tilde{u}| = \int_{\mathbb{R}} Per_\varphi(\{x\in\Omega :\ \tilde{u}(x) > t\})\, dt\,,$$

we can select the levels with minimal perimeter. This defines the Caccioppoli partition.

Comparison with classical Read-Shockley formula

Read-Shockley formula: Elastic energy$= E_0\theta(1+|\log\theta|)$.

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Question: Are there some relevant energy regimes in between?

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- Supercritical regime analysis starting from a non-linear energy?

  Müller, Scardia, Zeppieri. *Geometric rigidity for incompatible fields and an application to strain-gradient plasticity.* Indiana University Mathematics Journal (2014).

Presentation Plan

1. **Geometric Patterns of Dislocations**
   - Dislocations
   - Semi-coherent interfaces
   - Linearised polycrystals

2. **Microgeometries in Composites**
   - Critical lower integrability
   - Convex integration
   - Proof of our main result

Presentation Plan

Gradient integrability for solutions to elliptic equations

$\Omega \subset \mathbb{R}^2$ bounded open domain. A map $\sigma \in L^\infty(\Omega; \mathbb{M}^{2\times 2})$ is **uniformly elliptic** if

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Problem

Study the gradient integrability of distributional solutions $u \in W^{1,1}(\Omega)$ to

$$\operatorname{div}(\sigma \nabla u) = 0, \tag{2.1}$$

when

$$\sigma = \sigma_1 \chi_{E_1} + \sigma_2 \chi_{E_2},$$

with $\sigma_1, \sigma_2 \in \mathbb{M}^{2\times 2}$ constant elliptic matrices, $\{E_1, E_2\}$ measurable partition of Ω.

Gradient integrability for solutions to elliptic equations

$\Omega \subset \mathbb{R}^2$ bounded open domain. A map $\sigma \in L^\infty(\Omega; \mathbb{M}^{2\times 2})$ is **uniformly elliptic** if

$$\sigma\xi \cdot \xi \geq \lambda |\xi|^2 , \qquad \forall \xi \in \mathbb{R}^2, x \in \Omega .$$

Problem

Study the gradient integrability of distributional solutions $u \in W^{1,1}(\Omega)$ to

$$\operatorname{div}(\sigma \nabla u) = 0 , \tag{2.1}$$

when

$$\sigma = \sigma_1 \chi_{E_1} + \sigma_2 \chi_{E_2} ,$$

with $\sigma_1, \sigma_2 \in \mathbb{M}^{2\times 2}$ constant elliptic matrices, $\{E_1, E_2\}$ measurable partition of Ω.

Application to composites:

- Ω is a section of a composite conductor obtained by mixing two materials with conductivities σ_1 and σ_2,
- the electric field ∇u solves (2.1),
- concentration of ∇u in relation to the geometry $\{E_1, E_2\}$.

Astala's Theorem

Theorem (Astala '94)

Let $\sigma \in L^\infty(\Omega; \mathbb{M}^{2\times 2})$ *be uniformly elliptic. There exists exponents* $1 < q < 2 < p$ *such that if* $u \in W^{1,q}(\Omega)$ *solves*

$$\operatorname{div}(\sigma \nabla u) = 0\,,$$

then $\nabla u \in L^p_{\mathrm{weak}}(\Omega; \mathbb{R}^2)$.

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Question

Are the exponents q *and* p *optimal among two-phase elliptic conductivities*

$$\sigma = \sigma_1 \chi_{E_1} + \sigma_2 \chi_{E_2}\,?$$

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Astala's exponents for two-phase conductivities

For two-phase conductivities Astala's exponents $q = q_{\sigma_1,\sigma_2}$ and $p = p_{\sigma_1,\sigma_2}$ have been characterised.

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Remark: it is sufficient to prove optimality in the case

$$\sigma_1 = \begin{pmatrix} 1/K & 0 \\ 0 & 1/S_1 \end{pmatrix}, \qquad \sigma_2 = \begin{pmatrix} K & 0 \\ 0 & S_2 \end{pmatrix},$$

where

$$K > 1 \qquad \text{and} \qquad \frac{1}{K} \leq S_j \leq K\,, \quad j = 1, 2\,.$$

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The corresponding critical exponents for Astala's theorem are

$$q_{\sigma_1,\sigma_2} = \frac{2K}{K+1}, \quad p_{\sigma_1,\sigma_2} = \frac{2K}{K-1}.$$

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Upper exponent optimality

Theorem (Nesi, Palombaro, Ponsiglione '14)

Let $\sigma_1 = \mathrm{diag}(1/K, 1/S_1), \sigma_2 = \mathrm{diag}(K, S_2)$ *with* $K > 1$ *and* $S_1, S_2 \in [1/K, K]$.

- (i) *If* $\sigma \in L^\infty(\Omega; \{\sigma_1, \sigma_2\})$ *and* $u \in W^{1,\frac{2K}{K+1}}(\Omega)$ *solves*

$$\mathrm{div}(\sigma \nabla u) = 0 \tag{2.2}$$

  then $\nabla u \in L^{\frac{2K}{K-1}}_{\mathrm{weak}}(\Omega; \mathbb{R}^2)$.

