Introduction to Magnetic Flux Expulsion in Bulk Niobium Cavities

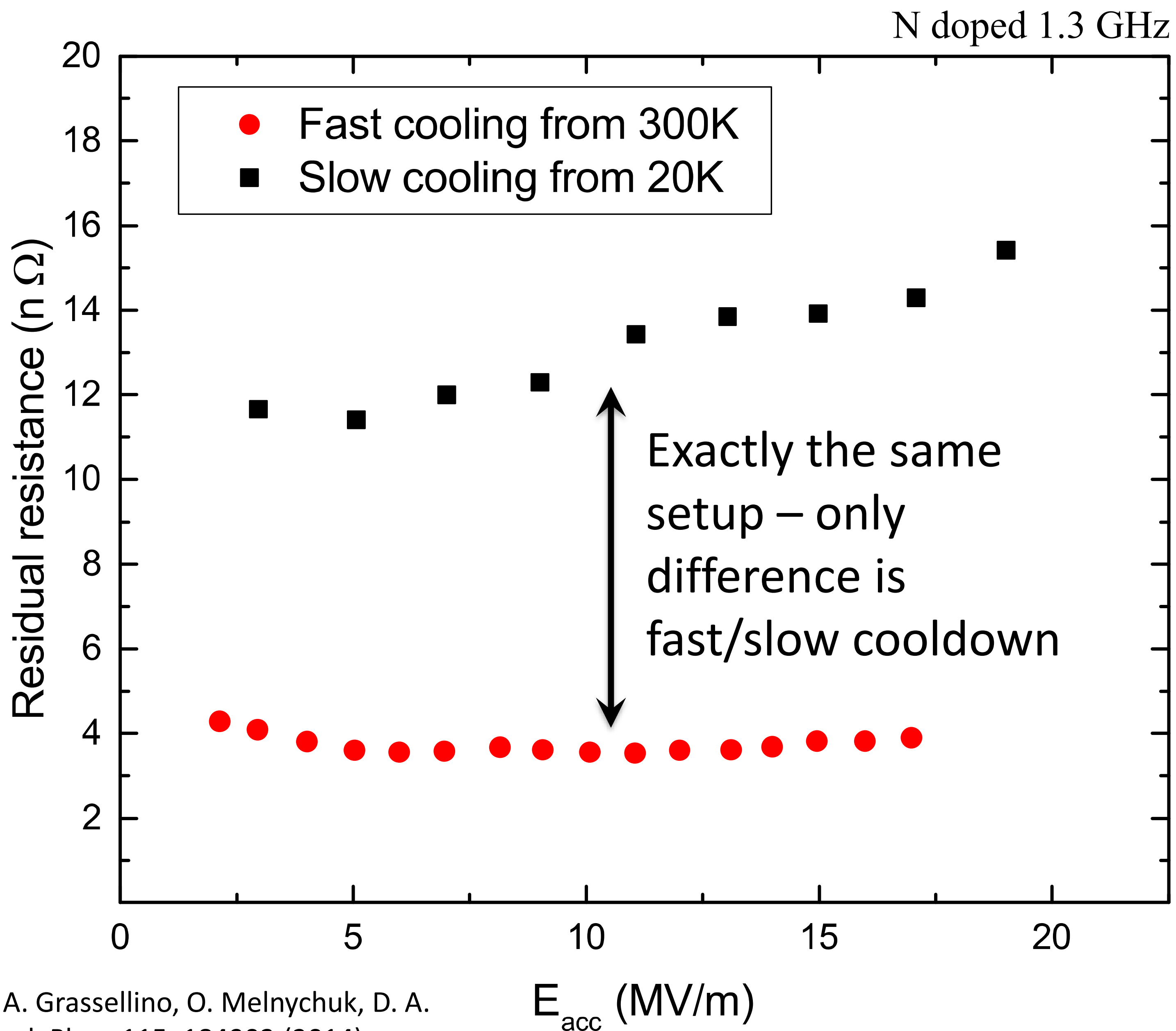
Sam Posen

TTC Topical Workshop on Flux

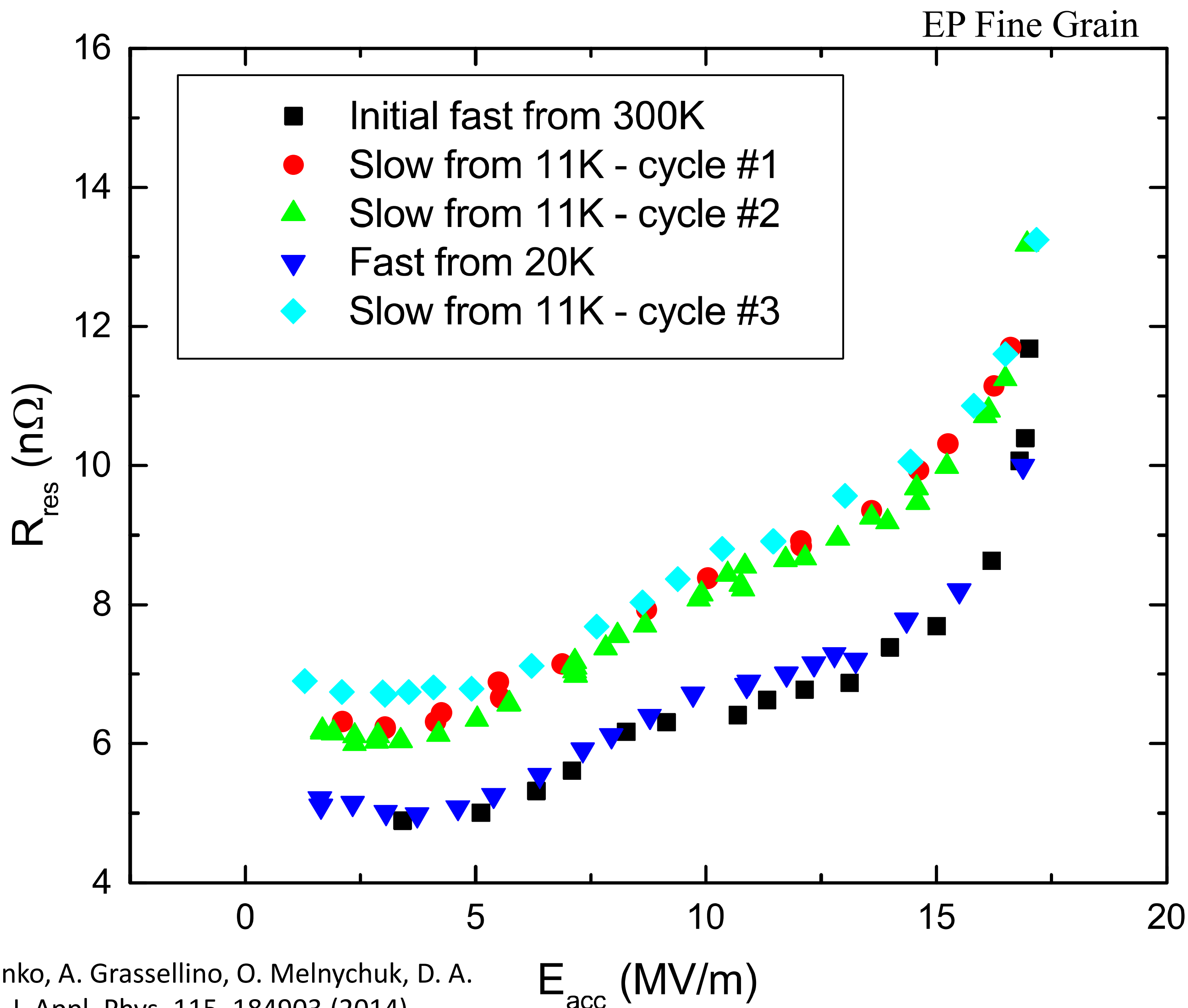
9 November 2018

CERN

Experiments to Probe the Physics of Flux Expulsion



A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)



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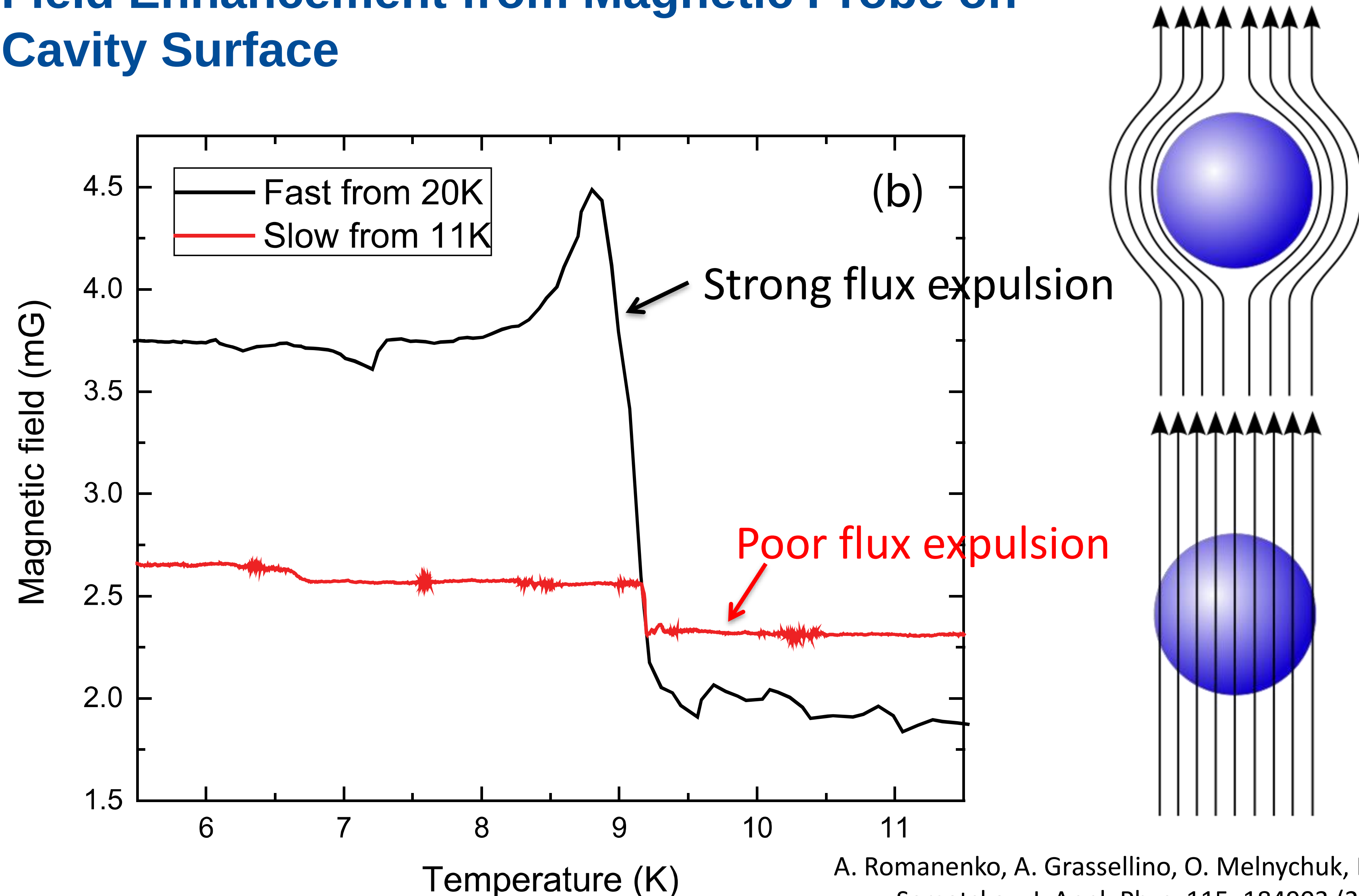
Field Enhancement from Magnetic Probe on Cavity Surface



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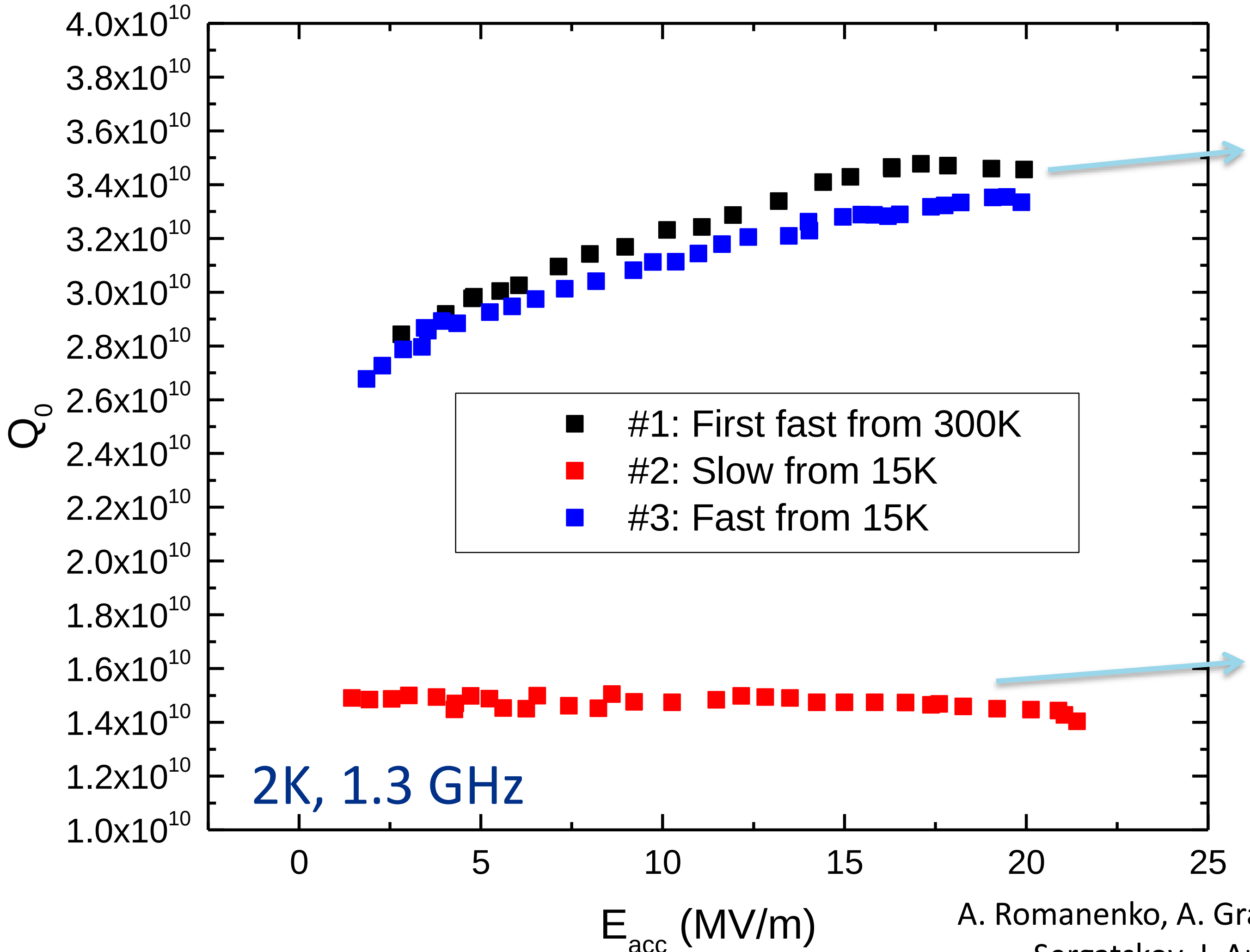
Magnetic Flux Expulsion

- Several factors influence Q_0-degradation from magnetic flux:
  - Ambient magnetic field
    - Local value of Earth's field, shielding, demagnetization, magnetic components, thermocurrents (static & dynamic), active compensation, etc. [*discussed earlier this morning*]
  - **Flux expulsion**
    - **Fraction of ambient flux is expelled out of superconductor vs becoming trapped in it during cooldown [*the rest of today*]**
  - Sensitivity
    - For a given amount of trapped flux, what is the added surface resistance [*several presentations on this subject tomorrow*]

1) Cooldown matters: cooldown can determine if ambient flux is trapped or expelled

Same cavity, just cooled differently through 9.2K



Flux expelled efficiently

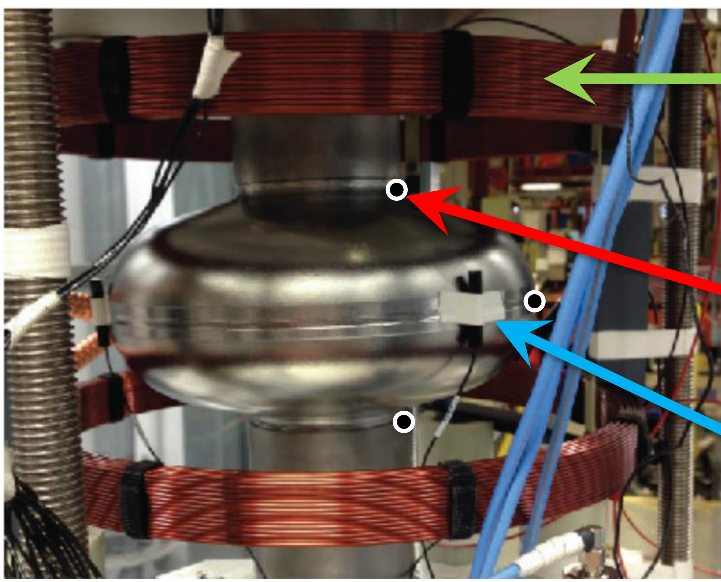
Flux mostly trapped

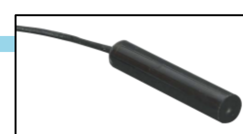
A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)

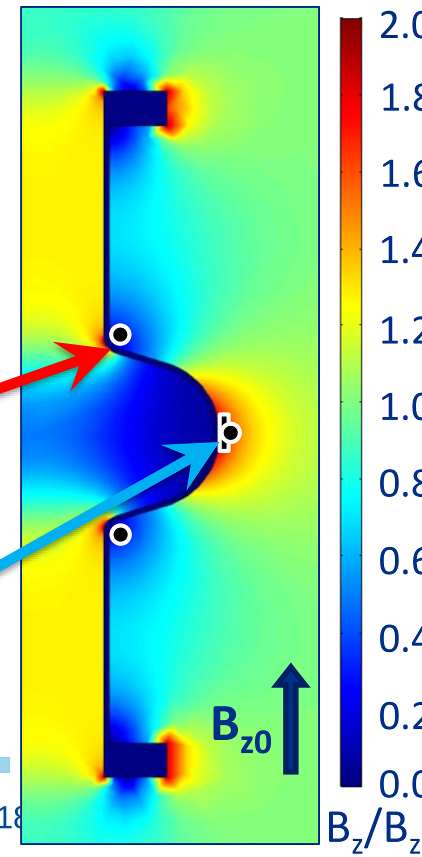
Systematic Method for Measuring Flux Expulsion

A. Romanenko et al., Appl. Phys. Lett. 105, 234103 (2014)
A. Romanenko et al., J. Appl. Phys. 115, 184903 (2014)

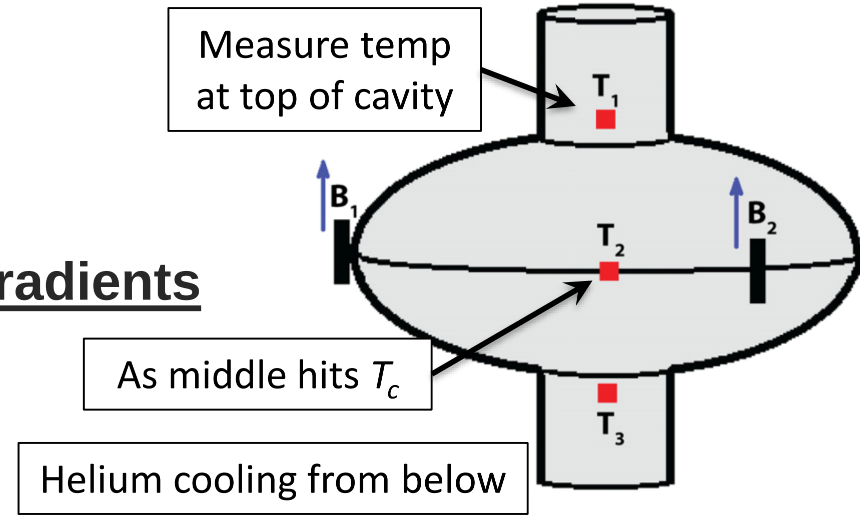
- An axial magnetic field is applied during cooldown. Fluxgate magnetometers at the equator measured the magnetic field before $\boldsymbol{B_{NC}}$ and after $\boldsymbol{B_{SC}}$ superconducting transition. Measurements are performed as a function of **dT/dx**.
  - Complete trapping: $B_{SC}/B_{NC} = 1$
  - Complete expulsion: $B_{SC}/B_{NC} \sim 1.7$



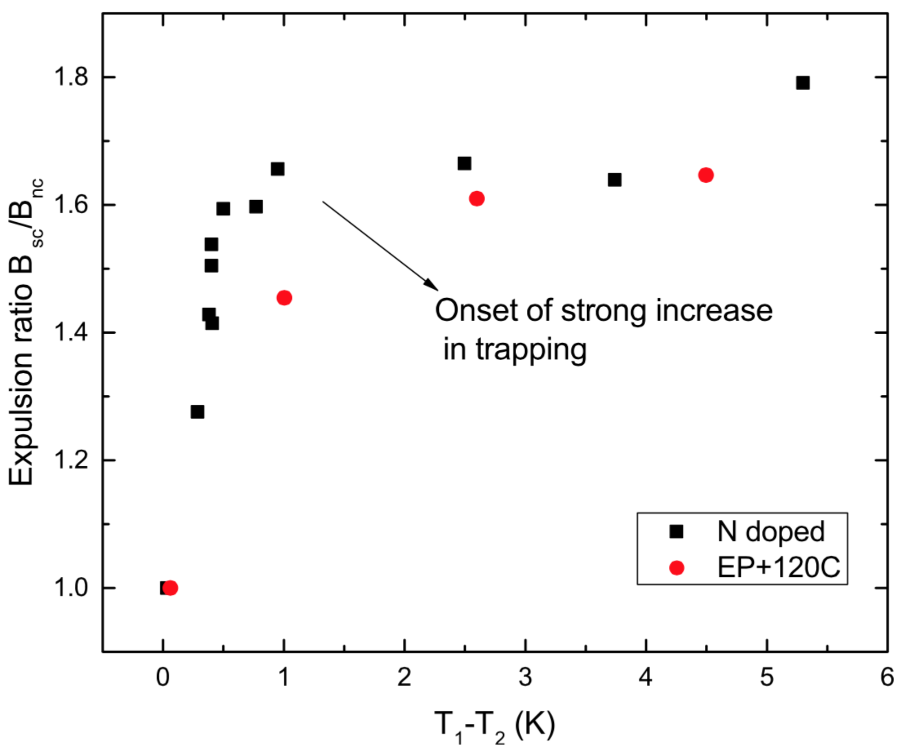


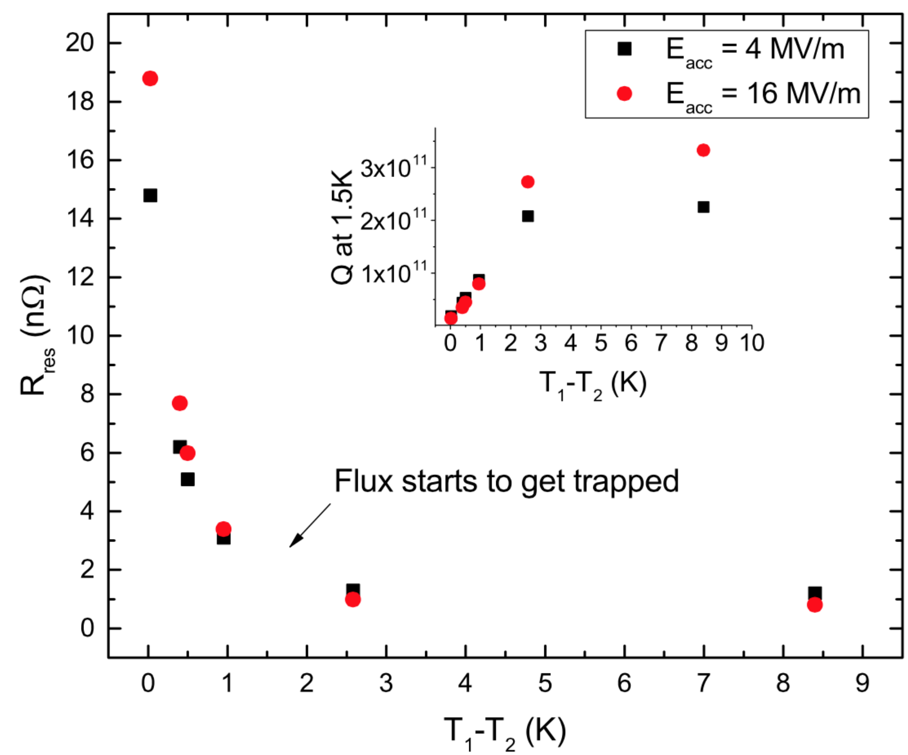


2) Large thermal gradients at T_c promote expulsion of flux



- **Fast cool-down** lead to **large thermal gradients** which promote efficient flux expulsion
- Slow cool-down → poor flux expulsion





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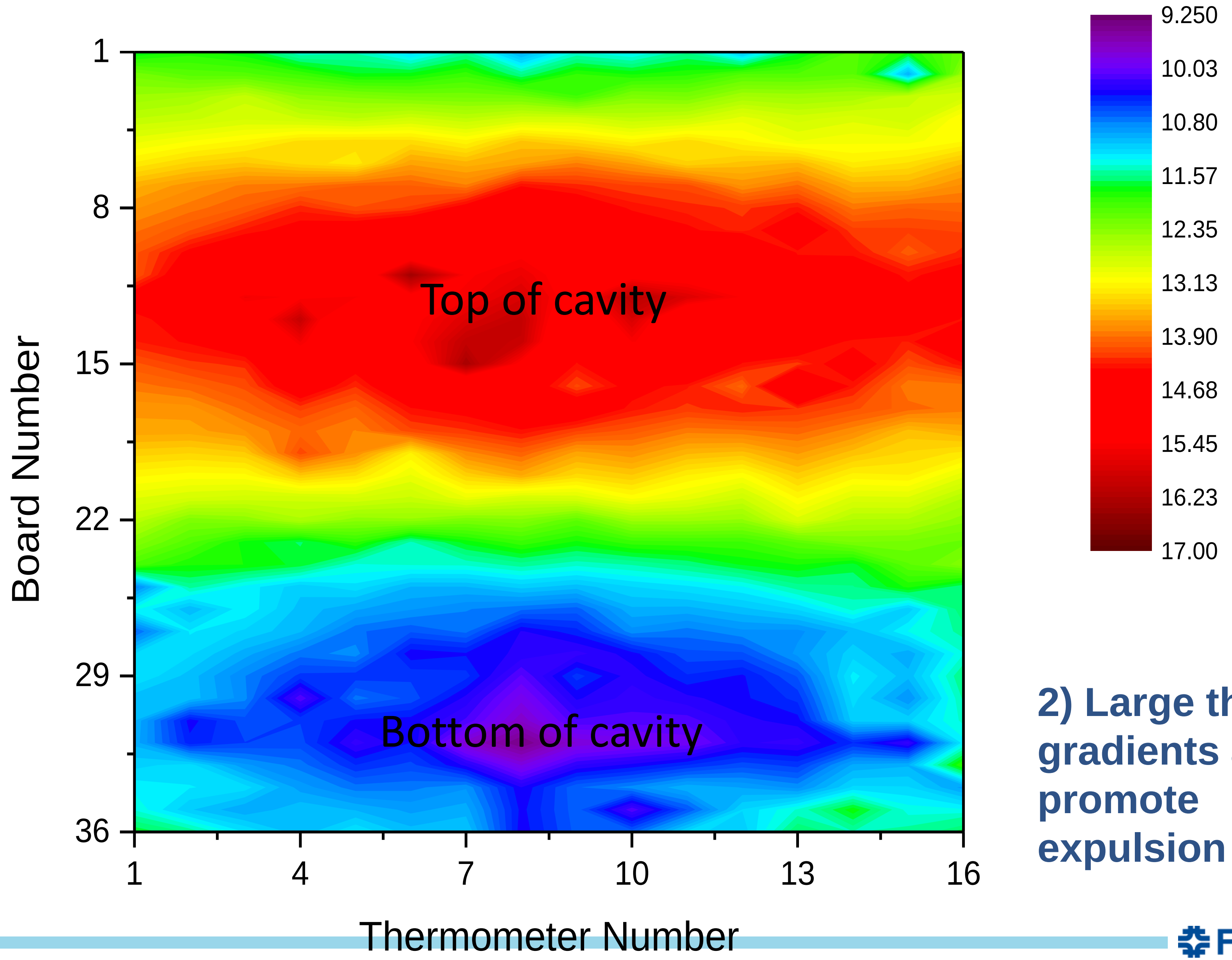

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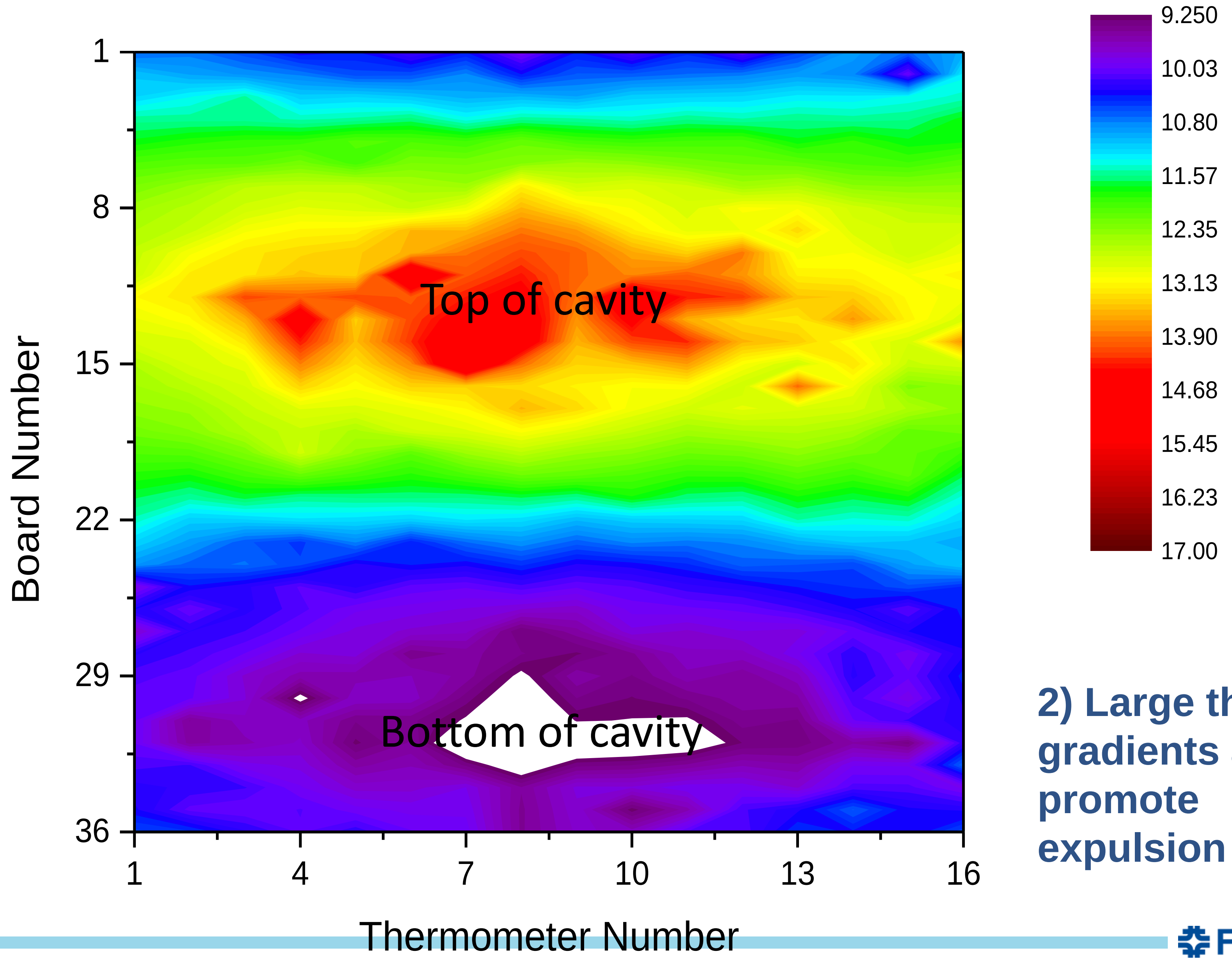

