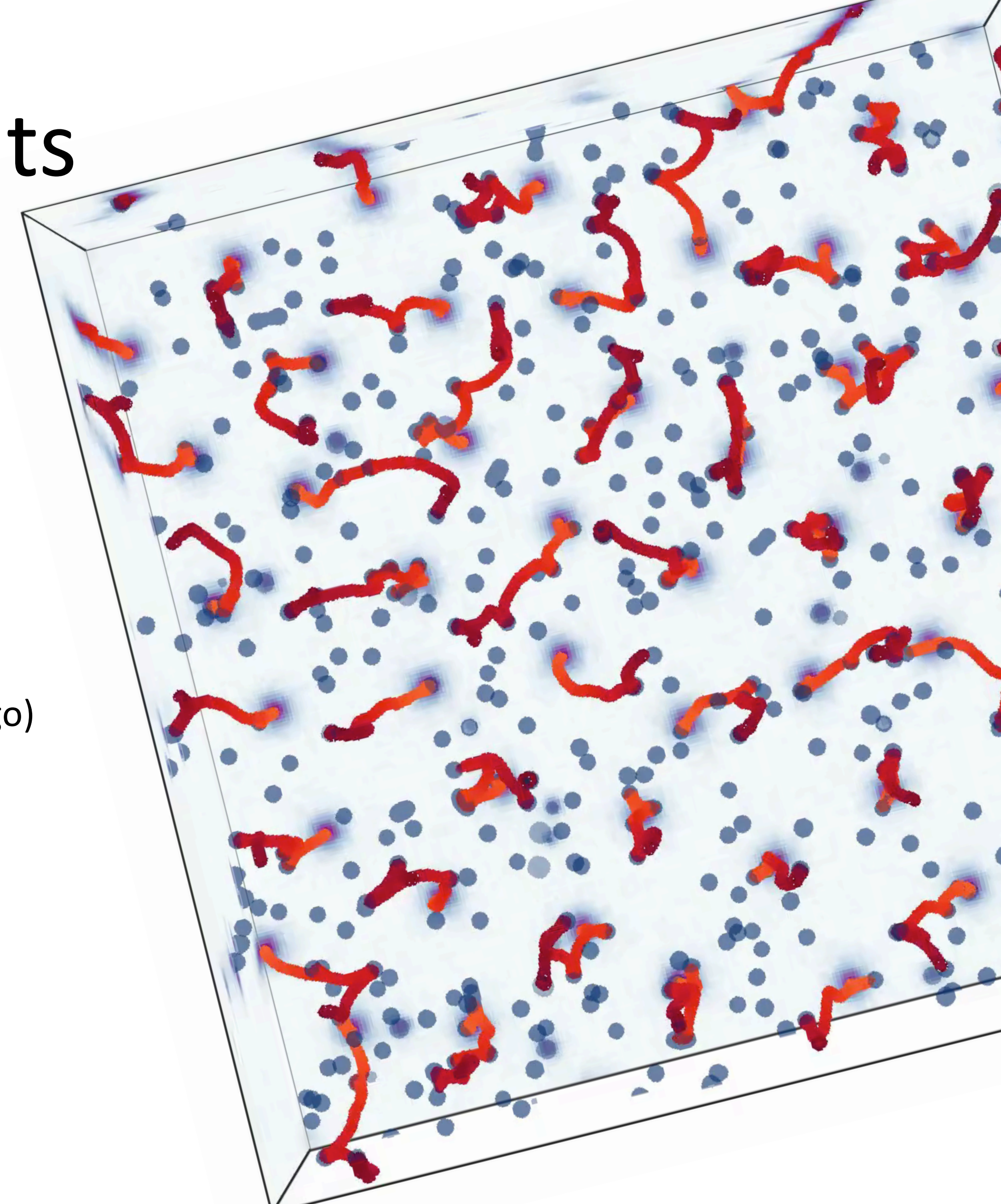
# Theoretical insights on pinning

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oscon-scidac.org

TTC Topical Workshop, Fermilab, 2017

# Outline

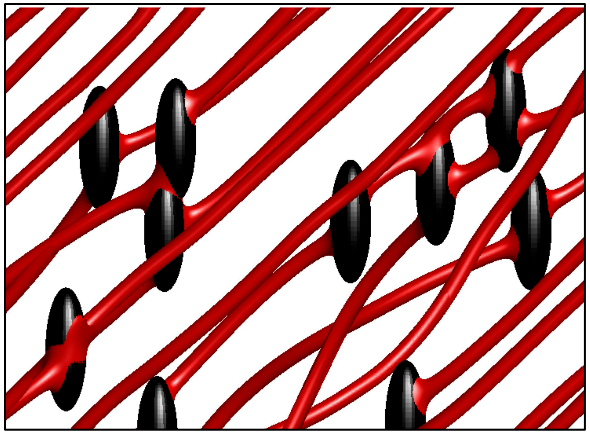
- Time-dependent Ginzburg-Landau approach
  - Large-scale solver and other numerical tools
  - Capabilities
  - Limitations
- Vortex pinning
  - Sizes of the defects
  - Shapes of the defects
- Preliminary simulations of SRF cavities
- Route towards quantitate description of SRF cavities

Pinning studies → Critical current enhancement

Pinning studies → SRF *Q*-factor enhancement

# Numerical tools

## Ginzburg-Landau solver

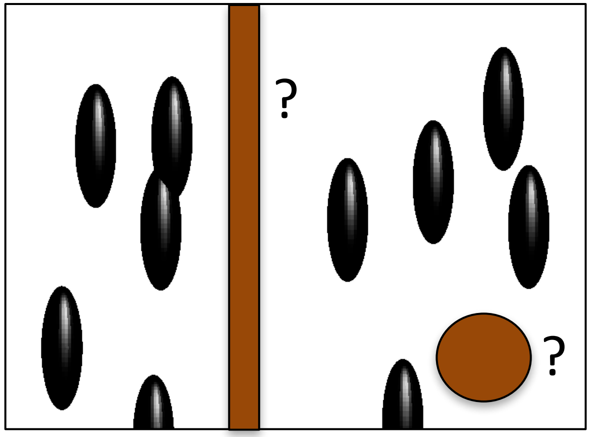


Input: Pinning landscape

*Solves time-dependent Ginzburg-Landau equations. C++/CUDA*

Output: $\psi(\mathbf{r},t)$

## Pinning optimizer

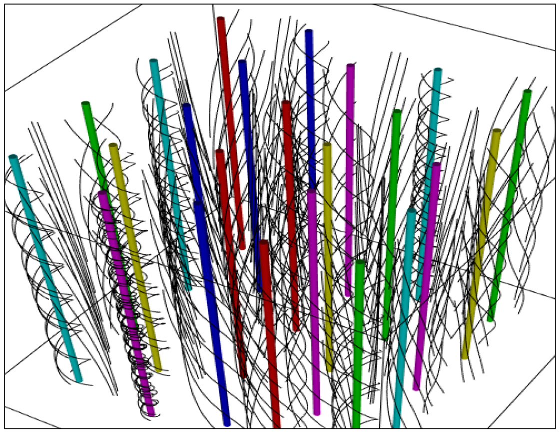



Input: Type of pinning landscape

*Looks for pinning landscape parameters to minimize objective function (e.g., dissipation level). Python*

