

# Lattice location and thermal stability of the implanted transition metals Fe, Ni and Co in silicon of different doping types

D.J. Silva<sup>1</sup>, U. Wahl<sup>2</sup>, J.G. Correia<sup>2</sup>, L.M.C. Pereira<sup>3</sup>, L. Amorim<sup>3</sup>, V. Augustyns<sup>3</sup>, A. Costa<sup>2</sup>, E. Bosne<sup>4</sup>, M. R. Silva<sup>5</sup> and J.P. Araújo<sup>1</sup>

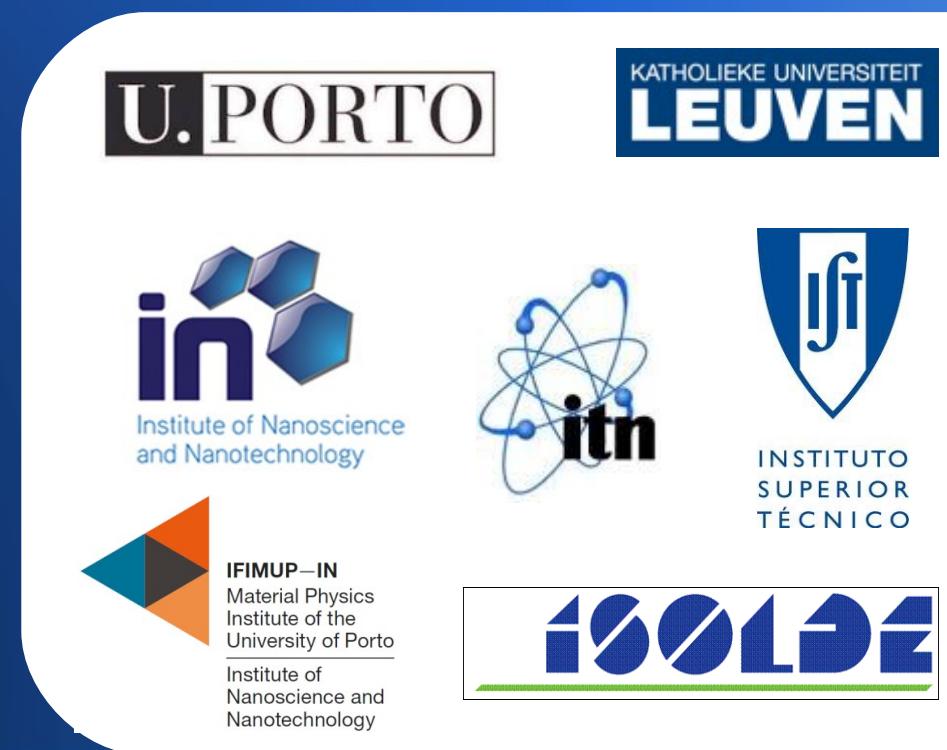
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<sup>2</sup> Instituto Superior Técnico, Instituto Tecnológico e Nuclear, Universidade de Lisboa, Portugal

<sup>3</sup> Instituut voor Kern- en Stralingsfysica, KU Leuven, Belgium

<sup>4</sup> Departamento de Física, Universidade de Aveiro, Portugal

<sup>5</sup> Centro Física Nuclear da Universidade de Lisboa, Portugal



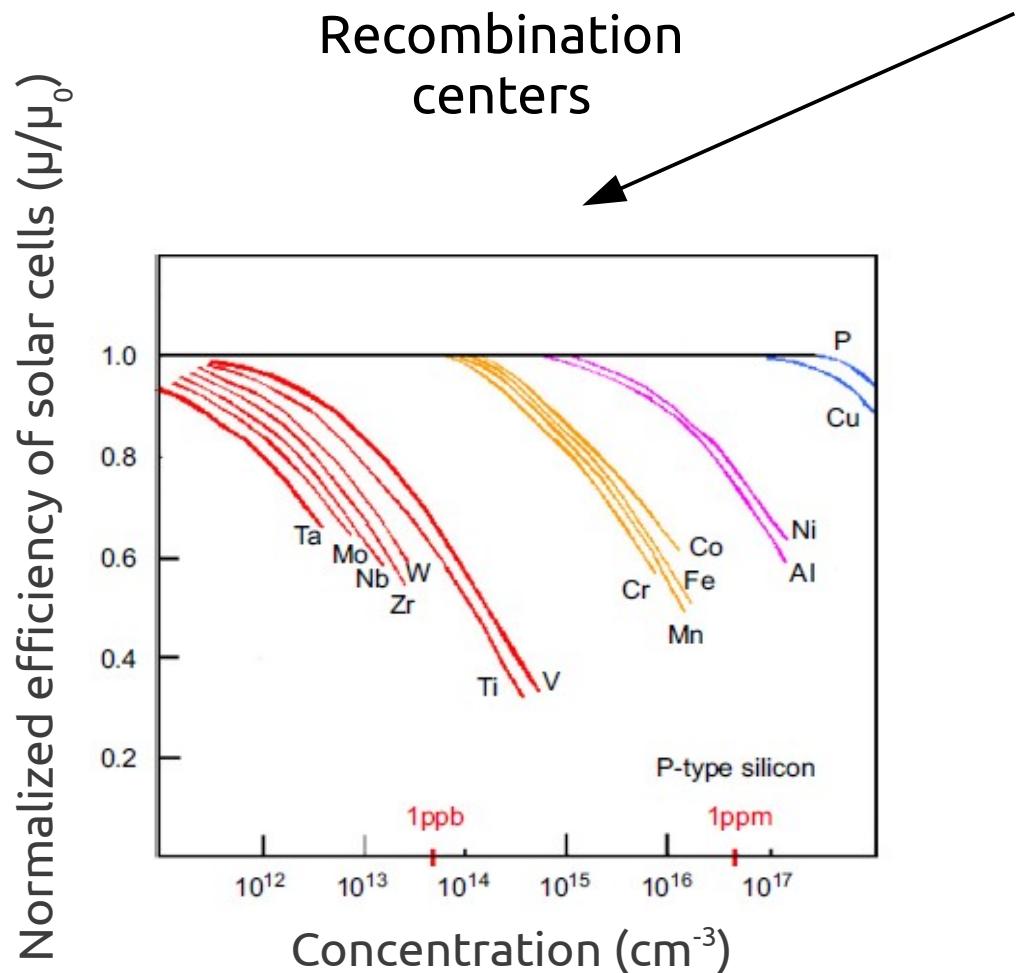
# Outline

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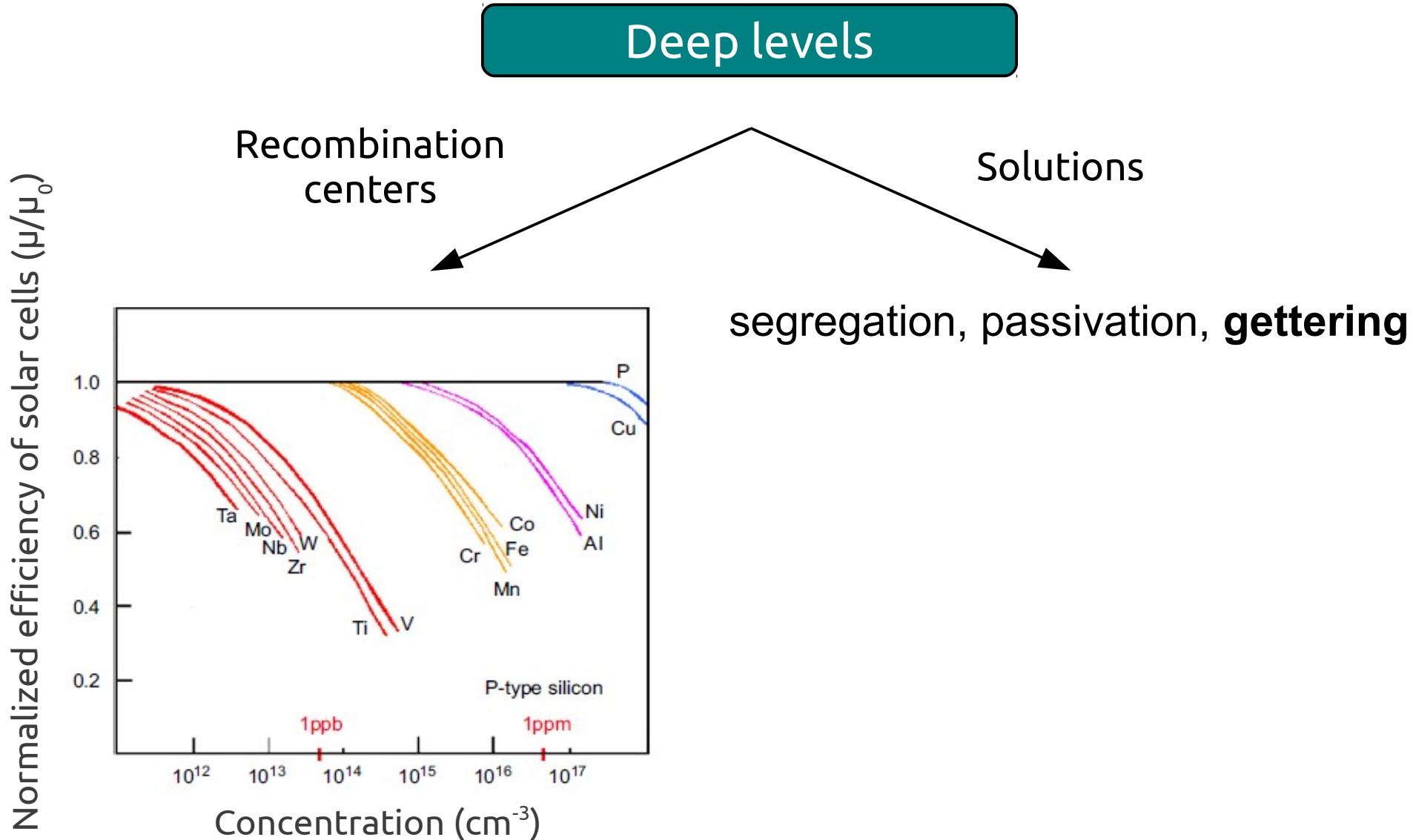
- Transition metals in Si
- Emission channeling
- Lattice location of  $^{59}\text{Fe}$  and  $^{65}\text{Ni}$  in Si
- Results on  $^{61}\text{Co}$  in n- and p<sup>+</sup>-type Si
- Conclusions