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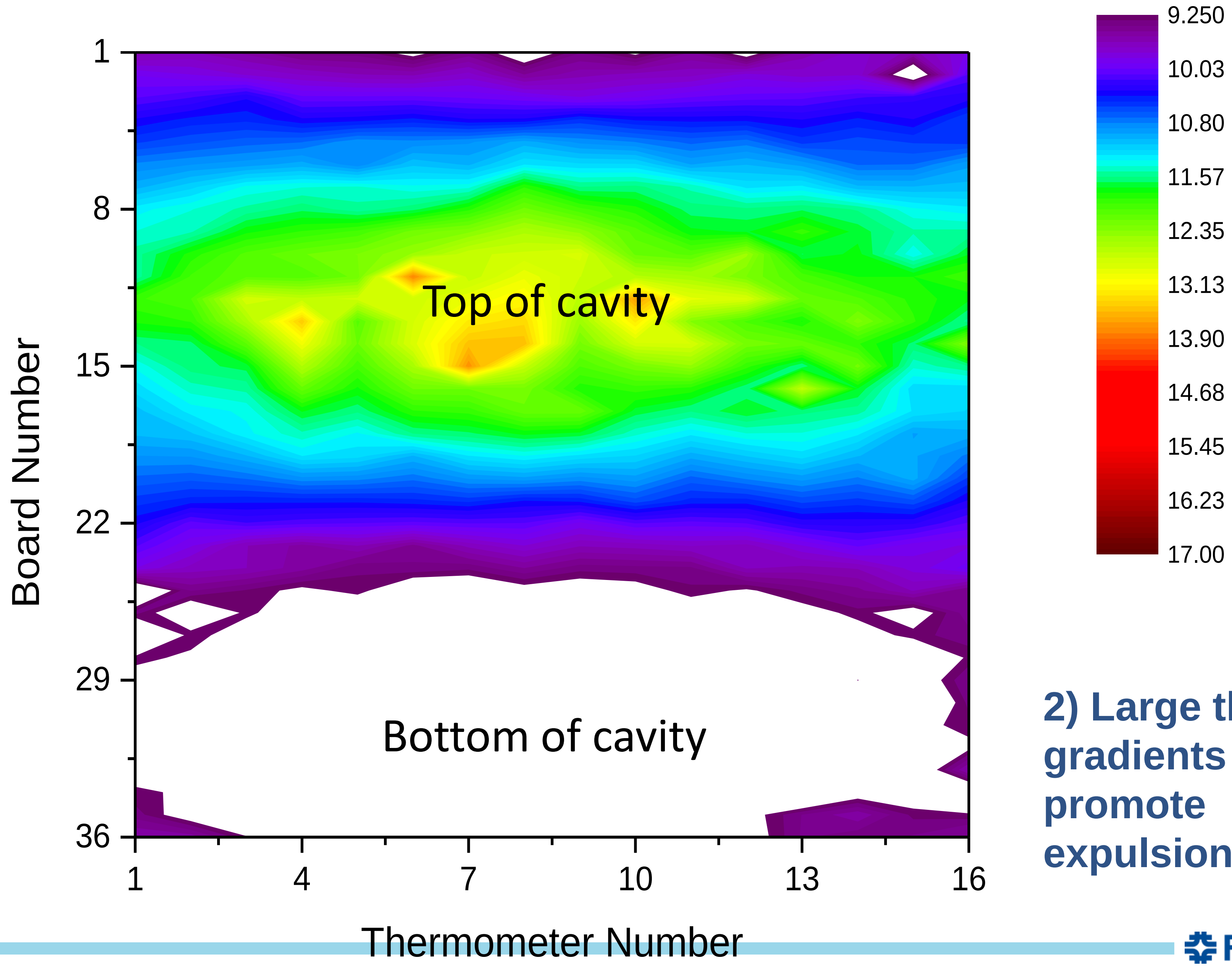

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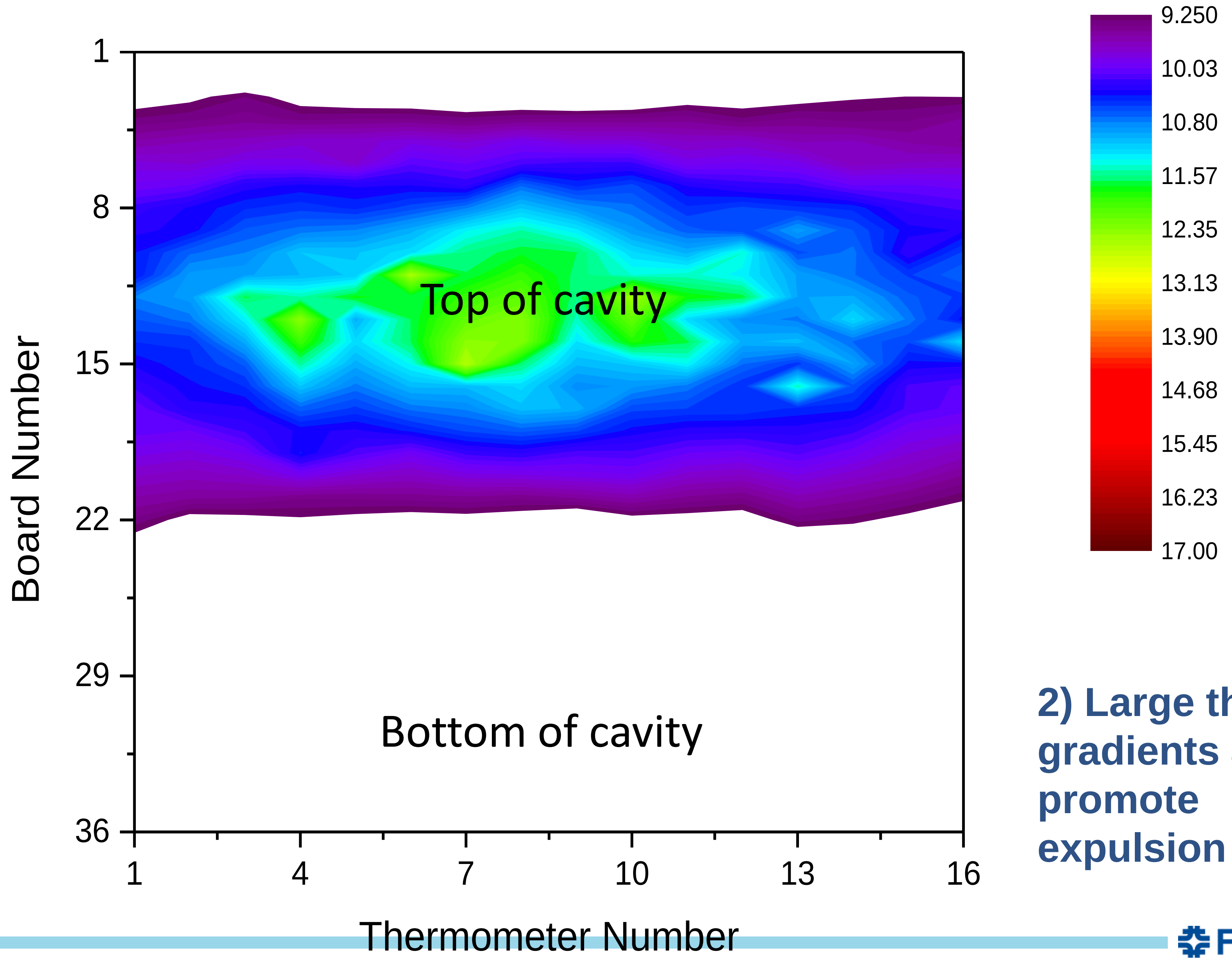

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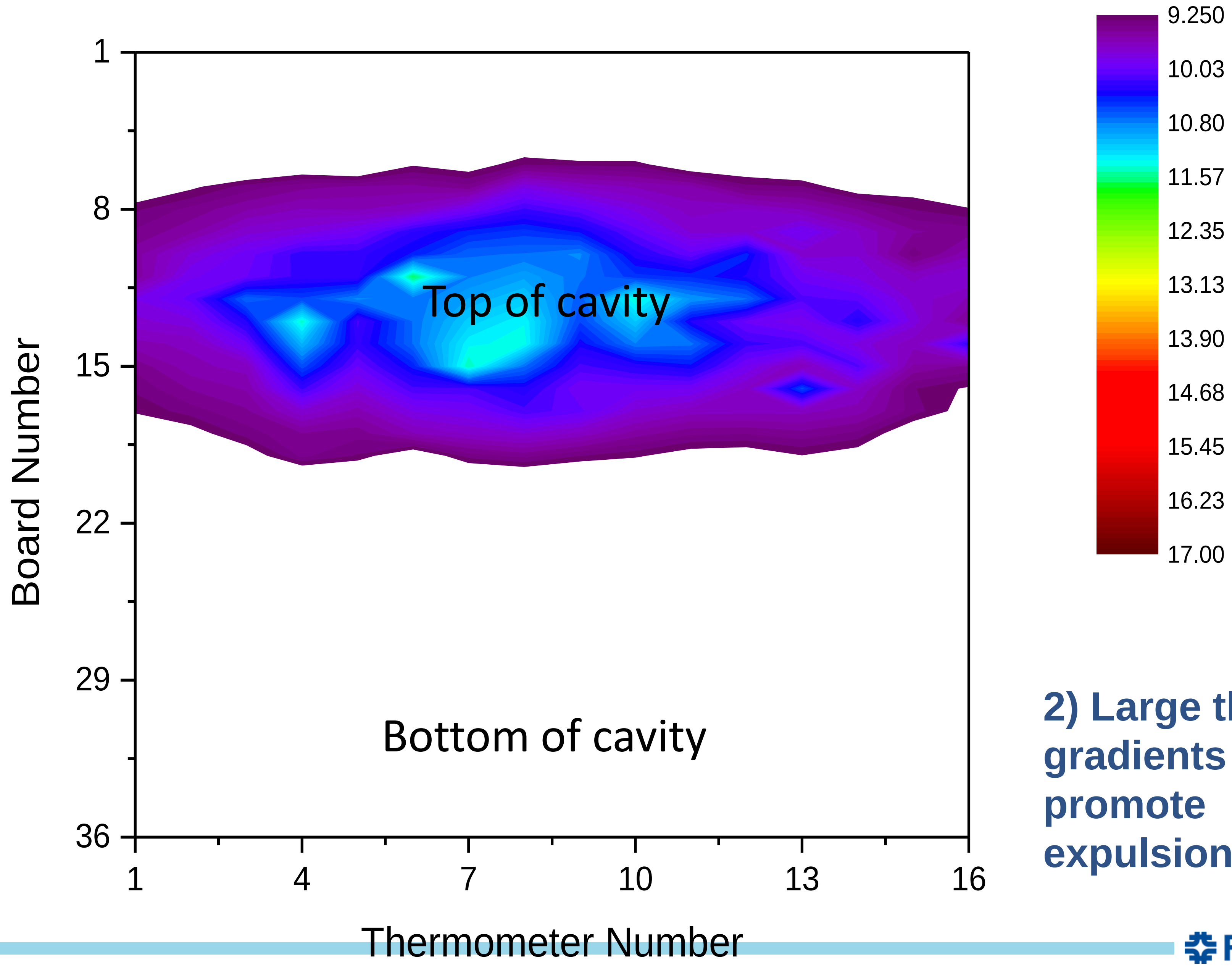

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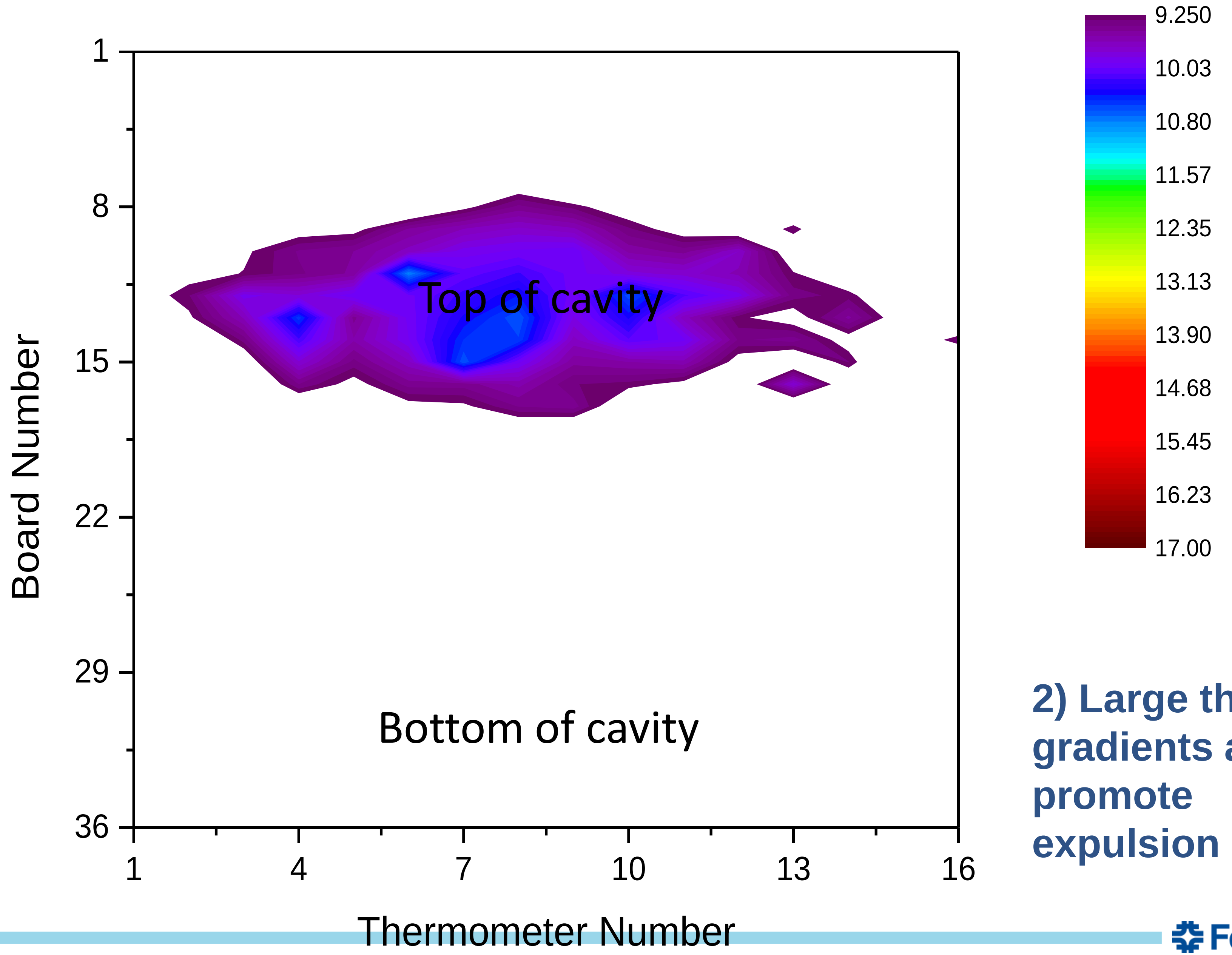

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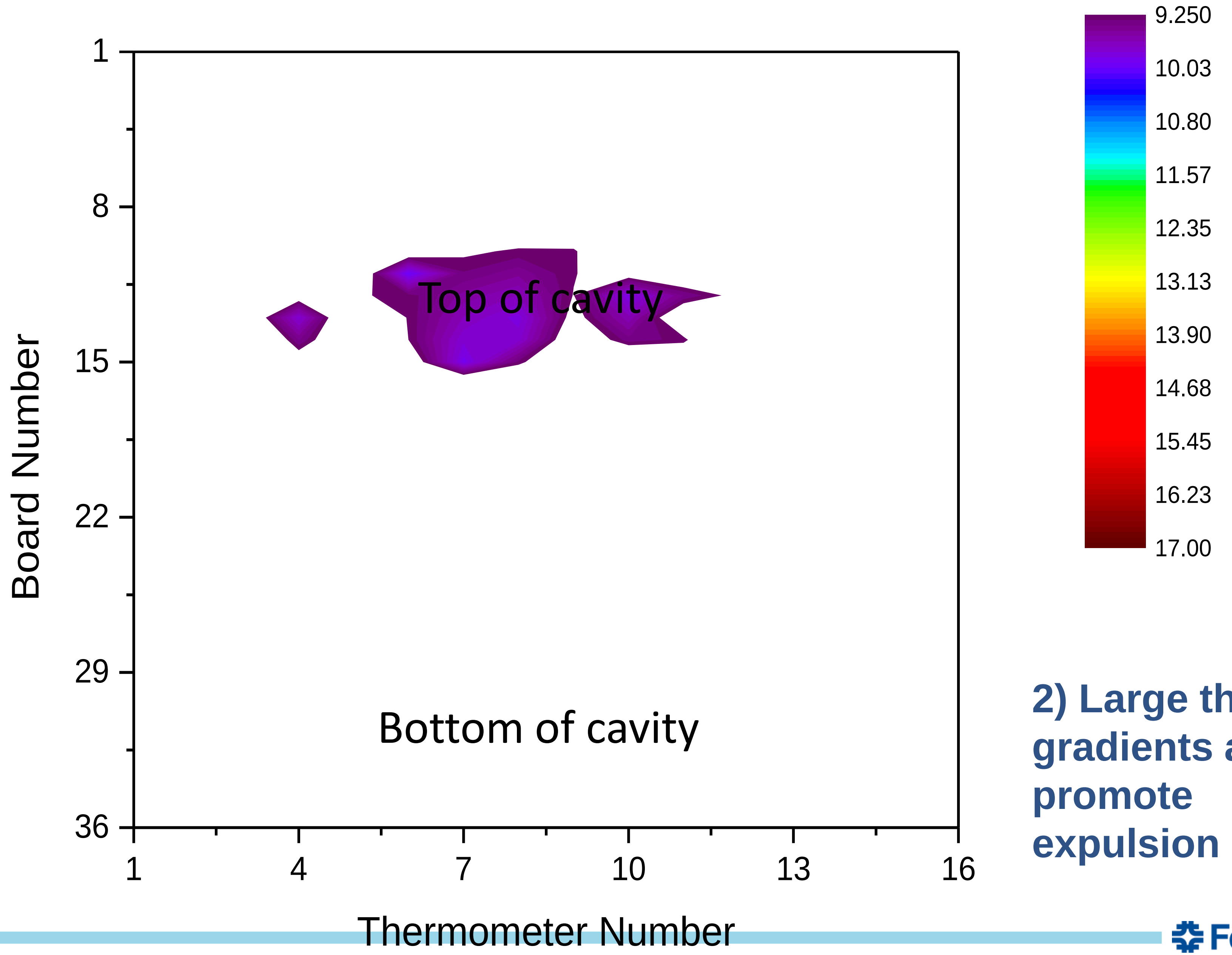

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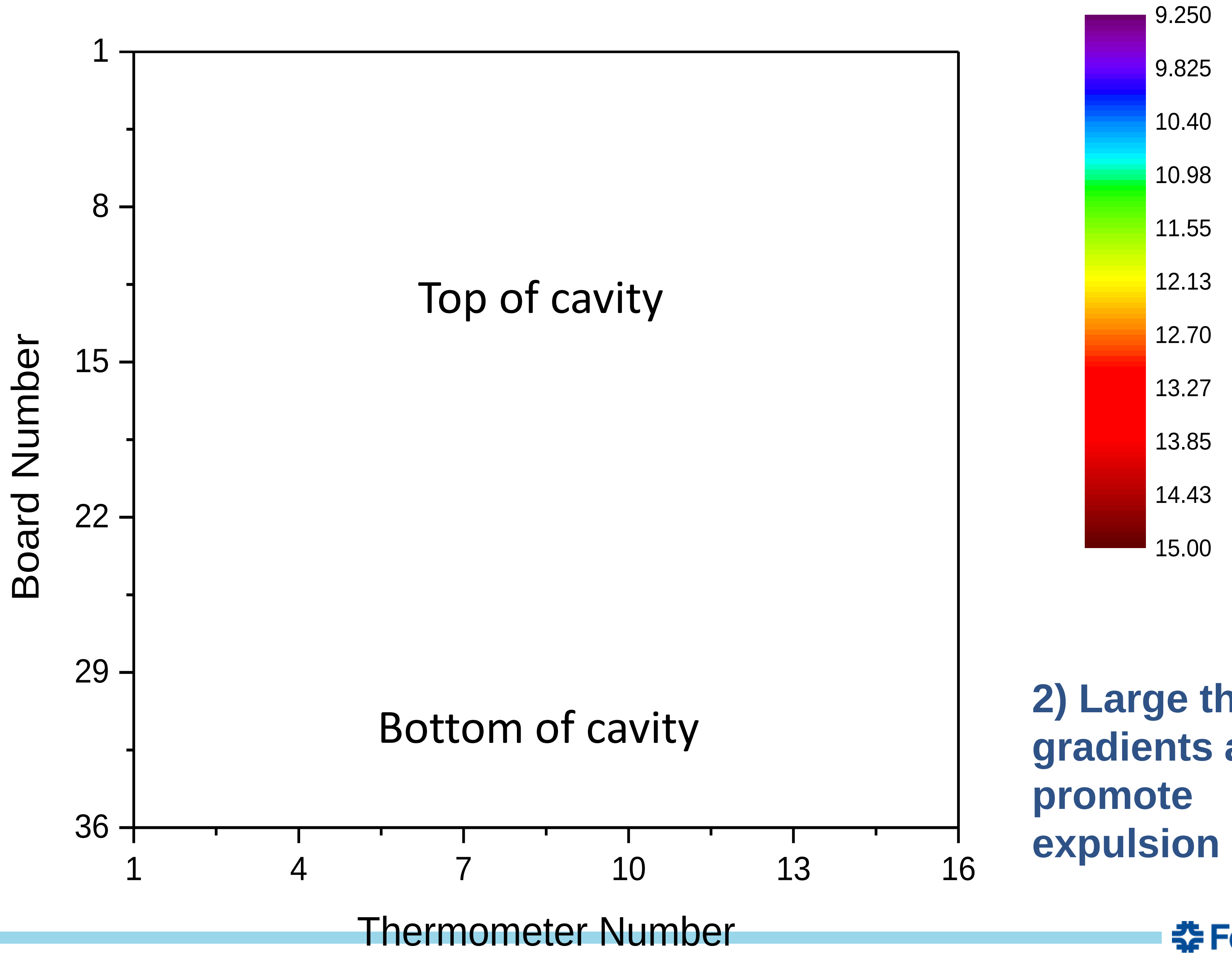
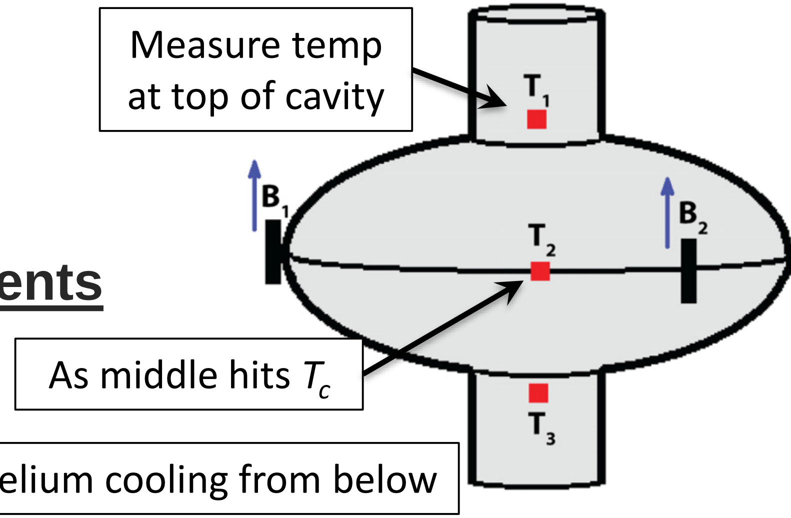
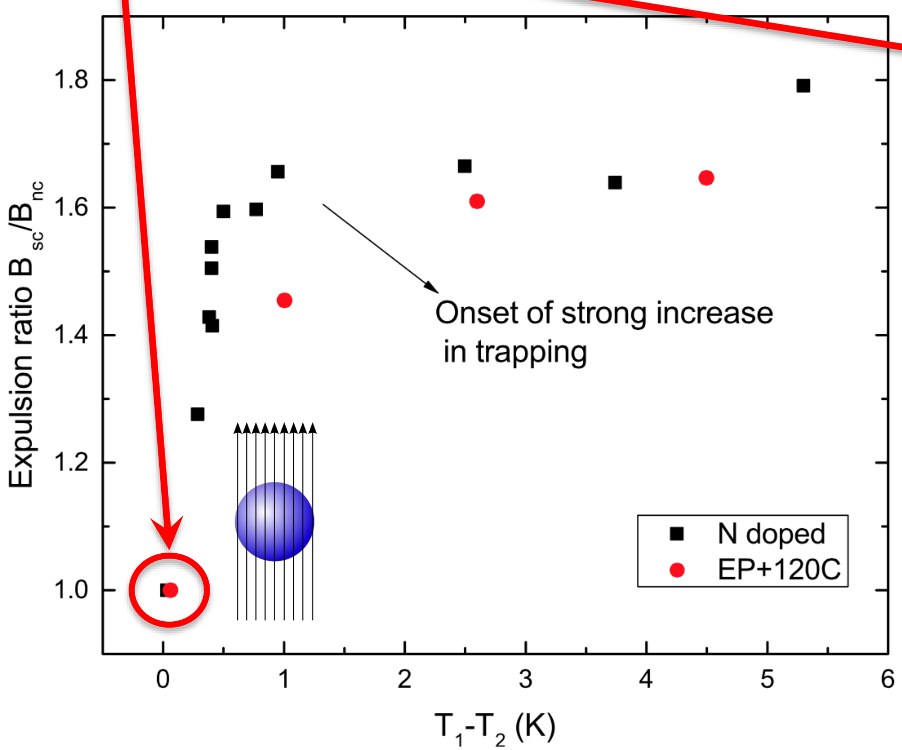


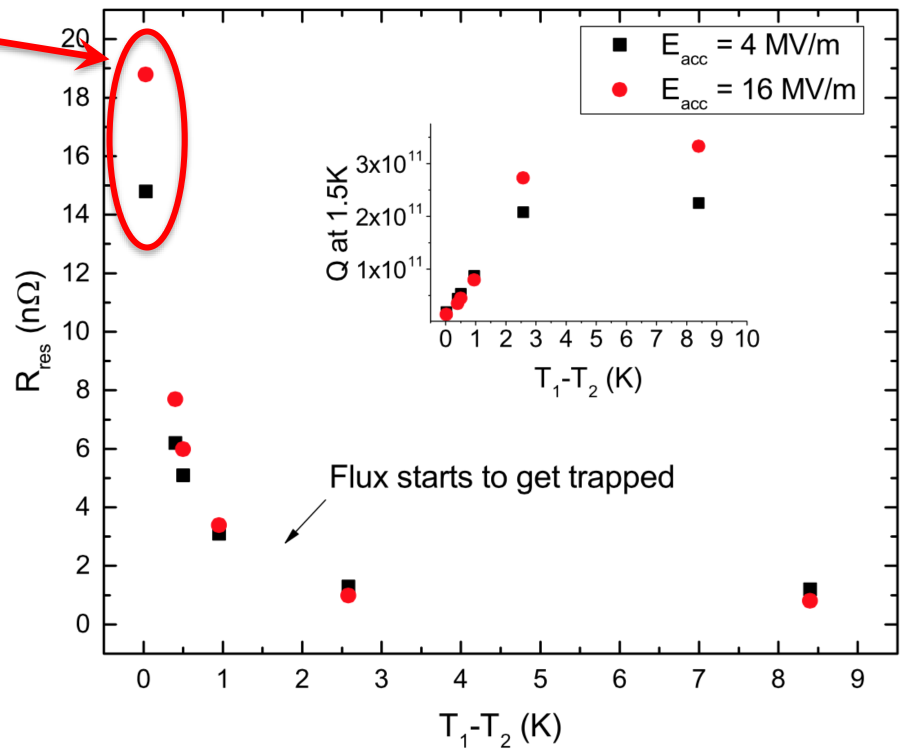
2) Large thermal gradients at T_c promote expulsion of flux

3) Slow, uniform cooldown tends towards trapping all flux – even if cavity expels well at large dT/dx

- Fast cool-down lead to **large thermal gradients** which promote efficient flux expulsion
- **Slow cool-down** → poor flux expulsion







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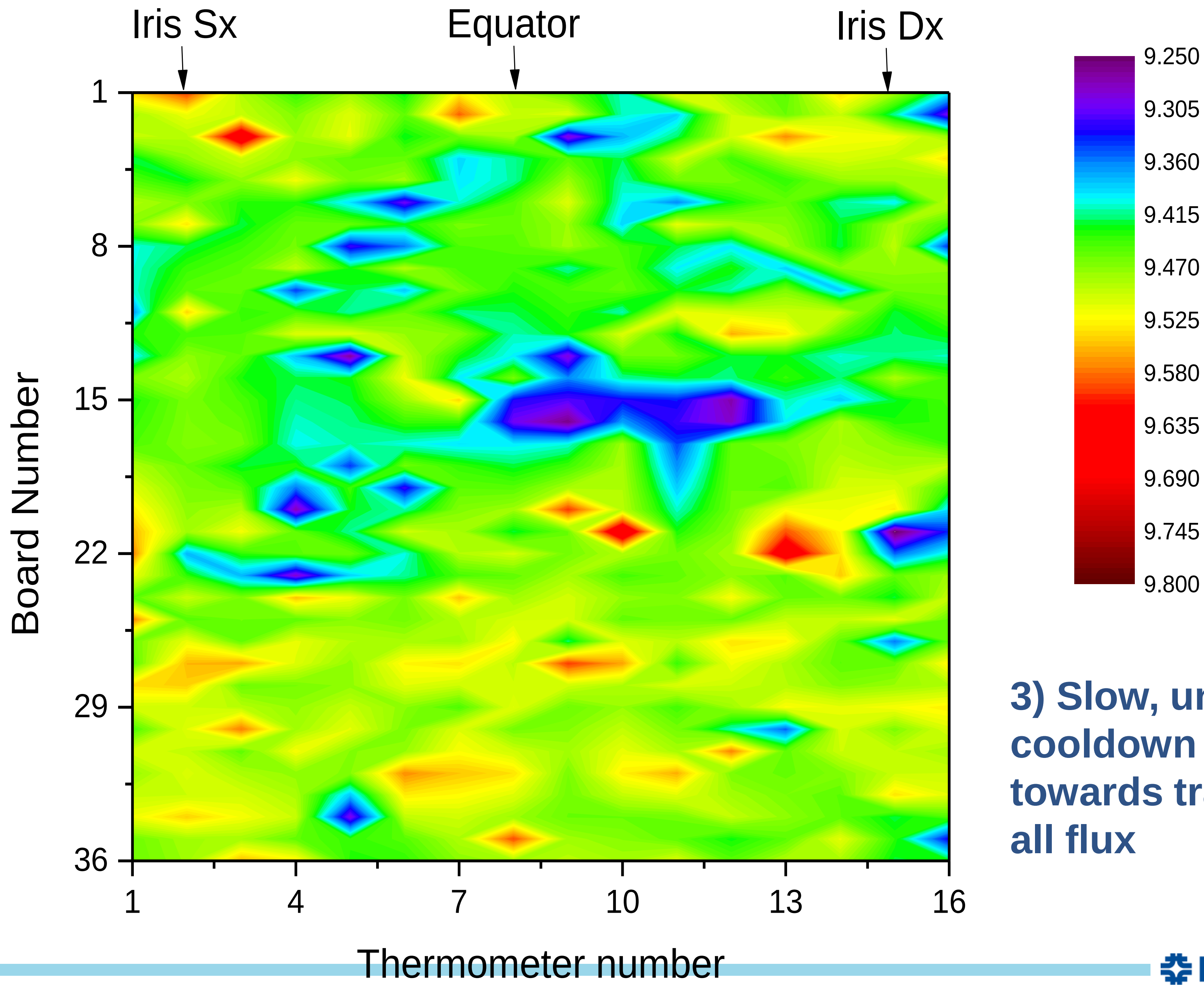

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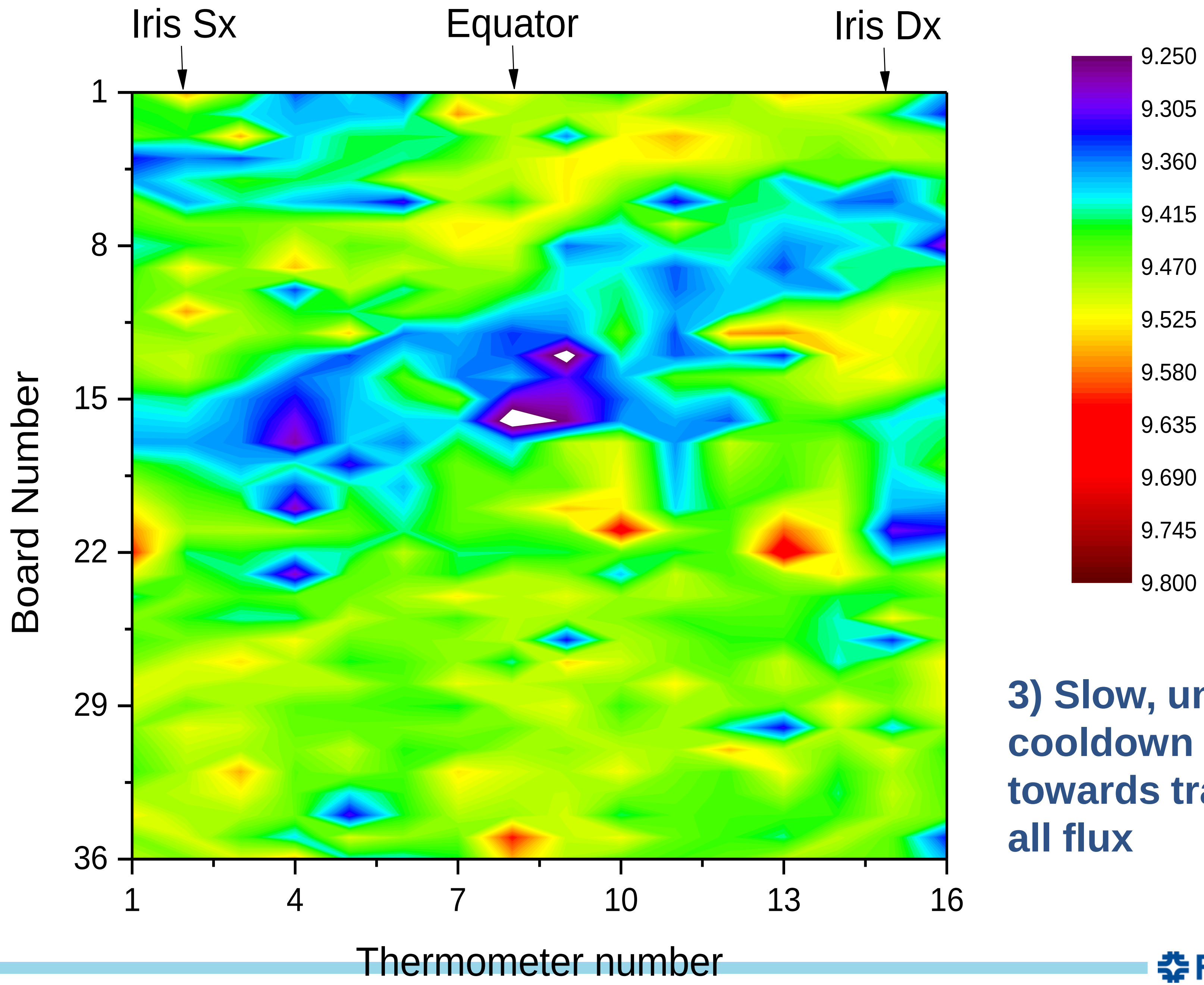
Fermilab