Output: optimal pinning parameters

## Vortex detector



Input: $\psi(\mathbf{r})$

*Detects and tracks positions of vortices. Python/C++*

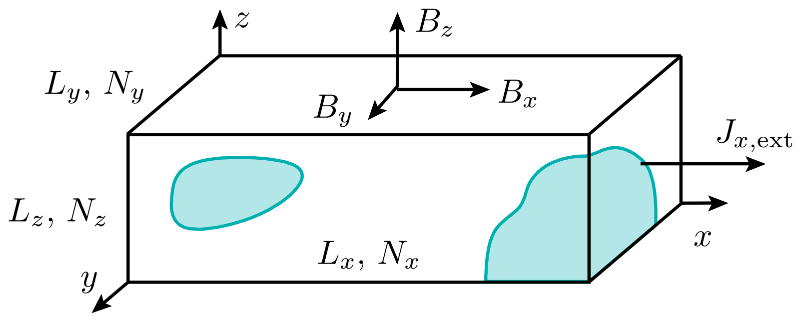
Output: Vortex line positions

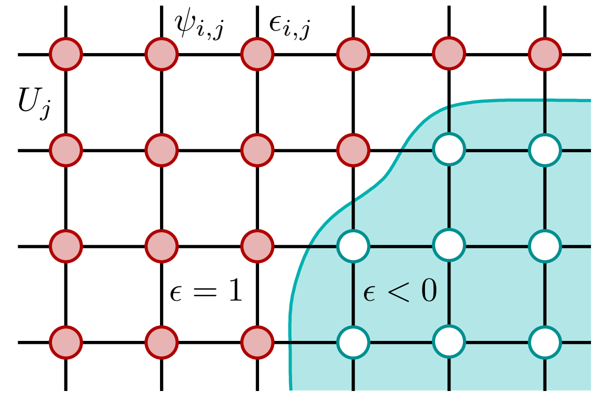
# TDGL solver

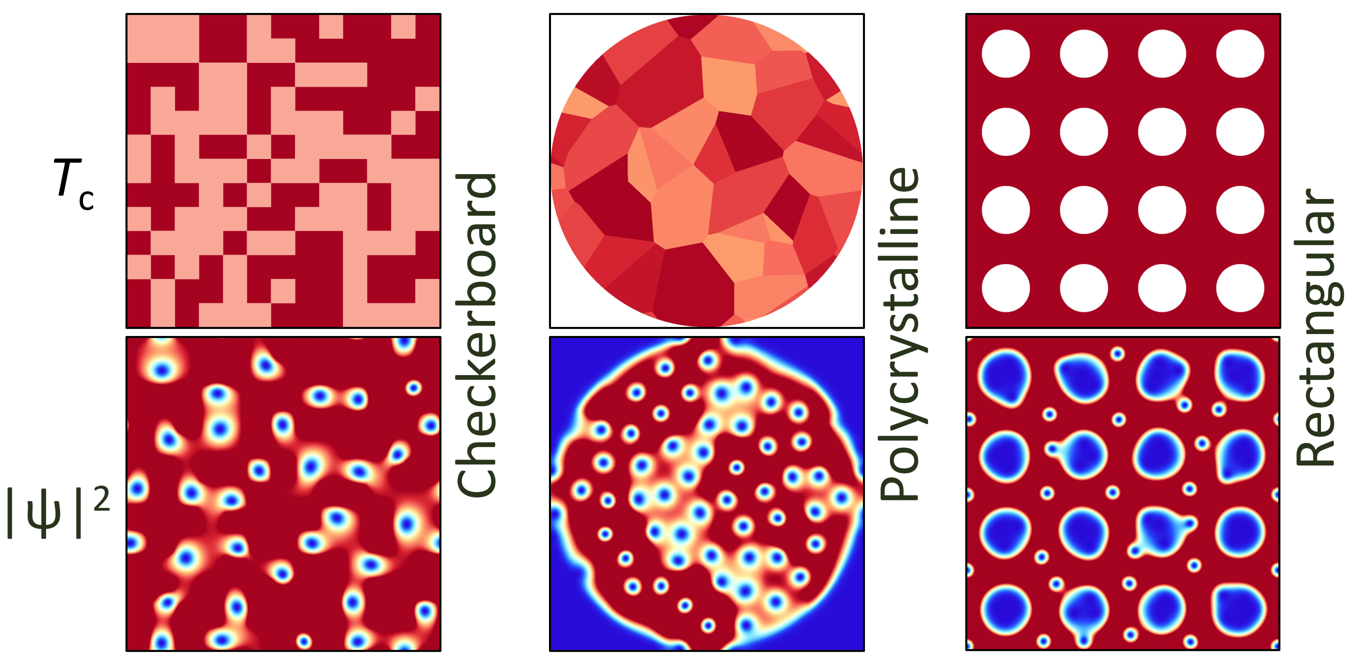
Time-dependent Ginzburg-Landau equation

$$u(\partial_t + i\mu)\psi = \epsilon(\mathbf{r})\psi - |\psi|^2\psi + (\nabla - i\mathbf{A})^2\,\psi + \zeta(\mathbf{r},t)$$

- ✓ GP GPU implementation
- ✓ 2D & <u>3D</u>
- ✓ Up to $690^3$ grid points in 3D




Inclusions are modeled by critical temperature $T_c(\mathbf{r})$ modulation – *arbitrary* pinning landscape

Sadovskyy *et al.*, J. Comp. Phys. (2015)

# Pinning optimizer

The routine maximizes/minimizes some noisy objective function (it can be critical current, dissipation level, etc) by varying parameters of the pinning landscape of a given type.

Each objective function evaluation takes from 30 minutes to 12 hours for a given pinning configuration.

*Local* optimization methods

- (Adaptive) coordinate descent
- Nelder-Mead

*Global* optimization methods

- Covariance matrix adaptation evolution strategy
- Particle swarm optimization

Titan @ Oak Ridge LCF

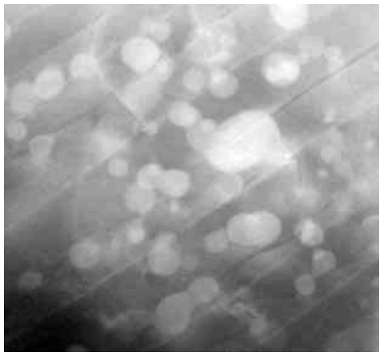

Cooley @ Argonne LCF


GAEA @ NIU

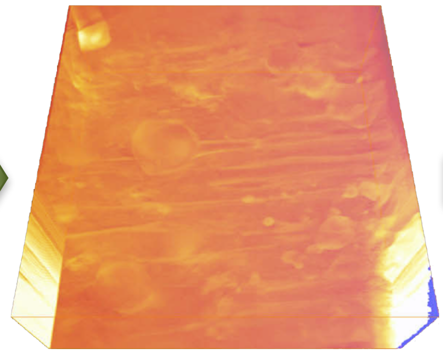
Kimmel, *et al*, 2017

# Experiment: Dy particles in YBCO

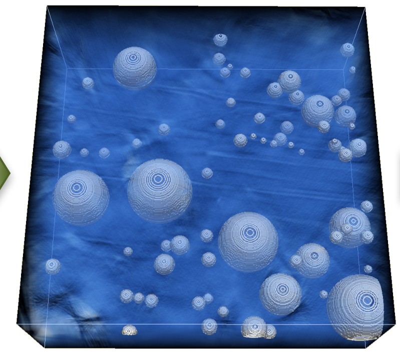
Actual positions and sizes of (almost) spherical Dy defects in $YBa_2Cu_3O_{7-\delta}$ were used in time-dependent Ginzburg-Landau simulations