# Transition metals in silicon

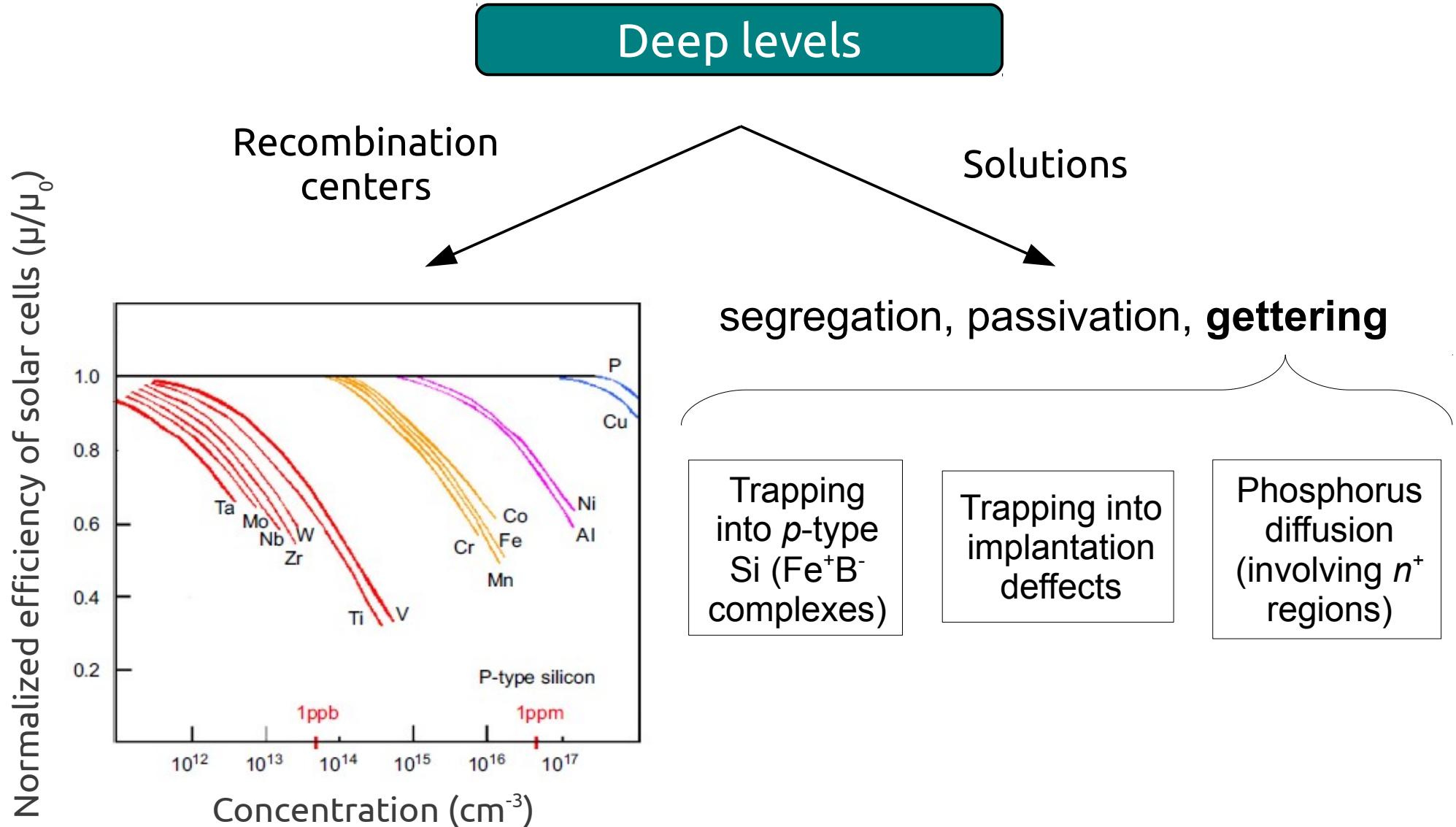
Deep levels



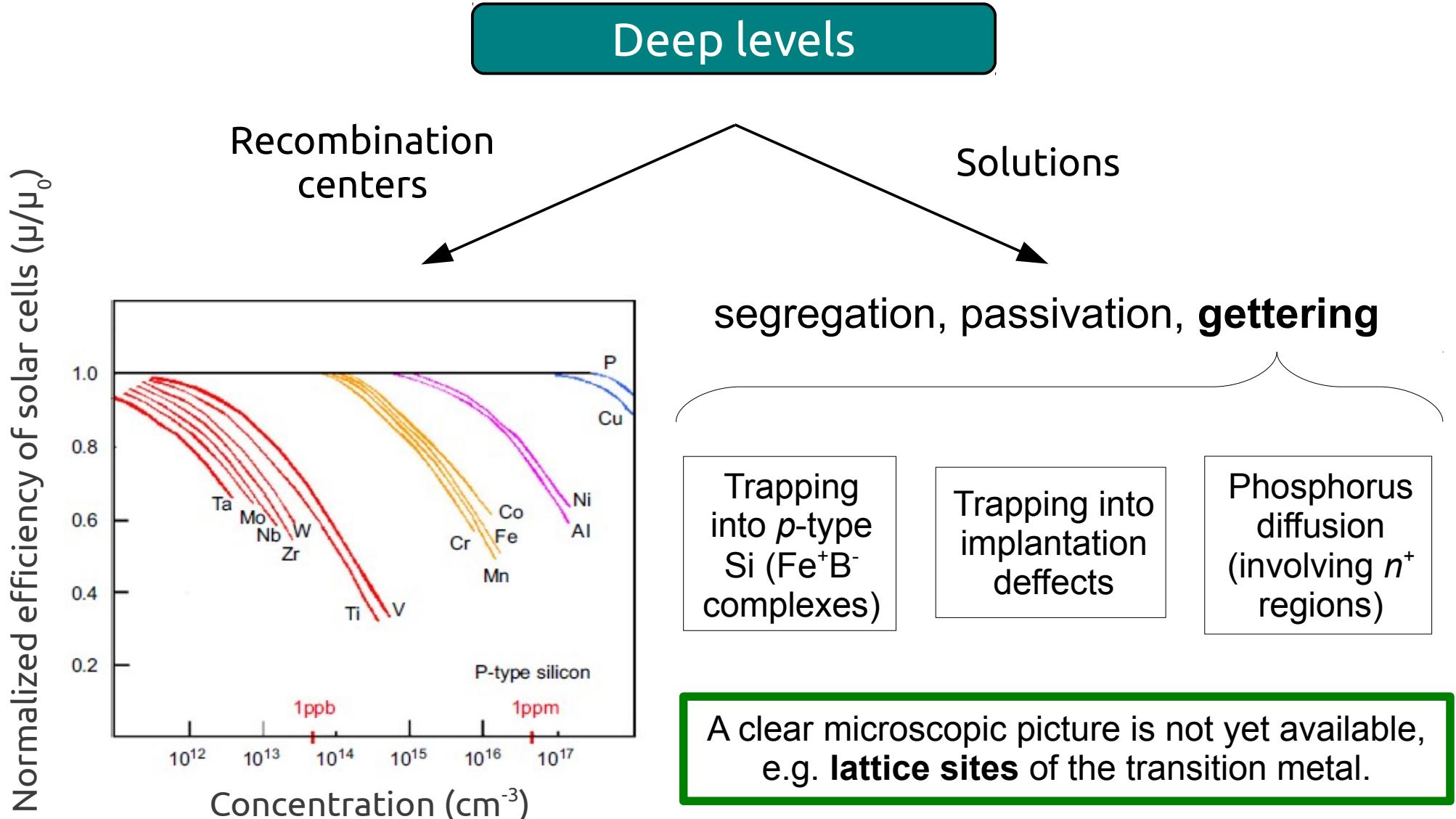
# Transition metals in silicon



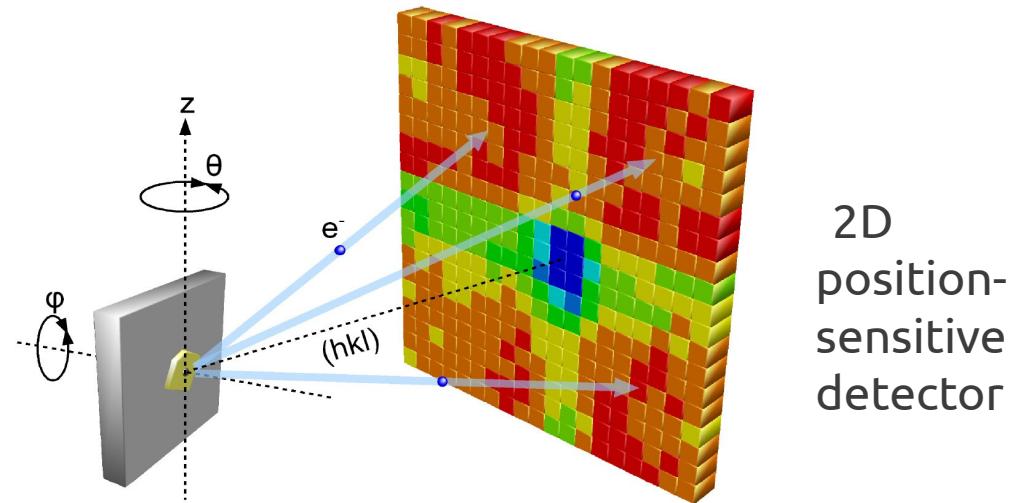
# Transition metals in silicon



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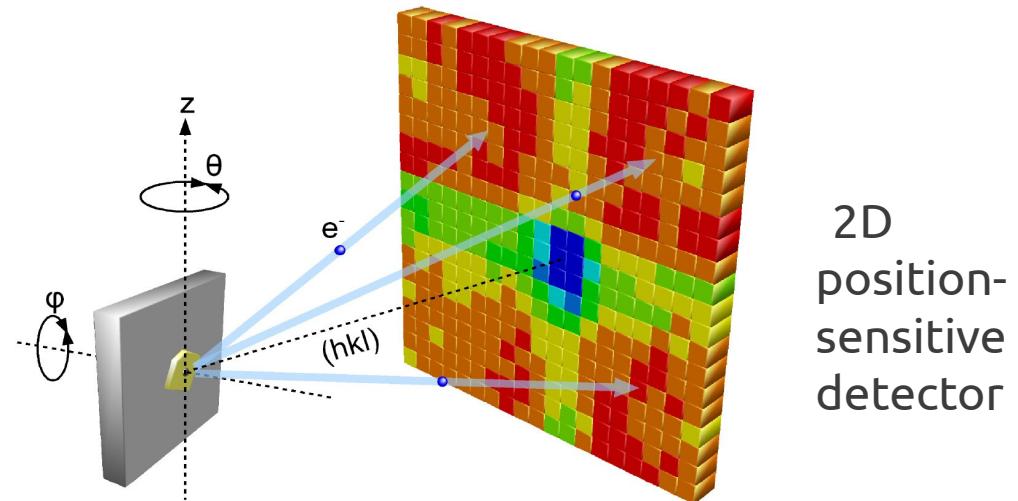
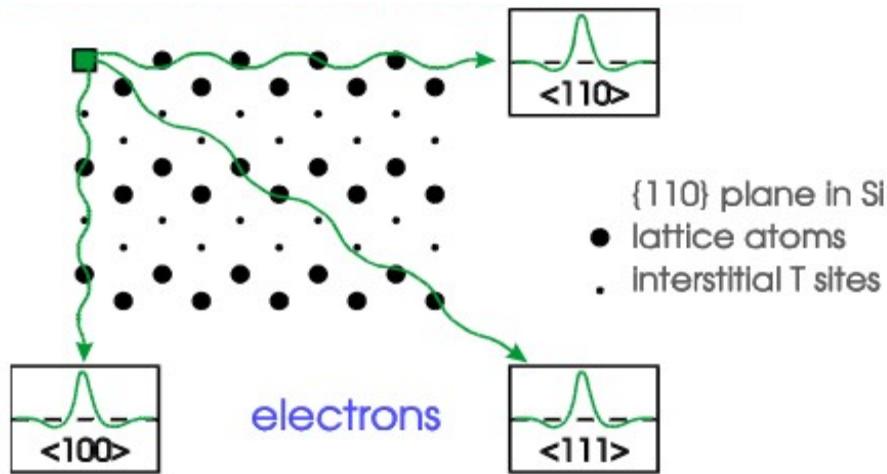


# Emission channeling



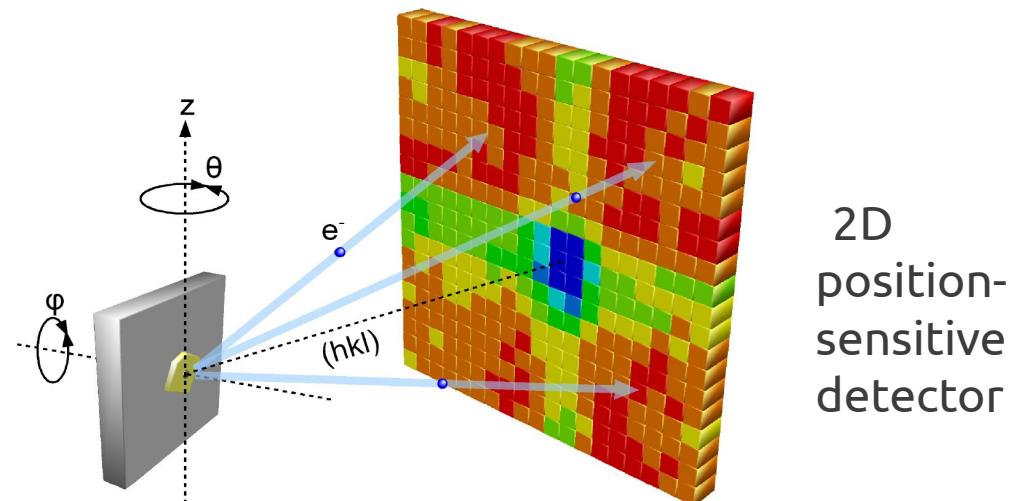
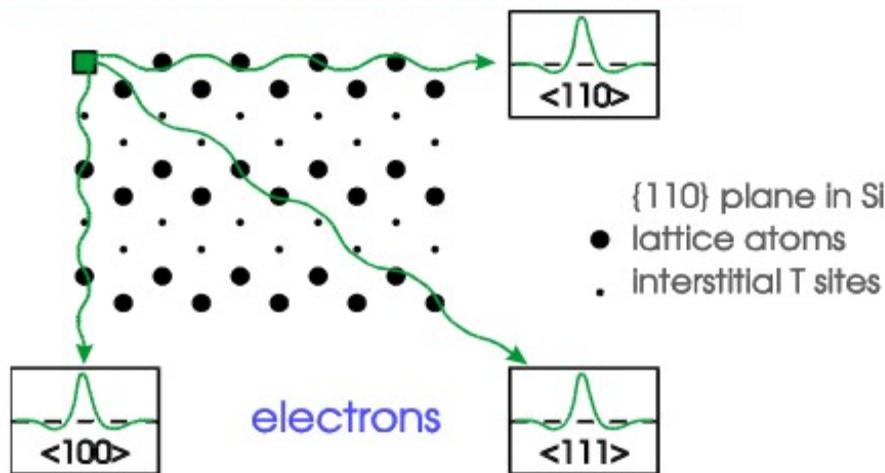
# Emission channeling