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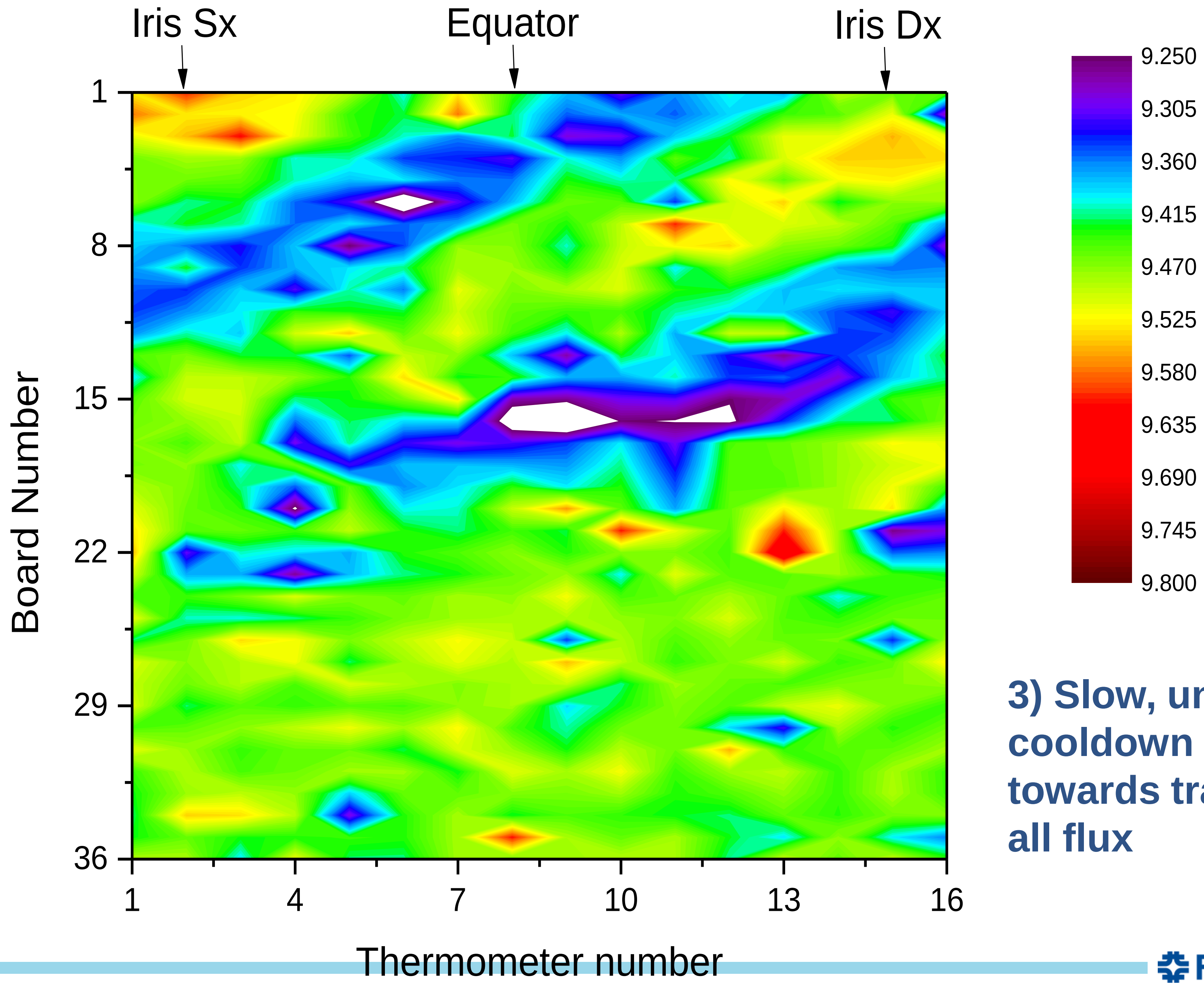

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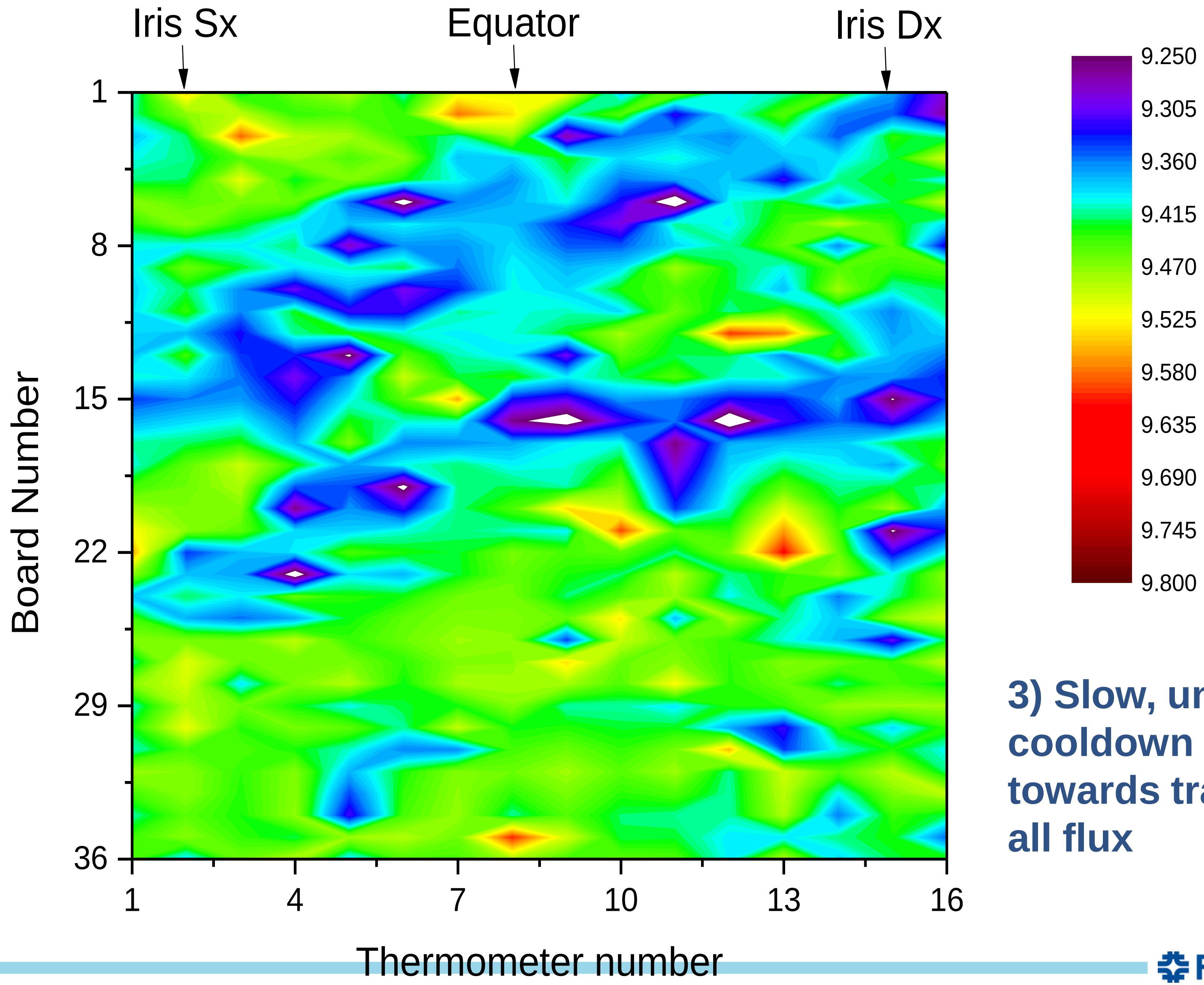

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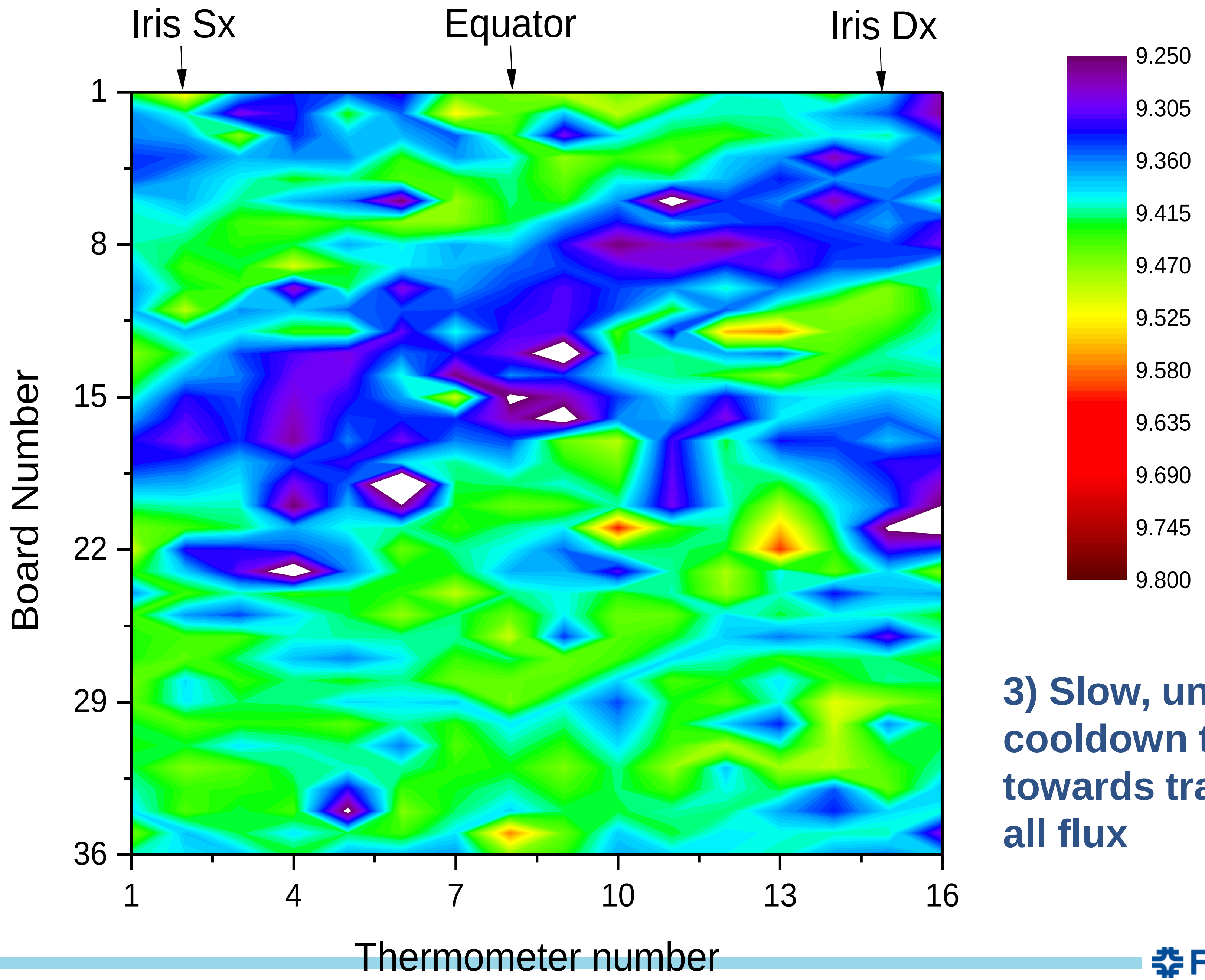

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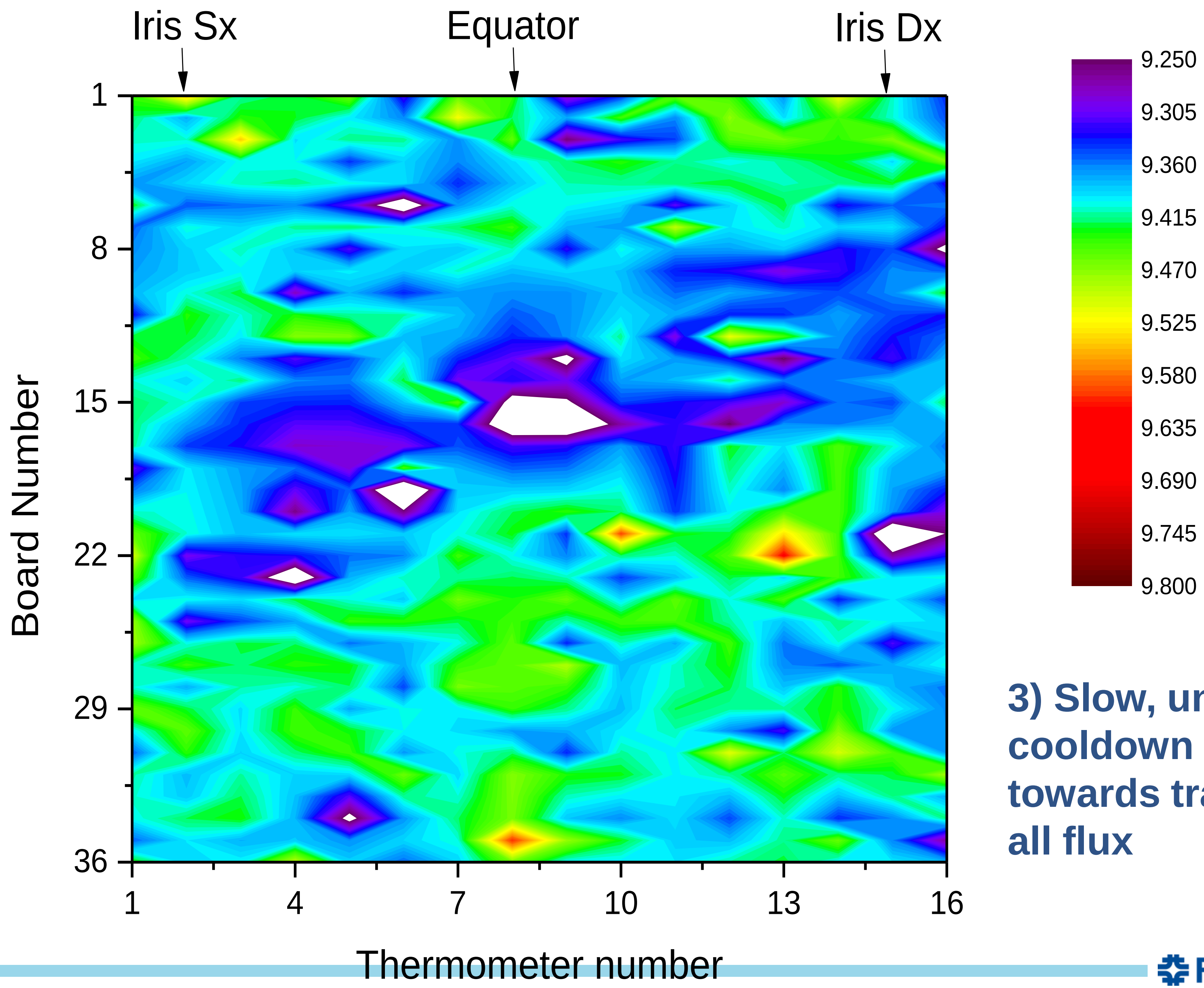

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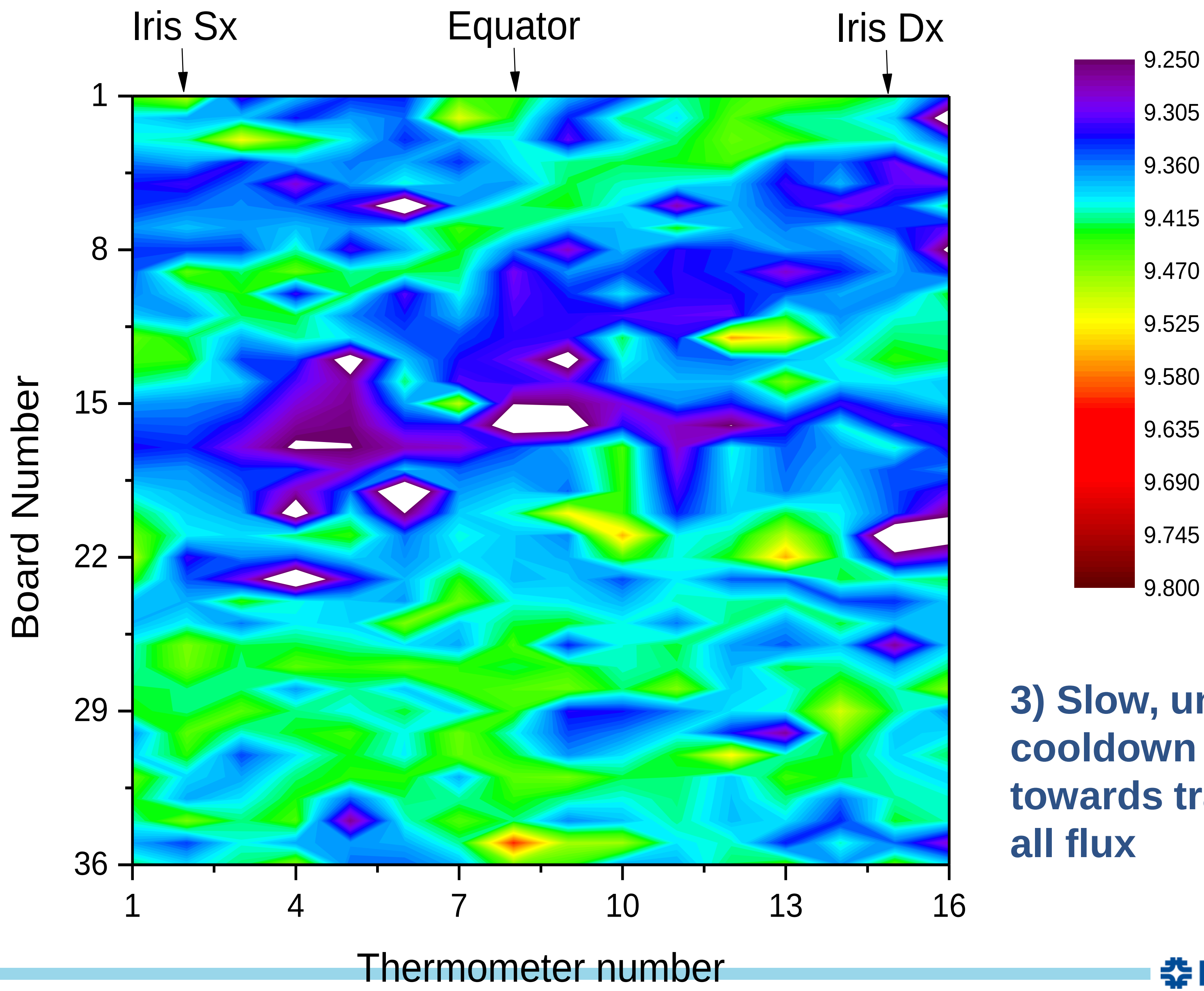

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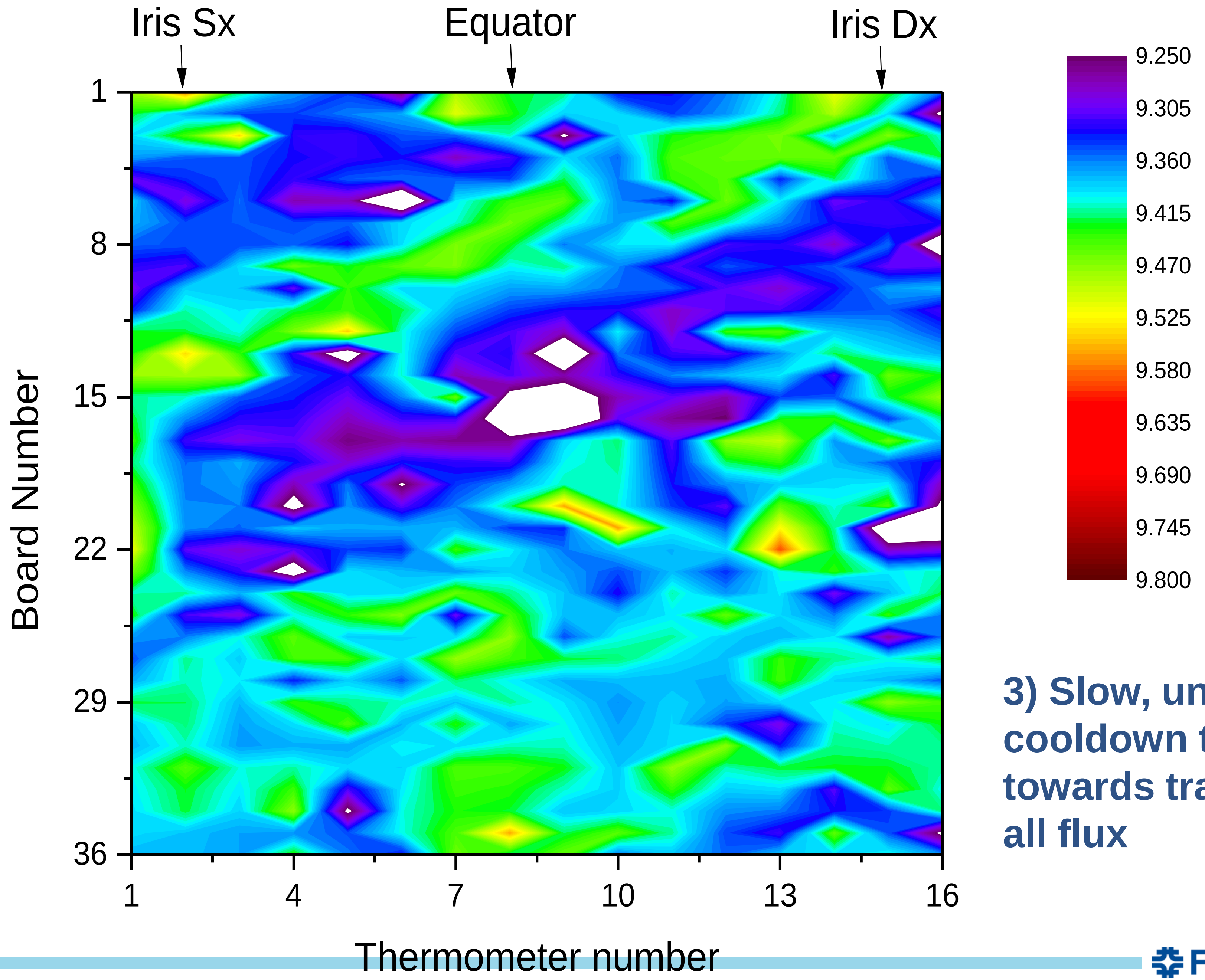

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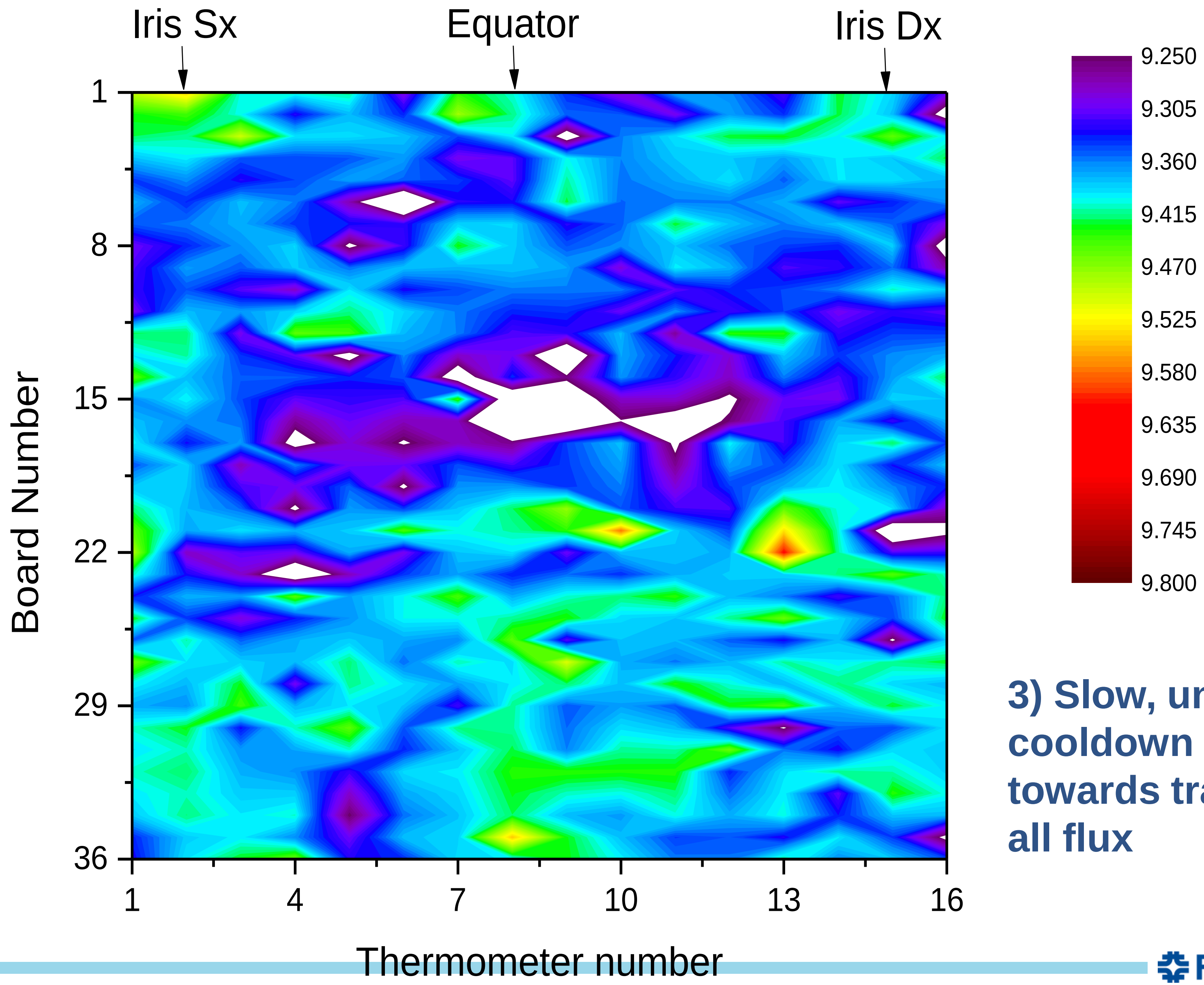

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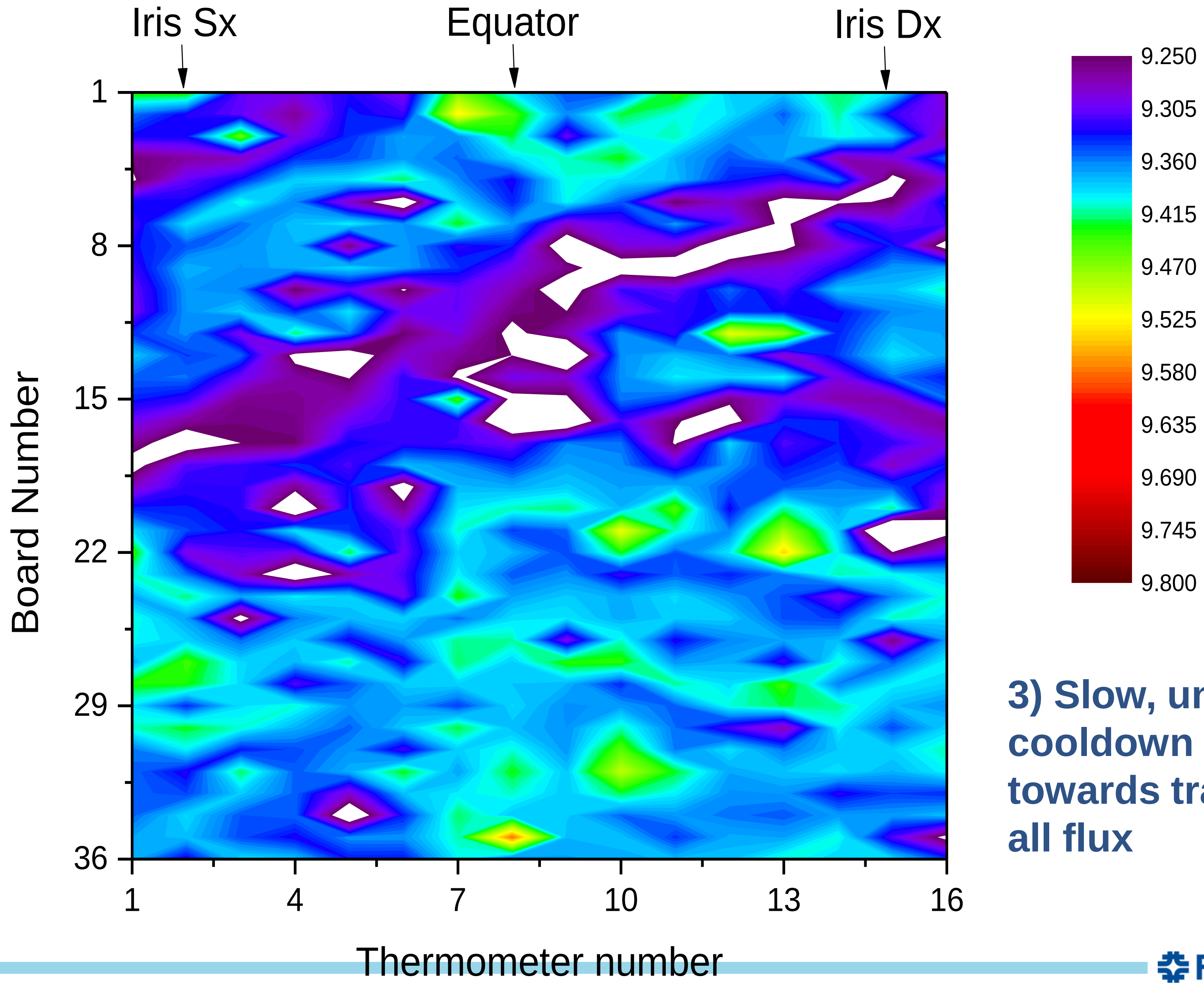