- (ii) *There exists* $\bar{\sigma} \in L^\infty(\Omega; \{\sigma_1, \sigma_2\})$ *and a weak solution* $\bar{u} \in W^{1,2}(\Omega)$ *to* (2.2) *with* $\sigma = \bar{\sigma}$, *satisfying affine boundary conditions and such that* $\nabla \bar{u} \notin L^{\frac{2K}{K-1}}(\Omega; \mathbb{R}^2)$.

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Question we address

Is the lower exponent $\frac{2K}{K+1}$ optimal?

Lower exponent optimality

Theorem (F., Palombaro '17)

Let $\sigma_1 = \mathrm{diag}(1/K, 1/S_1), \sigma_2 = \mathrm{diag}(K, S_2)$ *with* $K > 1$ *and* $S_1, S_2 \in [1/K, K]$. *There exist*

- *coefficients* $\sigma_n \in L^\infty(\Omega; \{\sigma_1; \sigma_2\})$,
- *exponents* $p_n \in \left[1, \frac{2K}{K+1}\right]$,
- *functions* $u_n \in W^{1,1}(\Omega)$ *such that* $u_n(x) = x_1$ *on* $\partial\Omega$,

such that

$$\mathrm{div}(\sigma_n \nabla u_n) = 0\,,$$

$$\nabla u_n \in L^{p_n}_{\mathrm{weak}}(\Omega; \mathbb{R}^2), \quad p_n \to \frac{2K}{K+1}, \quad \nabla u_n \notin L^{\frac{2K}{K+1}}(\Omega; \mathbb{R}^2)\,.$$

F., Palombaro. Calculus of Variations and Partial Differential Equations (2017)

Presentation Plan

1. **Geometric Patterns of Dislocations**
   - Dislocations
   - Semi-coherent interfaces
   - Linearised polycrystals

2. **Microgeometries in Composites**
   - Critical lower integrability
   - Convex integration
   - Proof of our main result

Solving differential inclusions

Theorem (Approximate solutions for two phases)

Let $A, B \in \mathbb{M}^{2\times 2}$, $C := \lambda A + (1-\lambda)B$ *with* $\lambda \in [0,1]$, *and* $\delta > 0$. *Assume that*

$$B - A = a \otimes n \quad \text{for some} \quad a \in \mathbb{R}^2, n \in S^1 . \qquad \text{(Rank-one connection)}$$

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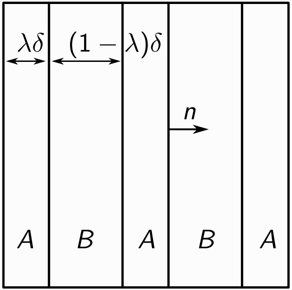
Solutions: built through **simple laminates**



Müller. *Variational models for microstructure and phase transitions.*

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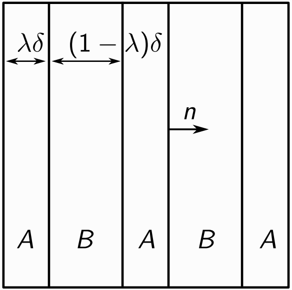

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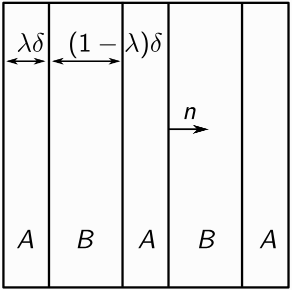

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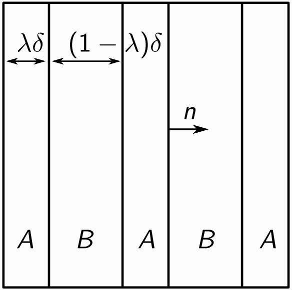

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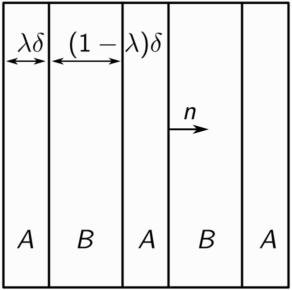
- this allows to recover boundary data C.



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Let $f\colon \Omega \to \mathbb{R}^2$ be Lipschitz. The **gradient distribution** of f is the Radon measure $\nabla f_\#(\mathcal{L}^2_\Omega)$ on $\mathbb{M}^{2\times 2}$ defined by

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- **Integrability** since for $p > 1$ we have

$$\frac{1}{|\Omega|}\int_\Omega |\nabla f_\delta|^p\, dx = \int_{\mathbb{M}^{2\times 2}} |M|^p\, d\nu_\delta(M)\,.$$

Iterating the Proposition

Let $C = \lambda A + (1-\lambda) B$ with $\lambda \in [0,1]$ and $\operatorname{rank}(B - A) = 1$. Let $f \colon \Omega \to \mathbb{R}^2$ such that $f(x) = Cx$ on $\partial\Omega$,

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Proposition (Convex integration)

Let $\nu = \sum_{i=1}^{N} \lambda_i \delta_{A_i}$ be a laminate of finite order, s.t.

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Proposition (Convex integration)

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- $\overline{\nu} = A$,
- $A = \sum_{i=1}^{N} \lambda_i A_i$ *with* $\sum_{i=1}^{N} \lambda_i = 1$.

Fix $\delta > 0$. $\exists$ *a* **piecewise affine Lipschitz** *map* $f : \Omega \to \mathbb{R}^2$ *s.t.* $\nabla f \sim \nu$, *that is,*

- $\operatorname{dist}(\nabla f, \operatorname{supp} \nu) < \delta$ *a.e. in* Ω,
- $f(x) = Ax$ *on* $\partial\Omega$,
- $|\{x \in \Omega : \ |\nabla f(x) - A_i| < \delta\}| = \lambda_i \, |\Omega|$.