## Substitutional radioactive impurity

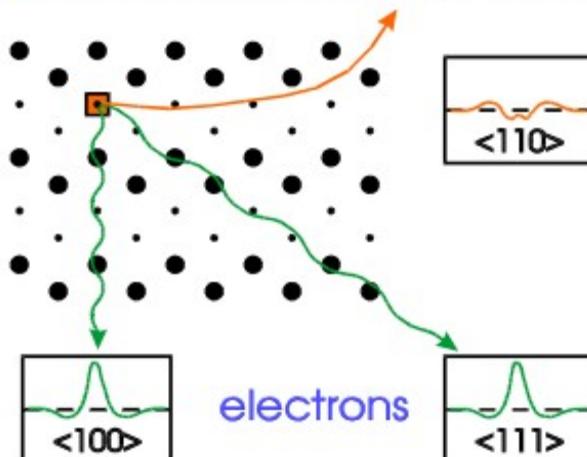


# Emission channeling

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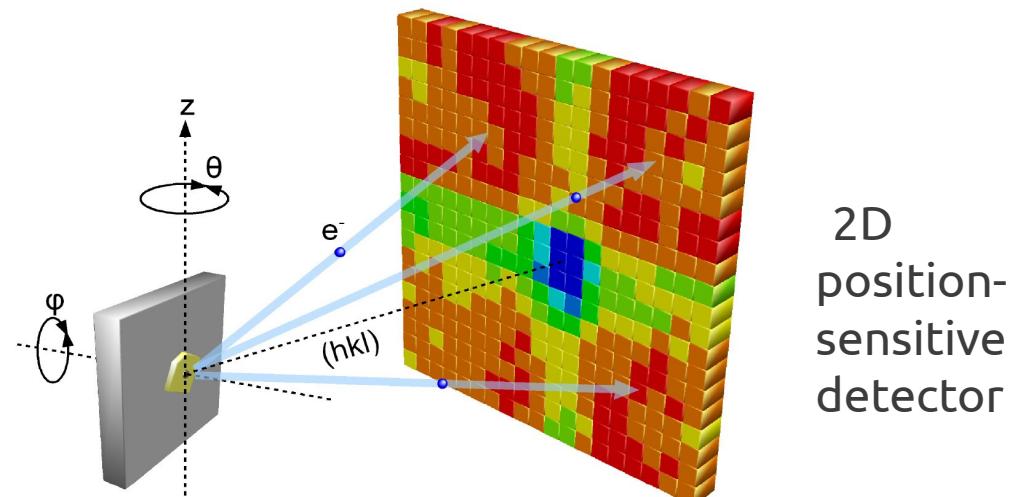
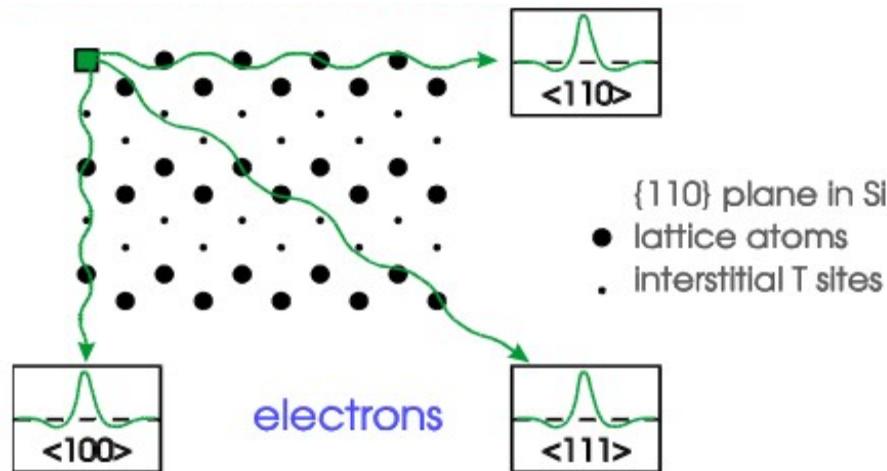


## Interstitial radioactive impurity



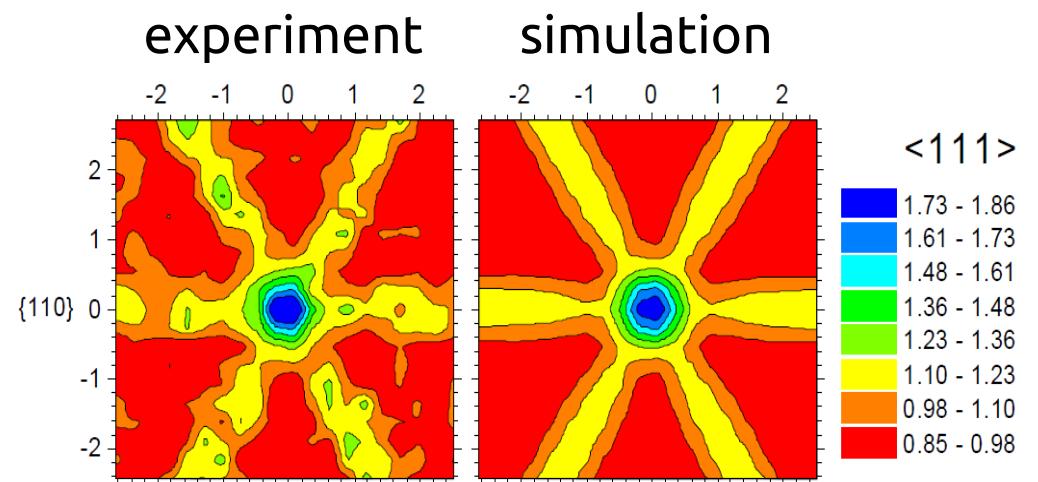
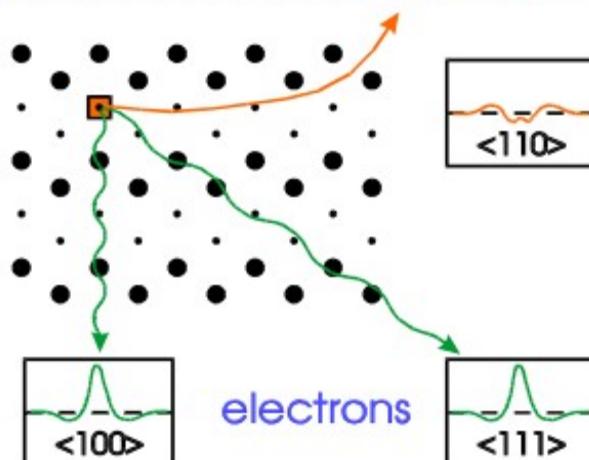
# Emission channeling

## Substitutional radioactive impurity



2D  
position-  
sensitive  
detector

## Interstitial radioactive impurity



# Lattice location of $^{59}\text{Fe}$ , $^{65}\text{Ni}$ and $^{61}\text{Co}$ in Si

21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn
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Long lived isotope (offline)

$^{59}\text{Fe}$

$t_{1/2} = 45 \text{ d}$

Short lived isotopes (online)

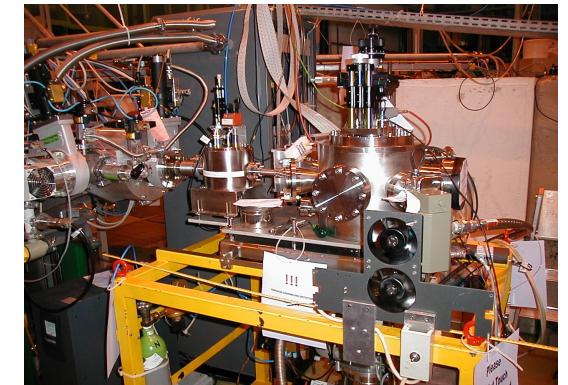
$^{61}\text{Co}$

$t_{1/2} = 1.6 \text{ h}$

$^{65}\text{Ni}$

$t_{1/2} = 2.5 \text{ h}$

**Online setup**



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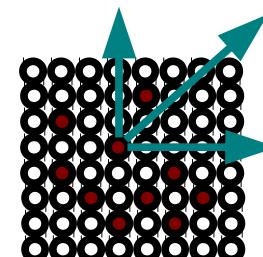
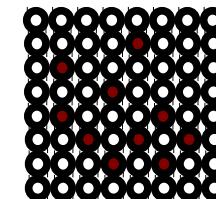
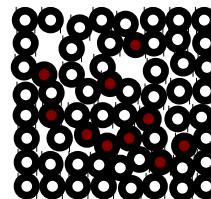
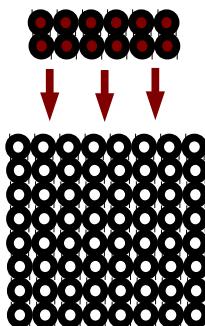
Implantation



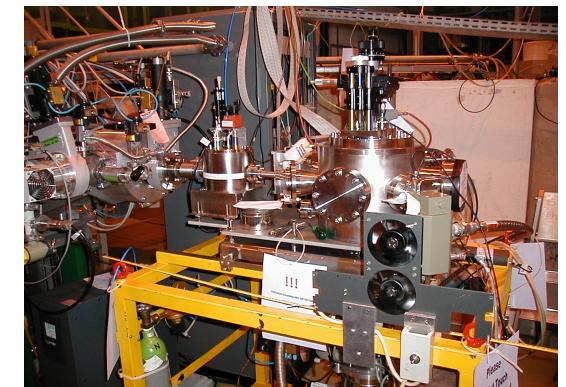
Annealing



Measurement



Online setup



# Lattice location of $^{59}\text{Fe}$ , $^{65}\text{Ni}$ and $^{61}\text{Co}$ in Si

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$^{59}\text{Fe}$

$t_{1/2}=45\text{ d}$  [1]

Short lived isotopes (online)

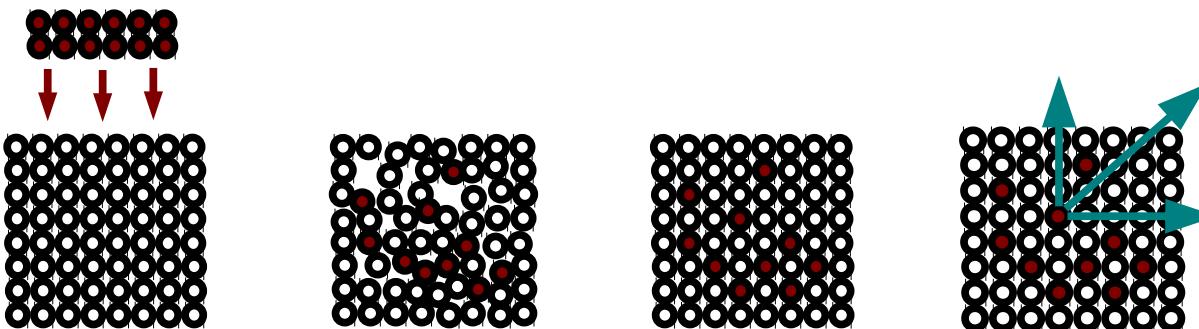
$^{61}\text{Co}$

$t_{1/2}=1.6\text{ h}$

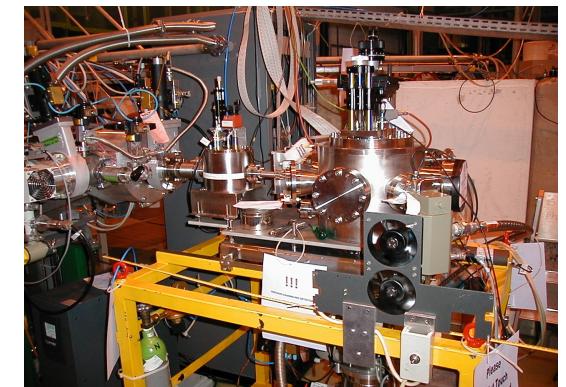
$^{65}\text{Ni}$

$t_{1/2}=2.5\text{ h}$  [2]

Implantation      →      Annealing      →      Measurement



Online setup

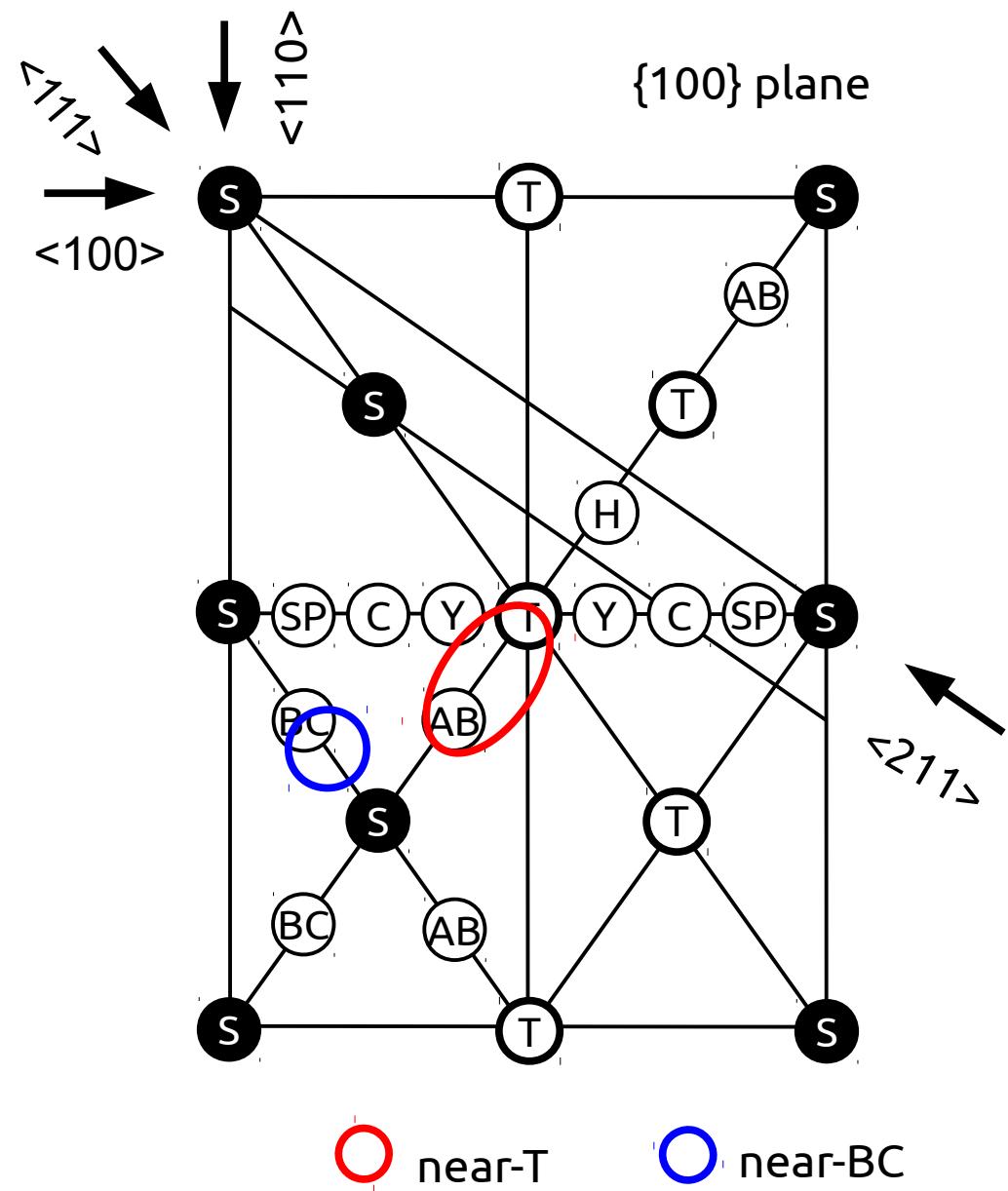
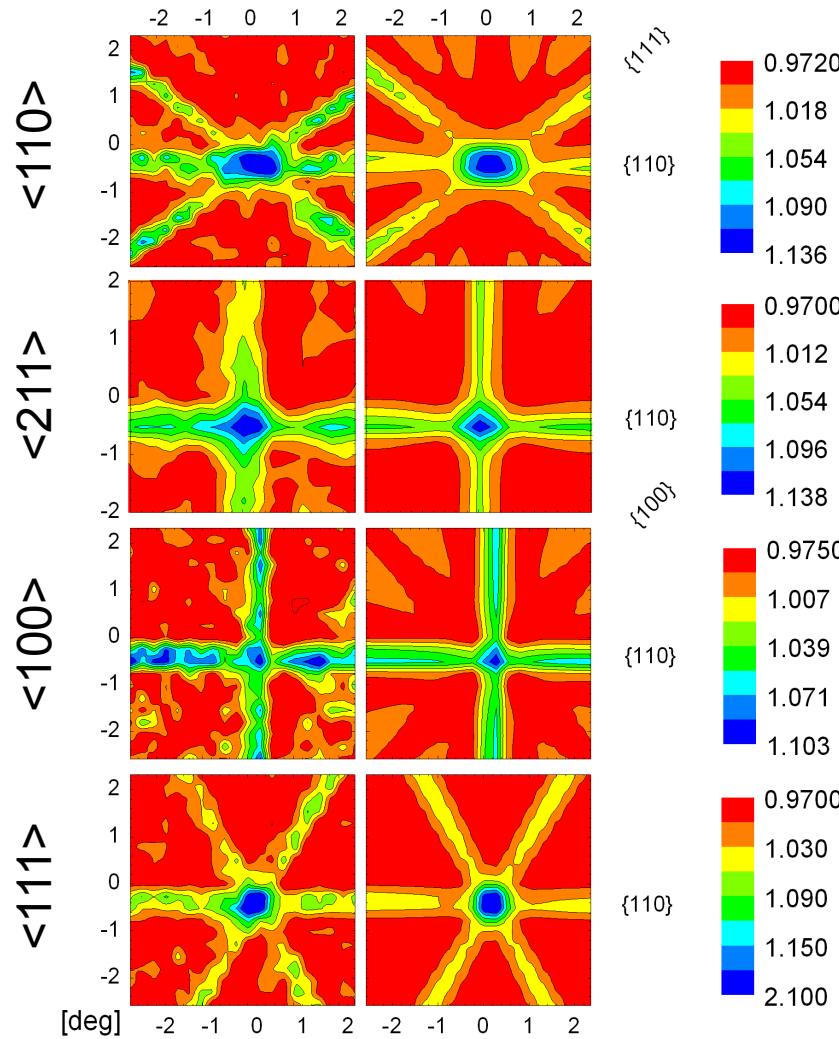