2D STEM image at different angles

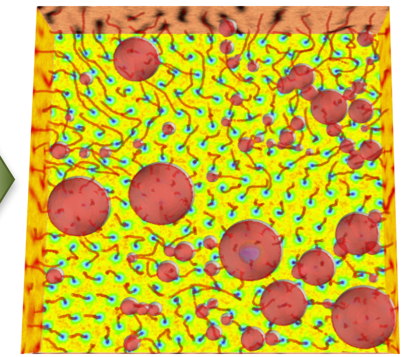


3D tomogram



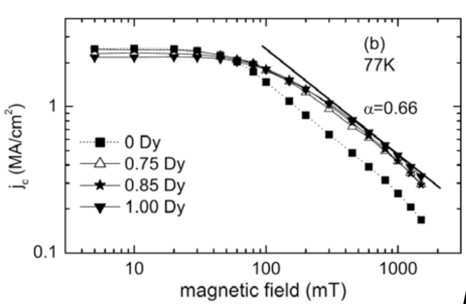
Reconstructed landscape

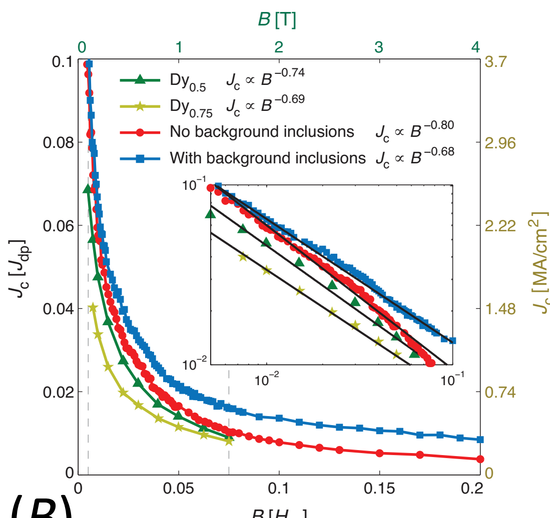
Ortalan, *et al.*, Phys. C (2009)



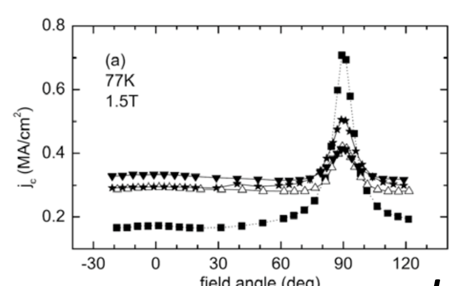
Simulated $J_c$

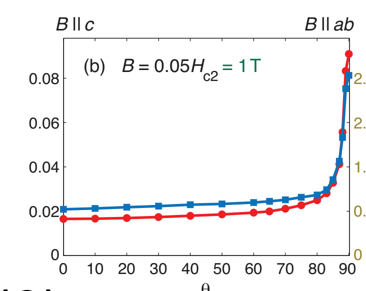
Sadovskyy, *et al.*, Phys. Rev. Applied (2016)