Presentation Plan

Strategy of the Proof

Strategy: explicit construction of u_n by **convex integration methods**.

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1. Rewrite the equation $\operatorname{div}(\sigma \nabla u) = 0$ as a differential inclusion

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In this way f solves (2.3) and
$$\nabla f \in L^q_{\mathrm{weak}}(\Omega;\mathbb{R}^2)\,, \;\; q \in \left(\frac{2K}{K+1} - \delta, \frac{2K}{K+1}\right]\,, \qquad \nabla f \notin L^{\frac{2K}{K+1}}(\Omega;\mathbb{R}^2)\,.$$

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These methods were developed for isotropic conductivities $\sigma \in L^\infty(\Omega;\{KI, \frac{1}{K}I\})$.
The adaptation to our case is non-trivial because of the lack of symmetry of the target set T, due to the anisotropy of σ_1 and σ_2.

Astala, Faraco, Székelyhidi. *Convex integration and the L^p theory of elliptic equations.*
Ann. Scuola Norm. Sup. Pisa Cl. Sci. (2008)

Rewriting the PDE as a differential inclusion

Let $K > 1$, $S_1, S_2 \in [1/K, K]$ and define

$$\sigma_1 := \operatorname{diag}(1/K, 1/S_1)\,, \quad \sigma_2 := \operatorname{diag}(K, S_2)\,, \qquad \sigma := \sigma_1 \chi_{E_1} + \sigma_2 \chi_{E_2}\,,$$

$$T_1 := \left\{ \begin{pmatrix} x & -y \\ S_1^{-1}\, y & K^{-1}\, x \end{pmatrix} \,:\, x, y \in \mathbb{R} \right\}, \quad T_2 := \left\{ \begin{pmatrix} x & -y \\ S_2\, y & K\, x \end{pmatrix} \,:\, x, y \in \mathbb{R} \right\}.$$

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Lemma (F., Palombaro '17)

A function $u \in W^{1,1}(\Omega)$ is solution to

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iff there exists $v \in W^{1,1}(\Omega)$ such that $f = (u, v) \colon \Omega \to \mathbb{R}^2$ satisfies

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Moreover $E_1 = \{x \in \Omega \colon \nabla f(x) \in T_1\}$ and $E_2 = \{x \in \Omega \colon \nabla f(x) \in T_2\}$.

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Key Remark: u and f enjoy the **same** integrability properties.

Targets in conformal coordinates

Conformal coordinates: Let $A \in \mathbb{M}^{2\times 2}$. Then $A = (a_+, a_-)$ for $a_+, a_- \in \mathbb{C}$, defined by

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$$T_1 = \{(a, d_1(\overline{a})) \ :\ a \in \mathbb{C}\}\,, \qquad T_2 = \{(a, -d_2(\overline{a})) \ :\ a \in \mathbb{C}\}\,,$$

where the operators $d_j \colon \mathbb{C} \to \mathbb{C}$ are defined as

$$d_j(a) := k \operatorname{Re} a + i\, s_j \operatorname{Im} a\,, \quad \text{with} \quad k := \frac{K-1}{K+1} \quad \text{and} \quad s_j := \frac{S_j - 1}{S_j + 1}\,.$$

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Let $\theta \in [0, 2\pi]$, $JR_\theta = (0, e^{i\theta})$.

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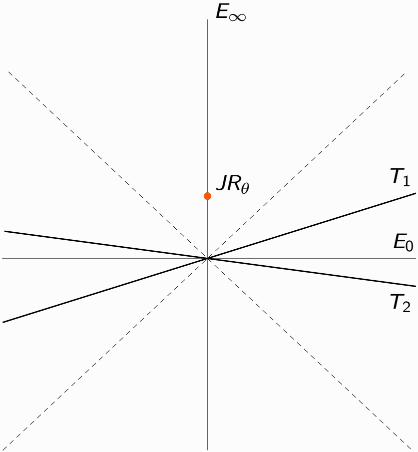

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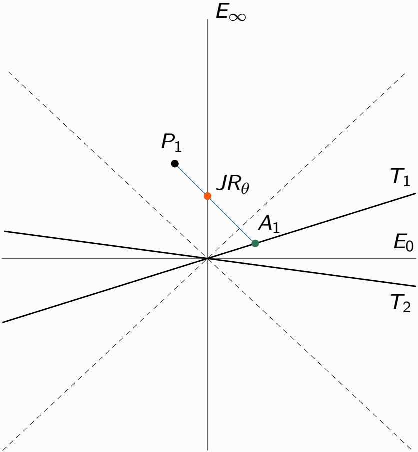

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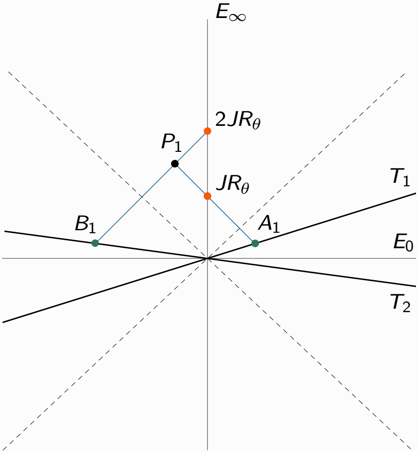