[1] D. J. Silva, U. Wahl, J. G. Correia and J.P. Araújo, *J. Appl. Phys.* **114** 103503 (2013)

[2] D. J. Silva, U. Wahl, J. G. Correia, L. M. C. Pereira, L. M. Amorim, M. R. da Silva, E. Bosne and J. P. Araújo, Accepted in *J. Appl. Phys.*

# Results: $^{65}\text{Ni}$ in Si ( $n$ -Si; $T_A = 400^\circ\text{C}$ )

Experiment   Simulation

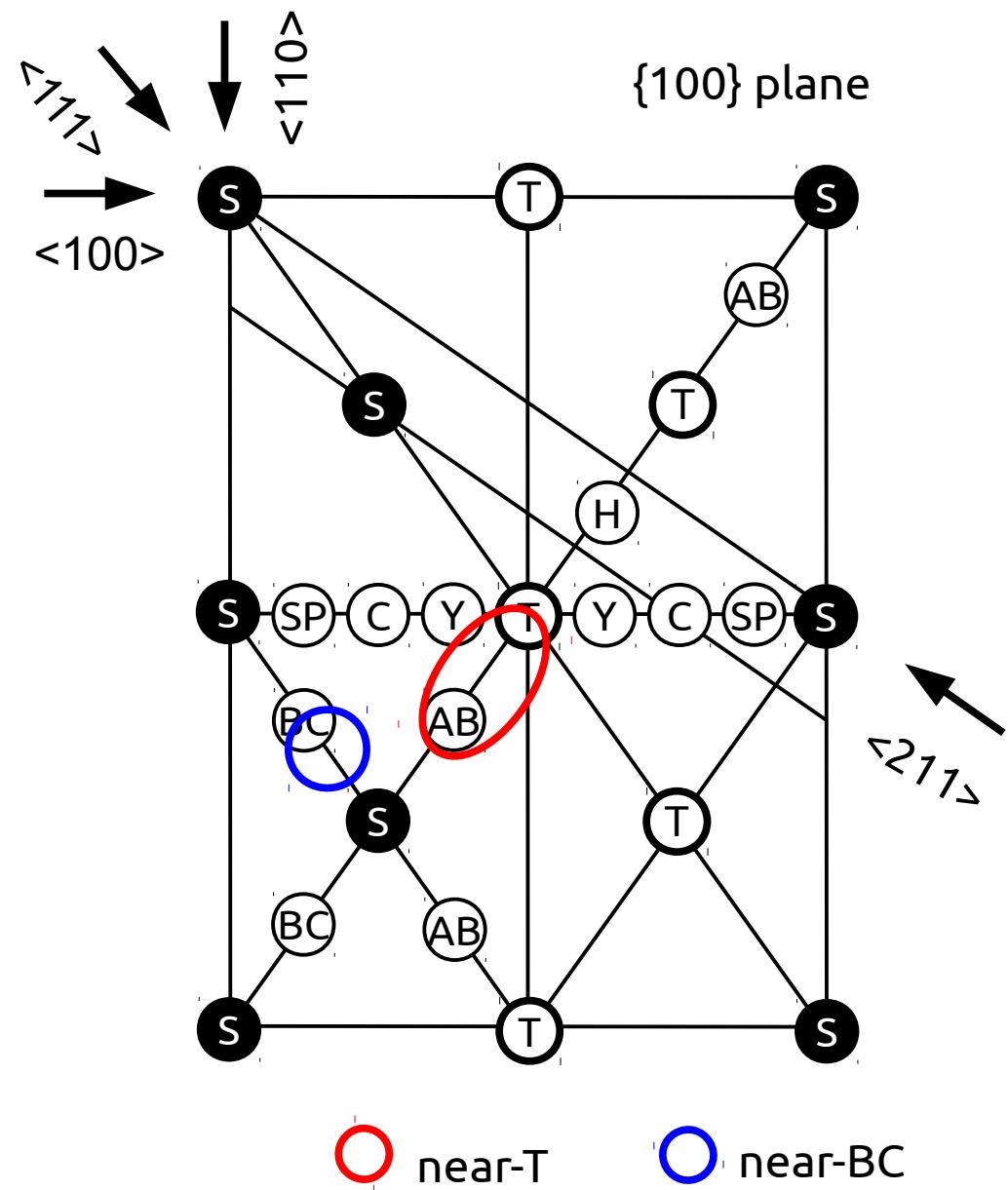
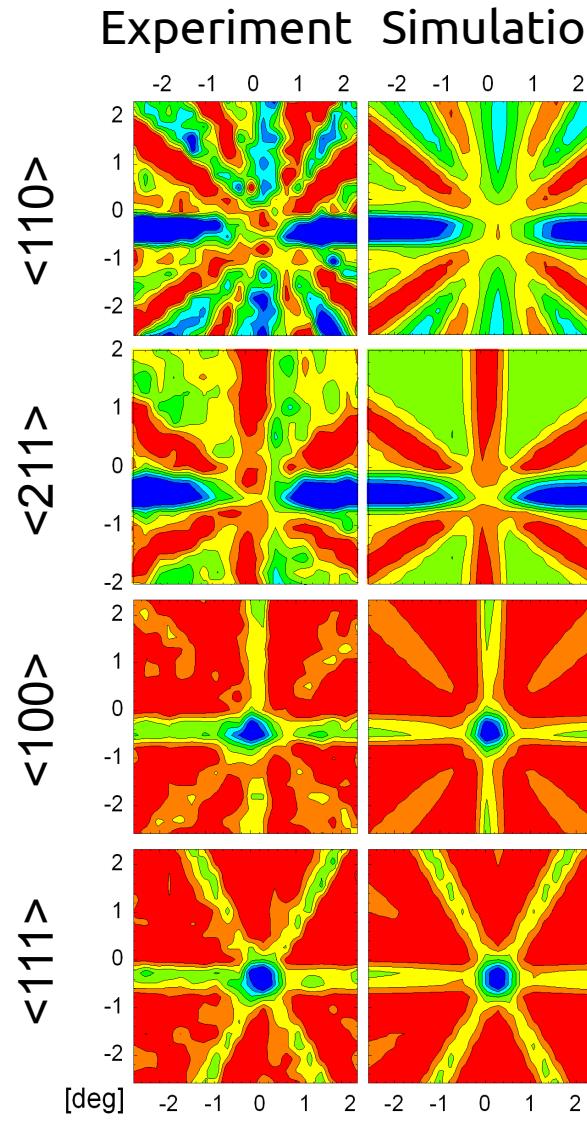


18% S + **43% near-BC** + 16% near-T

near-T

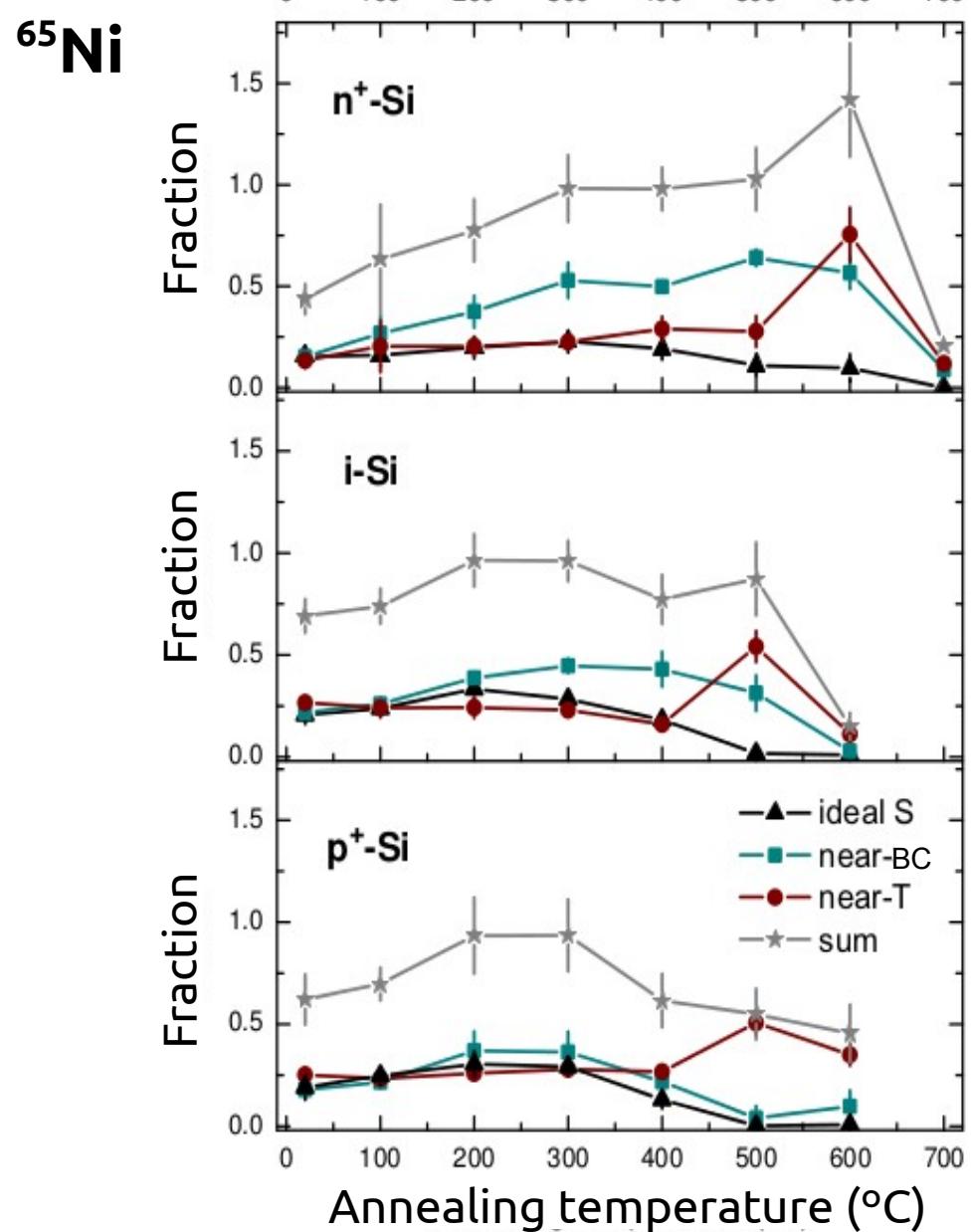
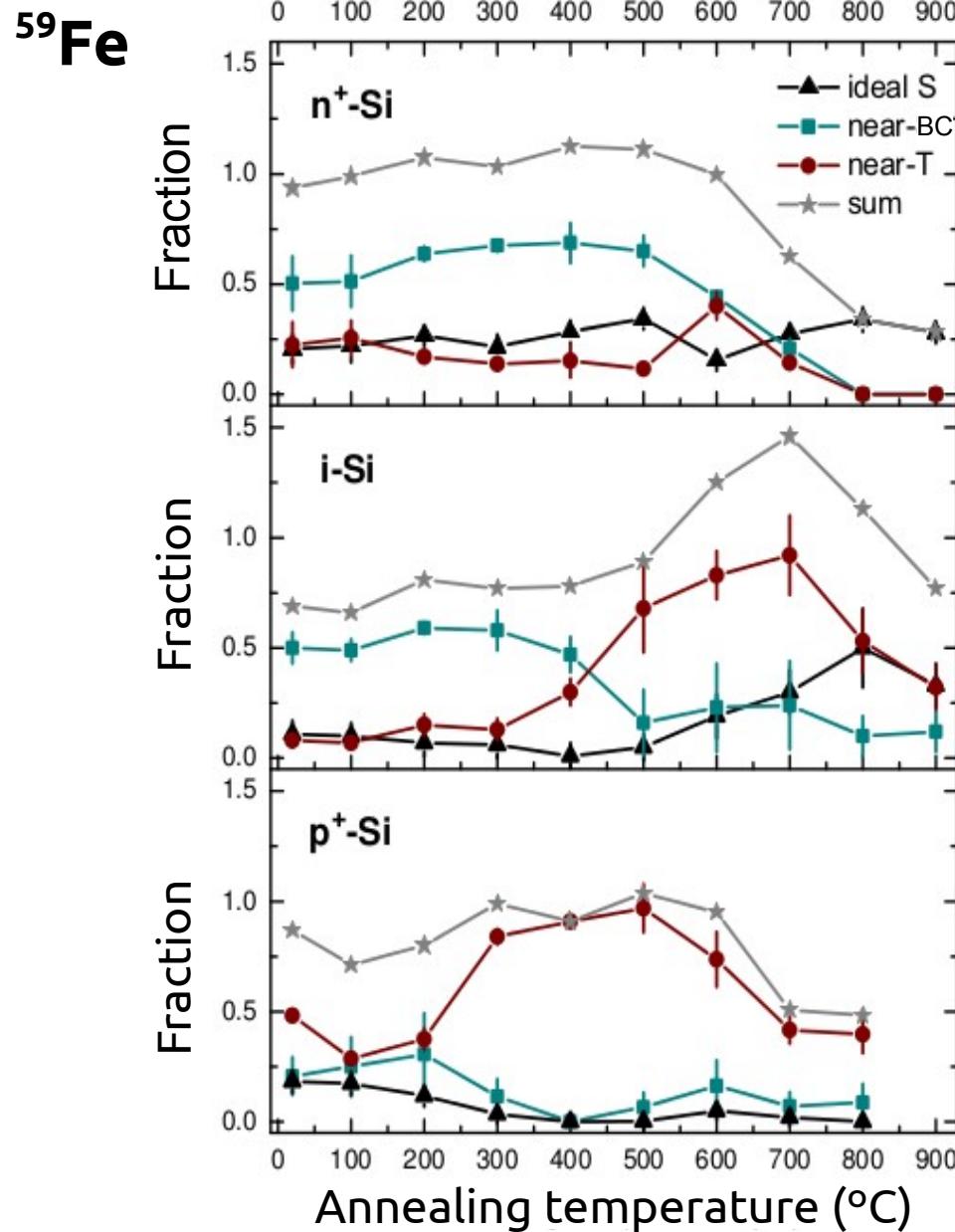
near-BC