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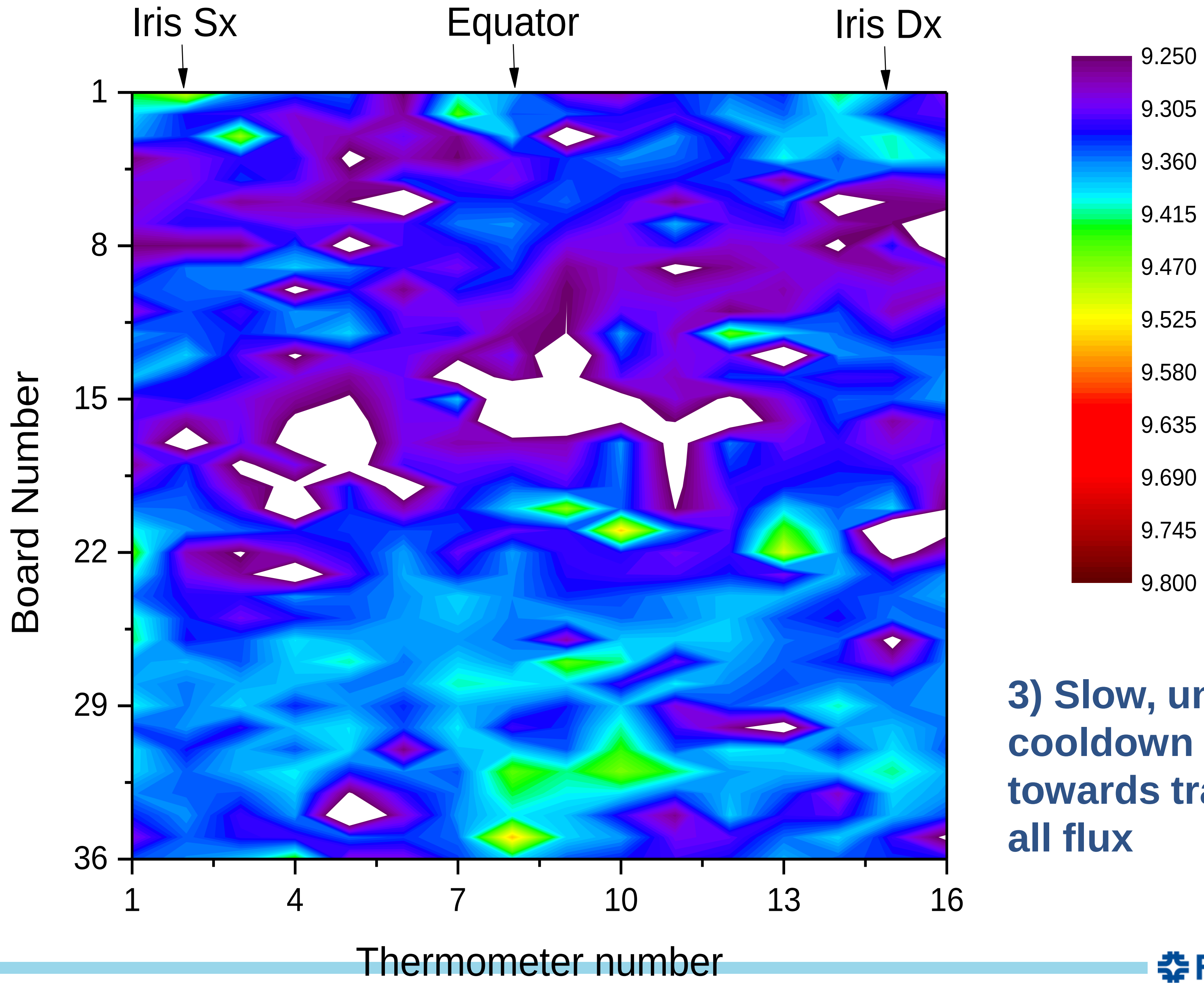

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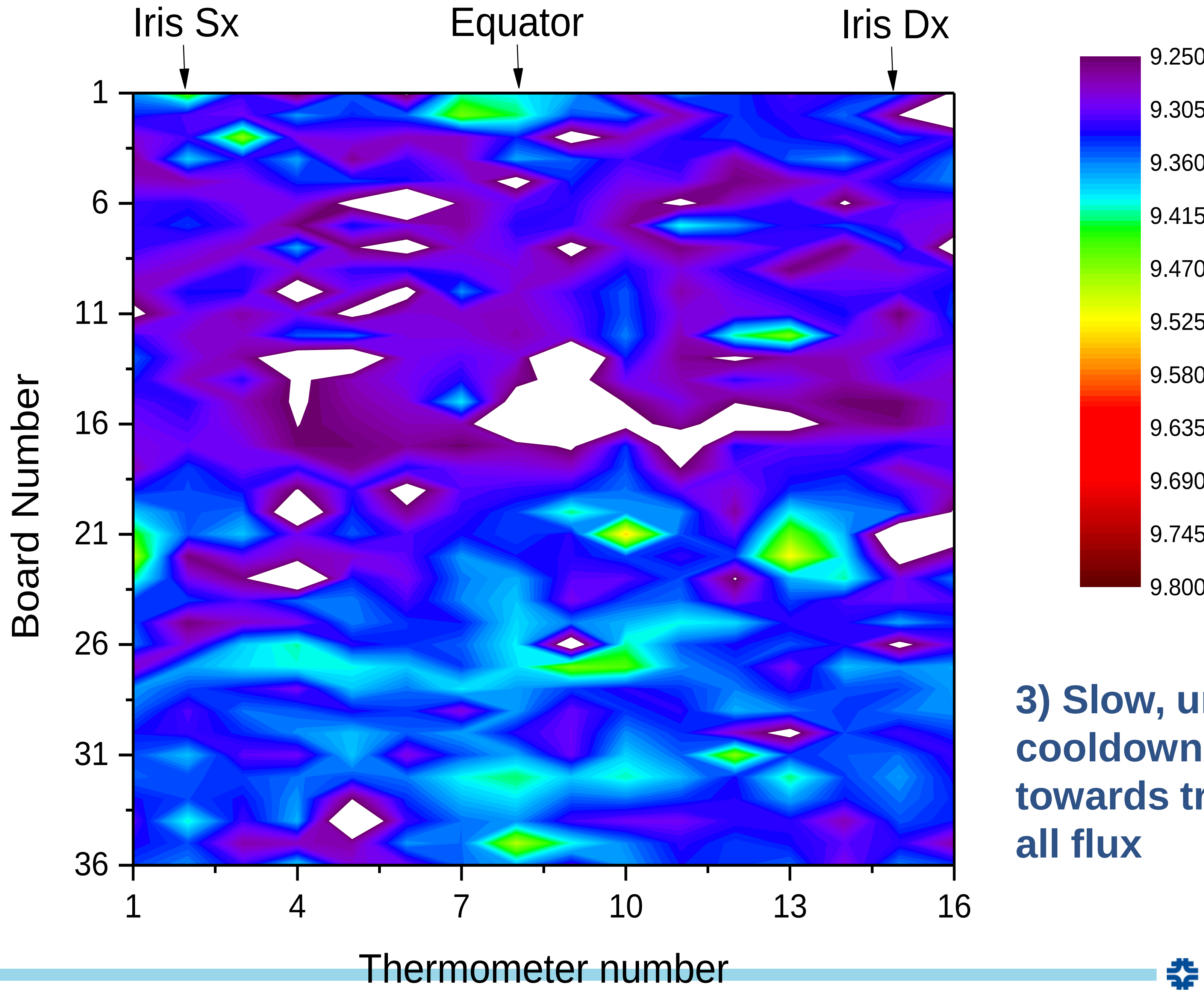

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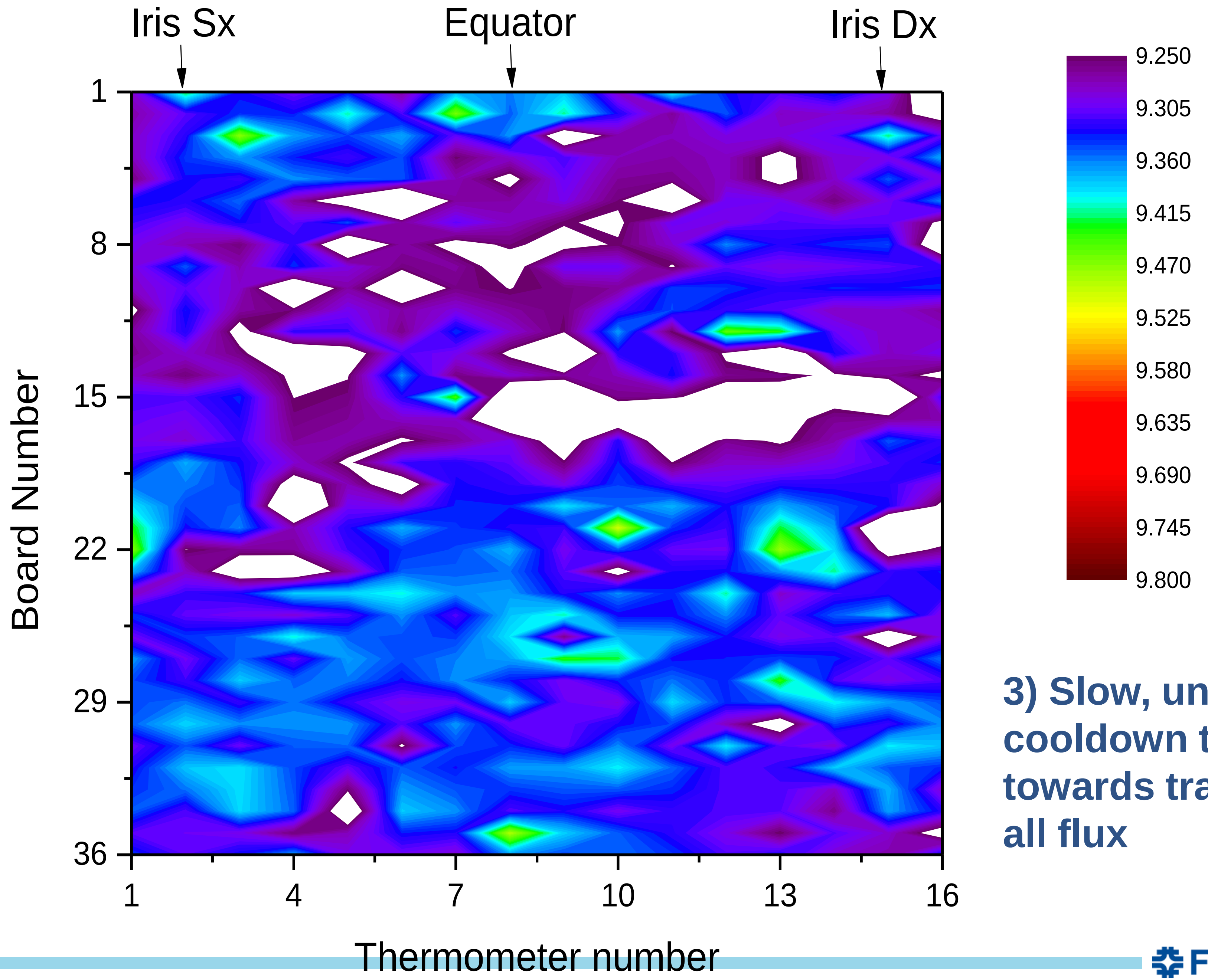

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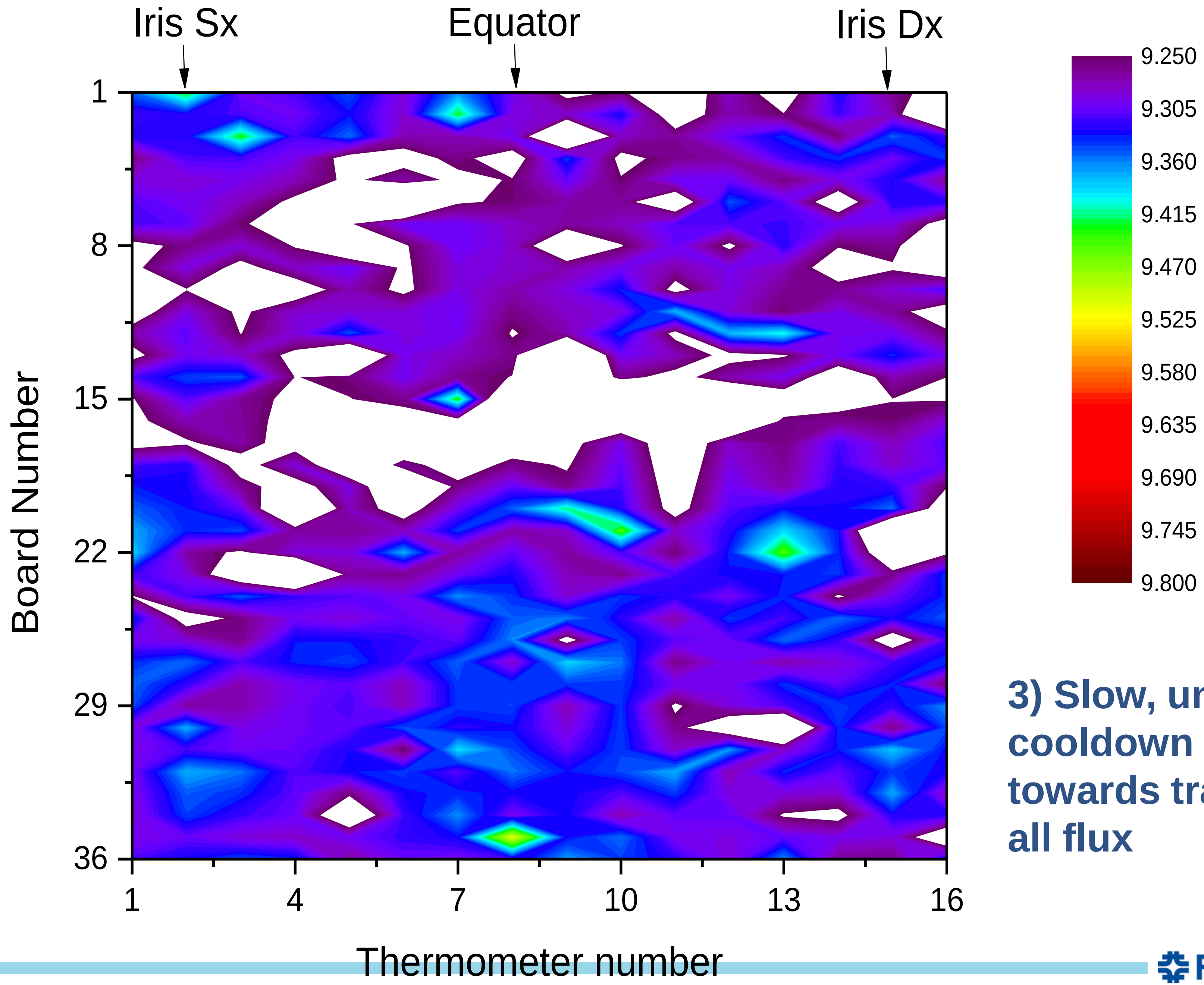

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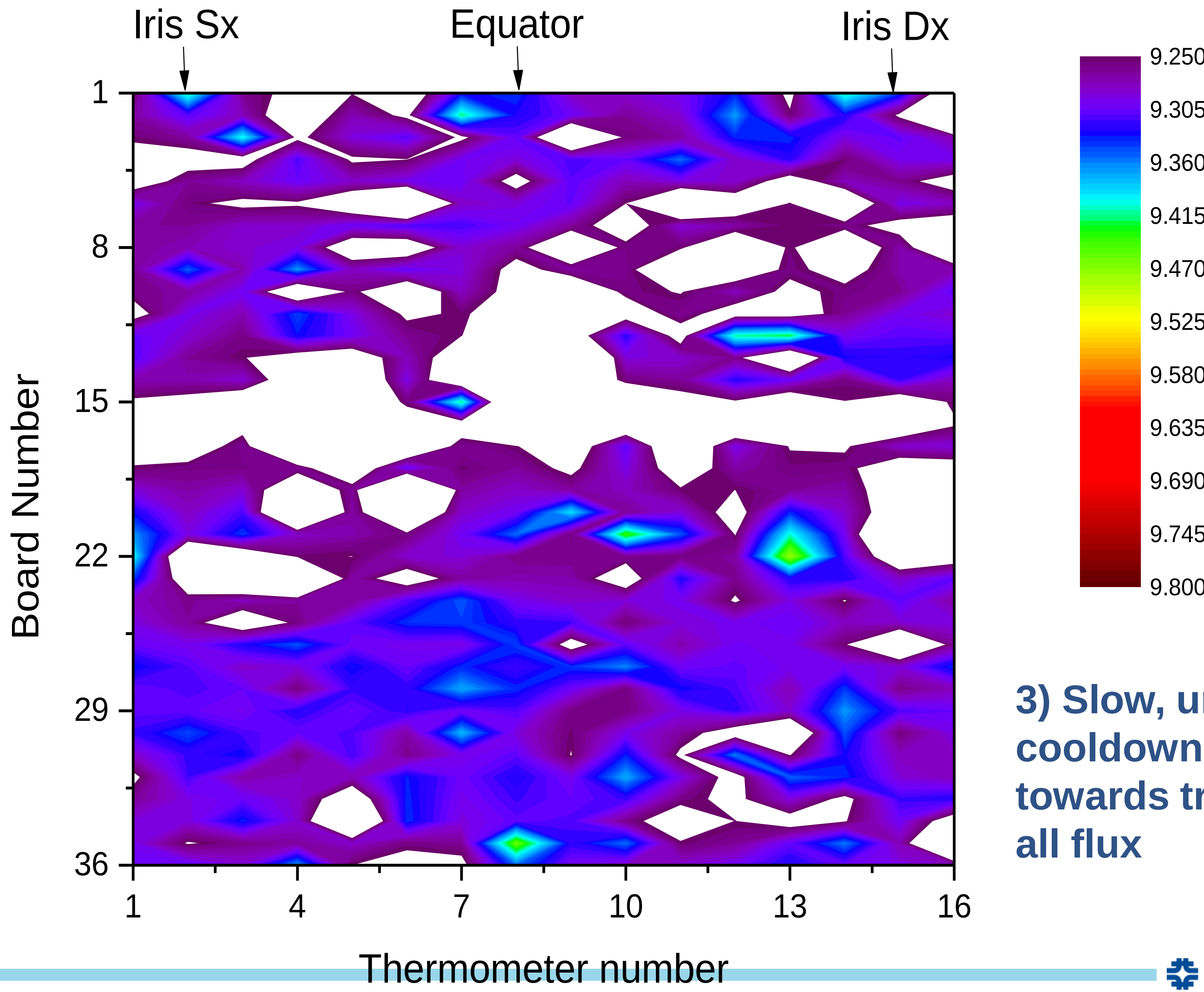

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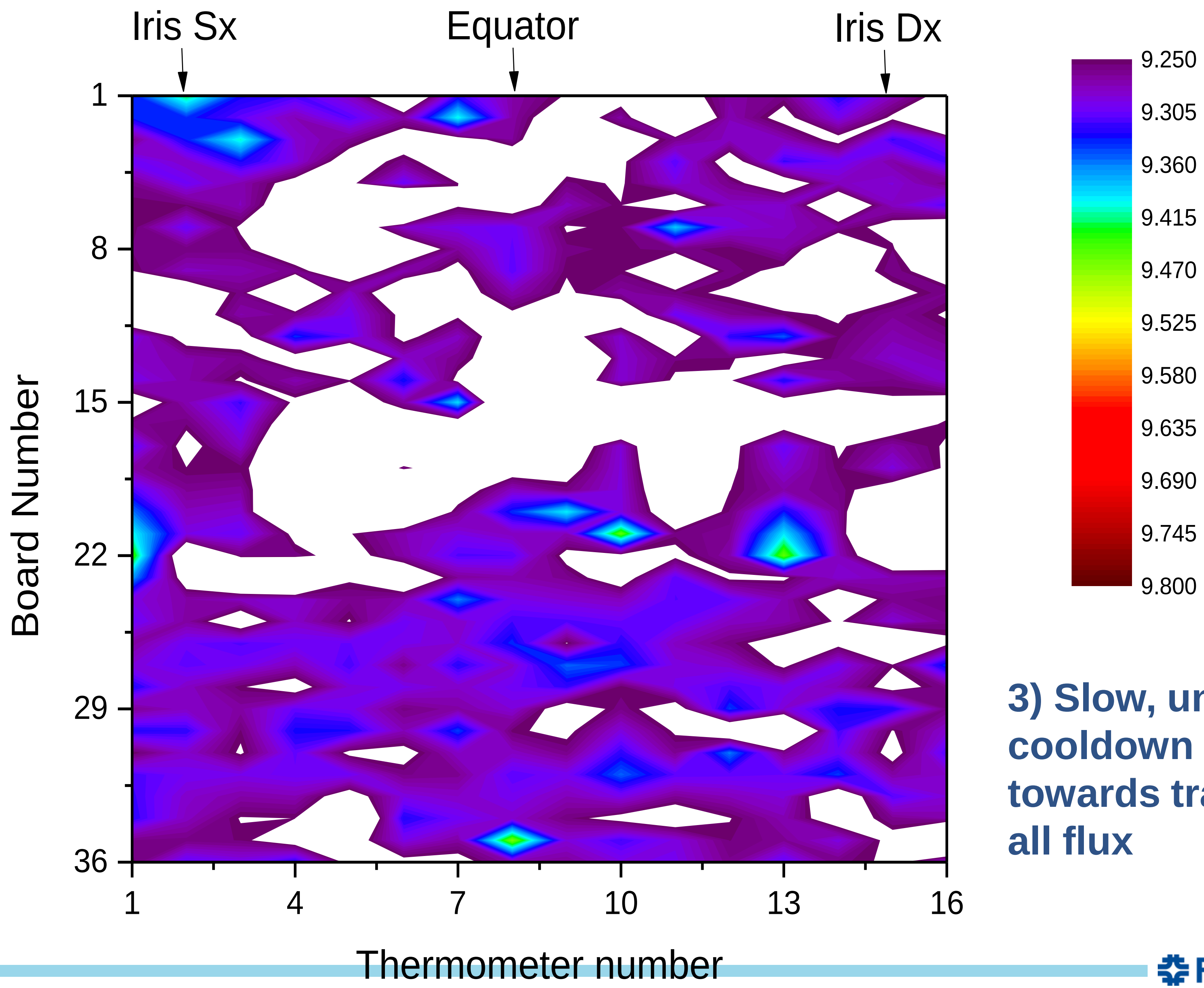

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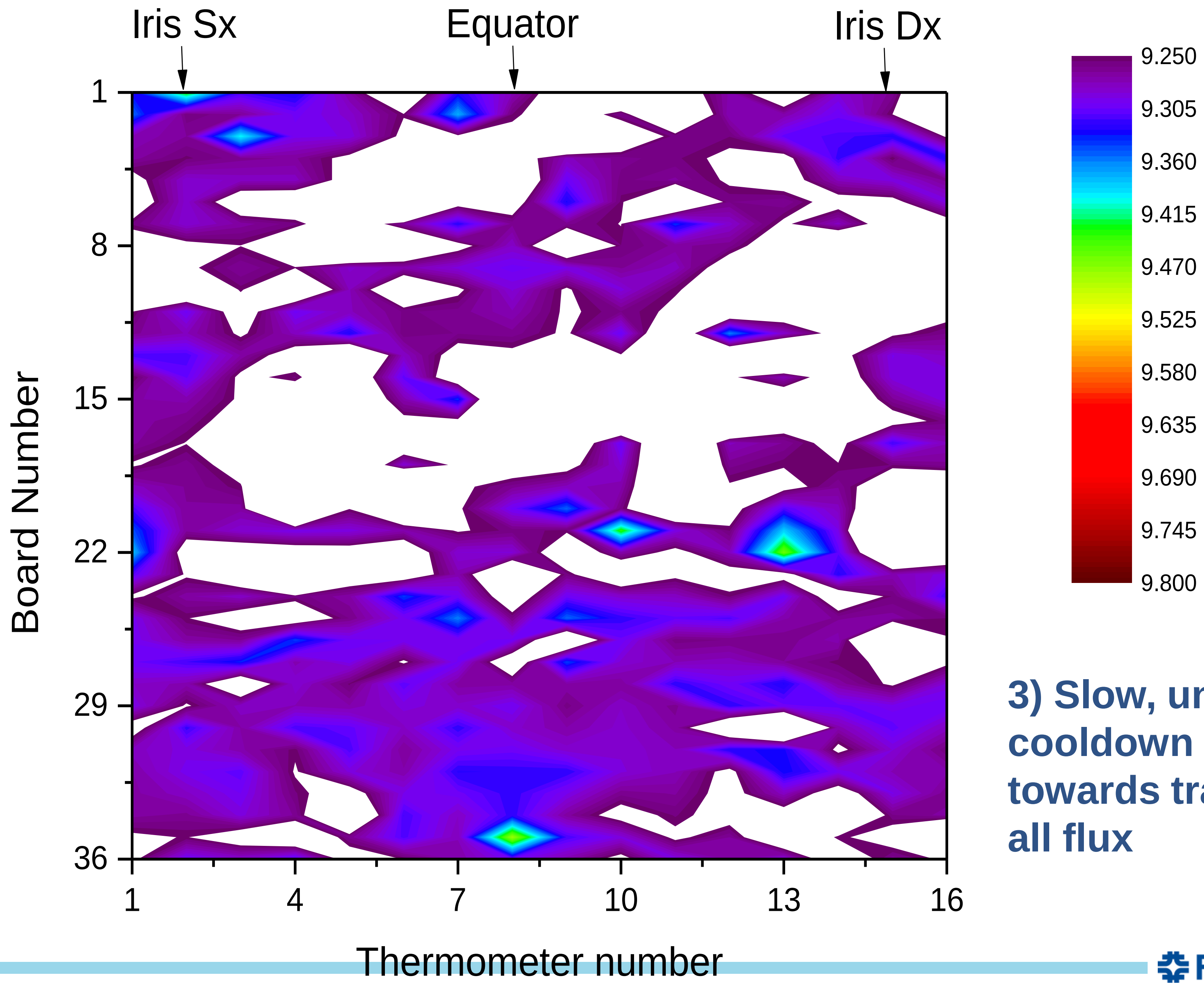

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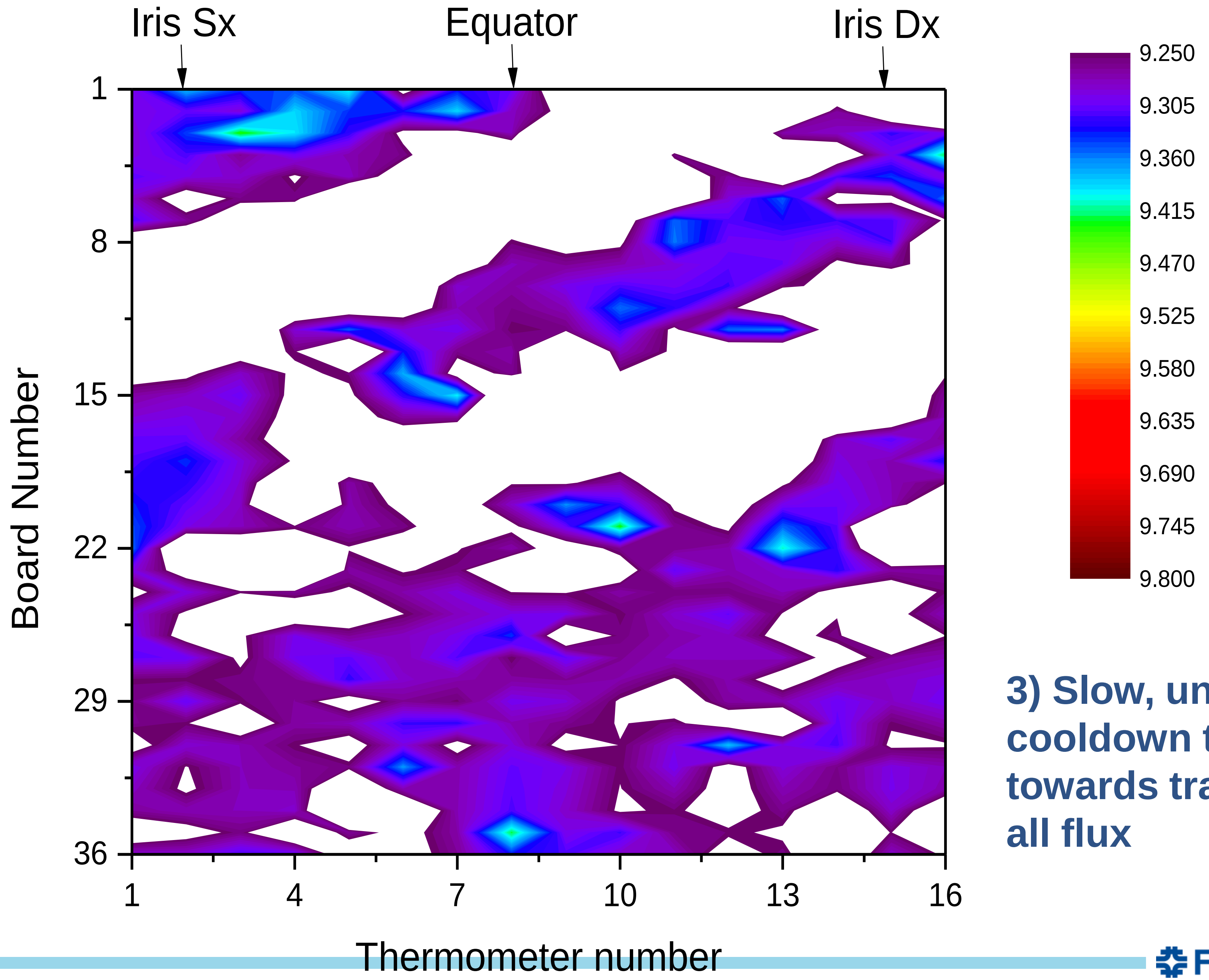

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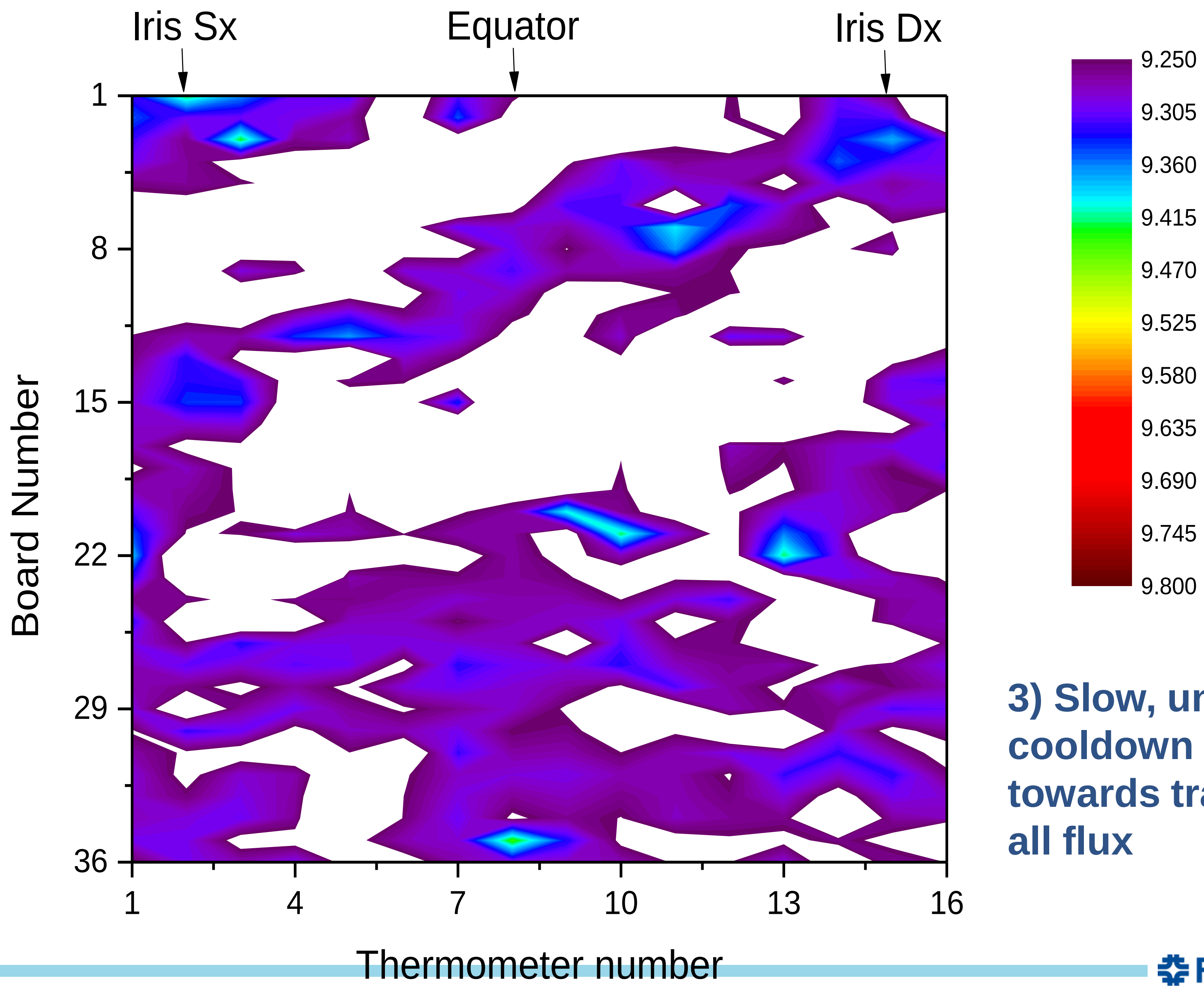