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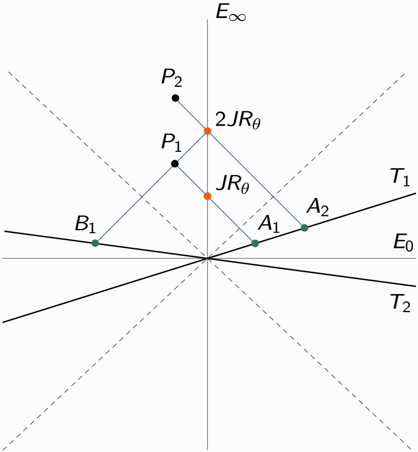

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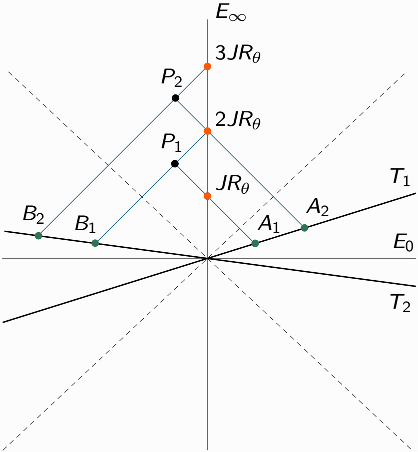

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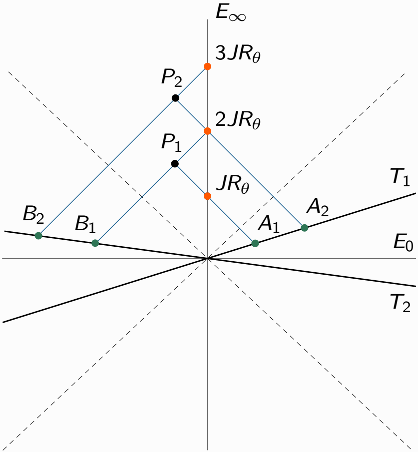

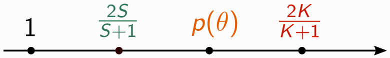

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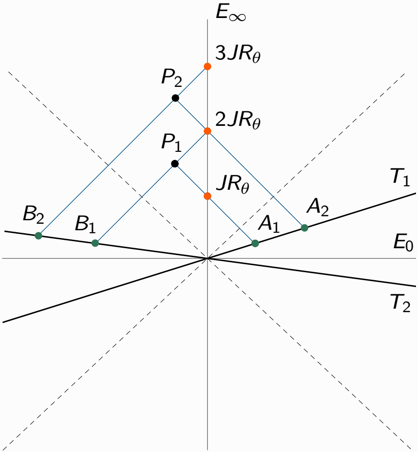

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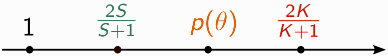

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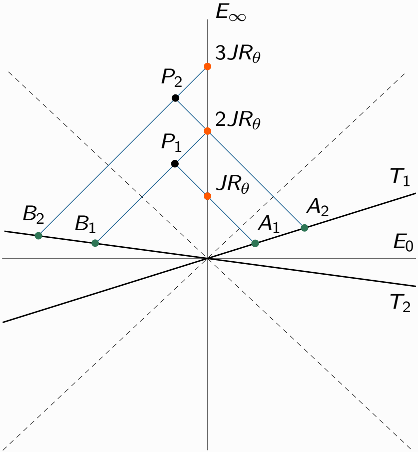

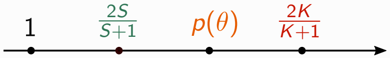

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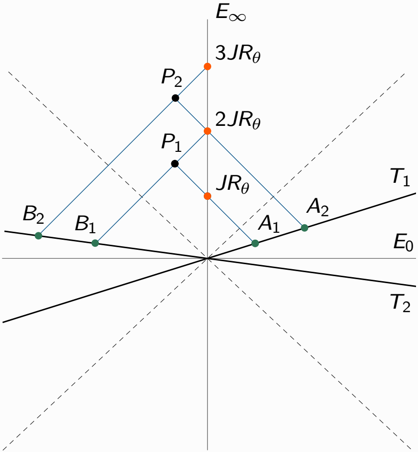

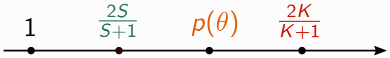

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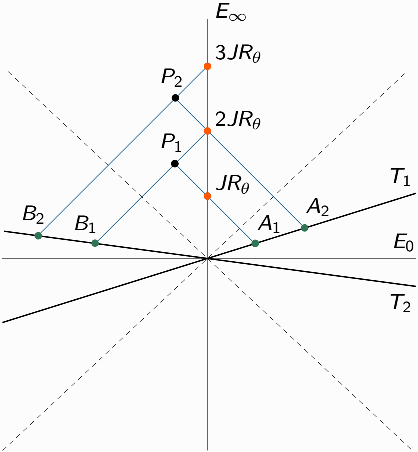

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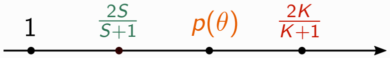