# Results: $^{65}\text{Ni}$ in Si ( $n$ -Si; $T_A = 500^\circ\text{C}$ )

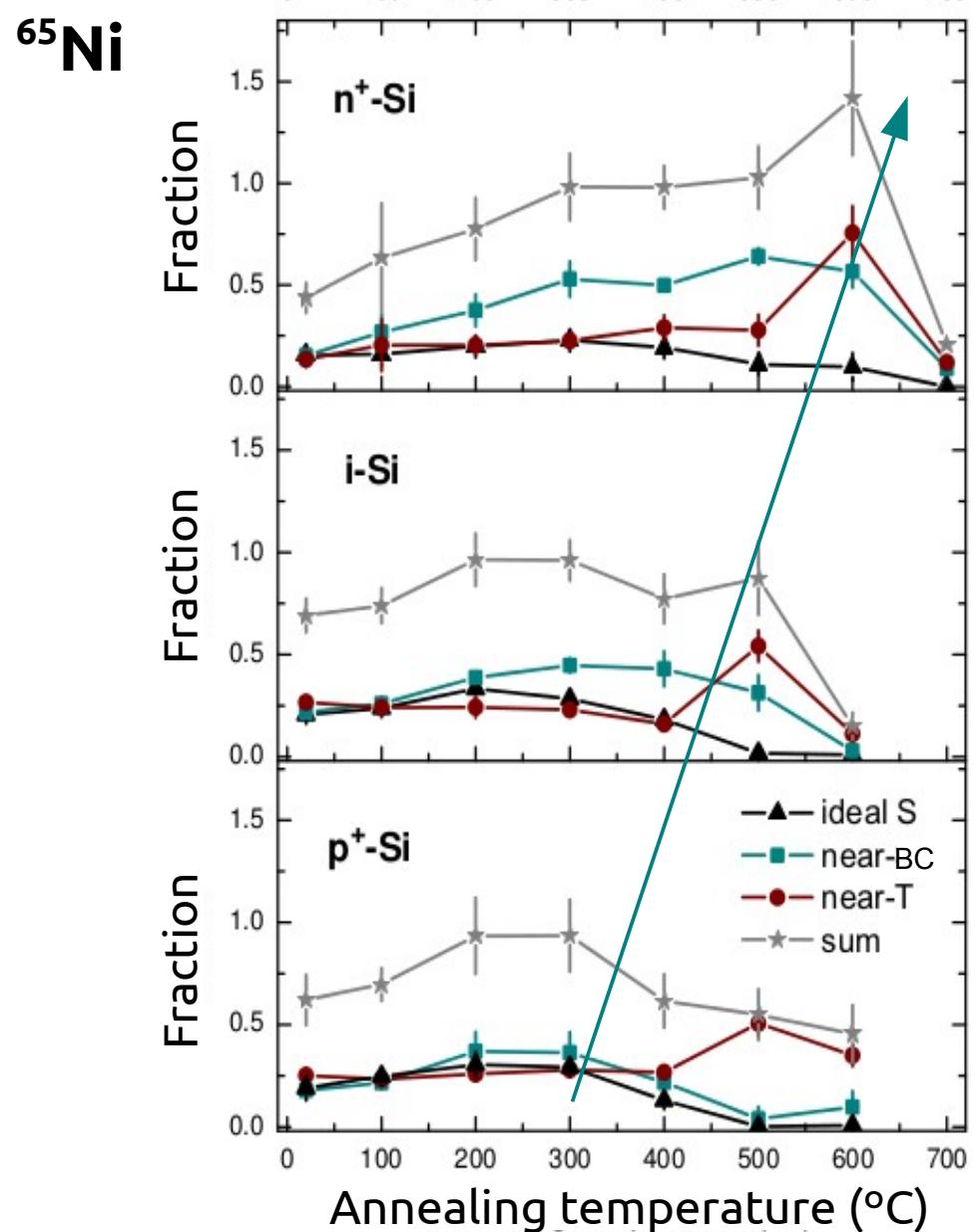
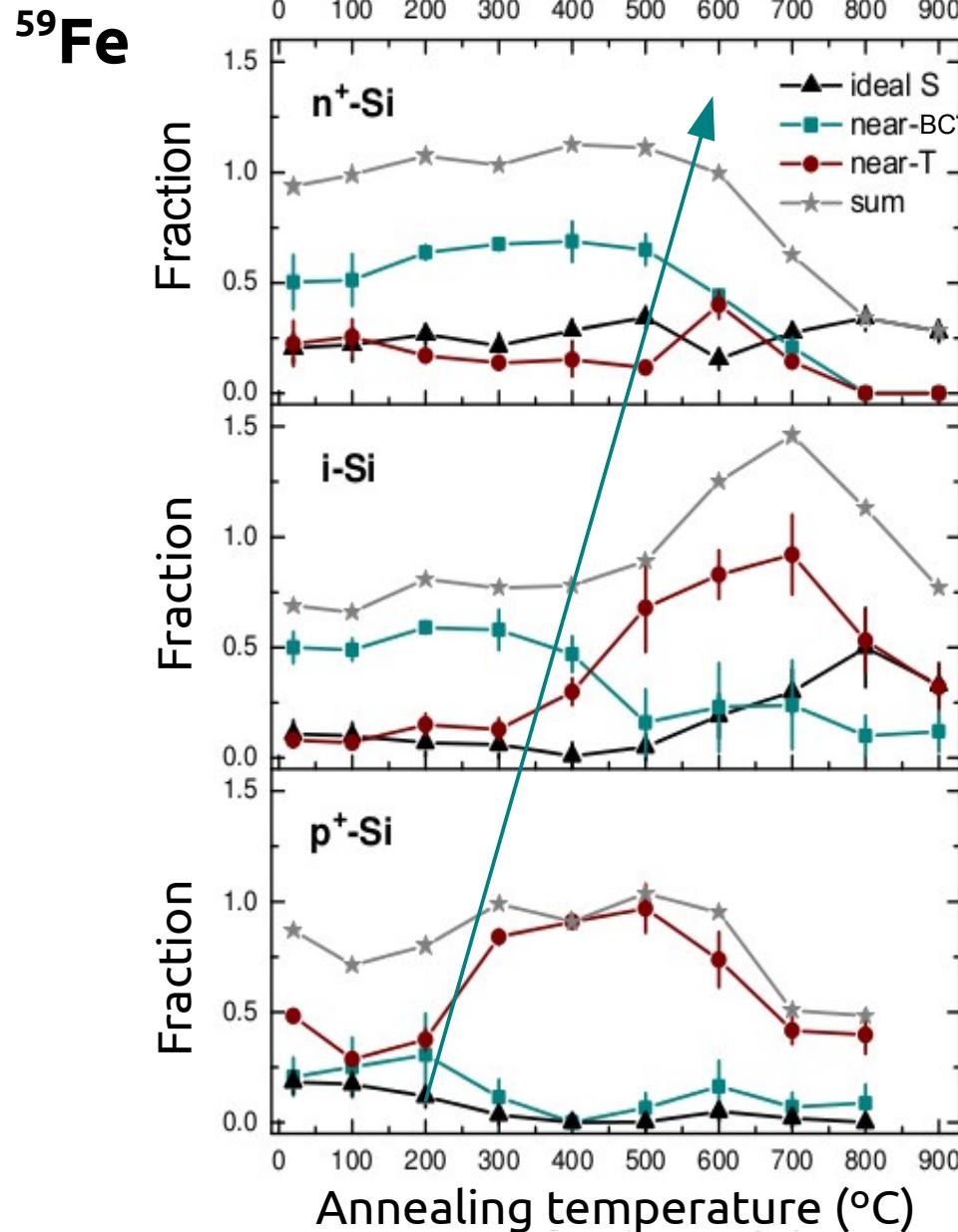


2% S + 31% near-BC + 54% near-T

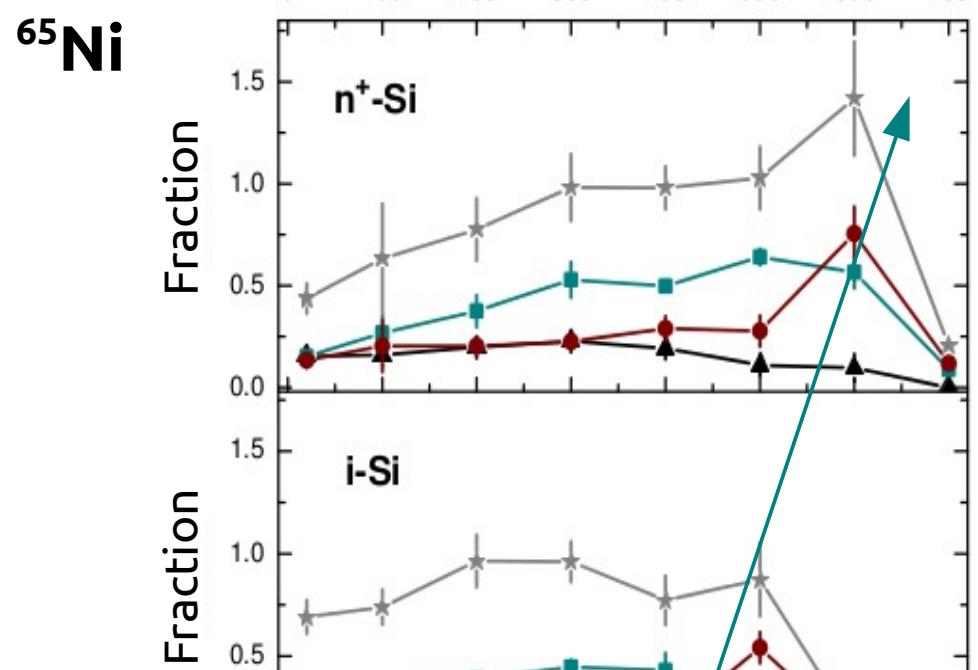
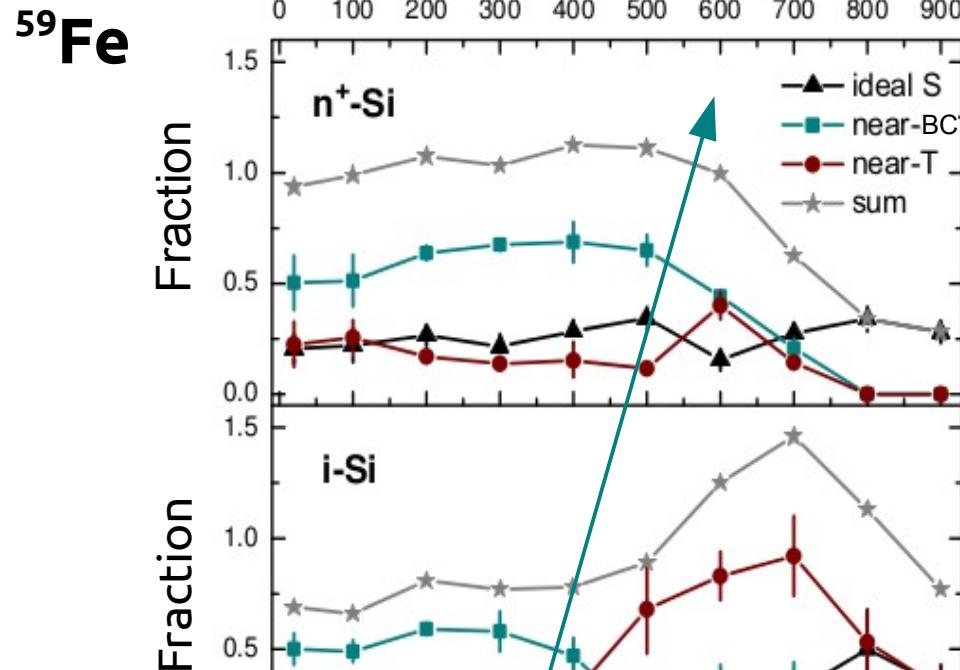
# Results: $^{59}\text{Fe}$ and $^{65}\text{Ni}$ in Si