$J_c(B)$

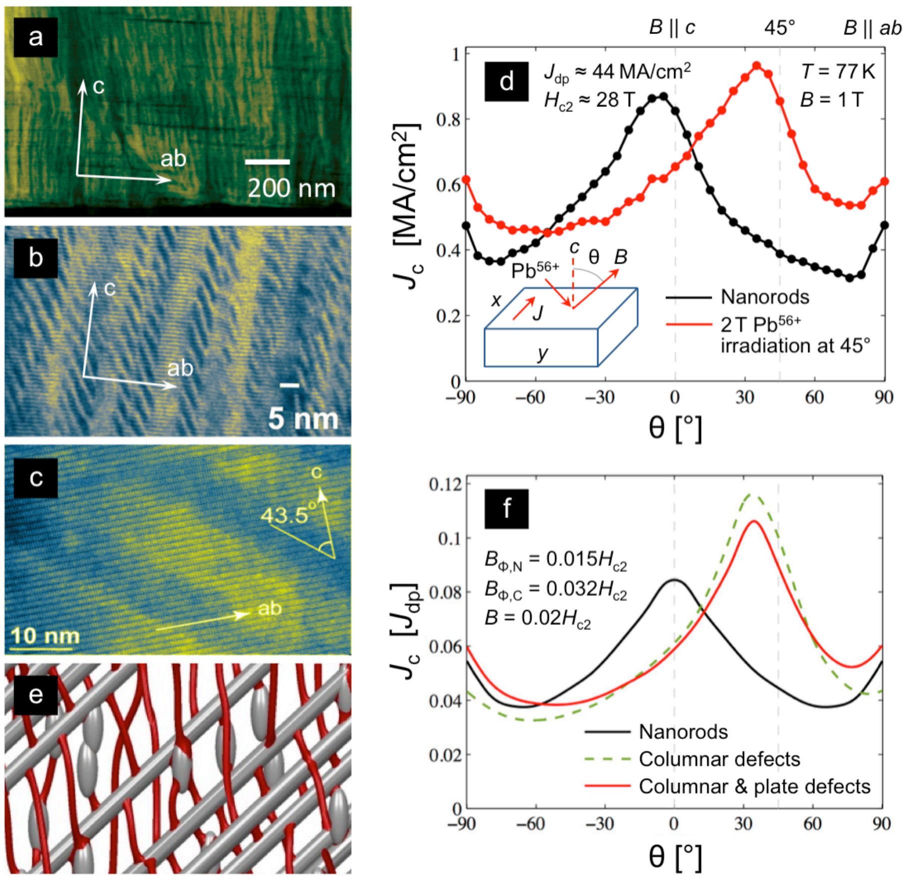


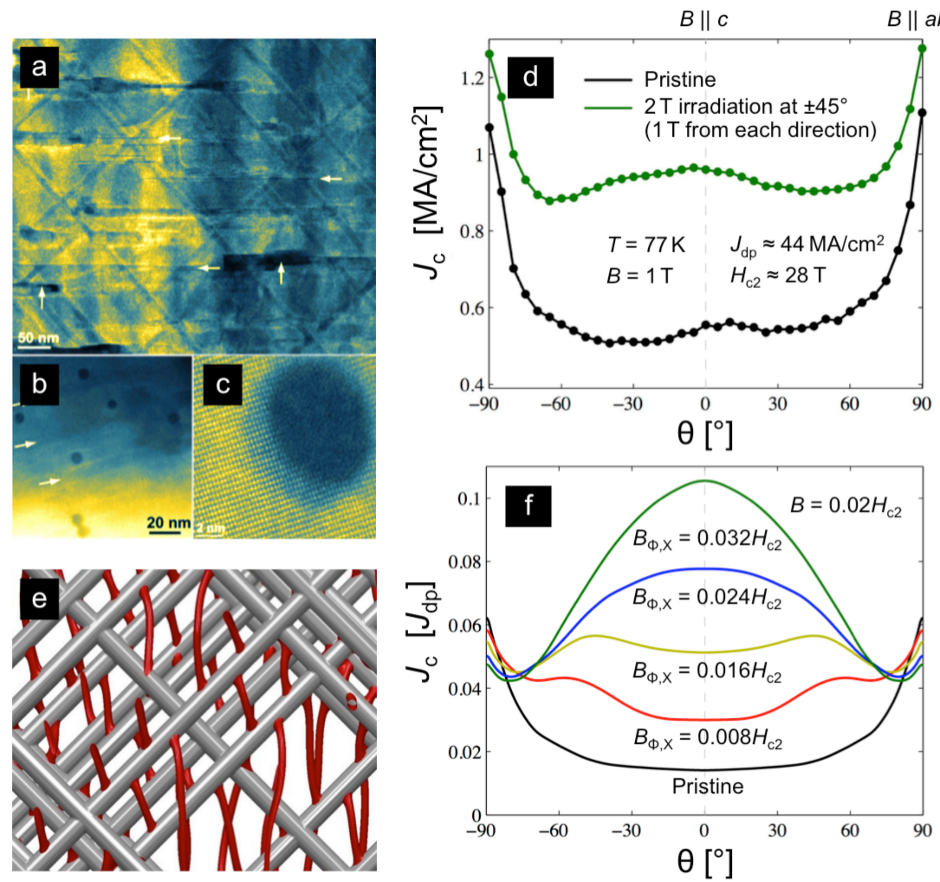

$J_c(\theta)$

# Experiment: Irradiated defects

Sample with pre-existing nanorods||*c* was irradiated by heavy ions at 45° to *c*-axis




Pristine sample was irradiated by heavy ions at ±45° to *c*-axis




Sadovskyy, *et al*, Adv. Mater. (2016)

# TDGL limitations

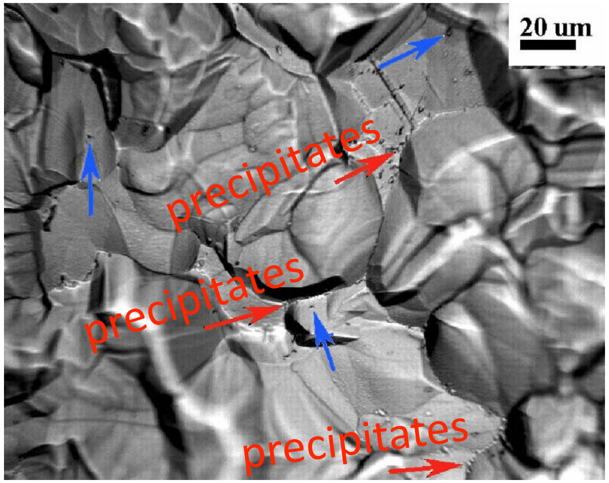

Time-dependent Ginzburg-Landau model has significant limitations

- It is capable for $T$ close to $T_c$ only
- TDGL model describes steady state, rather than non-equilibrium state
- Heating effects are not considered