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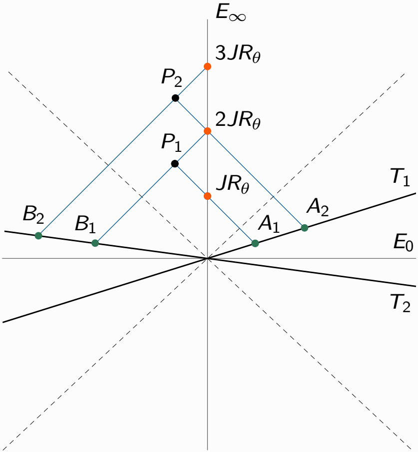

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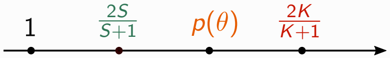
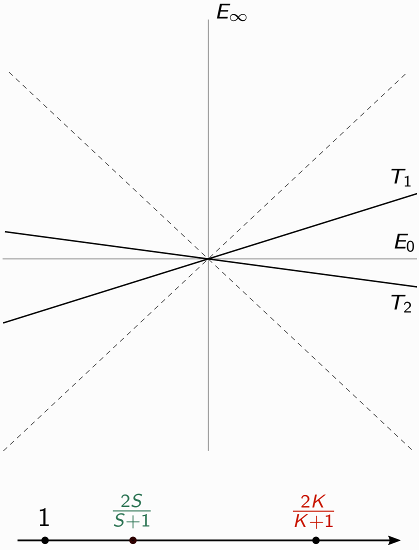


Remark: barycentre J gives the right growth.

Constructing approximate solutions

We want to construct $f : \Omega \to \mathbb{R}^2$ such that



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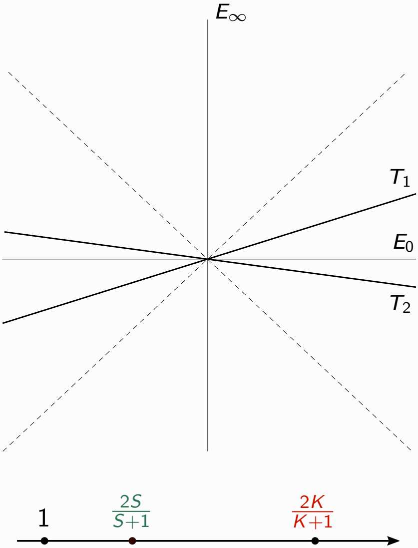

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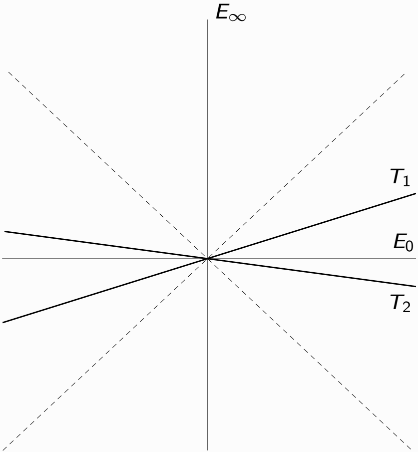

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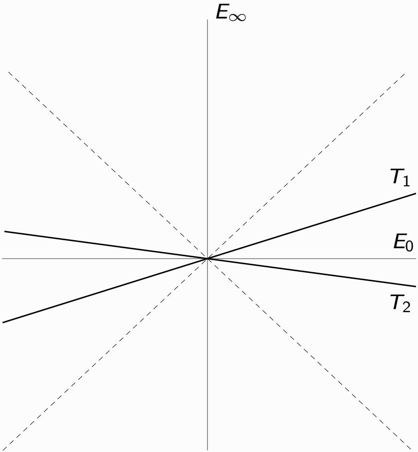

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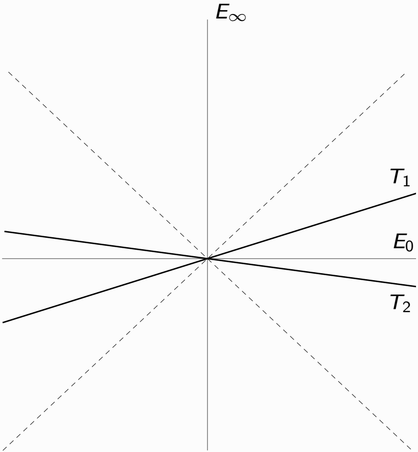

Constructing approximate solutions

We want to construct $f : \Omega \to \mathbb{R}^2$ such that

- $\operatorname{dist}(\nabla f, T_1 \cup T_2) < \varepsilon$ a.e. in Ω,
- $f = Jx$ on $\partial\Omega$,
- $\nabla f \in L^q_{\text{weak}}$, $q \in I_\delta := \left(\frac{2K}{K+1} - \delta, \frac{2K}{K+1} \right]$,
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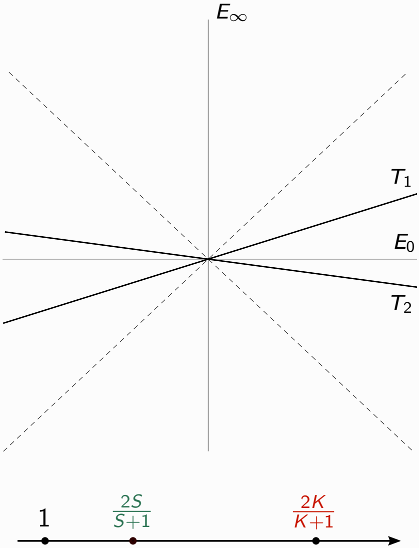
Idea: alternate one step of the staircase laminate with the convex integration Proposition.