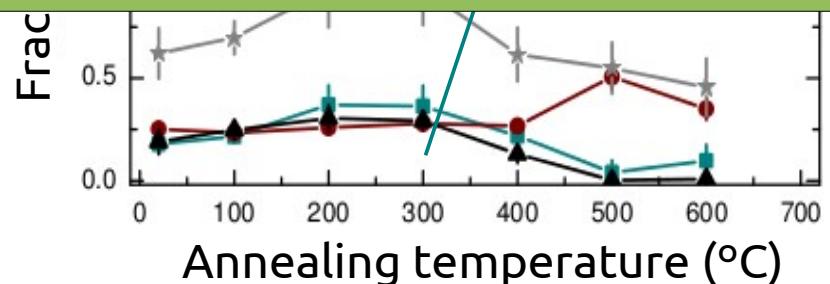
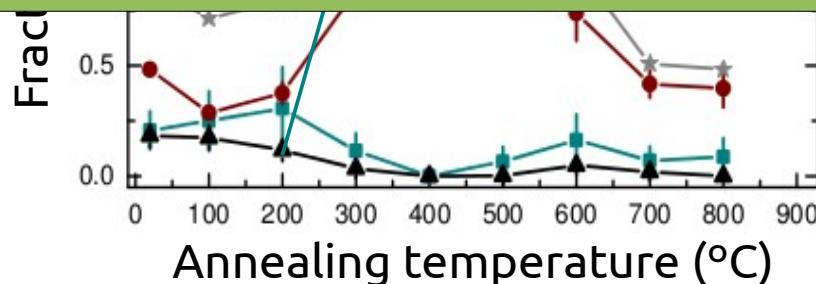
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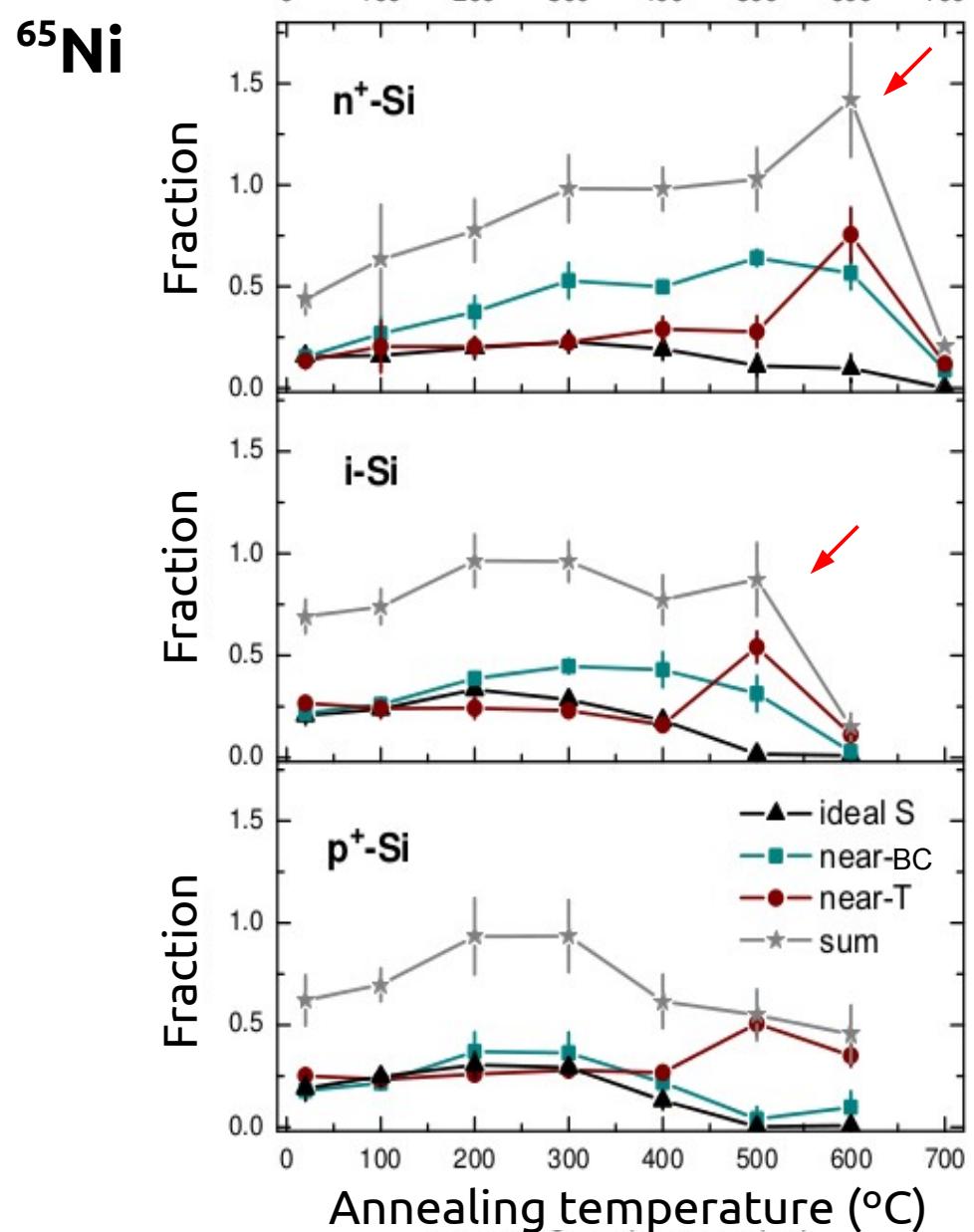
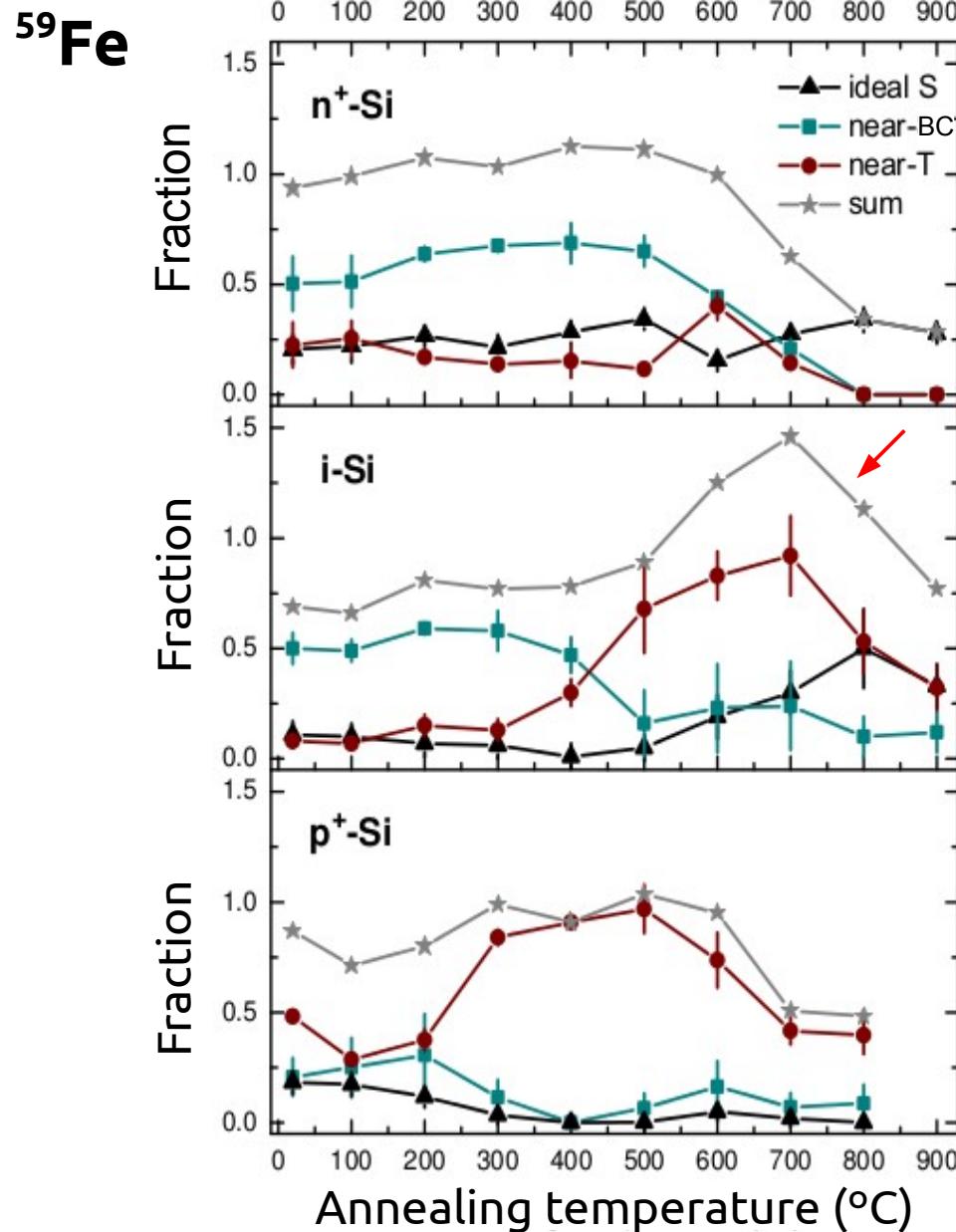
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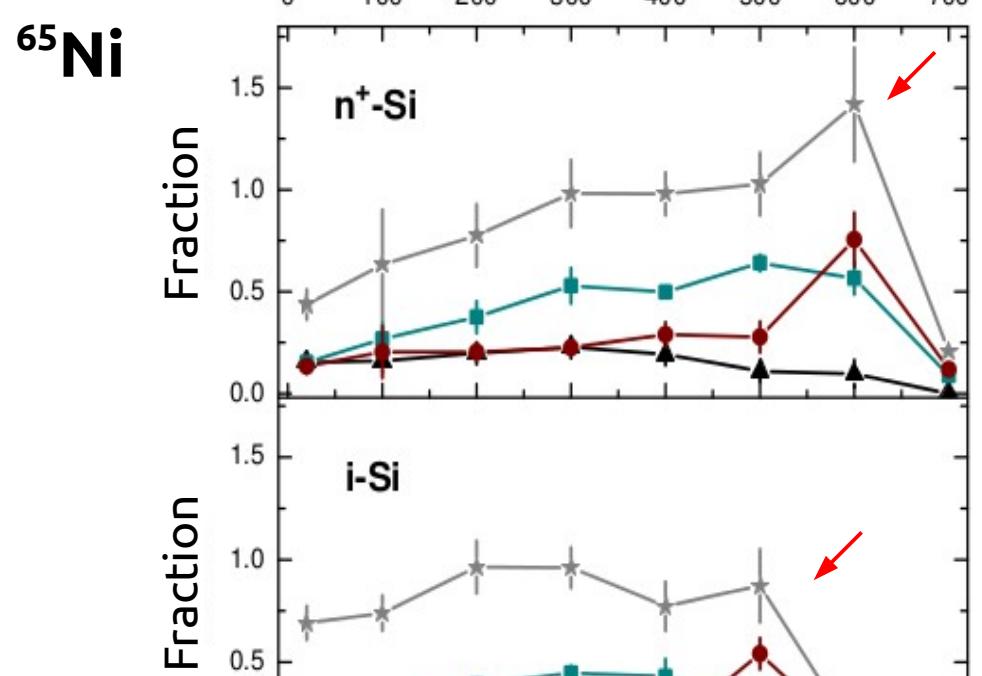
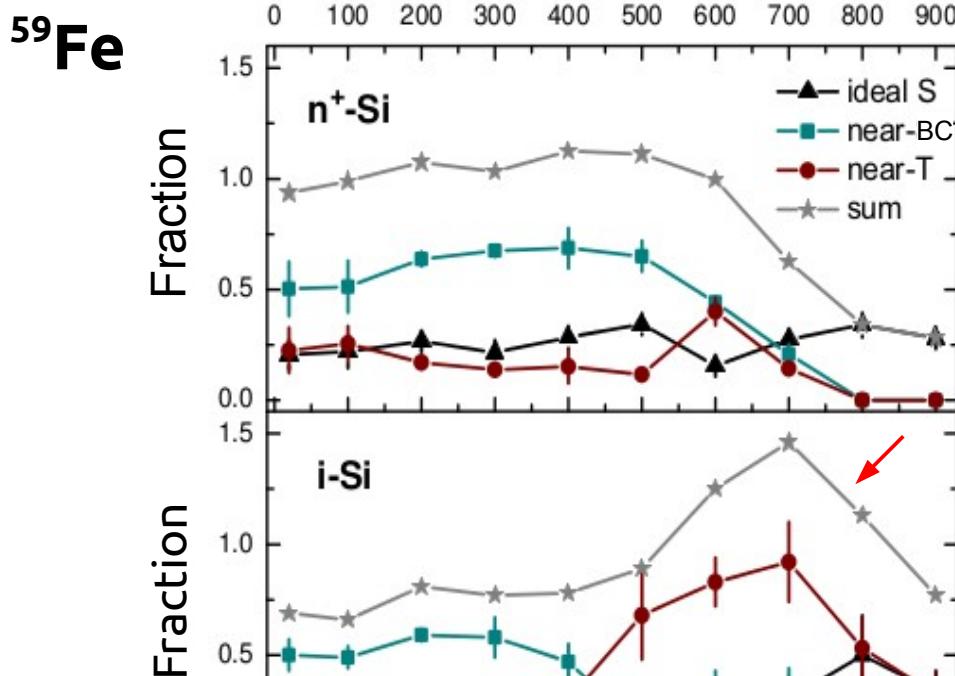
Complexes where Ni and Fe occupy near-BC sites might play a role on phosphorus diffusion gettering.