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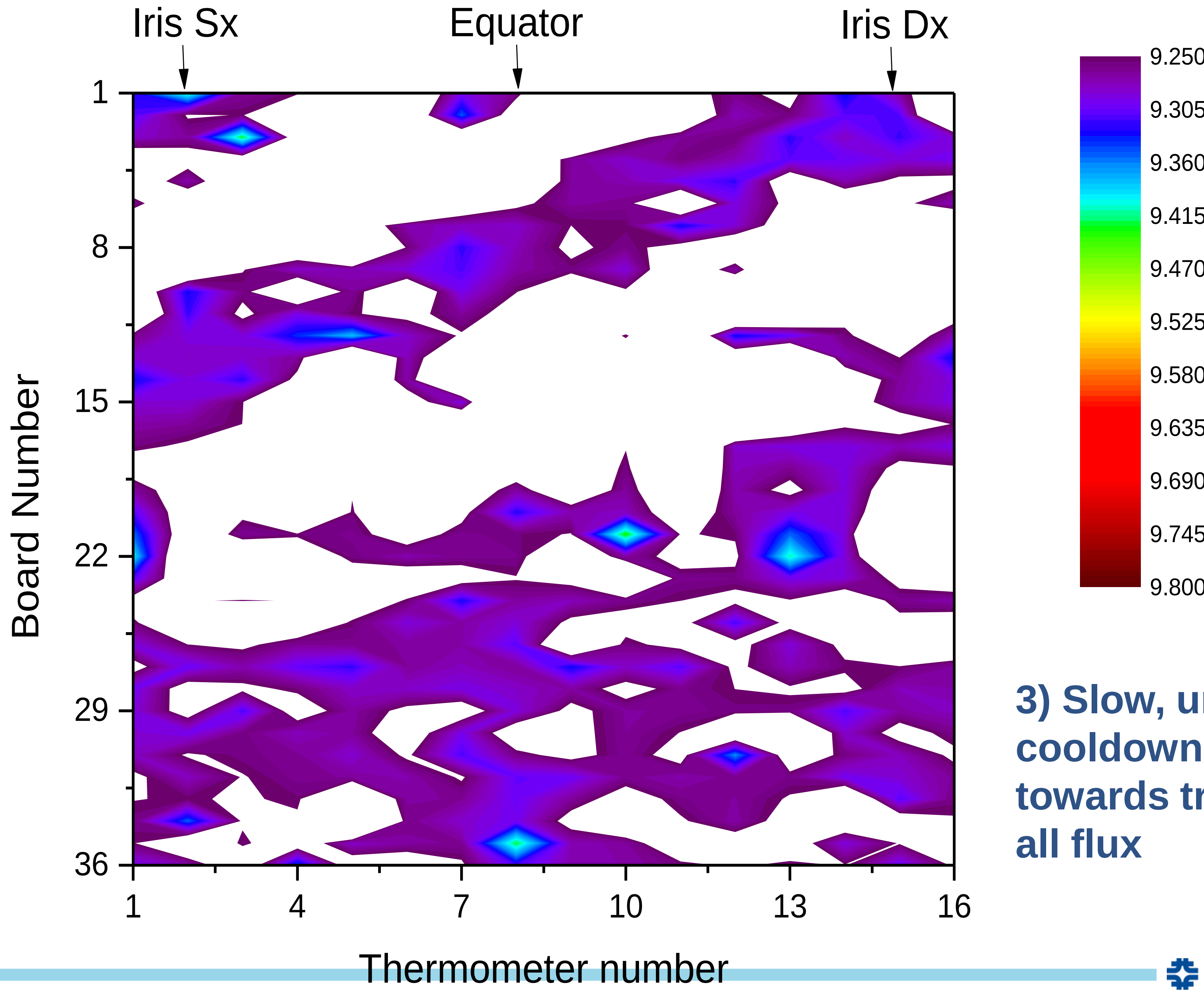

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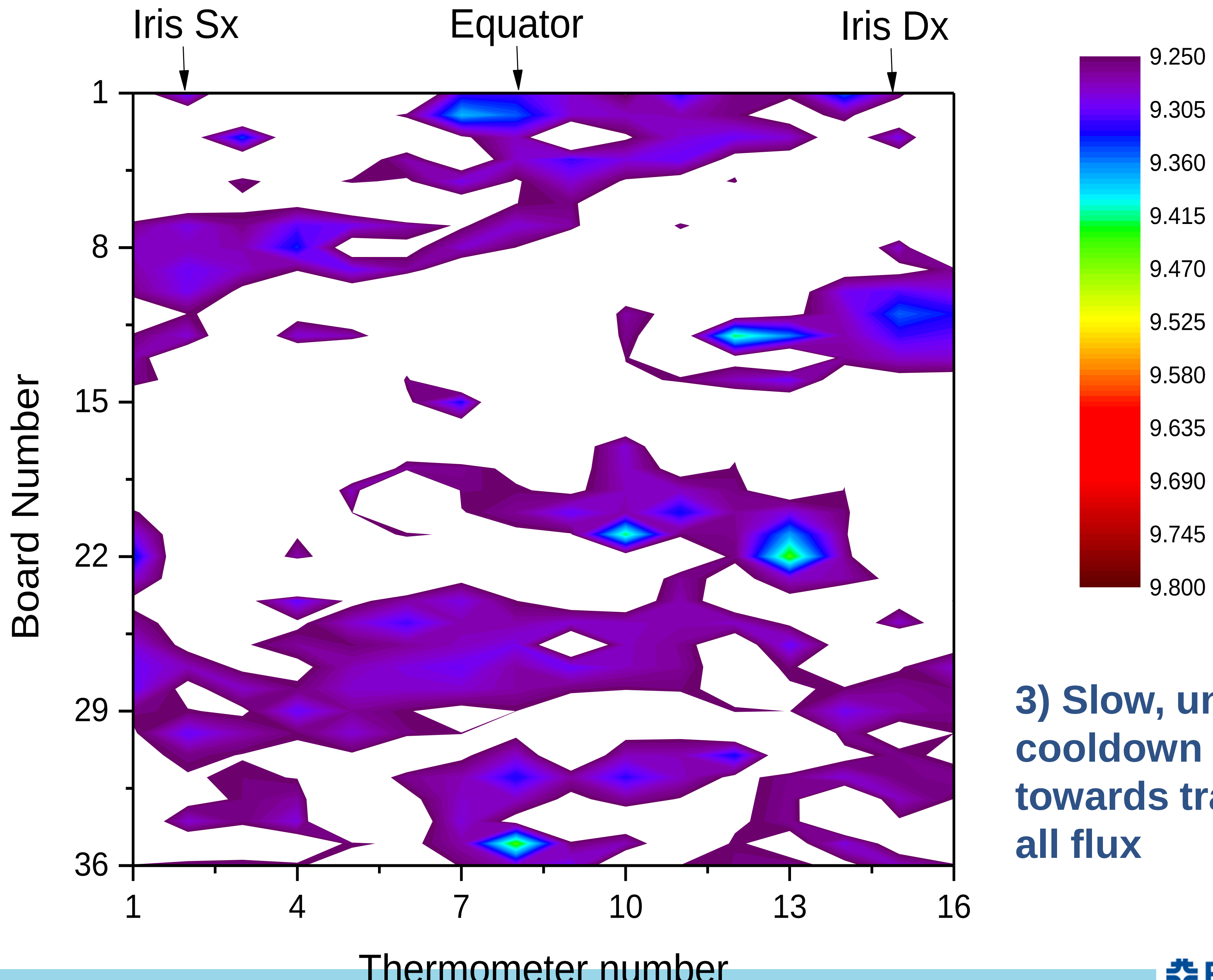

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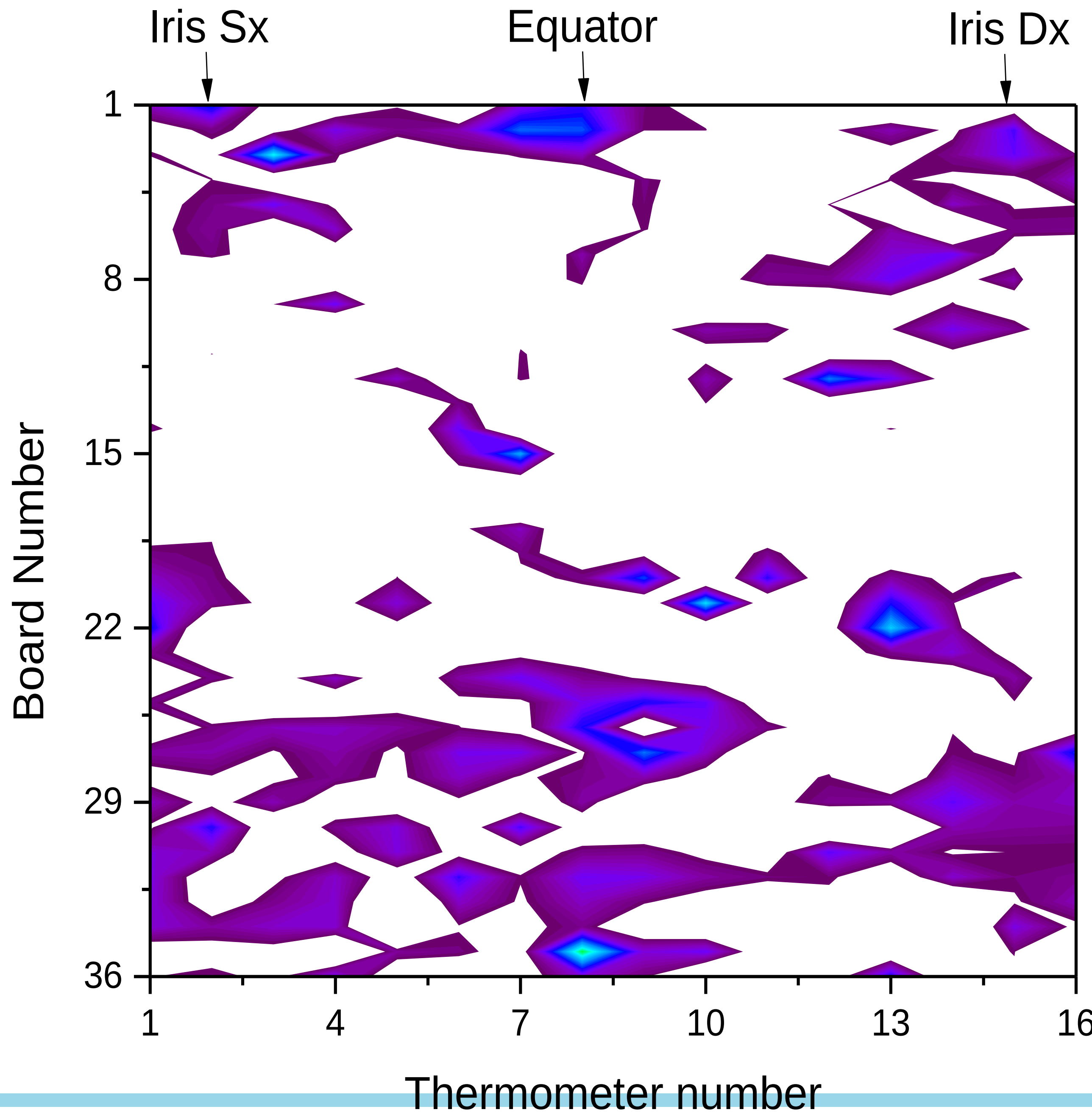

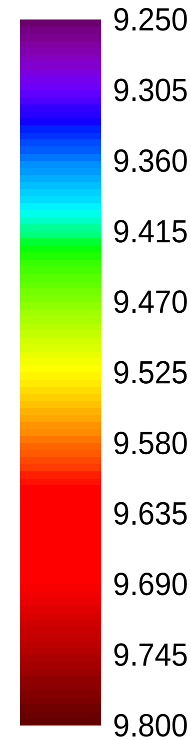

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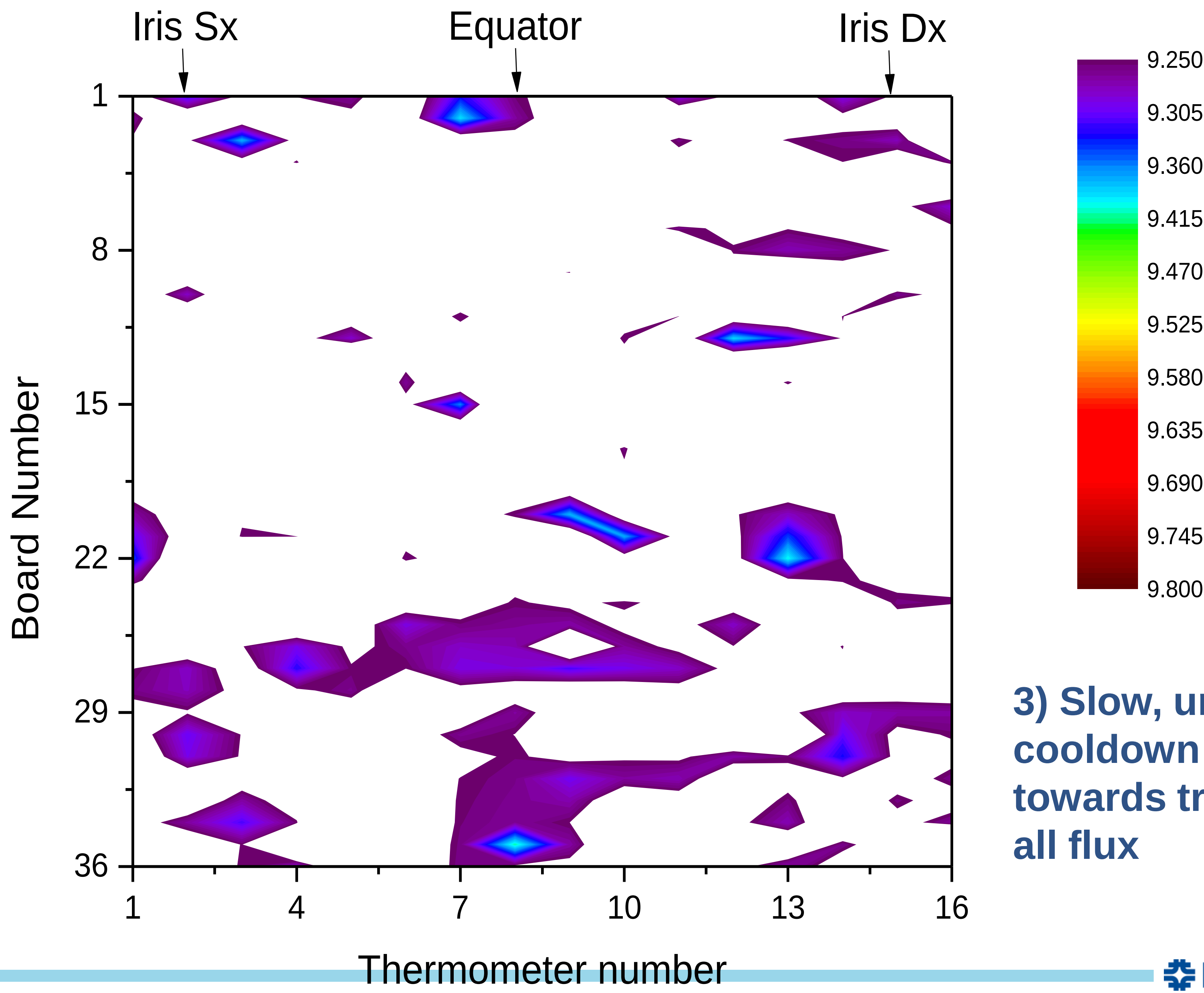

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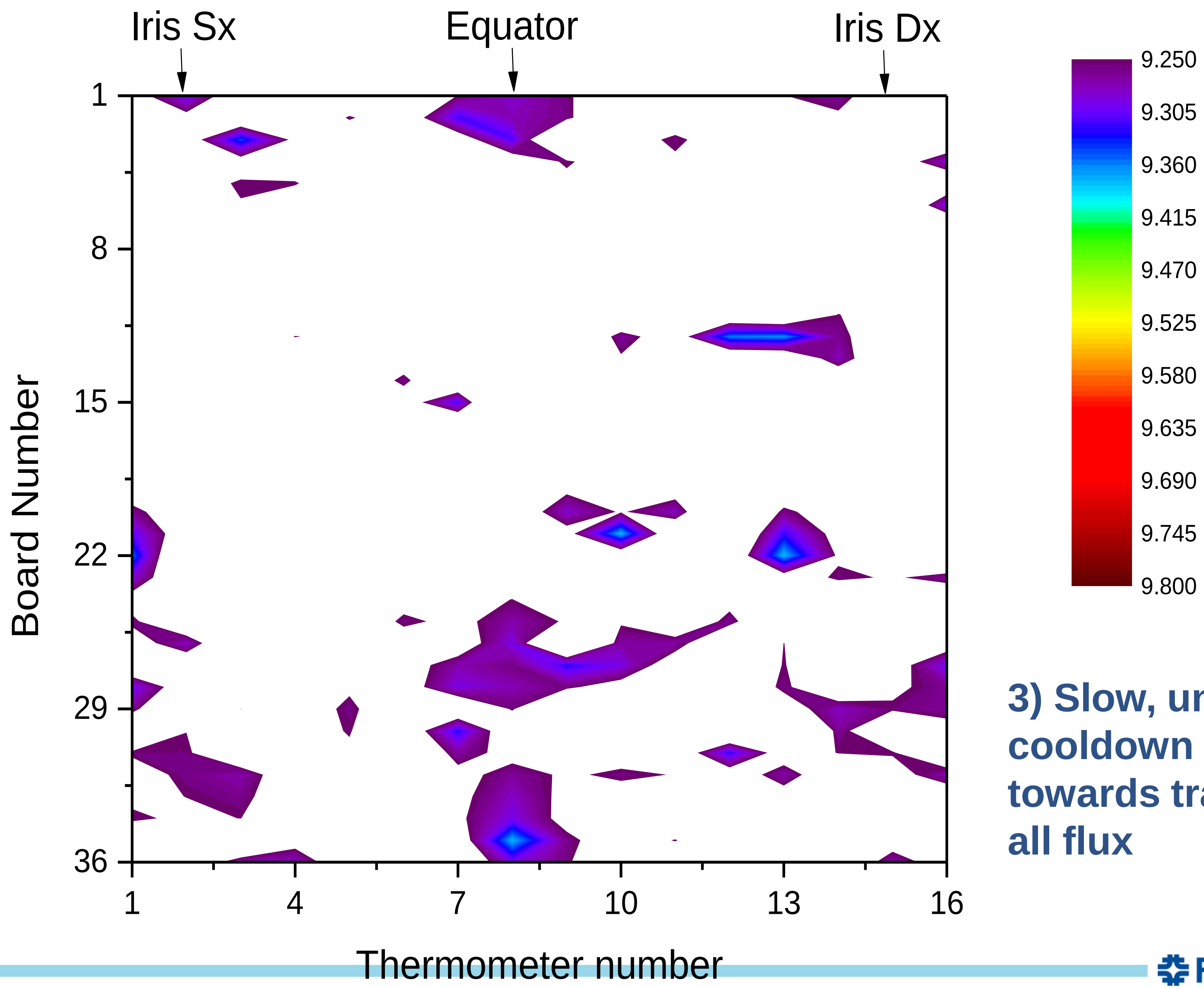

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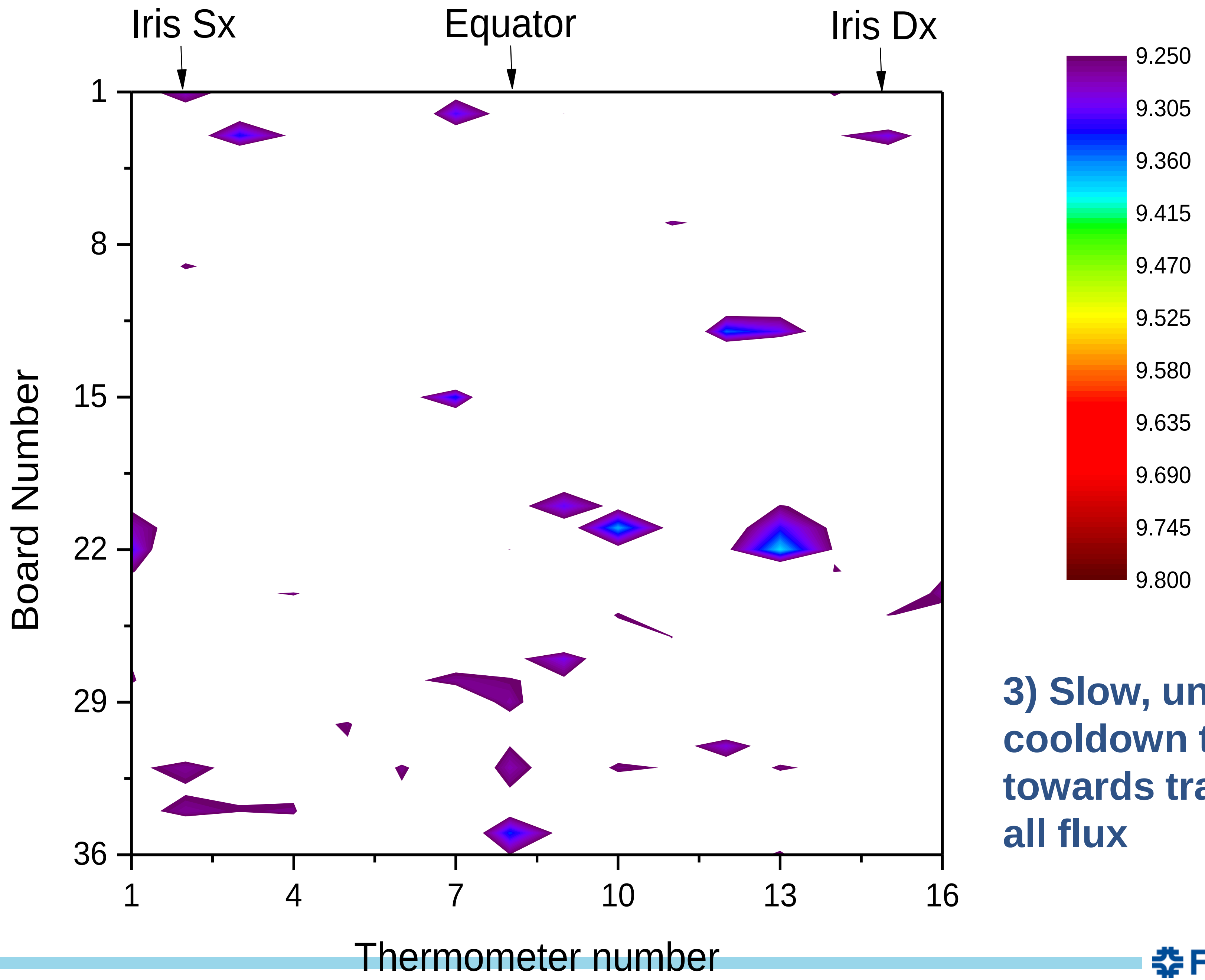

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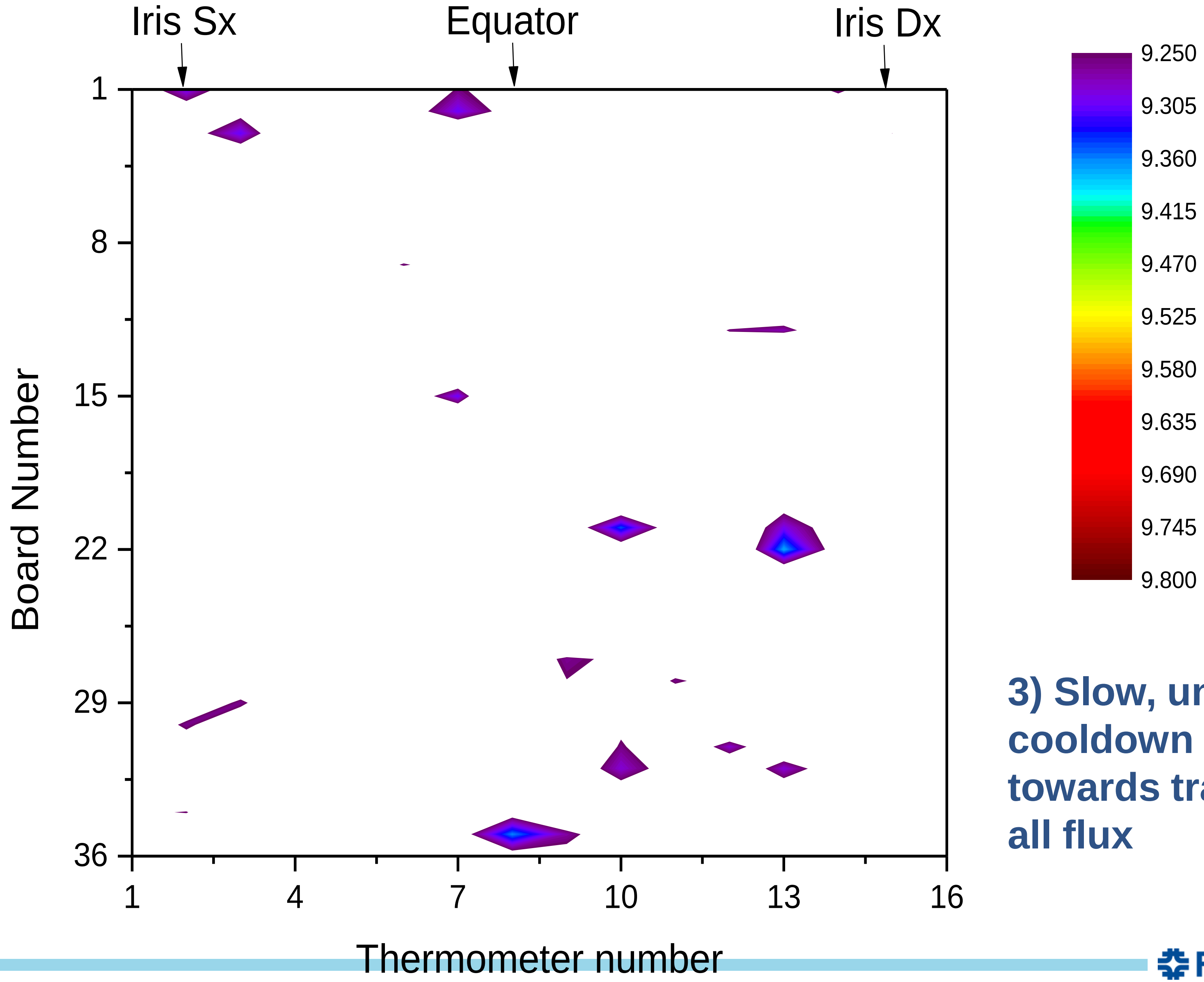

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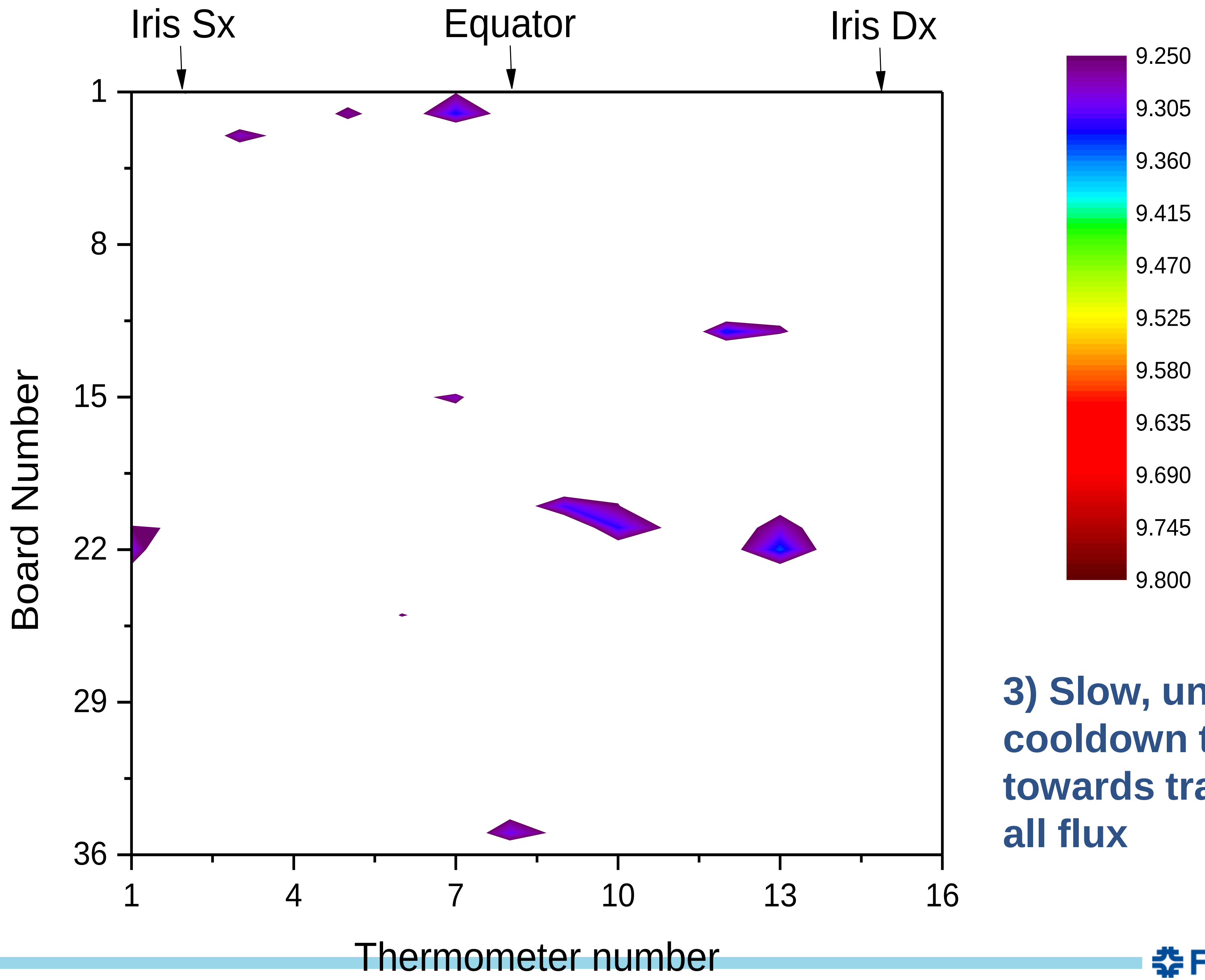

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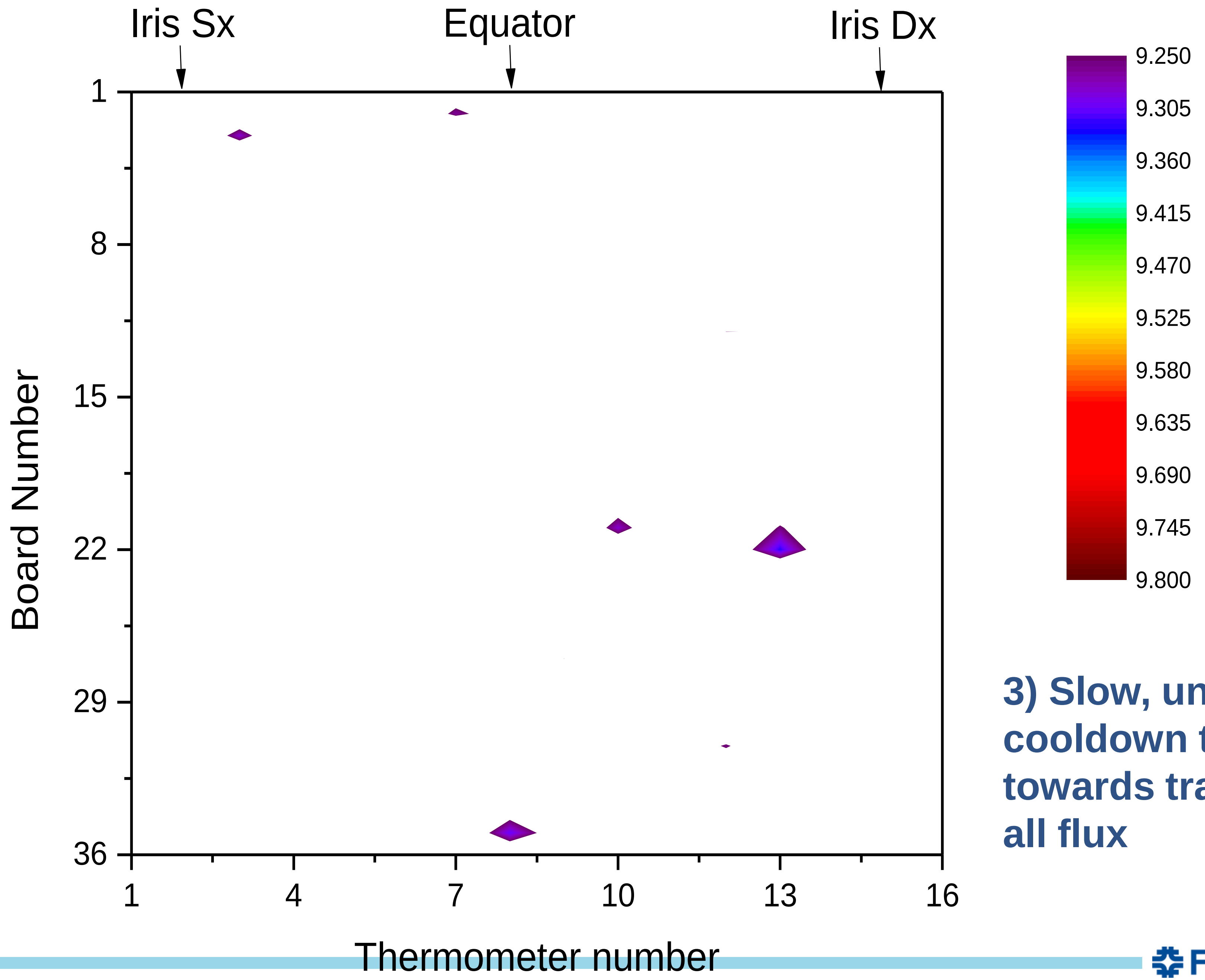