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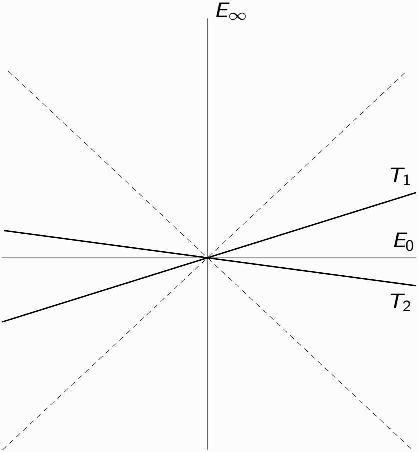

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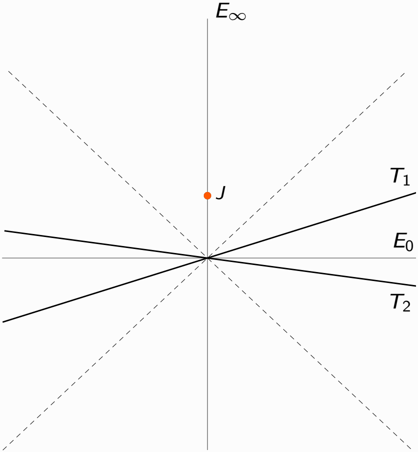

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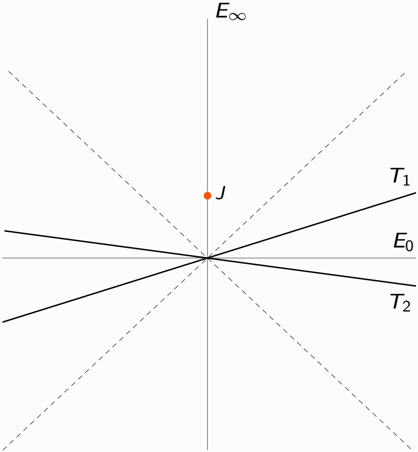

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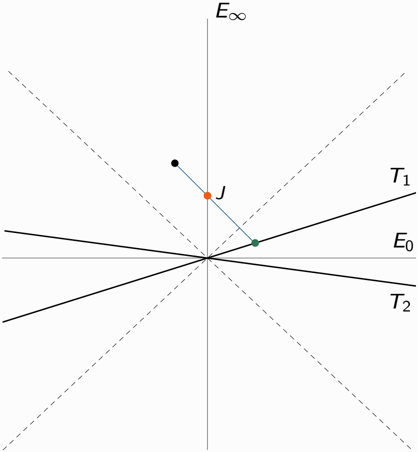

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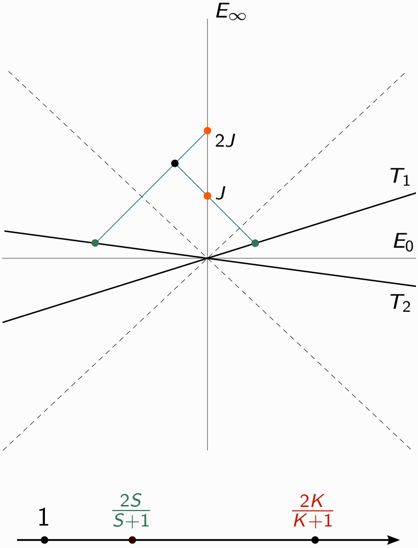

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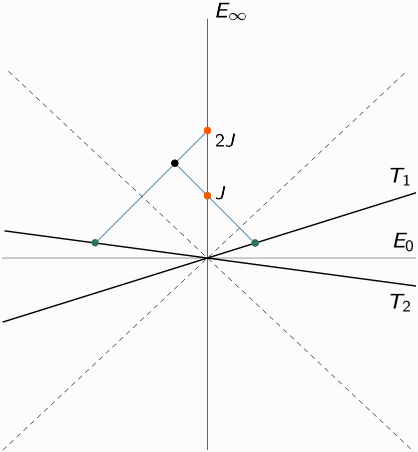
This determines the exponent range I_δ



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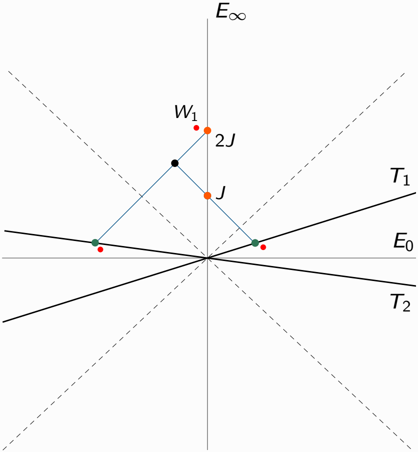

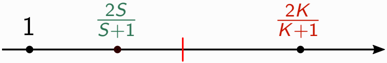

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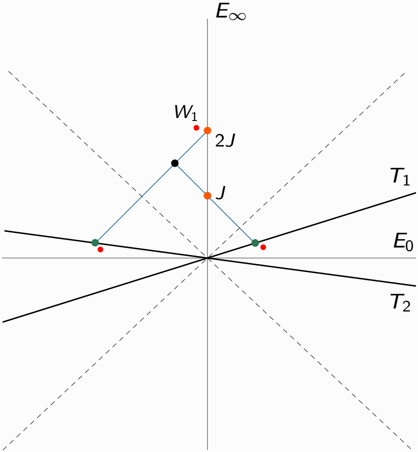