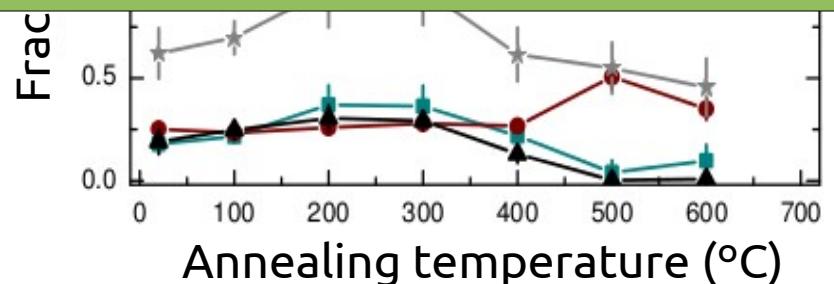
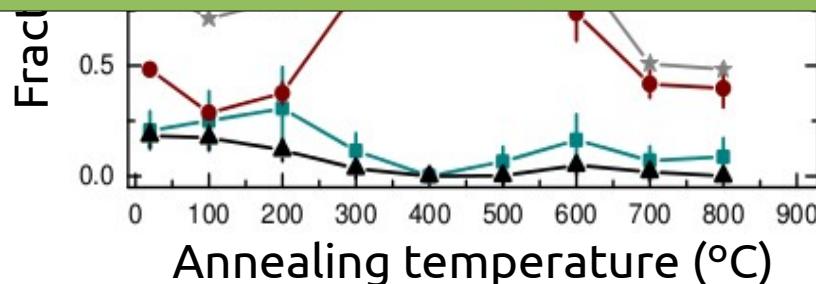
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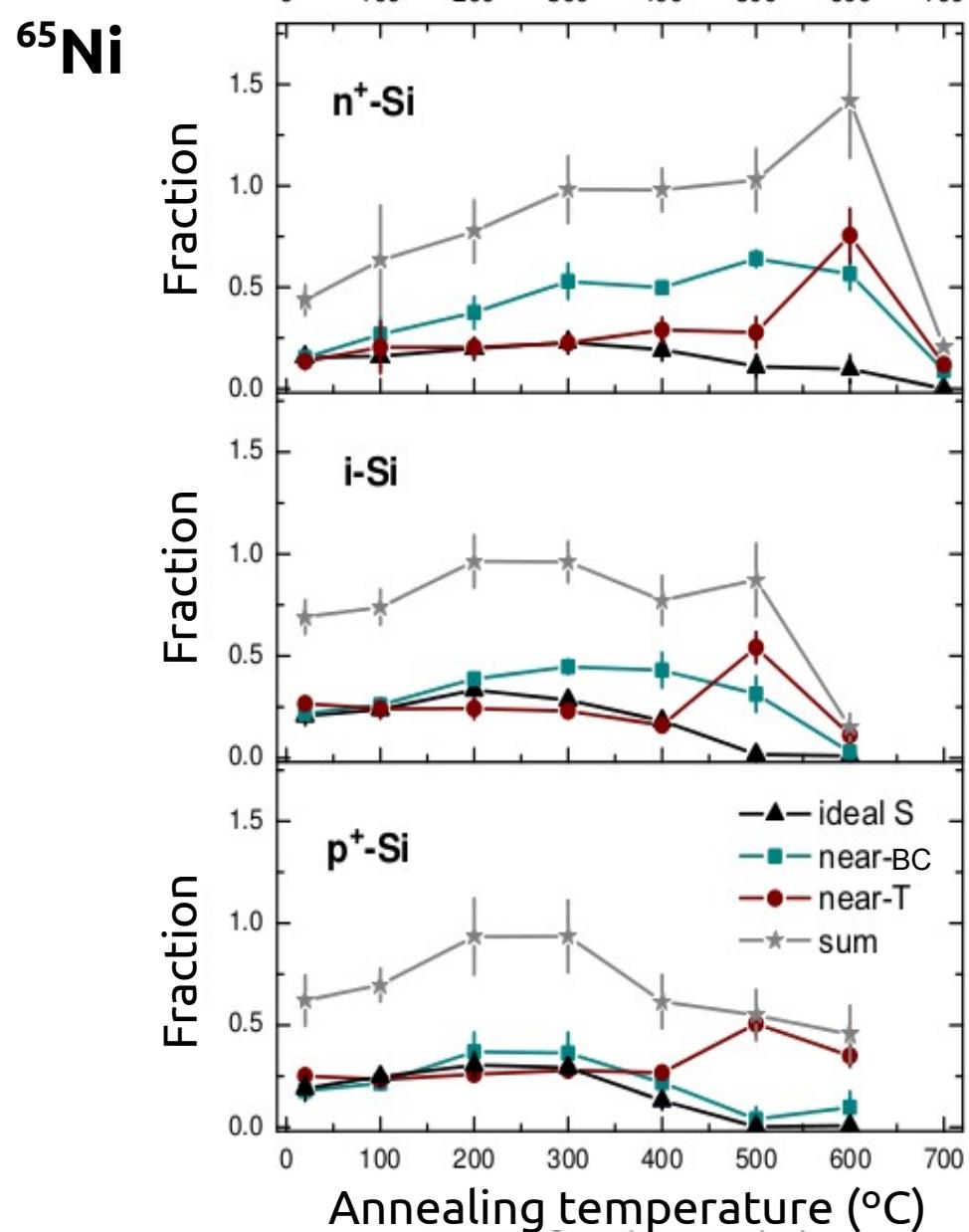
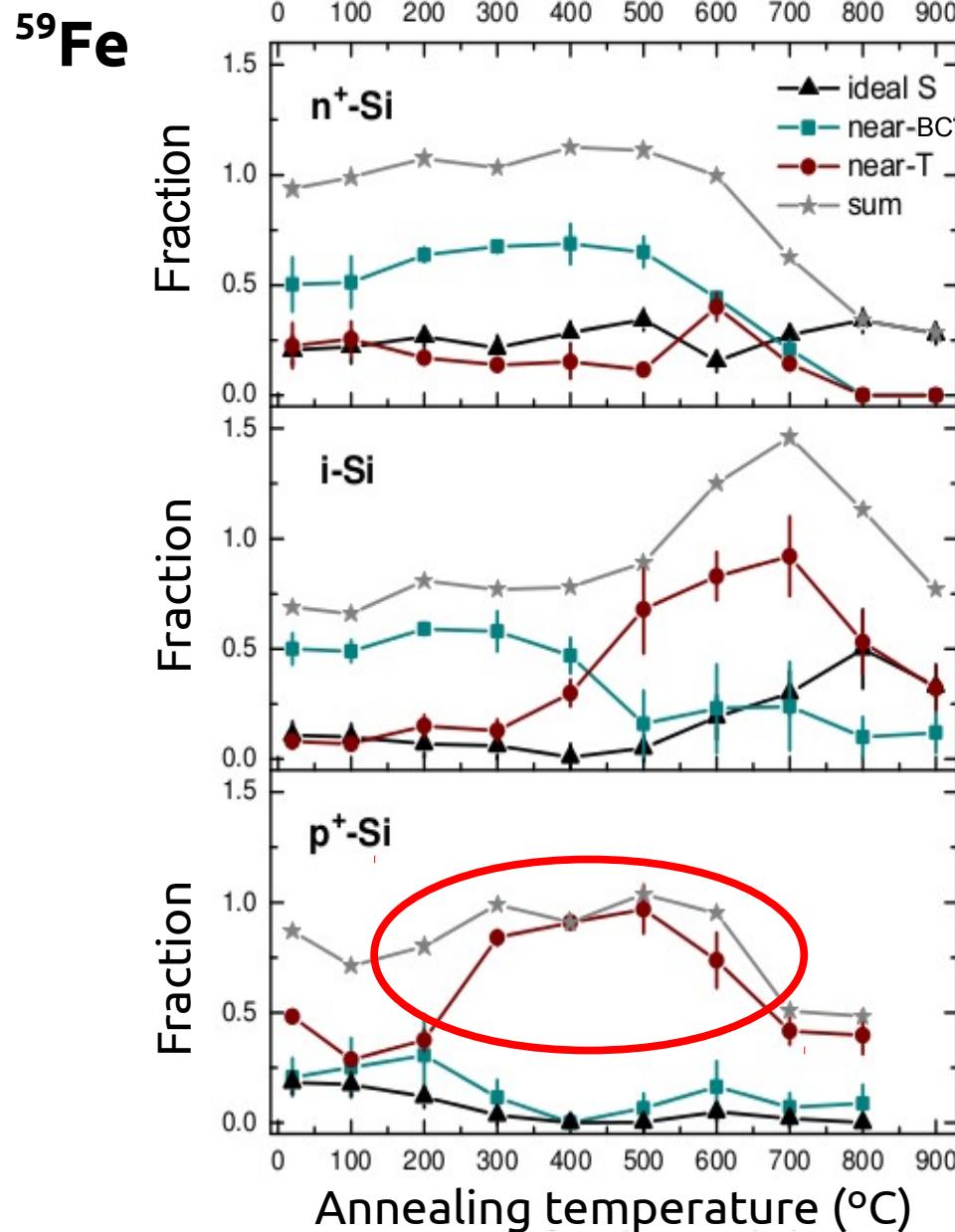
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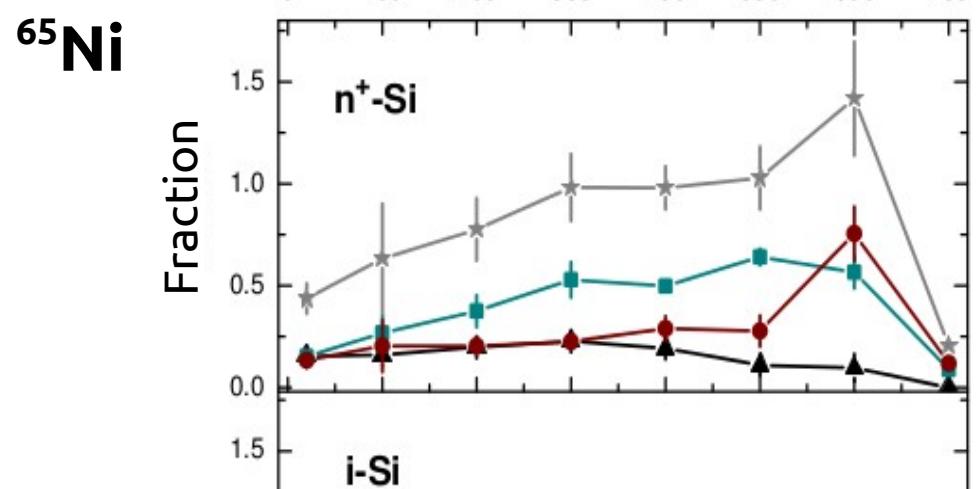
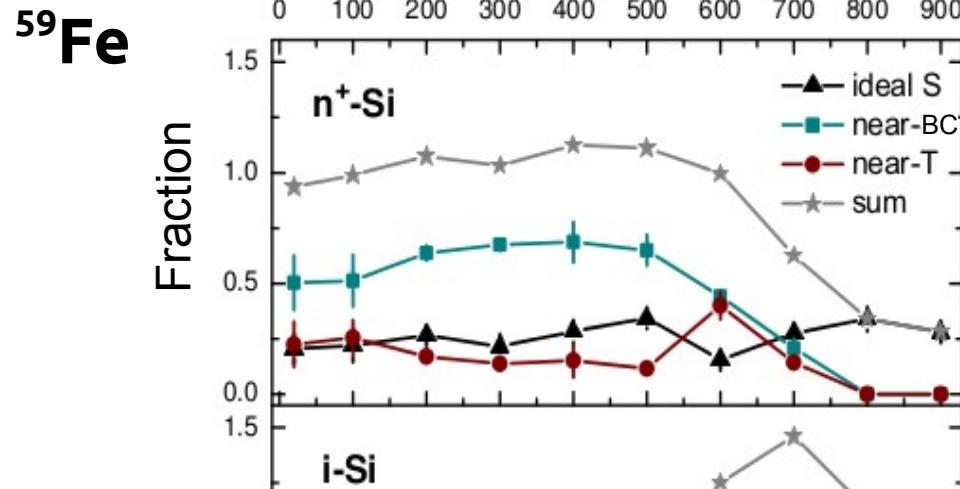
Ni and Fe are trapped into the  $R_p/2$  region on near-T sites.