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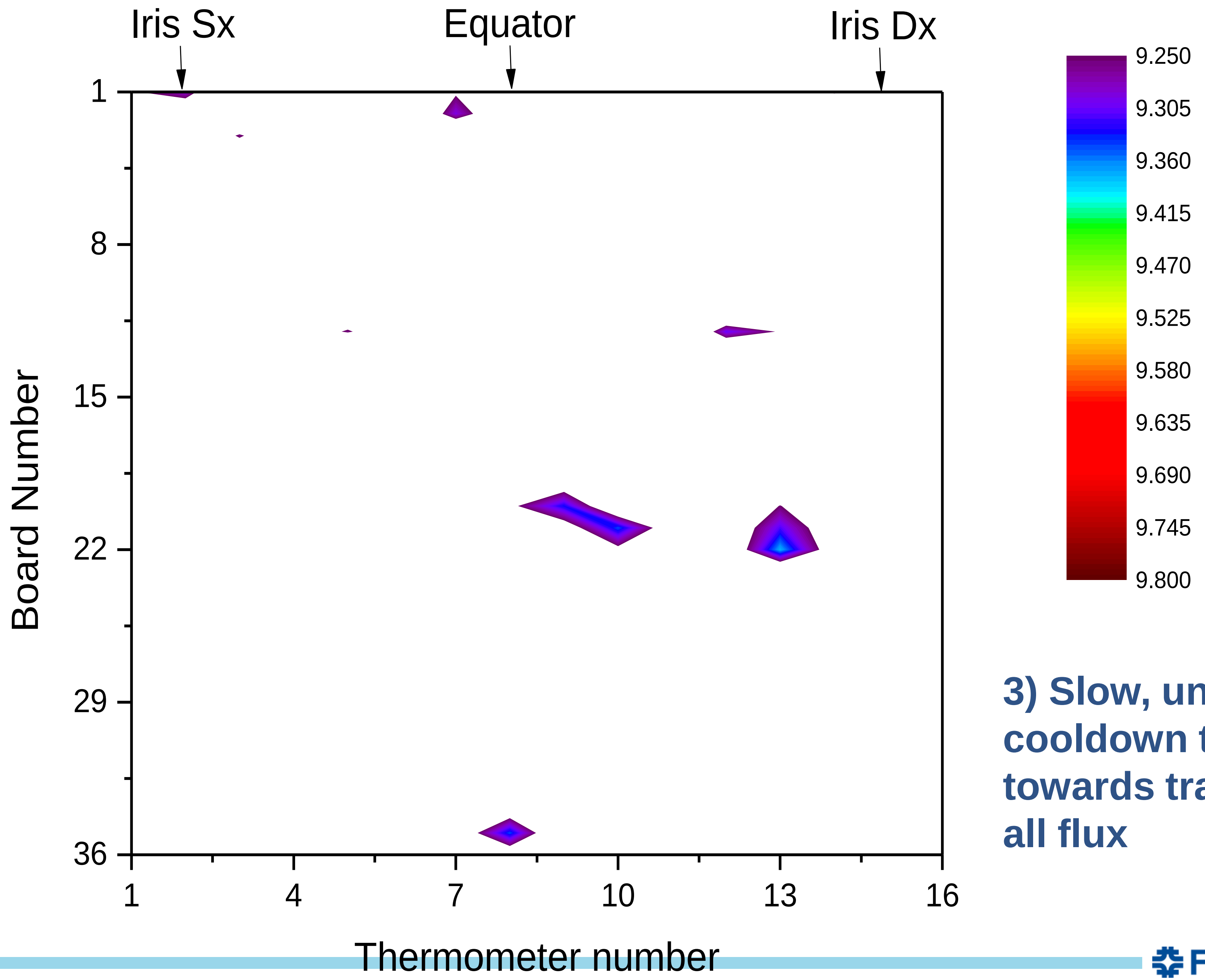

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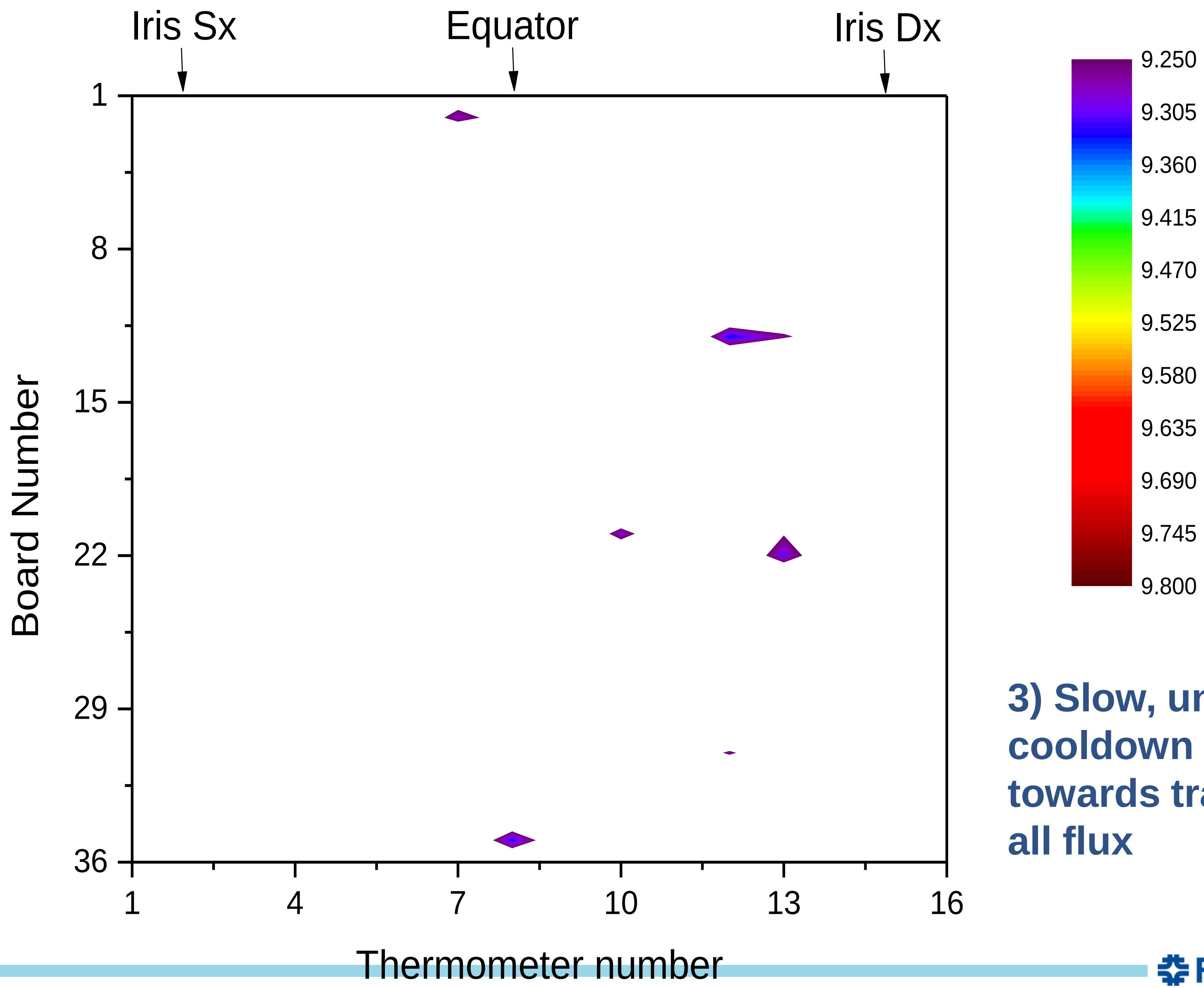

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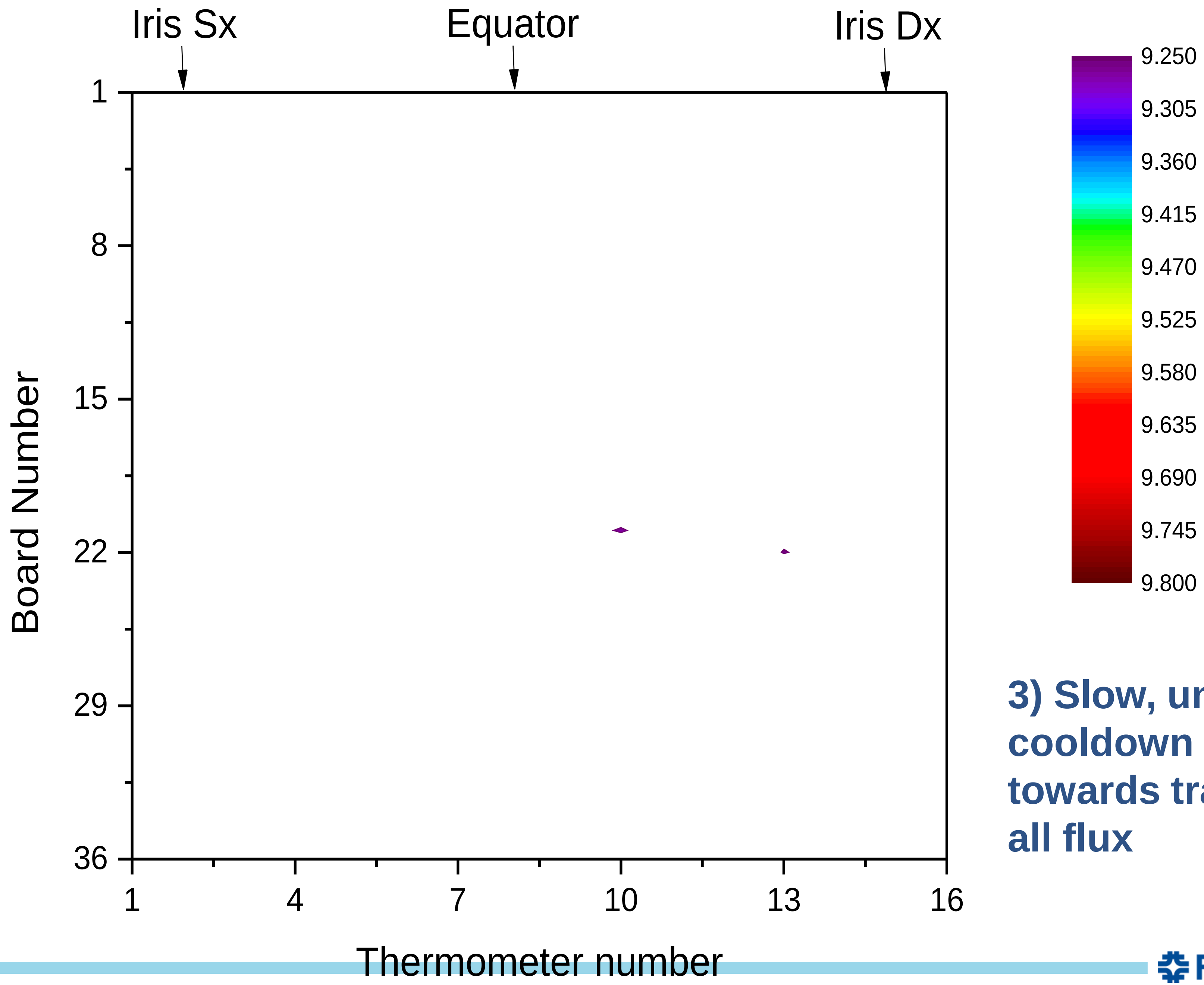
Fermilab



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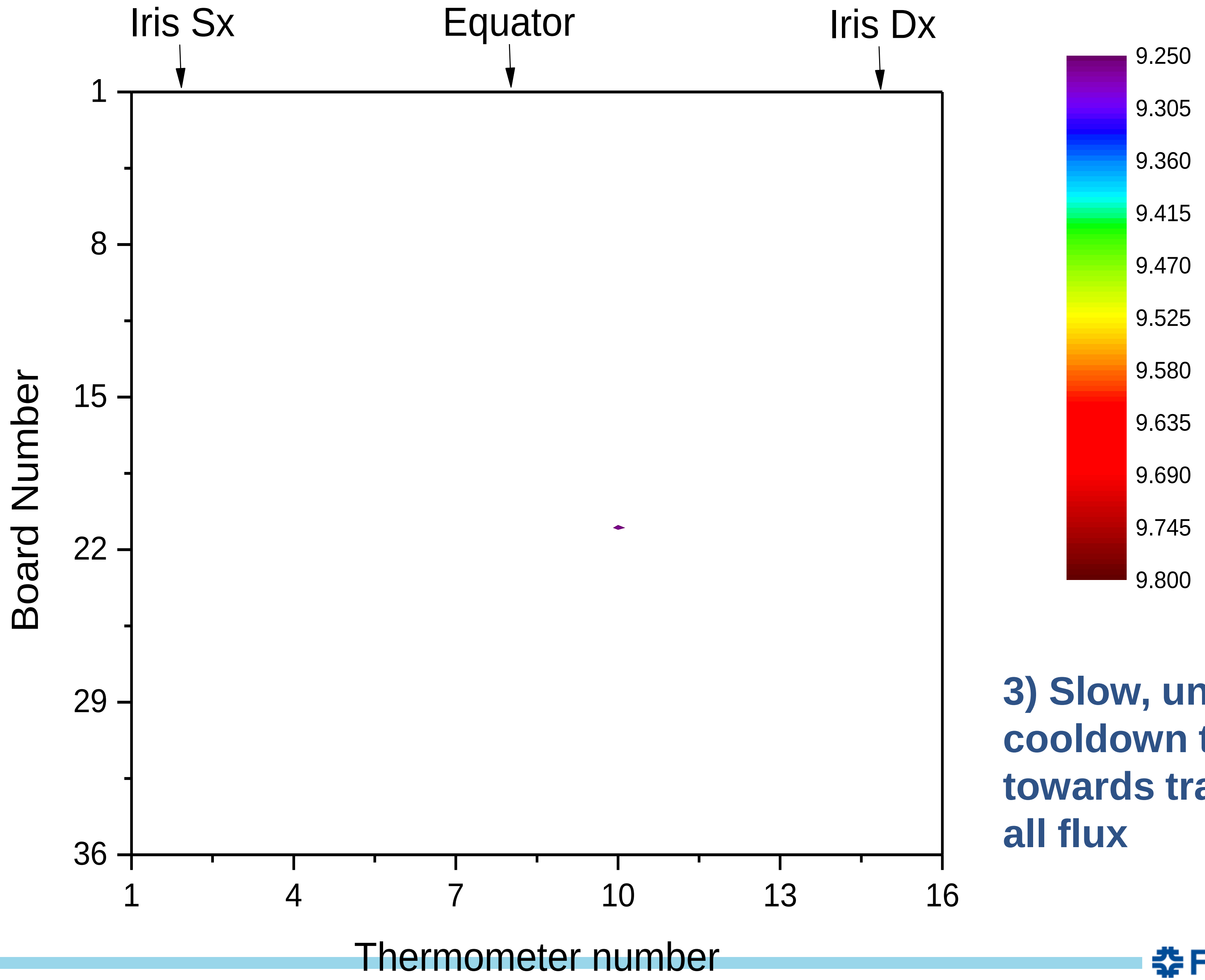
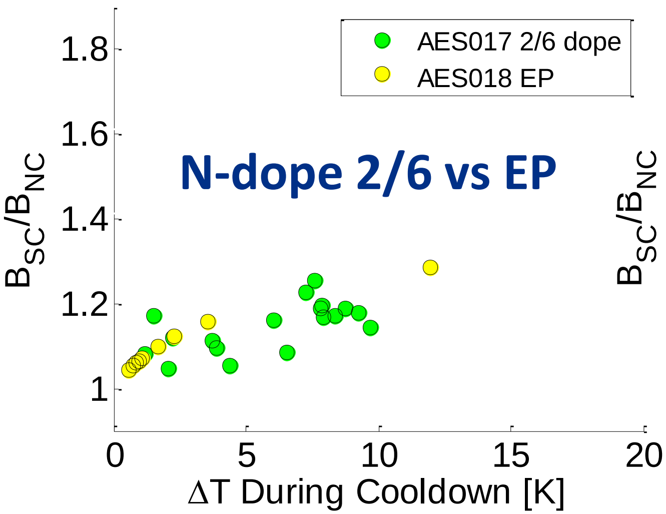
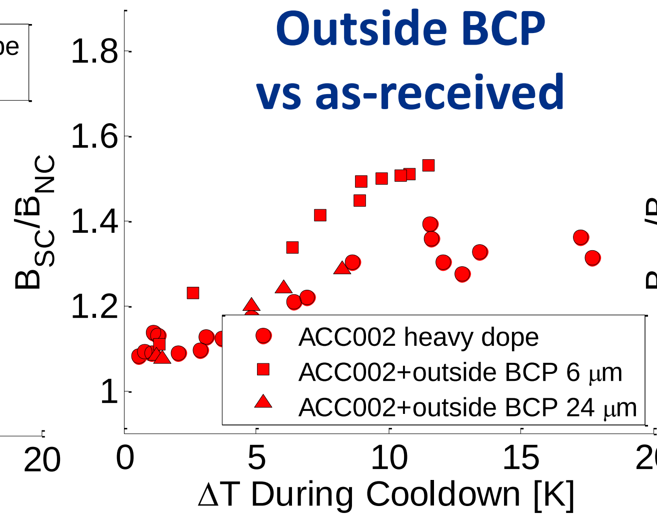
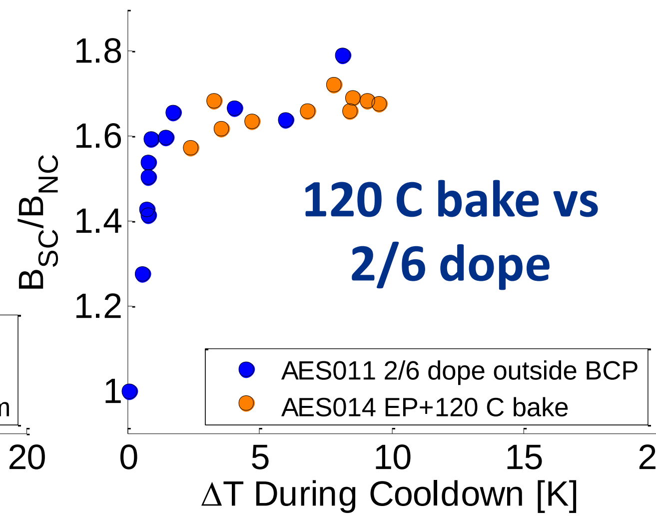


3) Slow, uniform cooldown tends towards trapping all flux

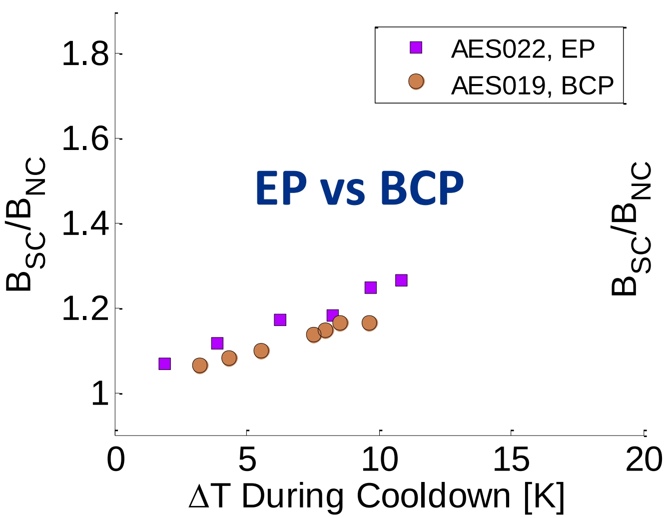
4) Surface treatments have insignificant impact

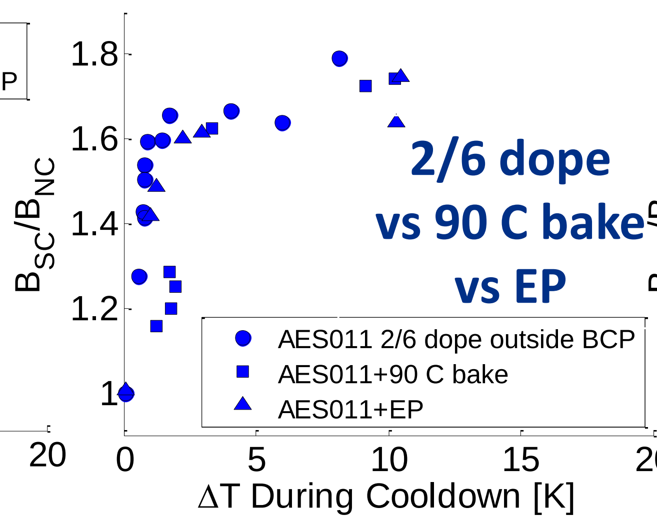


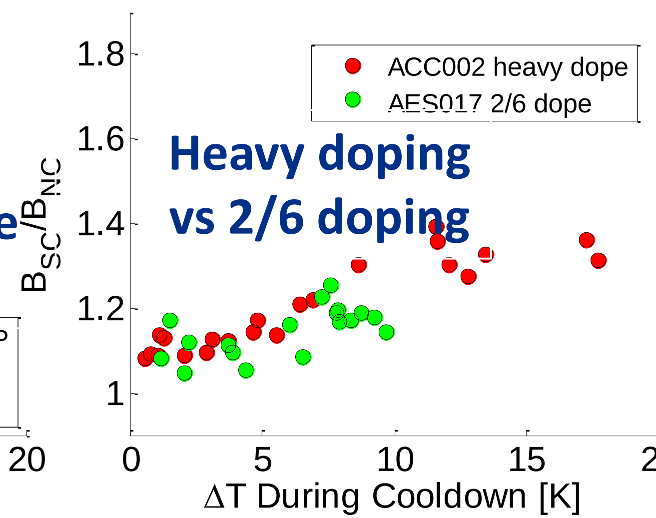




Different surface conditions in cavities with similar bulk history: similar expulsion







S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

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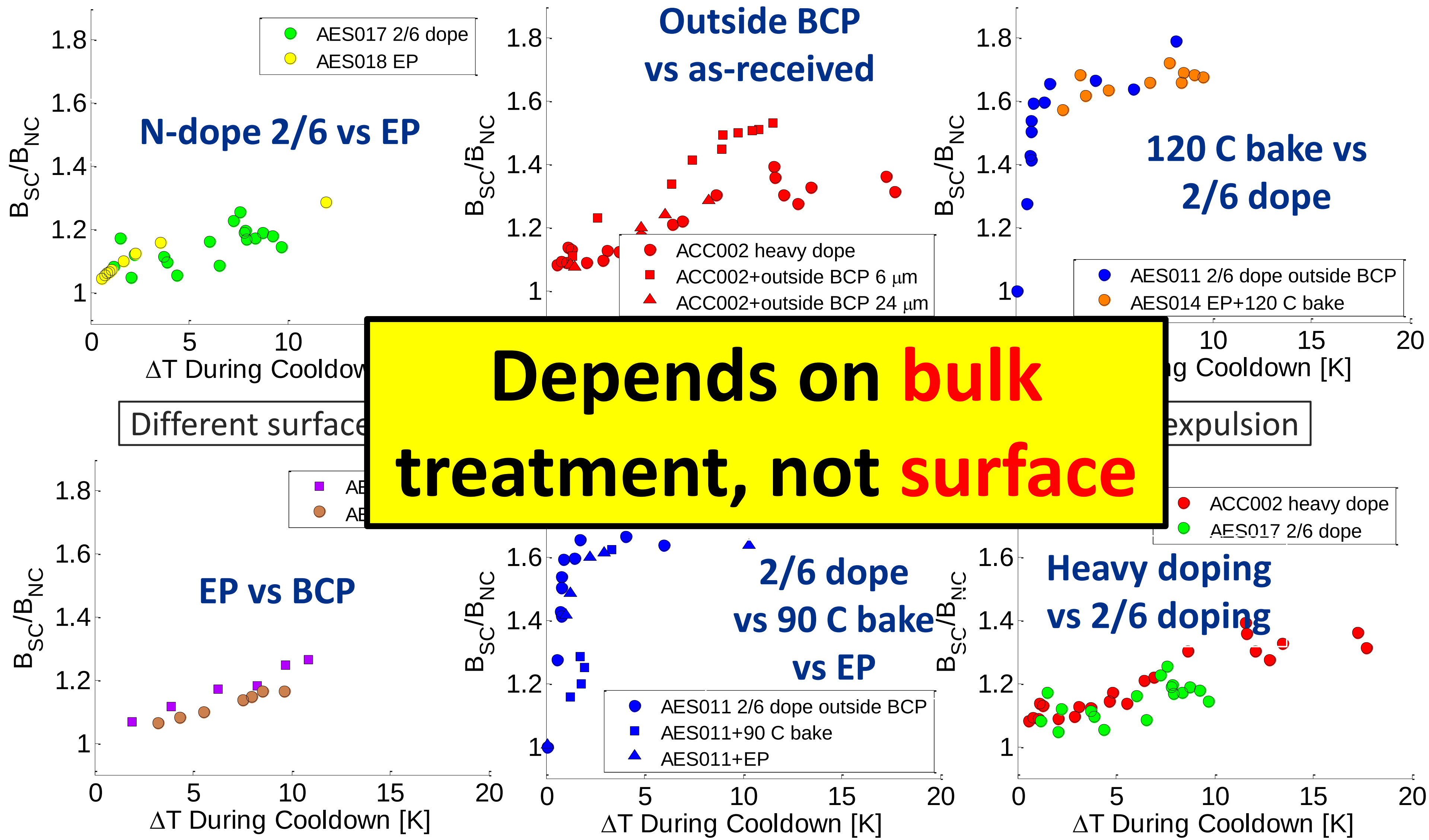

Depends on bulk treatment, not surface

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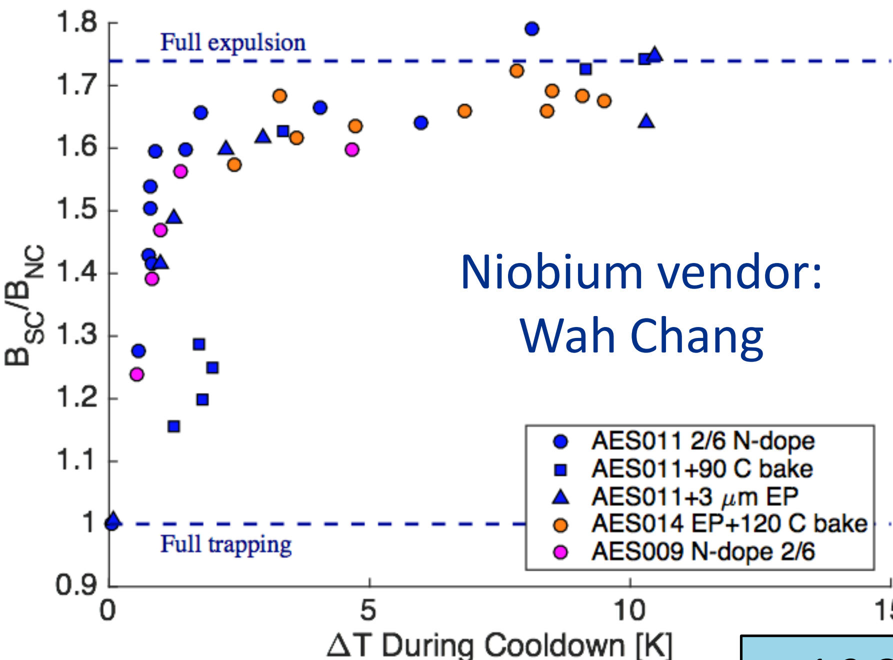
Fermilab

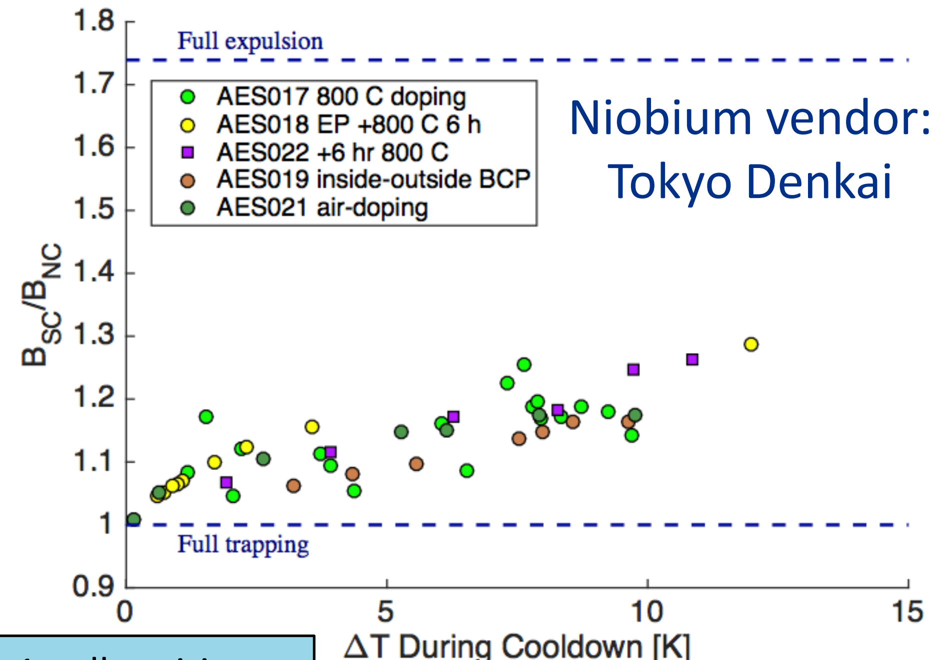
Magnetic Flux Expulsion

- Several factors influence Q_0-degradation from magnetic flux:
  - Ambient magnetic field
    - Local value of Earth's field, shielding, demagnetization, magnetic components, thermocurrents (static & dynamic), active compensation, etc. [*discussed earlier this morning*]
  - **Flux expulsion** ← Major influence from **bulk** of superconductor
    - **Fraction of ambient flux is expelled out of superconductor vs becoming trapped in it during cooldown [*the rest of today*]**
  - Sensitivity ← Major influence from **surface** of superconductor
    - For a given amount of trapped flux, what is the added surface resistance [*several presentations on this subject tomorrow*]

5) Some niobium production runs have very poor expulsion – even with large ΔT

- Seems to be a great deal of variability in as-received material
- Variability from batches even within a single vendor



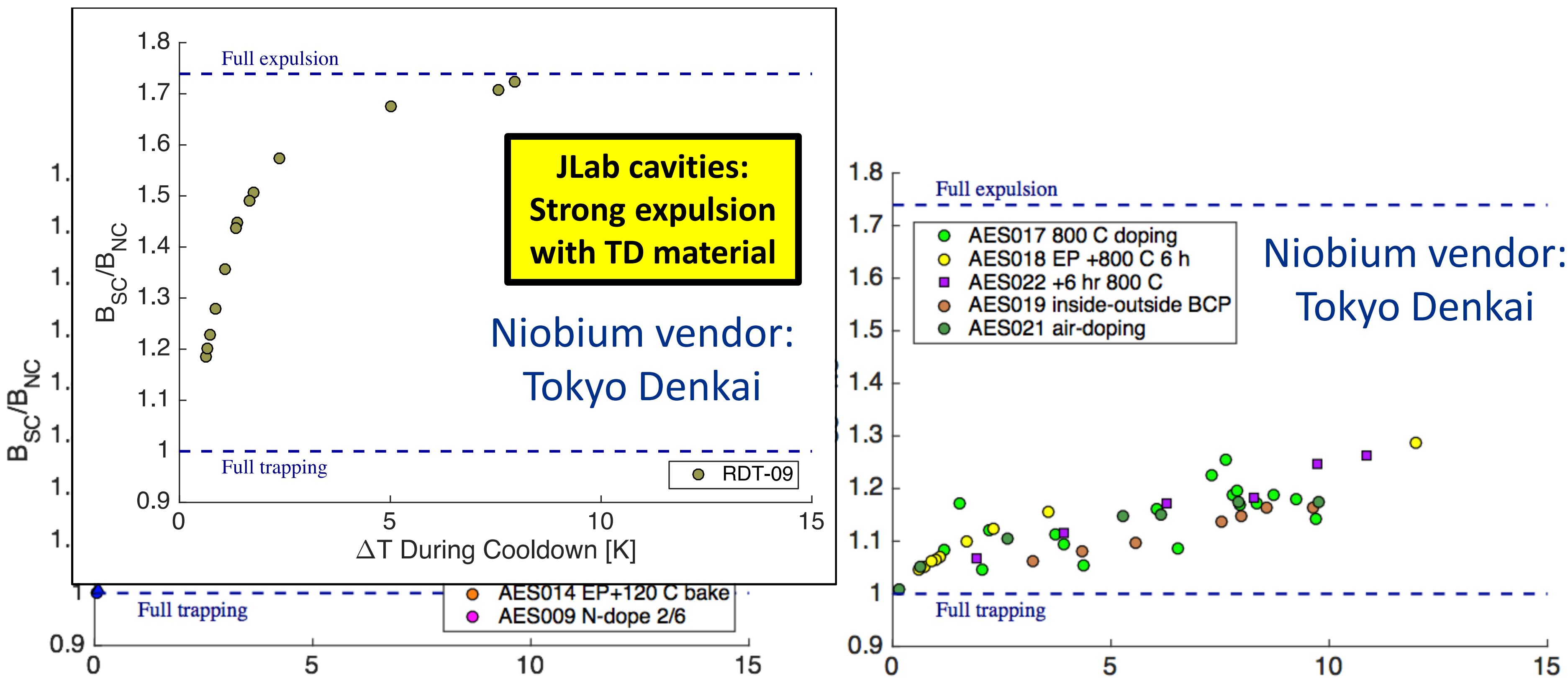


1.3 GHz 1-cell cavities

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

5) Some niobium production runs have very poor expulsion – even with large ΔT

- Seems to be a great deal of variability in as-received material
- Variability from batches even within a single vendor