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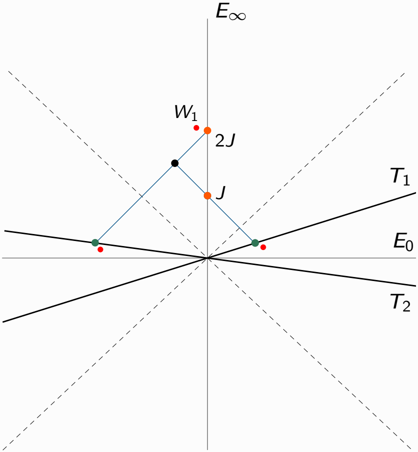

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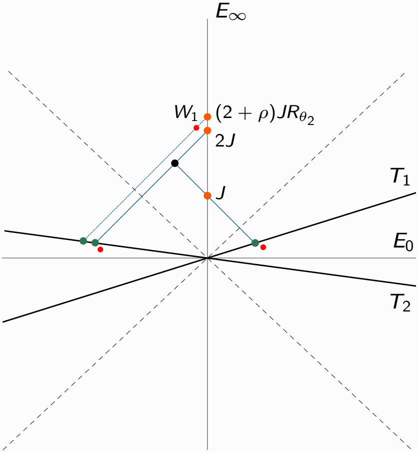

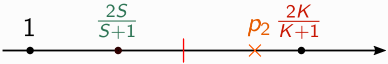

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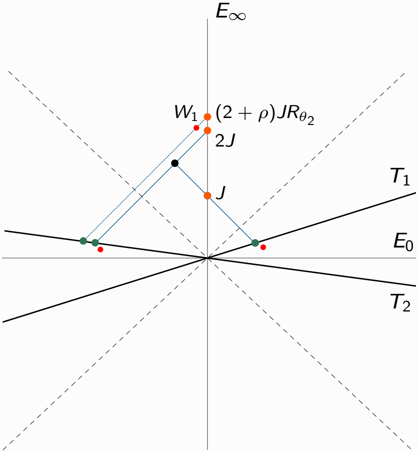

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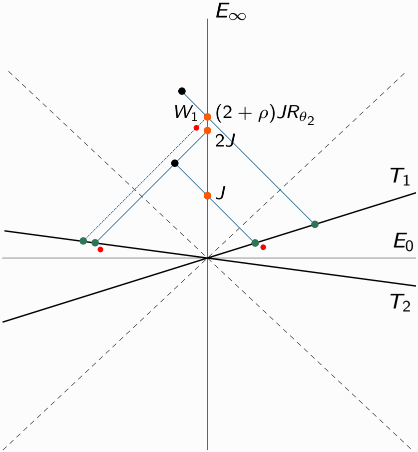

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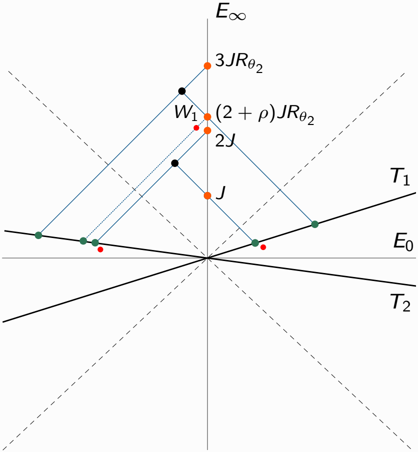

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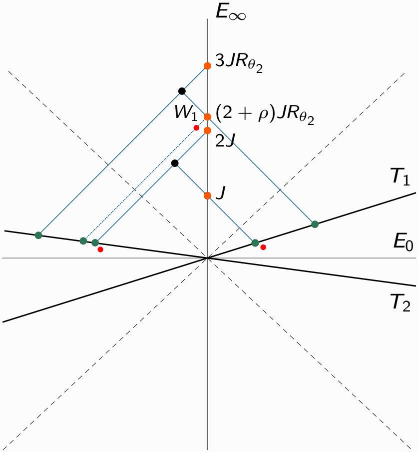

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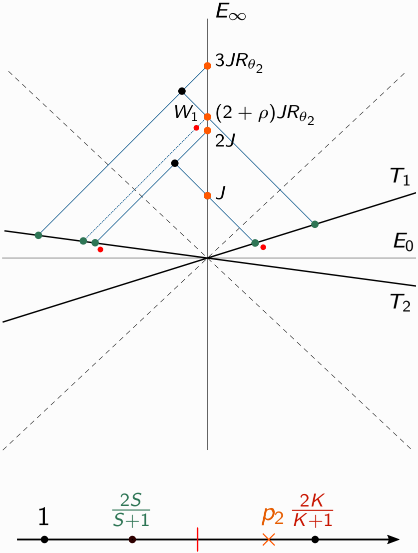

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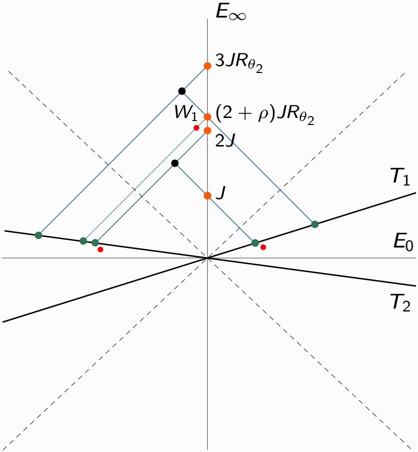