Results might be translated to low temperature regime with caution

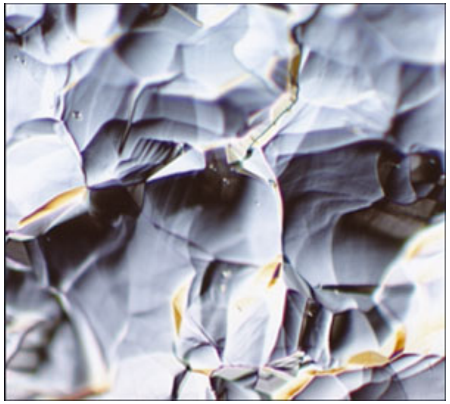
# Defects in niobium

## Surface defects

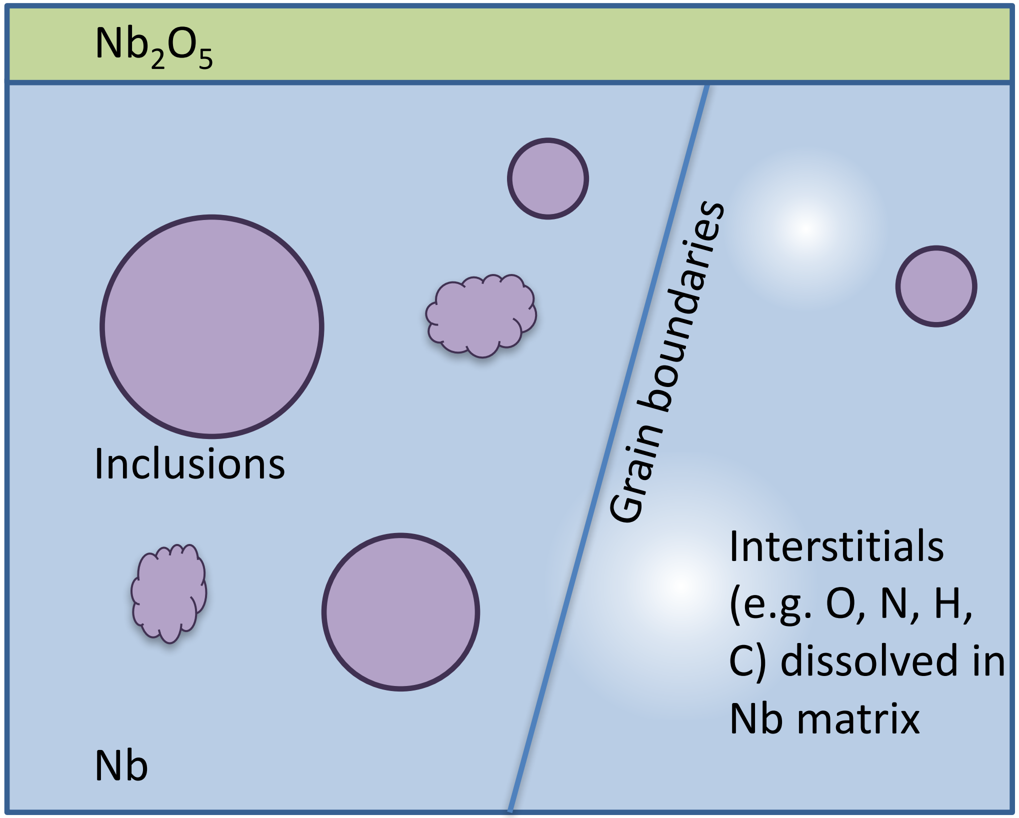



Delayen, *el al*, 2001

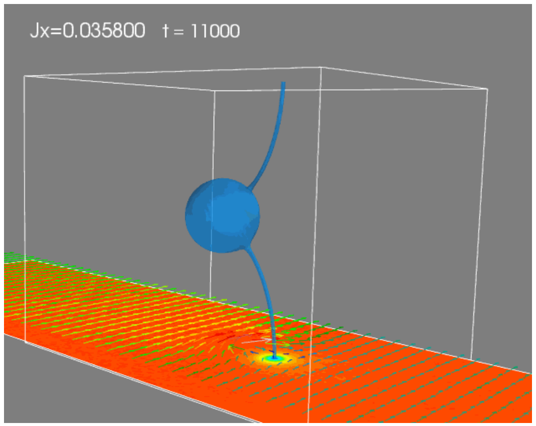
DESY

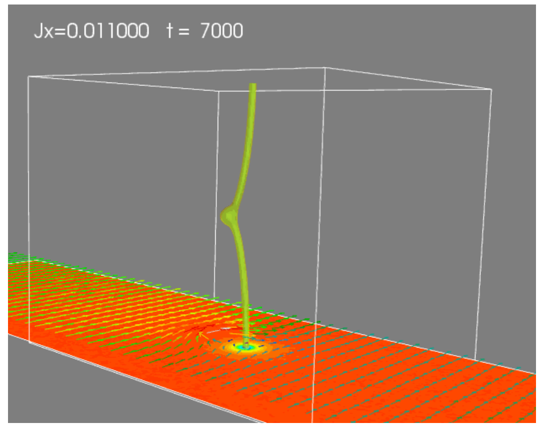


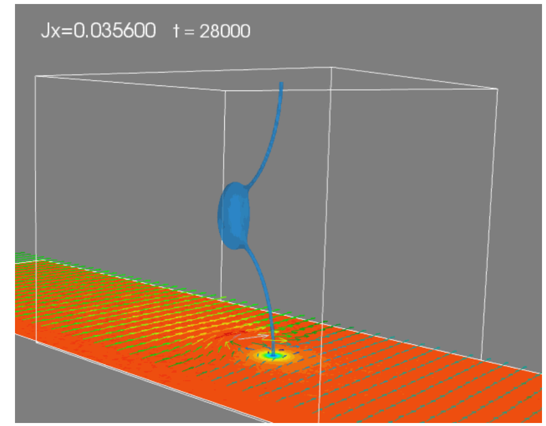
## Bulk defects



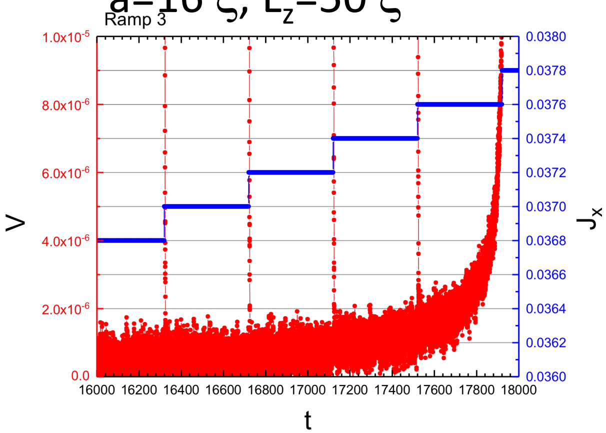
# Depinning from isolated particle



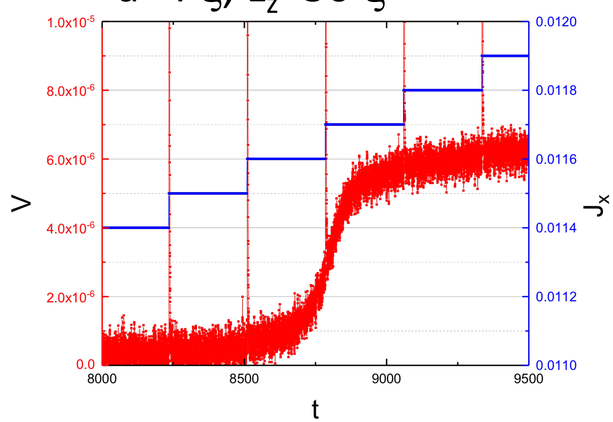



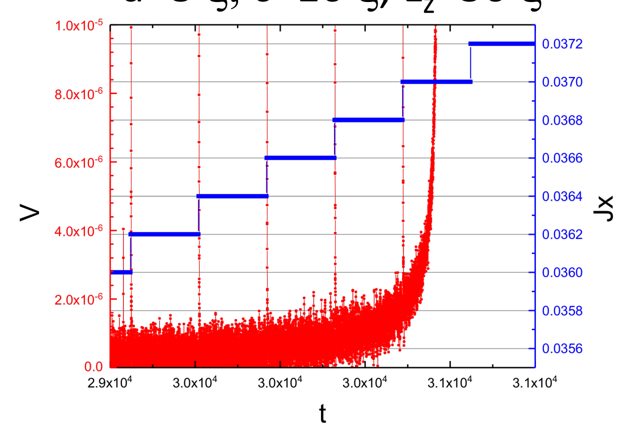

$a=16\ \xi,\ L_z=50\ \xi$




$a=4\ \xi,\ L_z=50\ \xi$

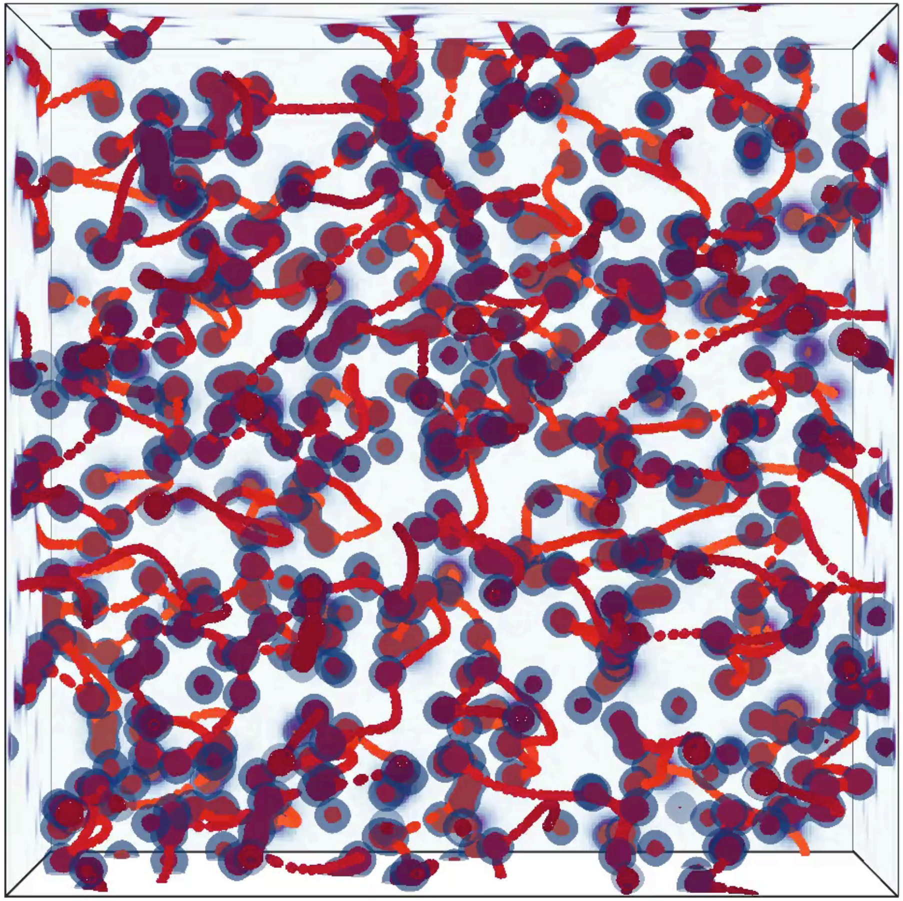



$a=8\ \xi,\ c=16\ \xi,\ L_z=50\ \xi$




- System response to the applied (DC or AC) external current and magnetic field
- Pinning force of the inclusion having given shape and size