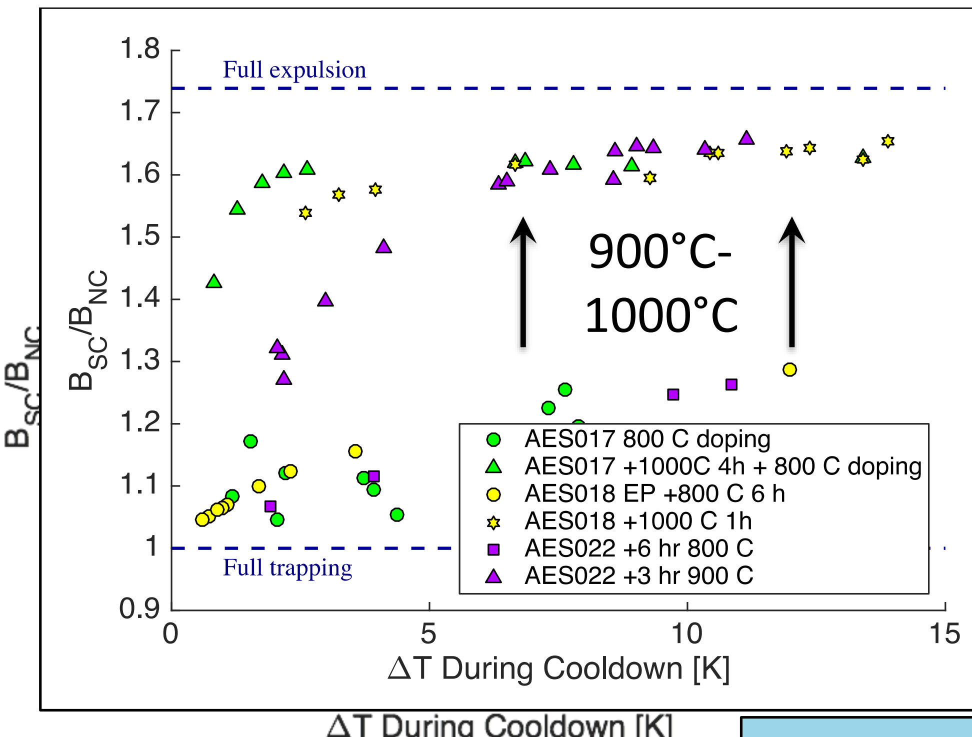


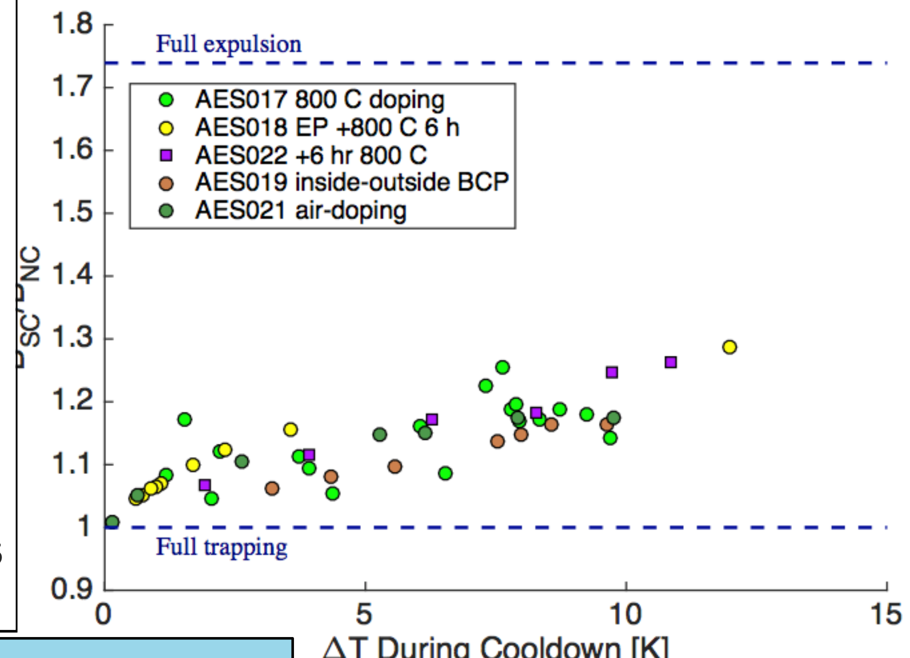
1.3 GHz 1-cell cavities

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

6) High temperature treatment can make poorly expelling material expel well even with small ΔT

- 900 C – 1000 C furnace treatment *improves* expulsion





1.3 GHz 1-cell cavities

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

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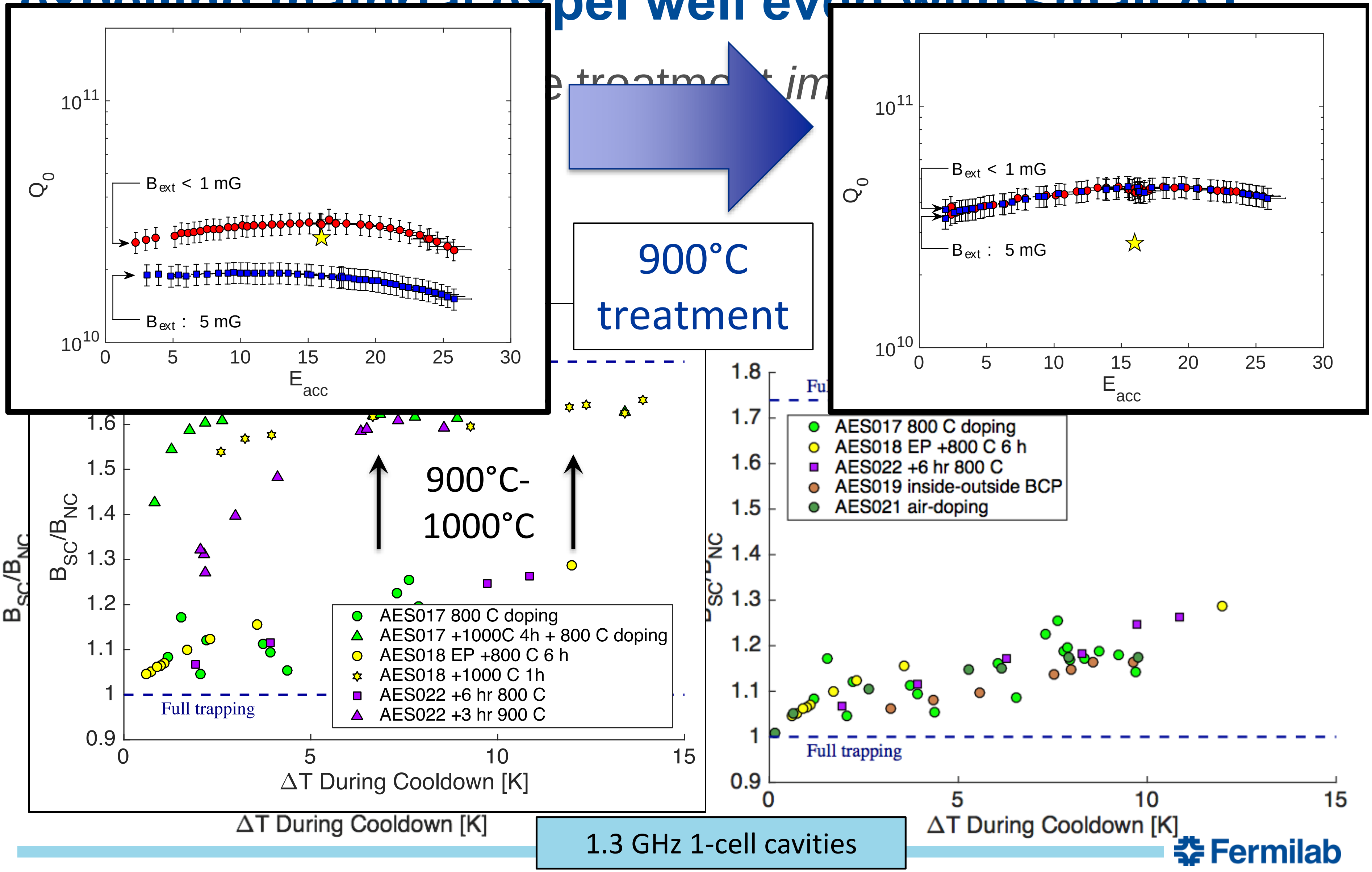
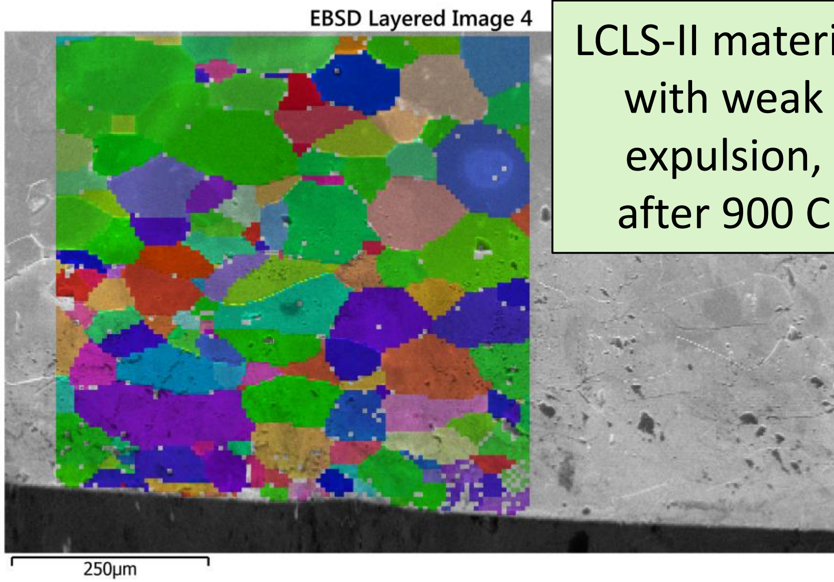
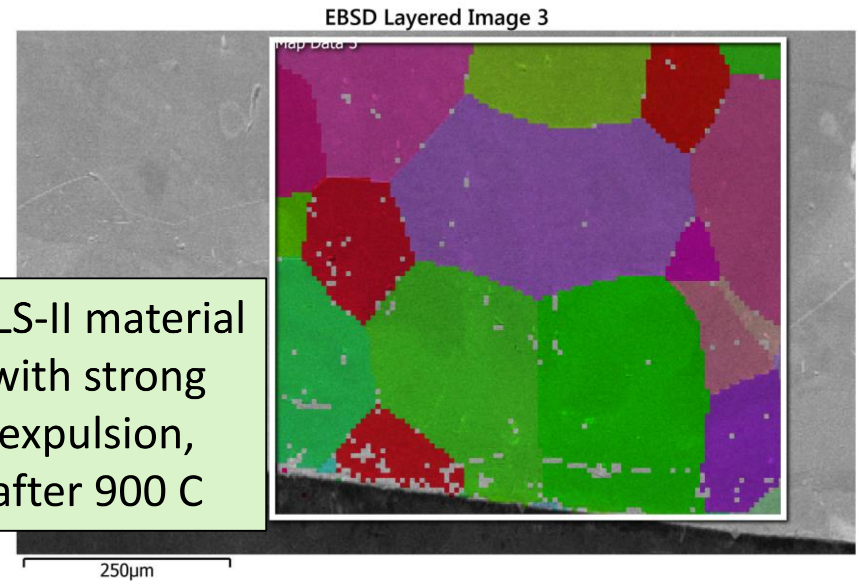


S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

7) Improvement in expulsion is correlated with grain growth



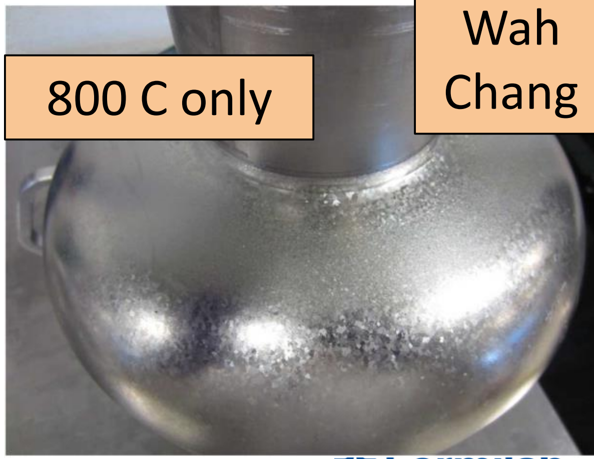
LCLS-II material with weak expulsion, after 900 C



LCLS-II material with strong expulsion, after 900 C

1000 C 4 hrs

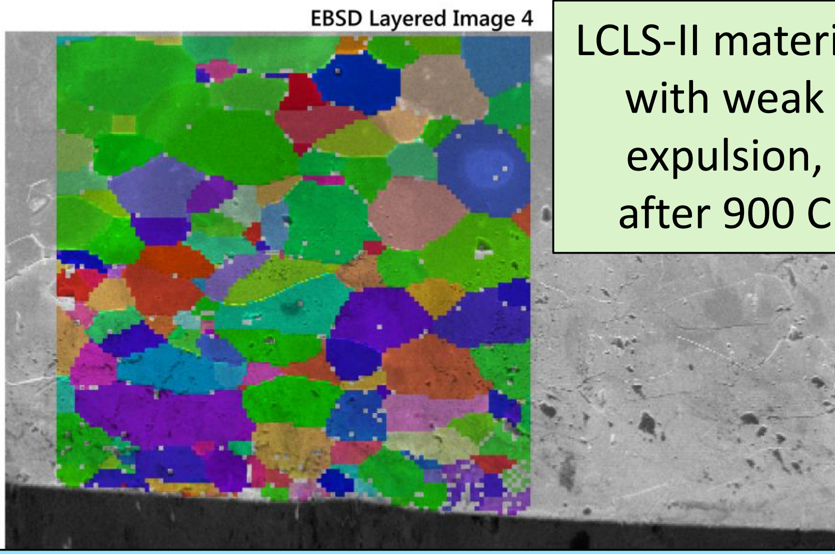
Tokyo Denkai



800 C only

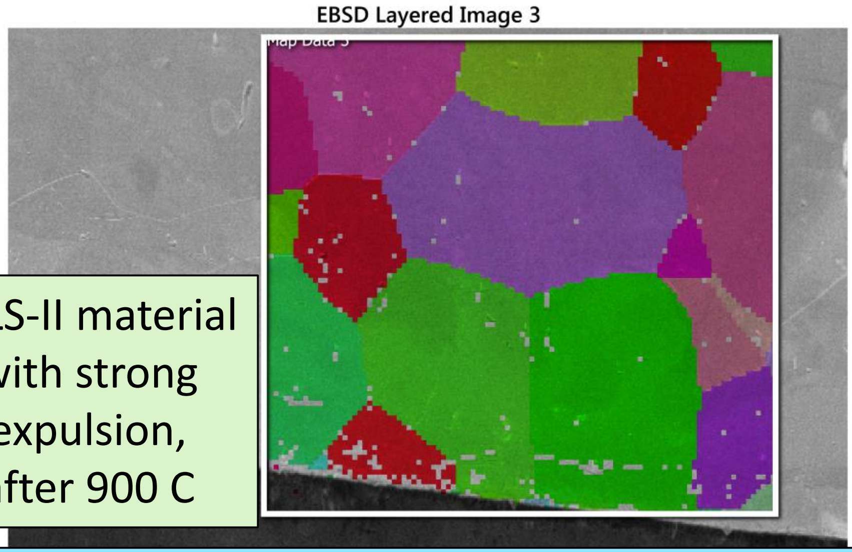
Wah Chang

7) Improvement in expulsion is correlated with grain growth



LCLS-II material with weak expulsion, after 900 C

LCLS-II material with strong expulsion, after 900 C

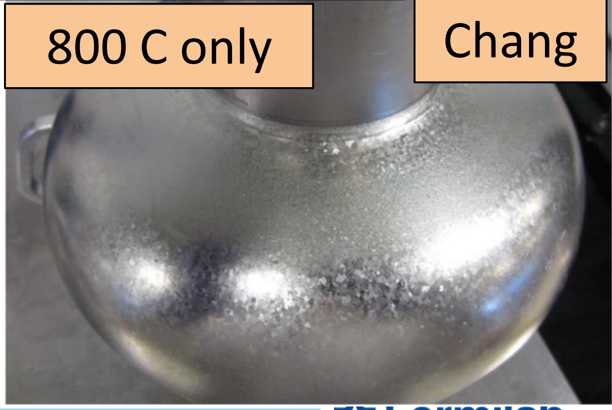


Why is 800 C enough to grow giant grains in some Nb but 1000 C required for others?

Impurities/RRR? Dislocations?

1000 C 4 hrs

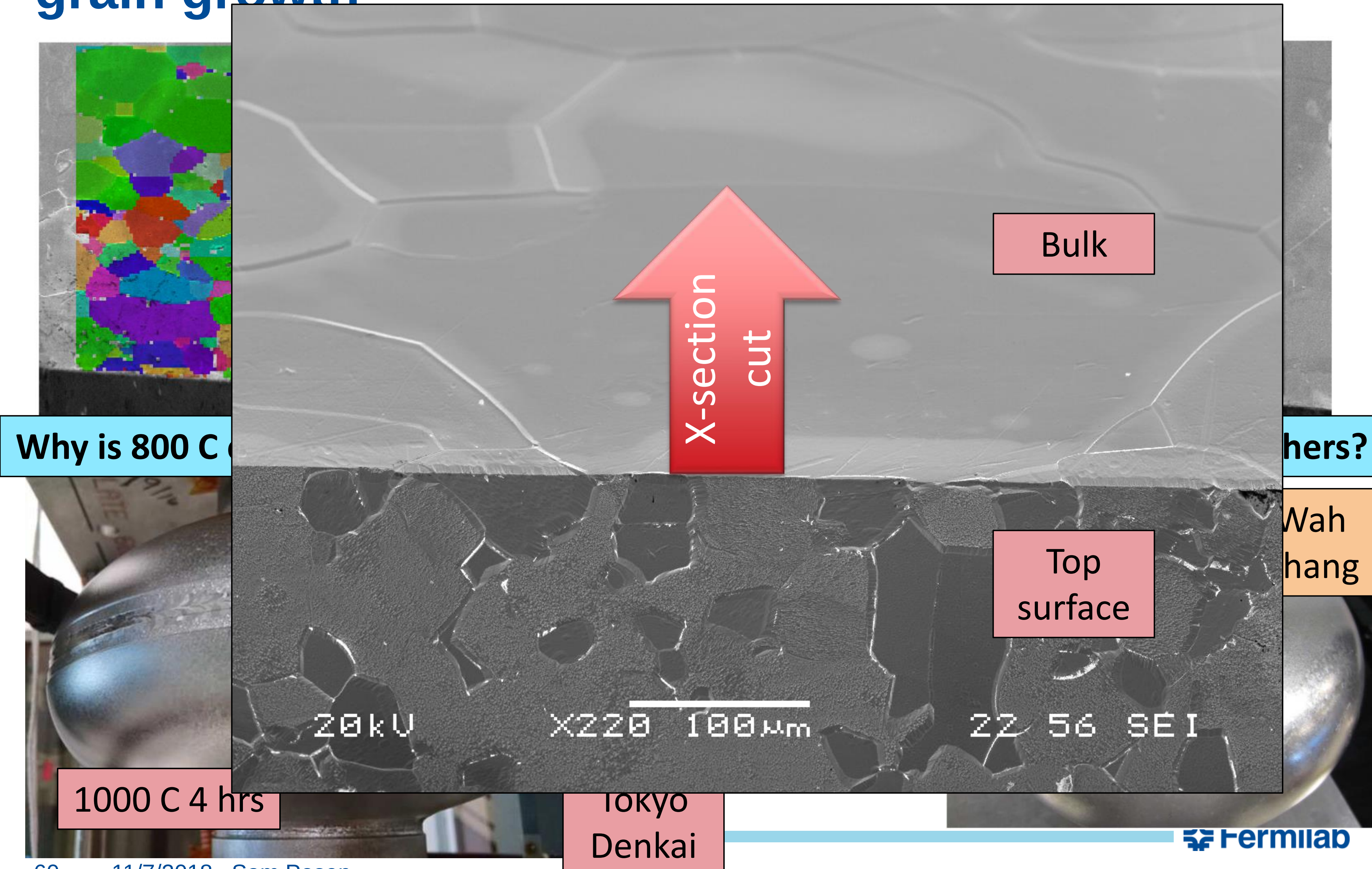
Tokyo Denkai



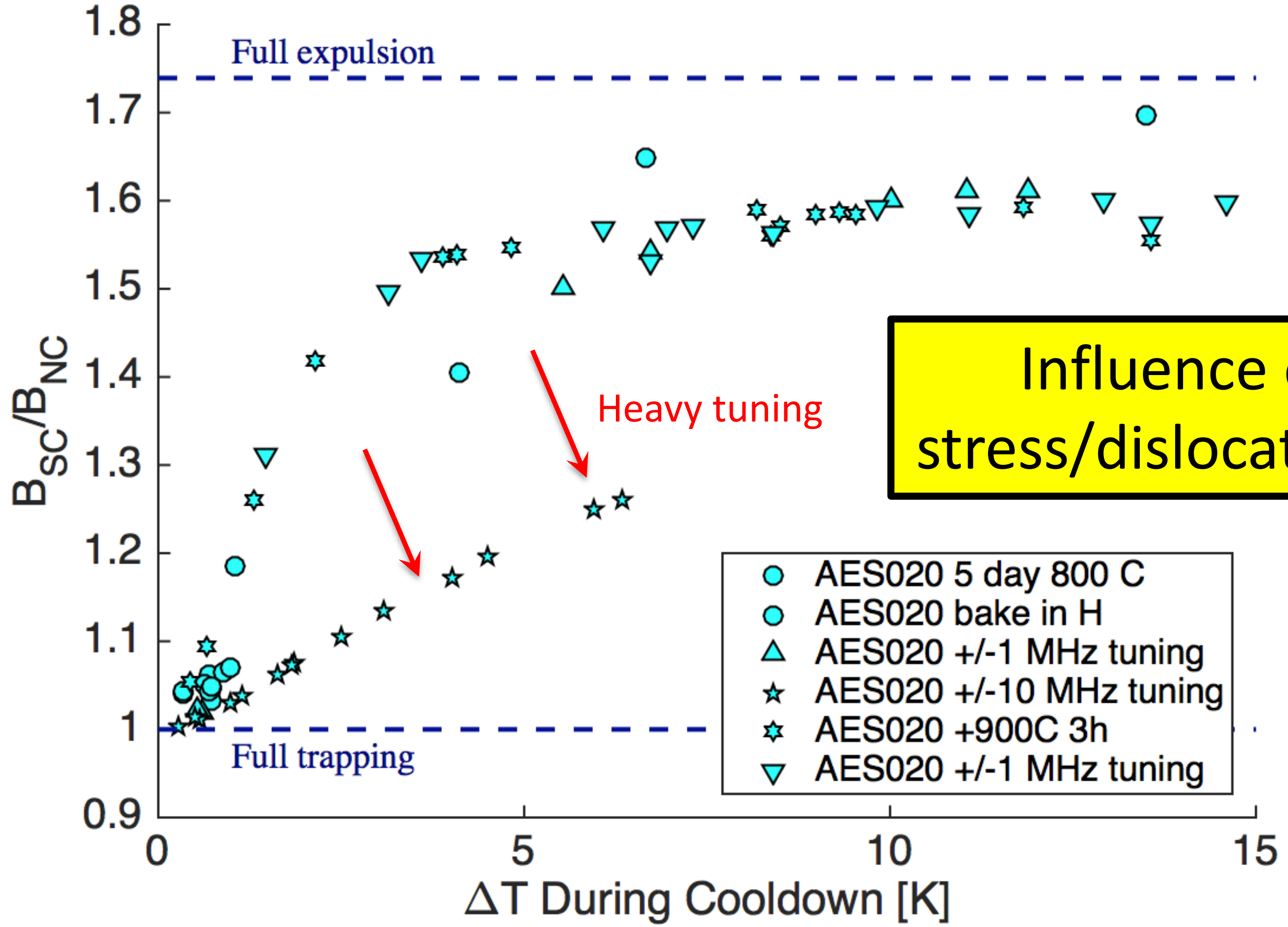
Wah Chang

800 C only

7) Improvement in expulsion is correlated with grain growth



8) Heavy deformation degrades expulsion behavior



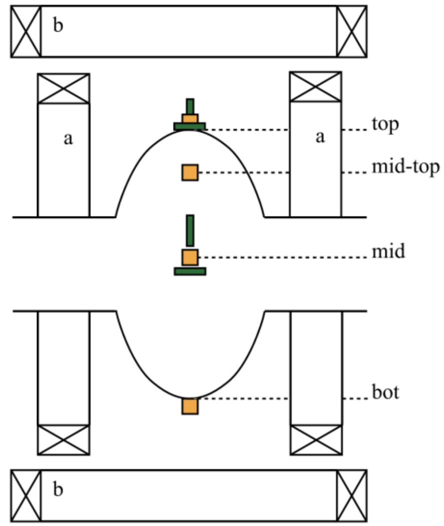
Influence of stress/dislocations?

9) Geometry affects expulsion

- Geometry can affect the location and intensity of trapped flux
- Trapping in the high magnetic field region can lead to substantial heating

M. Martinello et al. Journal of Applied Physics 118, 044505 (2015)

2 talks on geometry this afternoon



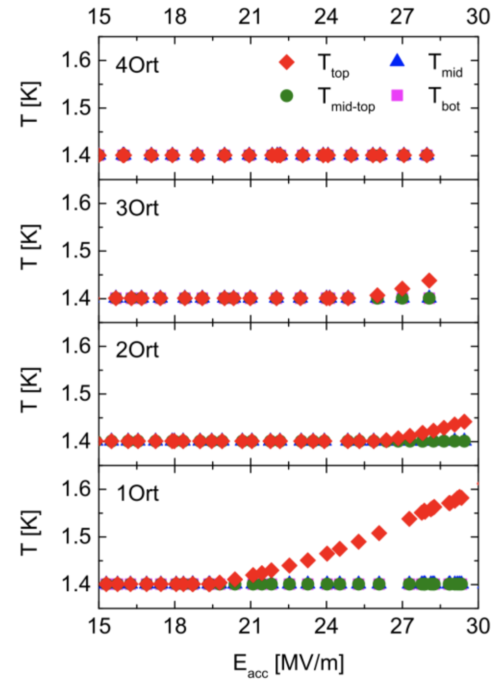


FIG. 7. Cavity top temperature variation versus the accelerating field.

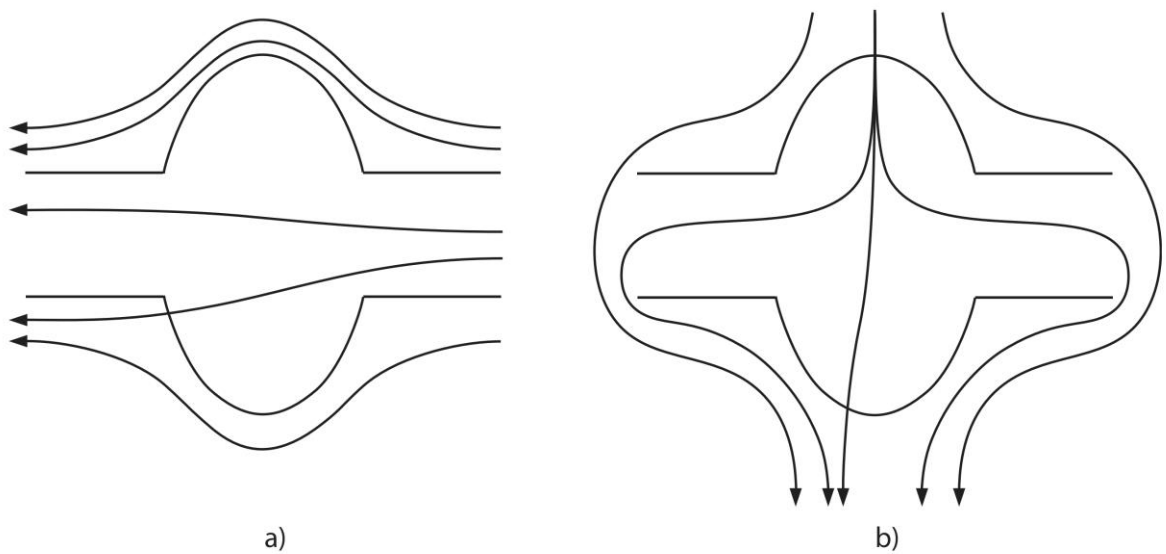
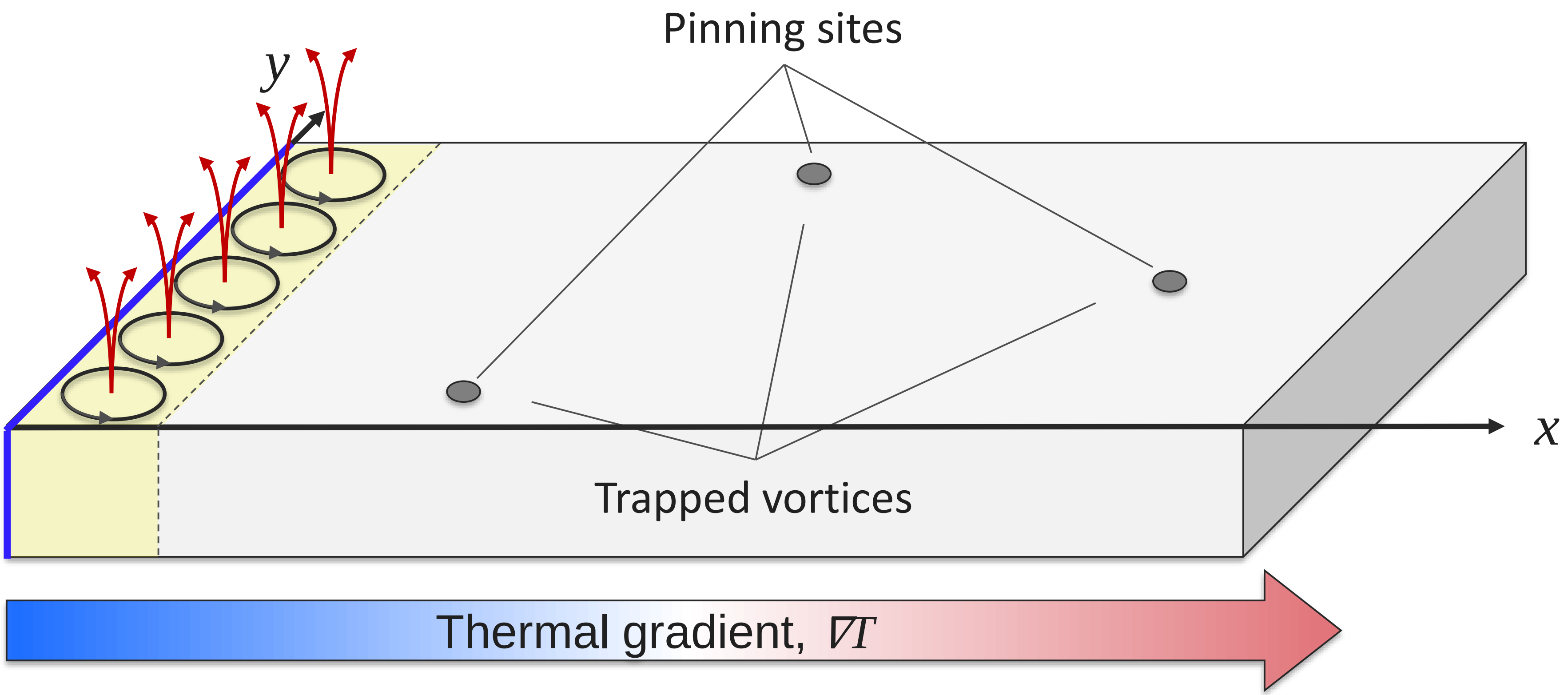


FIG. 2. Field redistribution in the Meissner state with magnetic field applied (a) axially and (b) orthogonally.