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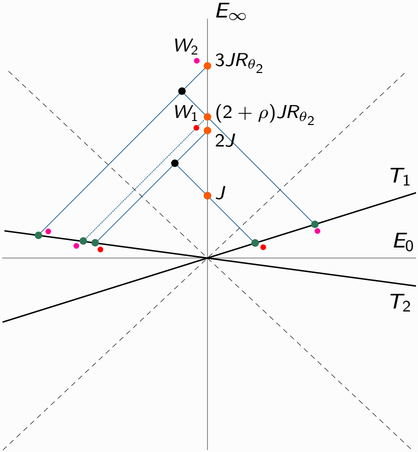

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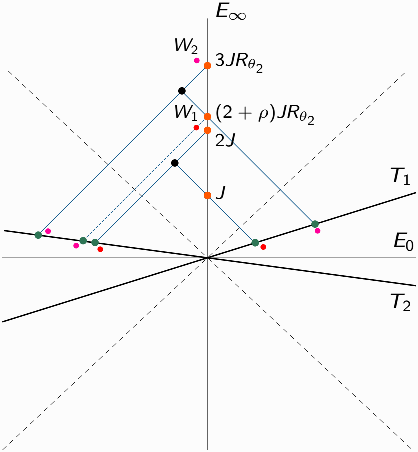

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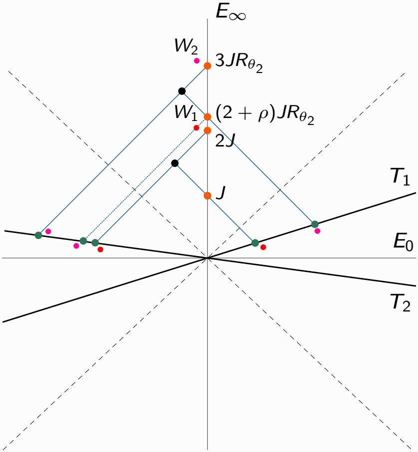

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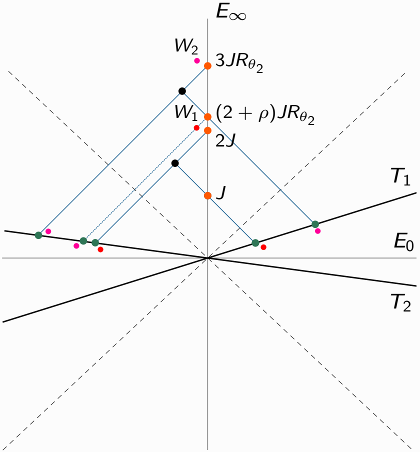

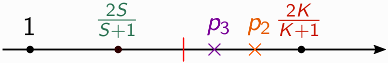

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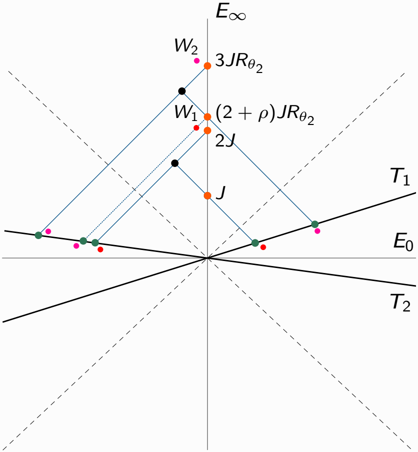
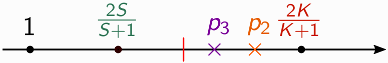
- Proposition $\implies \exists$ map g s.t. $g = W_1x$ on $\partial\Omega$ and $\nabla g \sim \operatorname{supp}\nu_2 \implies \nabla g$ grows like p_2
- Set $f_3 := g$ in the set $\{\nabla f_2 \sim W_1\}$ and $f_3 := f_2$ otherwise $\implies \nabla f_3$ grows like p_2

Step 1. Split $W_2 \rightsquigarrow$ Laminate ν_3 with growth $p_3 \in I_\delta$

Iterating: $\rightsquigarrow f_n$ obtained by successive modifications on nested sets going to zero in measure $\implies f_n \to f$





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when $\sigma \in \{\sigma_1, \sigma_2\}$ for $\sigma_1, \sigma_2 \in \mathbb{M}^{2\times 2}$ elliptic.

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- Stronger result for lower critical exponent: showing $\exists\ u \in W^{1,1}(\Omega)$ solution to (2.4) and s.t. $\nabla u \in L^{\frac{2K}{K+1}}_{\mathrm{weak}}(\Omega;\mathbb{R}^2)$ but $\nabla u \notin L^{\frac{2K}{K+1}}(B;\mathbb{R}^2)$, $\forall$ ball $B \subset \Omega$.
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- Extend these results to three-phase conductivities $\sigma \in \{\sigma_1, \sigma_2, \sigma_3\}$.
- Dimension $d \geq 3$? Even only in the isotropic case $\sigma \in \{KI, K^{-1}I\}$ for $K > 1$.
  Main difficulty: Astala's Theorem is missing in higher dimensions.


Thank You!