# Defect sizes for strongest pining

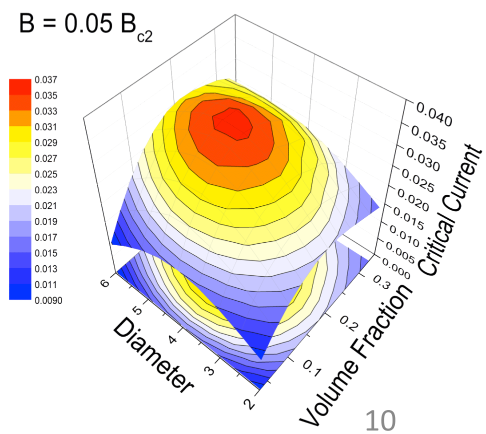


Uncorrelated spherical defects

Ginzburg-Landau simulations for strong type-II superconductor

Koshelev, *et al*, 2016

Critical current density (or pinning force density) at a given magnetic filed has a maximum as a function of defect diameter and defect density

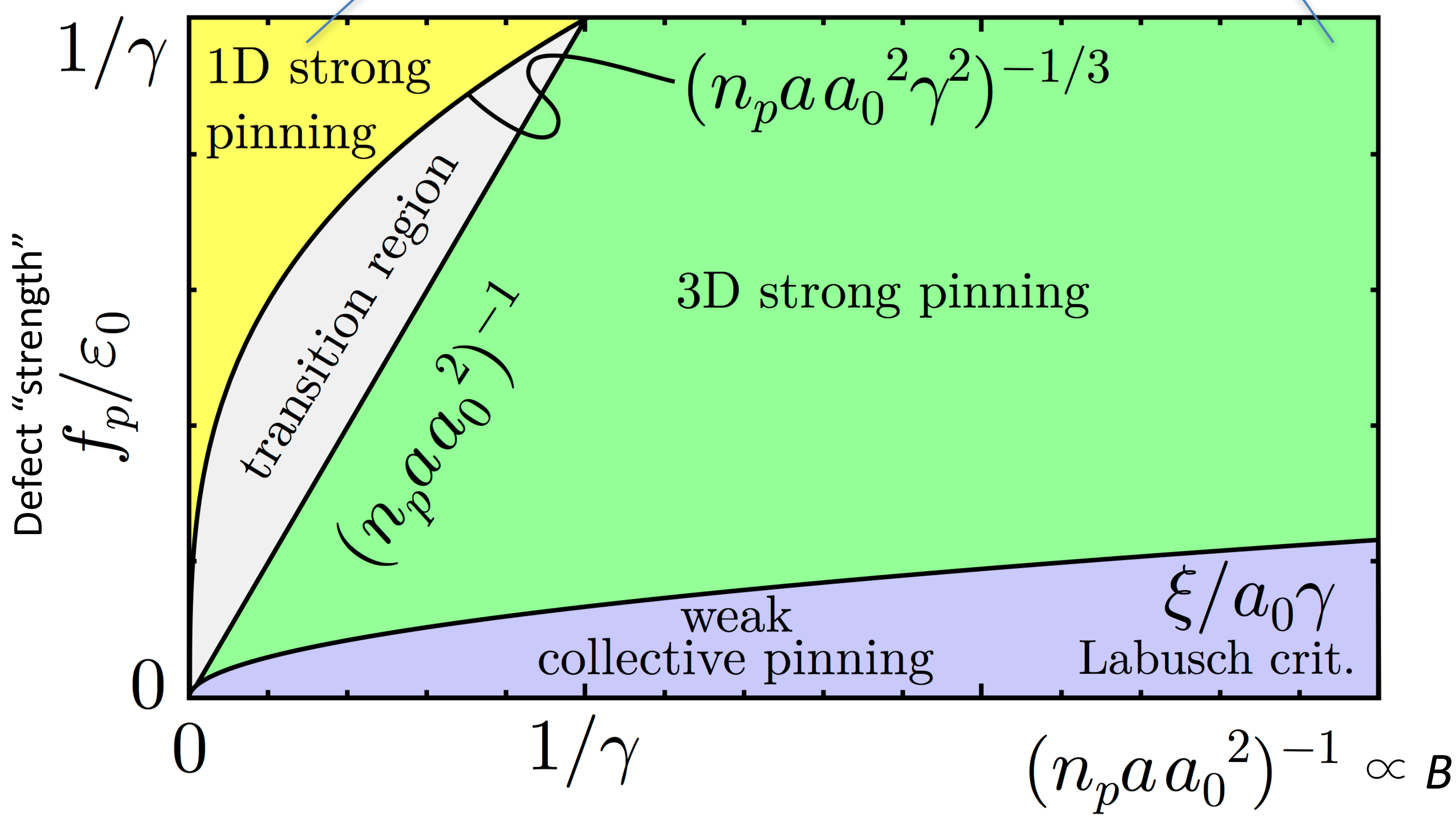



Diameter for highest vortex pinning,
$d_{opt}$ = 3–4 ξ(*T*)

# Pining regimes

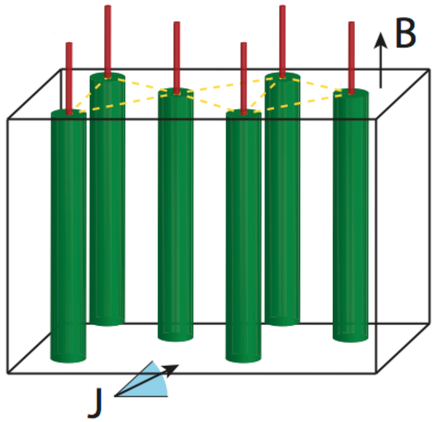
Low vortex density, weak vortex-vortex interaction

Weekly deformed Abrikosov lattice



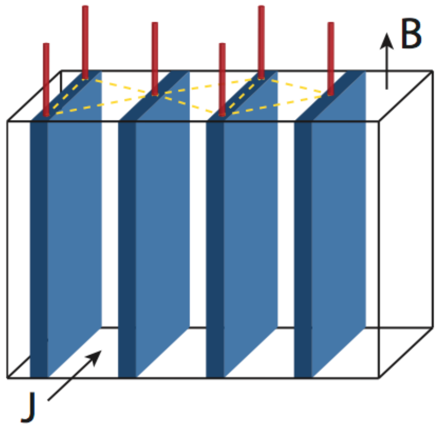

Willa, *et al*, 2017

# Defect sizes for strongest pining




Columnar-shaped defects:
optimal diameter, $D_{opt}$ = 2–3 ξ($T$)

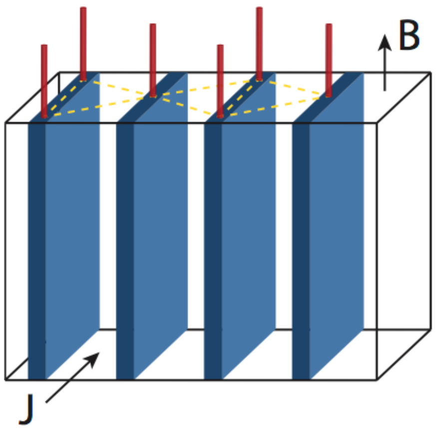
Kimmel, *et al*, 2017




Wall-shaped defects (strongest!):
optimal wall thickness, $b_{opt}$ = 0.5–1 ξ(T)