Comparison of Theoretical Models

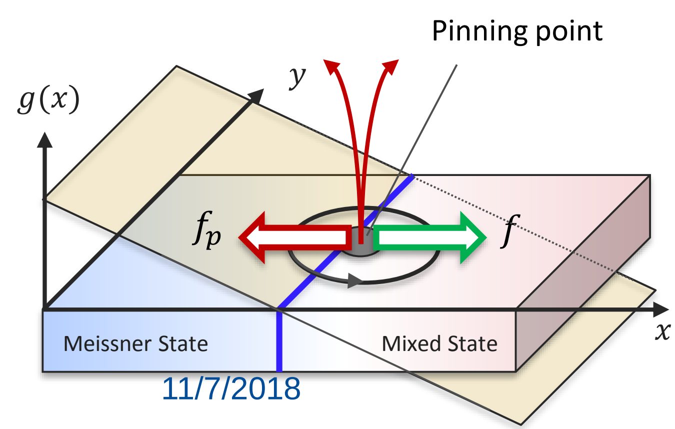
Model for Flux Expulsion – Competition Between Forces



- Competition between two forces:
  - Pinning force from pinning sites
  - Depinning force from thermal gradient

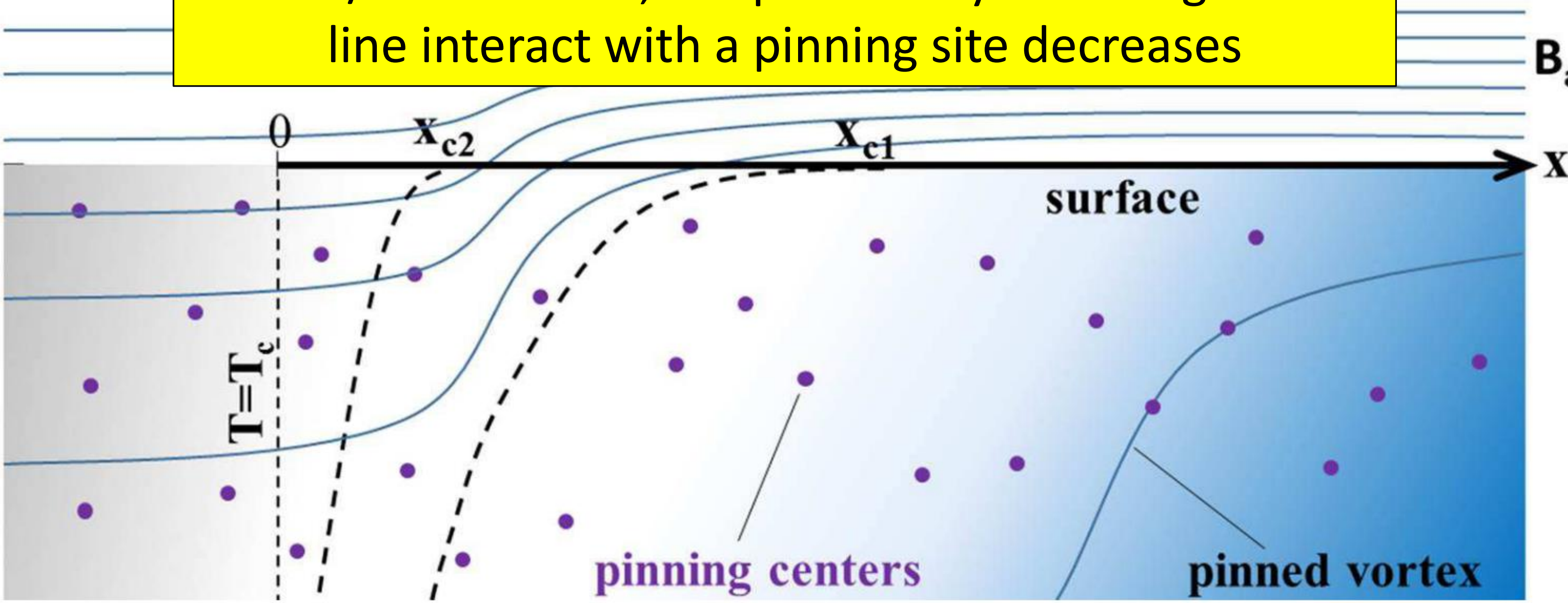
A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)

See also M. Checchin, SRF 2017



Model for F.E. – Probability for Hitting Strong Pinning Sites

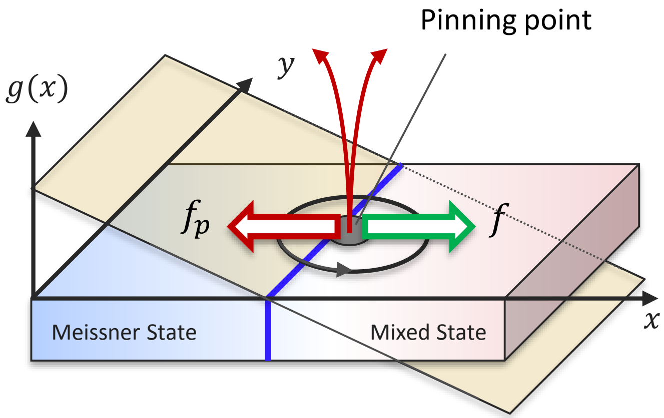
As dT/dx increases, the probability of having a flux line interact with a pinning site decreases

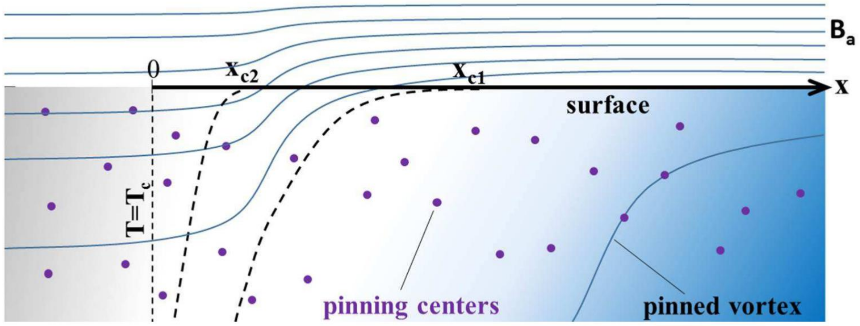


and ξ^*. The existence of the factor $|\tilde{T}'|^{-1}$ in Eq. (13) can be understood as follows. As a temperature gradient increases, a thickness of the vortex state domain decreases [see Eq. (7)], and a number of vortices contained in the vortex state domain decreases. Then a reaction probability decreases, and a number of trapped vortices, $N_{\rm trap}$, decreases. Note that, when

See T. Kubo, PTEP 2016 053G01

Theoretical Model Comparison



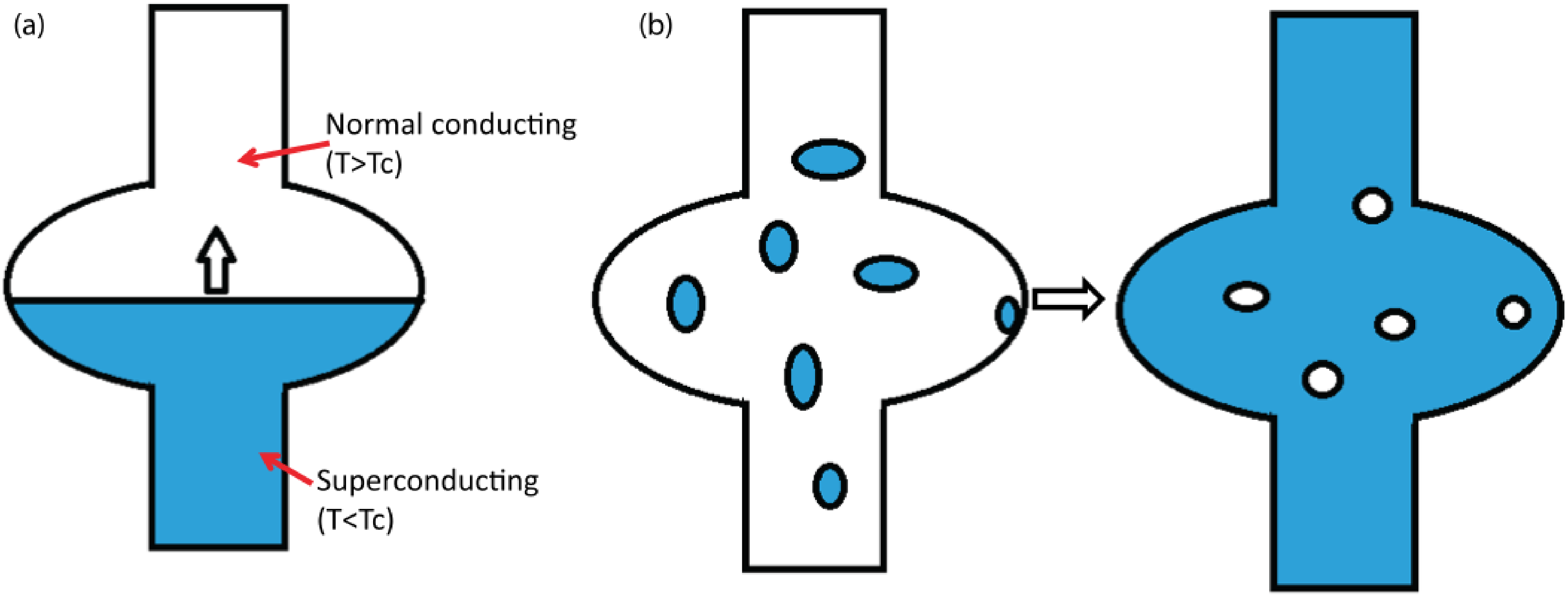


As dT/dx increases, the **depinning force** on a flux line increases

As dT/dx increases, the **probability** of having a flux line interact with a pinning site decreases

Fermilab

Very Slow/Uniform Cooldown



Large Thermal Gradient

Slow/Uniform Cooldown

A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)

Identifying the Features Responsible for Pinning Flux During Cooldown in SRF-Grade Bulk Niobium

Criteria for Features

- It is dominated by **bulk** properties - not impacted by standard surface treatment
- Pinning is made weaker by **heat treatment** for several hours in temperature range of 900±100 C, and the temperature depends on the material
- Pinning is made stronger by **cold work** of material

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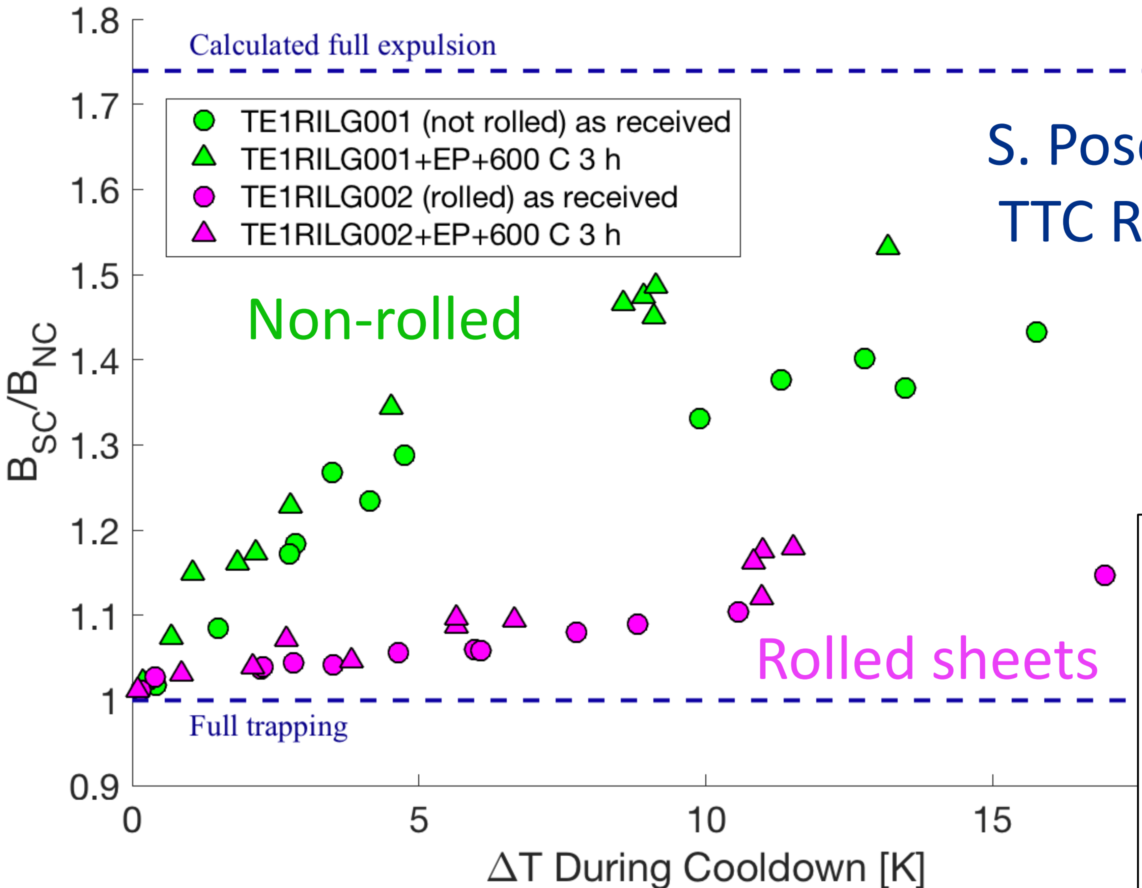
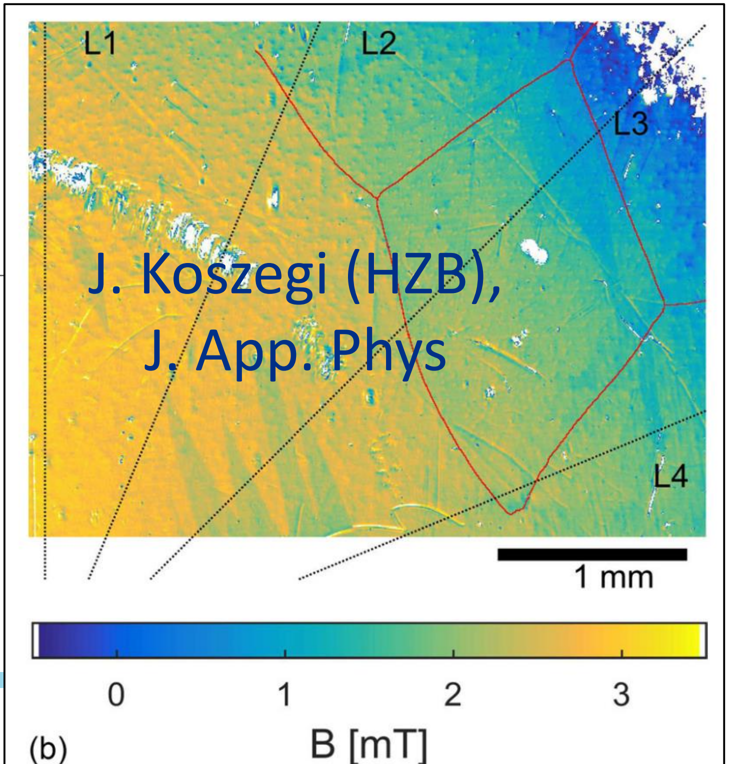
Some Possible Candidates

- ~~Grain boundaries~~
- ~~Impurities (possibly segregated at grain boundaries)~~
- Dislocations (possibly congregated as tangles or walls)

Grain Boundaries



S. Posen (FNAL), TTC Riken 2018

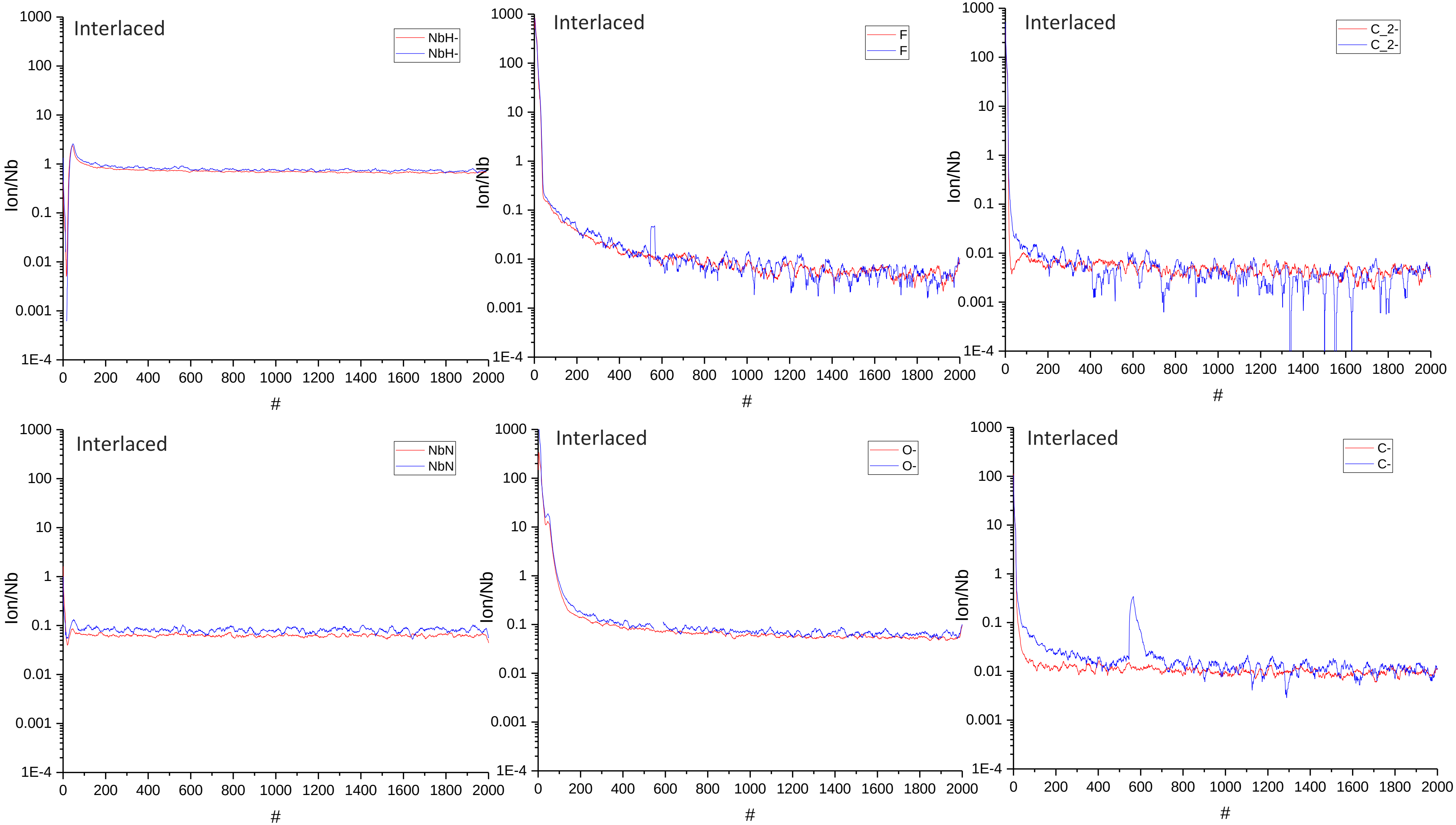


J. Koszegi (HZB), J. App. Phys

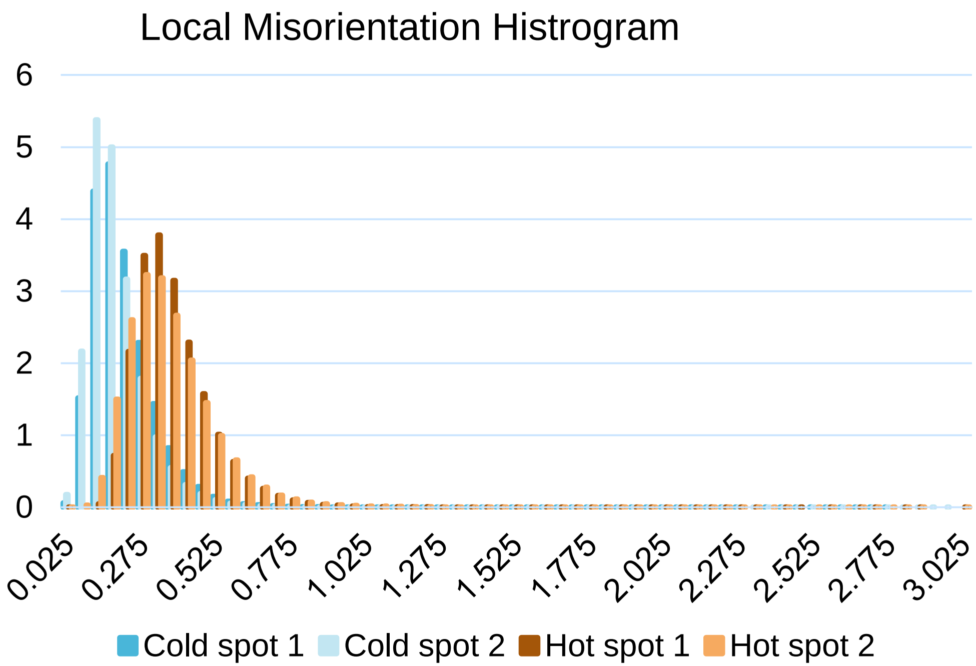
Impurities

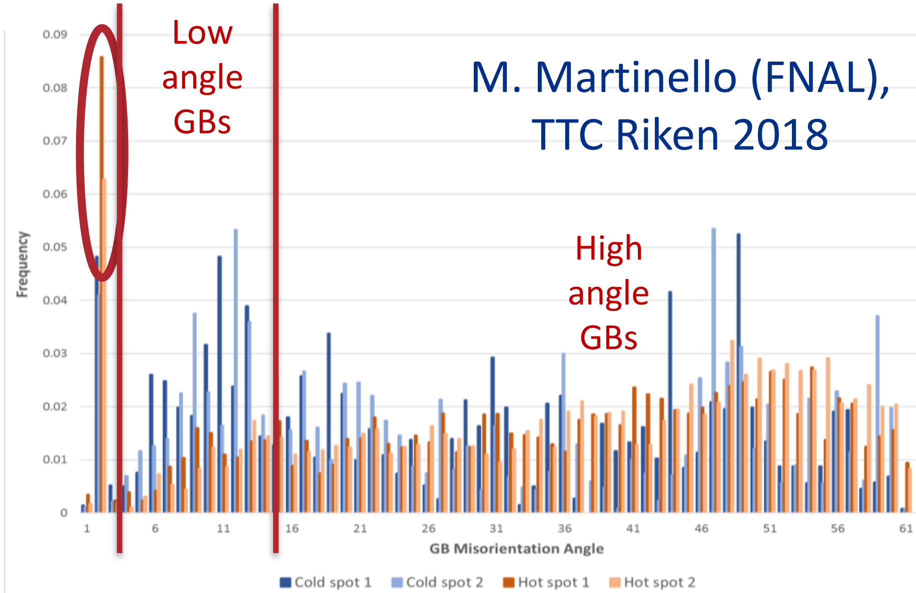
M. Martinello (FNAL), TTC Riken 2018

Legend: Red line: hot spot, Blue line: cold spot

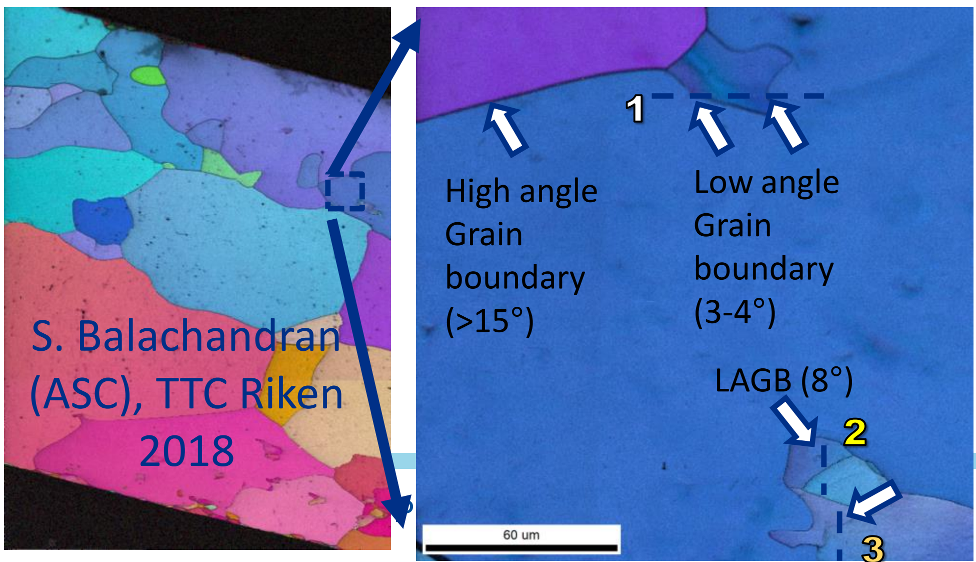


Dislocations

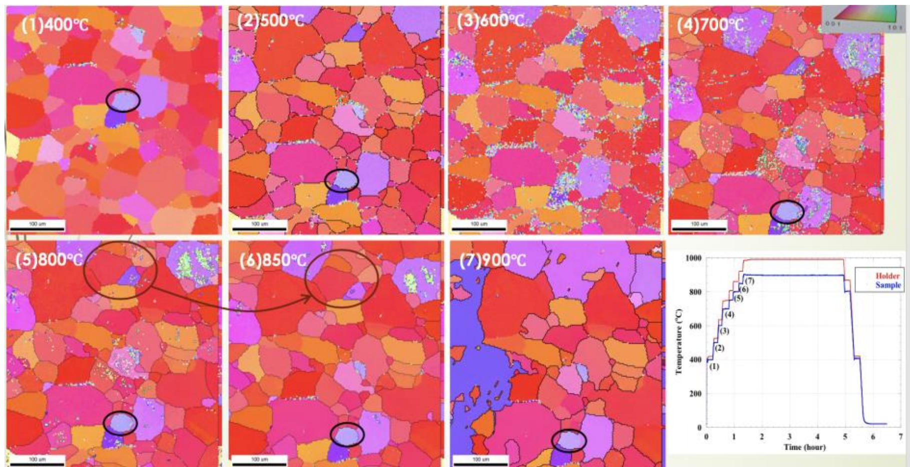




M. Martinello (FNAL), TTC Riken 2018



S. Balachandran (ASC), TTC Riken 2018



T. Konomi (KEK), TTC Riken 2018

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- Pinning is made stronger by **cold work** of material

Some Possible Can

Grain boundaries unlikely to be dominant factor based on LG cavities, Magneto-optics

- ~~Grain boundaries~~
- ~~Impurities (possibly segregated at grain boundaries)~~
- Dislocations (possibly congregated as tangles or walls)

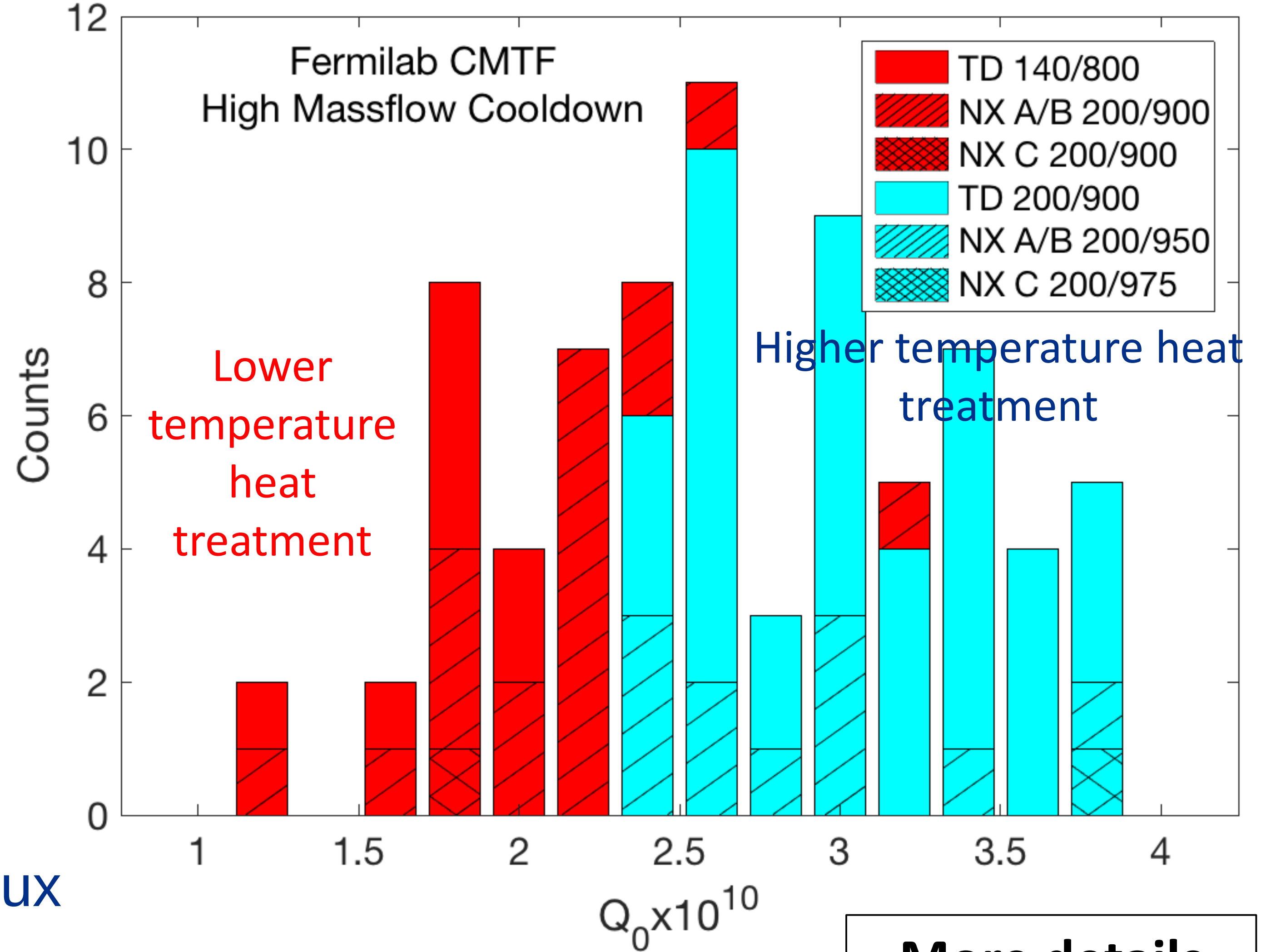
Impurities unlikely to be dominant factor based on SIMS studies

Dislocations under intense study with EBSD, ECCI

Conclusion

Flux Expulsion R&D Outcome: Strong Q_0 Improvement in CM

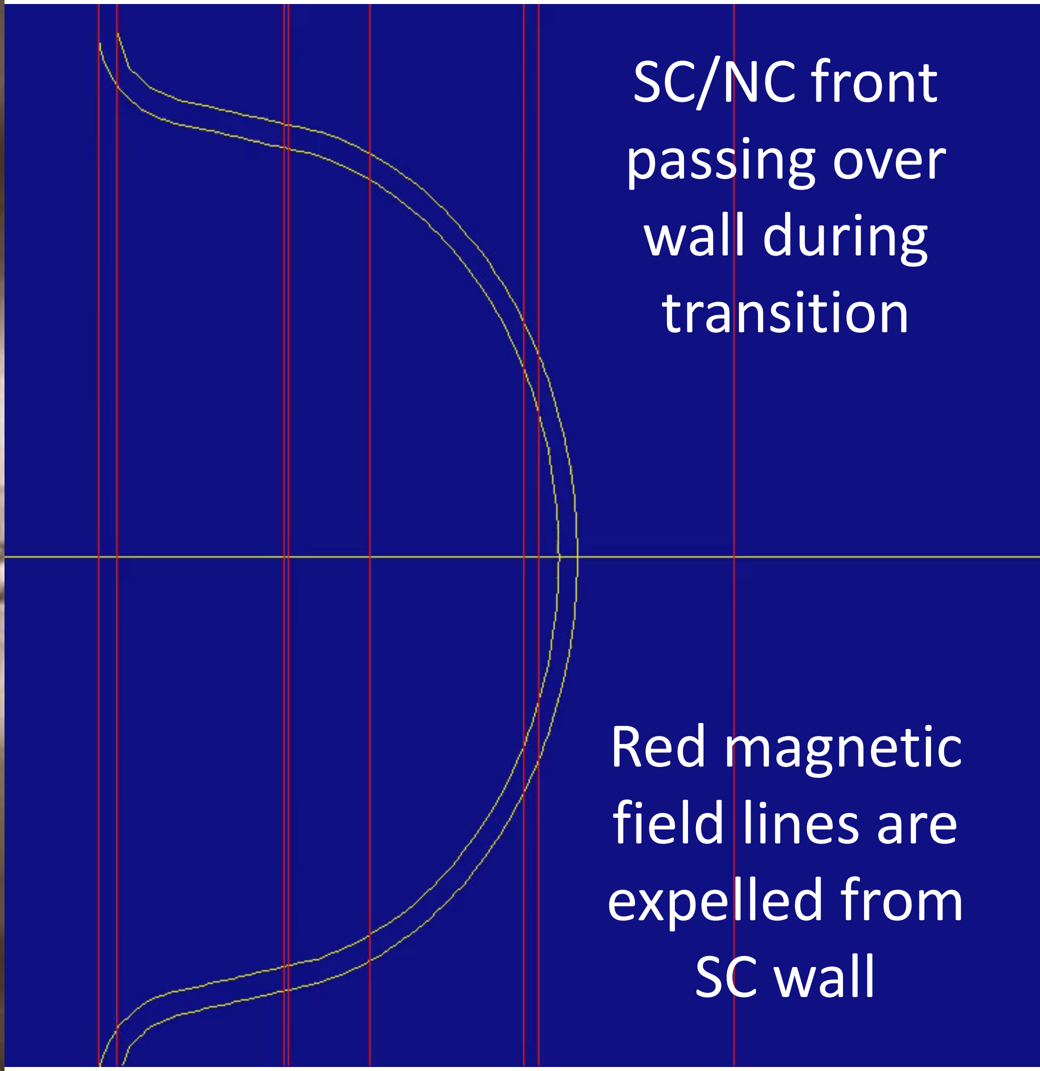
- LCLS-II production cavities in Fermilab cryomodules
- Red – early cavity processing procedure
- Blue – processing procedure modified for flux expulsion



More details this afternoon

Crucial Questions

- What microscopic phenomena make different niobium production runs have such different flux expulsion behavior? (including different heat treatment temperatures required)
- What practical measurable quantities can we use to specify flux expulsion behavior in niobium?
- Can we modify specifications to give predictable flux expulsion behavior for a given heat treatment without compromising mechanical properties?



Simulation courtesy E. Cenni, CEA