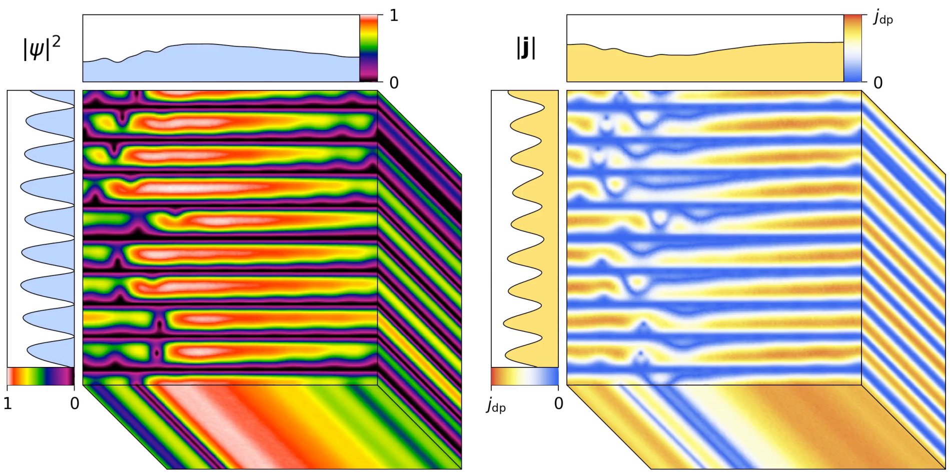
Sadovskyy, *et al*, in preparation

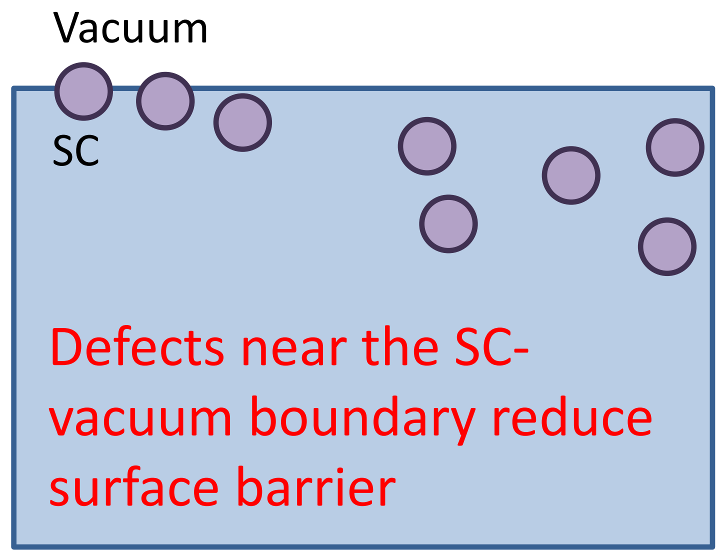
# Surface barrier




Ideal wall-shaped defects have the strongest pinning capabilities

SC-vacuum boundary can be considered as a strong pinning center

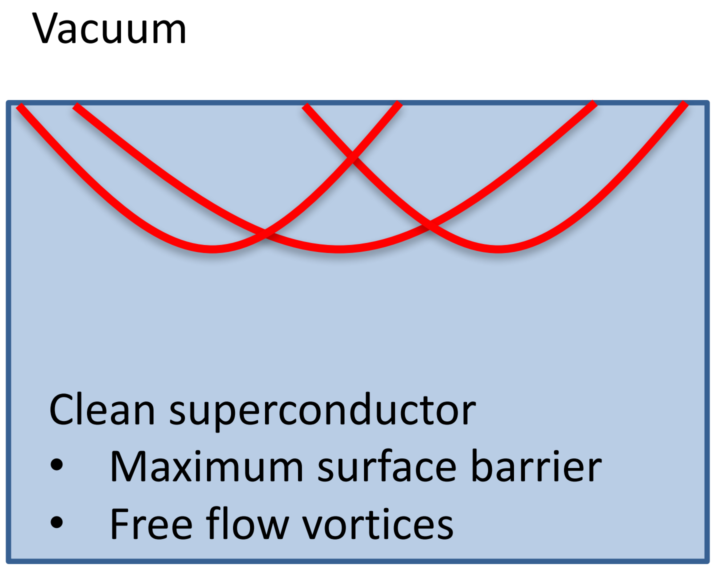


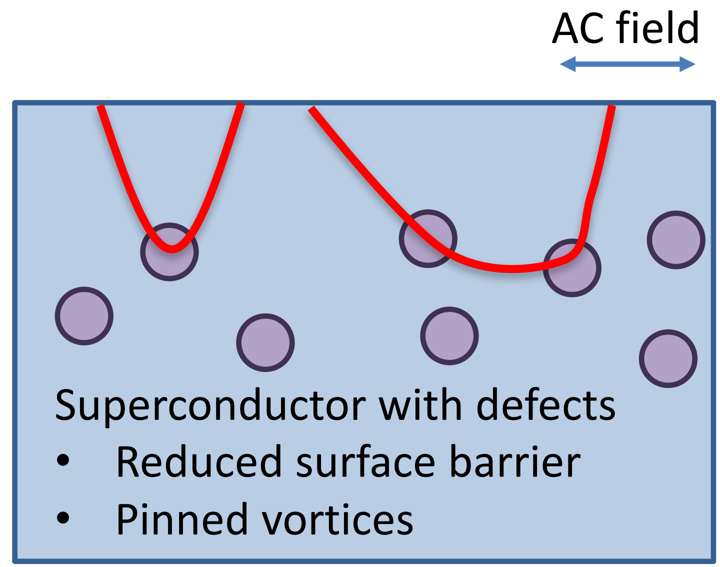




Sadovskyy, *et al*, in preparation

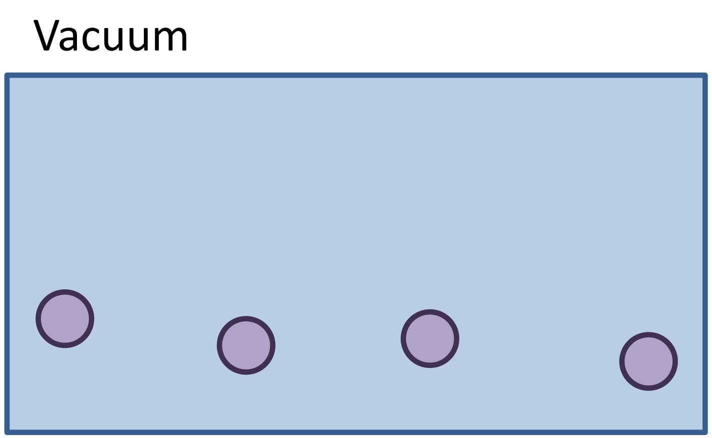
Kimmel, *et al*, in preparation

# Vortices captured by defects



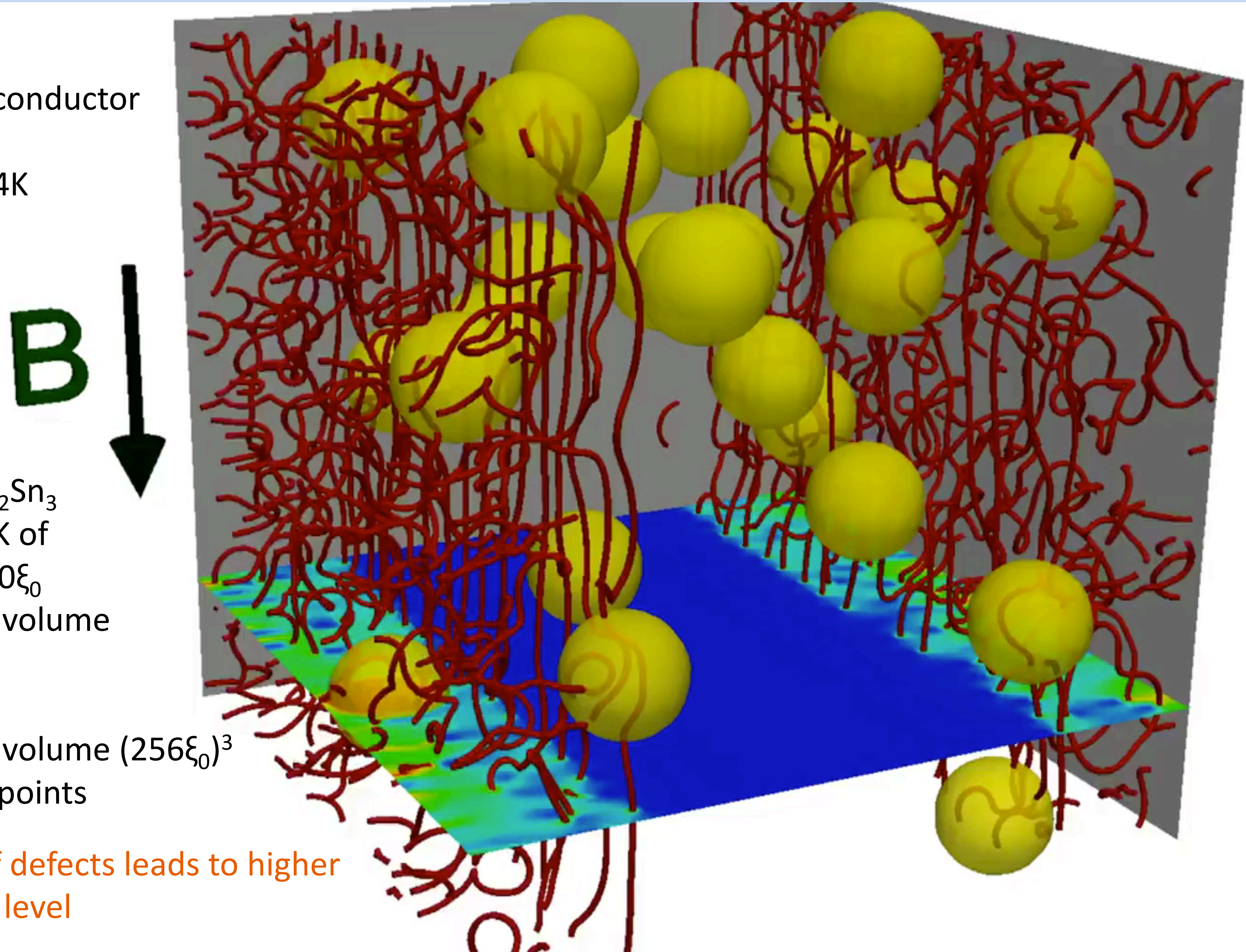

Defects near SC surface can capture vortices




Optimum?

# Simulations in parallel AC fields

Bulk superconductor
$Nb_3Sn_2$
with $T_c$ = 14K

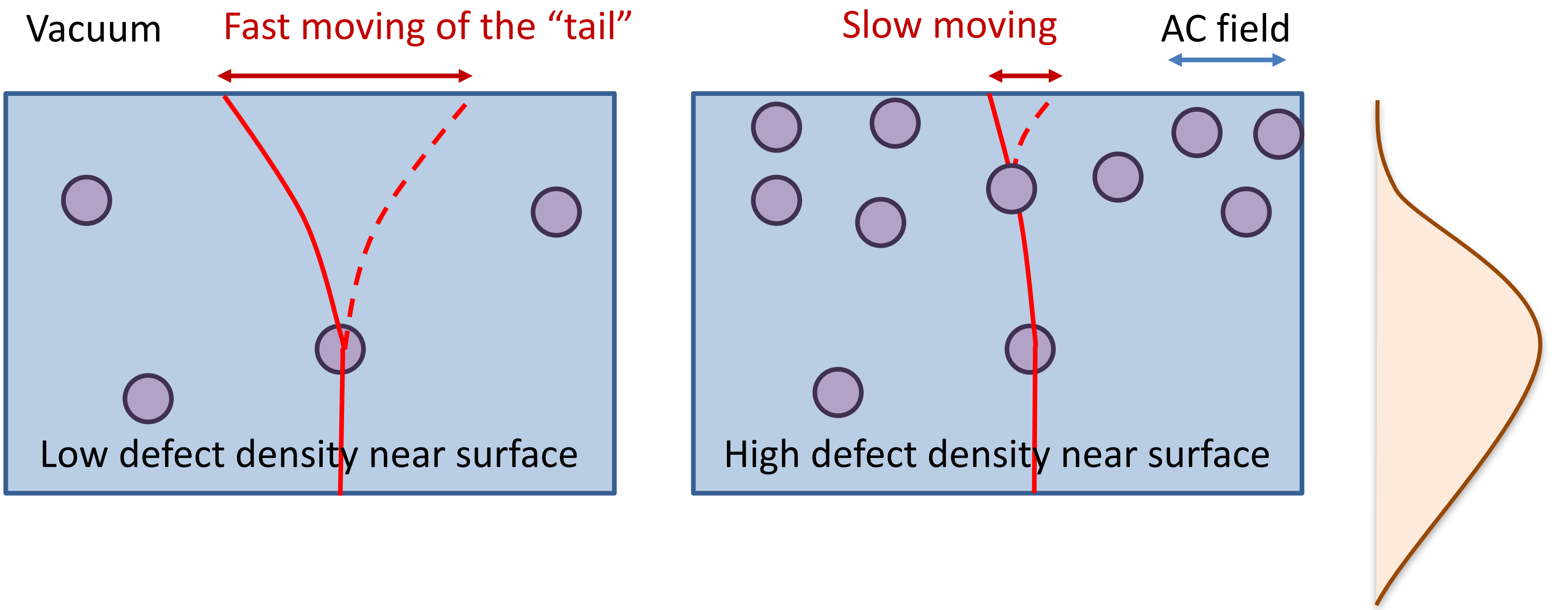



Defects $Nb_2Sn_3$
with $T_c$ = 6K of
diameter $40\xi_0$
occupy 5% volume
fraction

Simulation volume $(256\xi_0)^3$
140M grid points

Addition of defects leads to higher dissipation level

# Frozen vortices

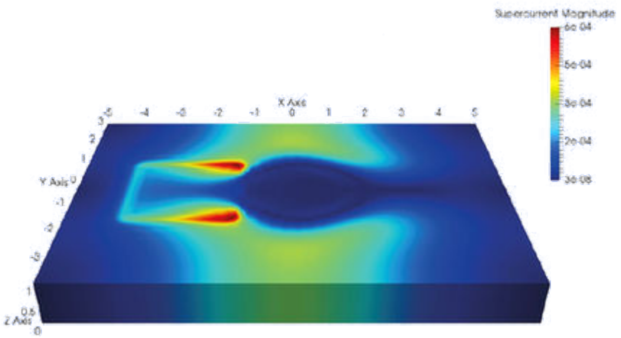



Optimal distribution of the defects density and sizes

# Route towards SRF cavities simulation

TDGL can describe vortex dynamics qualitatively, not quantitavely

1. Replacement of the TDGL equation by Usadel/Eilenberger or Bogoliubov–de Gennes equation
   - ➢ Quantitative description of vortex matter in SRF cavities



2. Heat transfer equation [Poisson equation]
   - ➢ Overheating for vortex avalanches