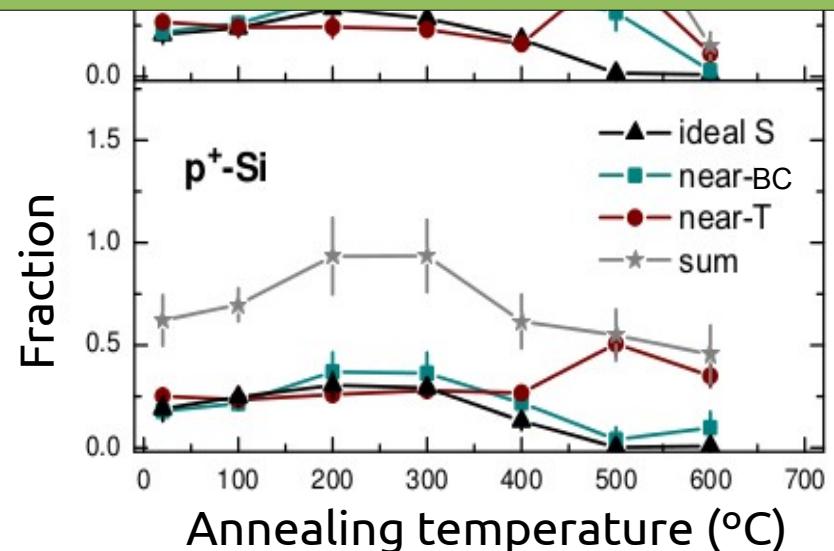
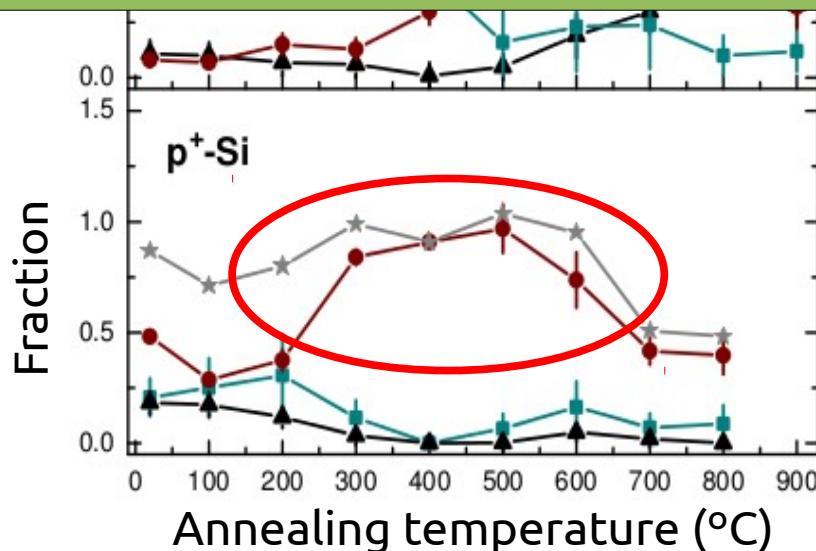
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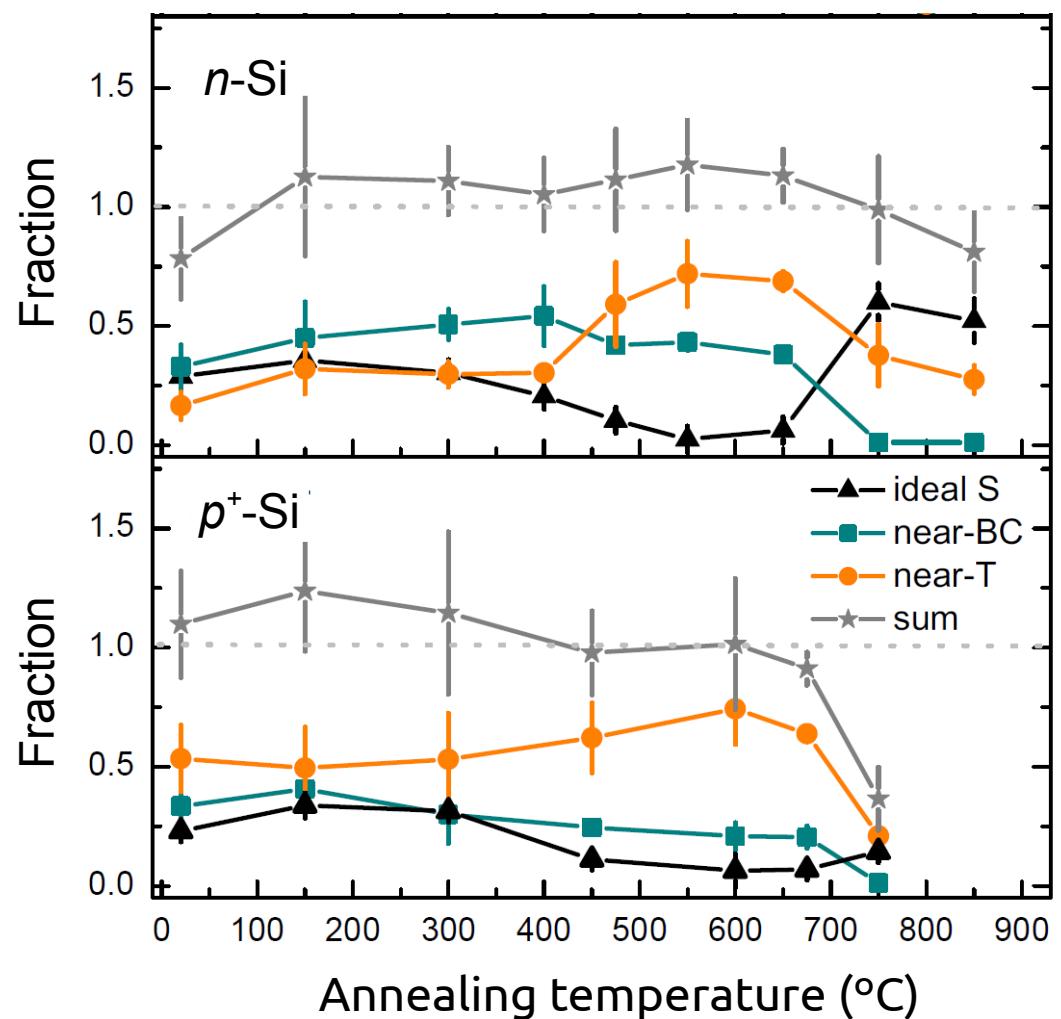


$\text{Fe}^+$  sits also on near-T sites when paired with  $\text{B}^-$ .



# Results: $^{61}\text{Co}$ in n- and p<sup>+</sup>-Si

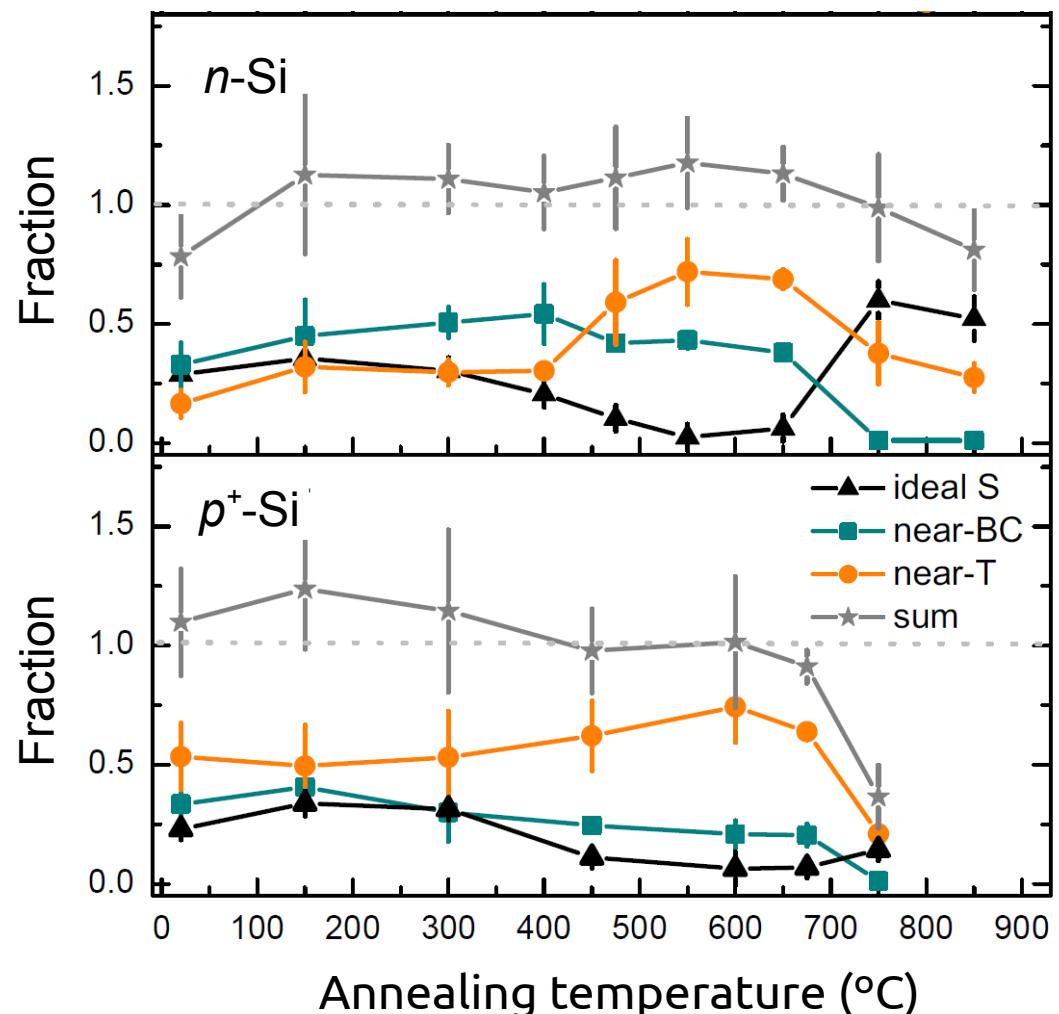
Same three lattice sites are observed  
**(S, near-BC, near-T)**



# Results: $^{61}\text{Co}$ in n- and p<sup>+</sup>-Si

Same three lattice sites are observed  
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- Formation of Co-dimers in n-type Si on **near-T** sites ( $T_A = 475\text{-}650^\circ\text{C}$ ), by comparing with [1]?

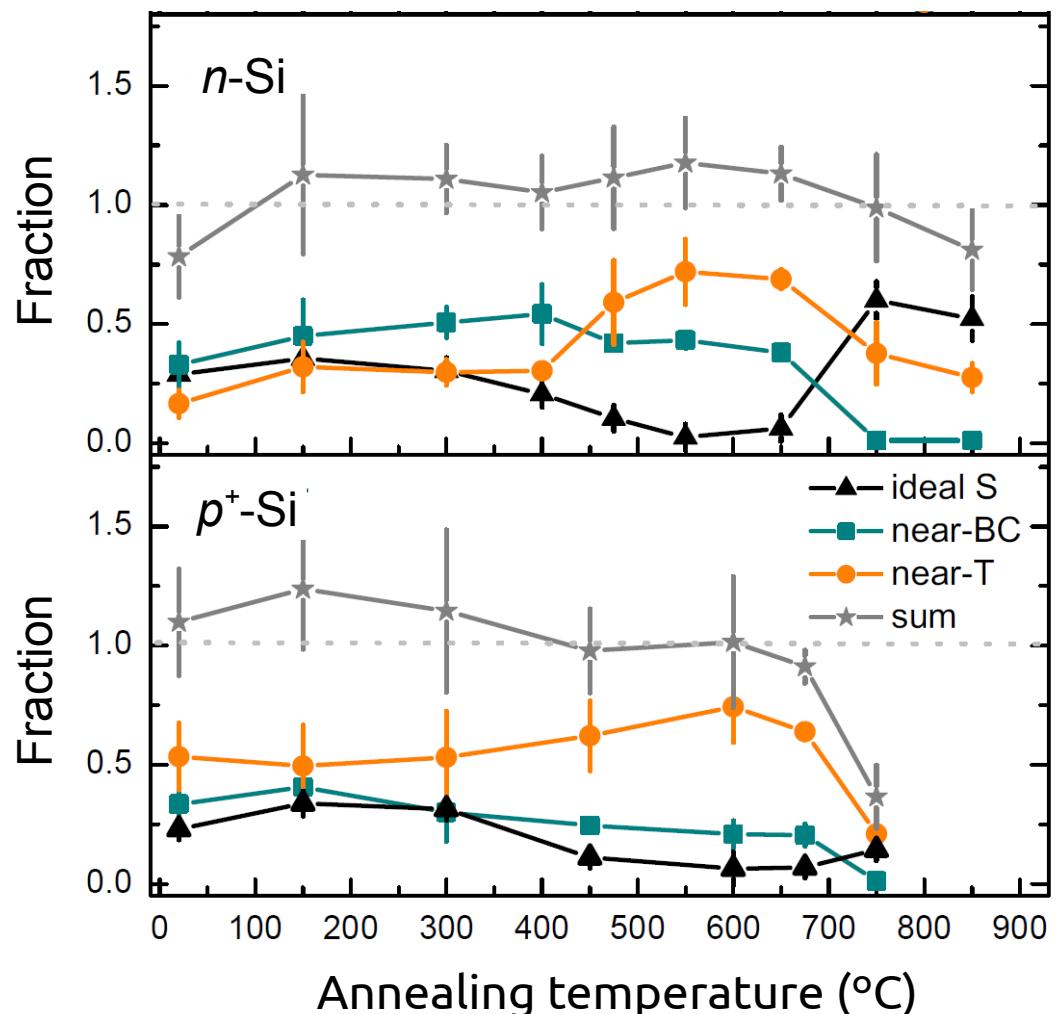


[1] G. Langouche, M. D. Potter, and D. Schroyen, Phys. Rev. Lett. 53, 1364 (1984)

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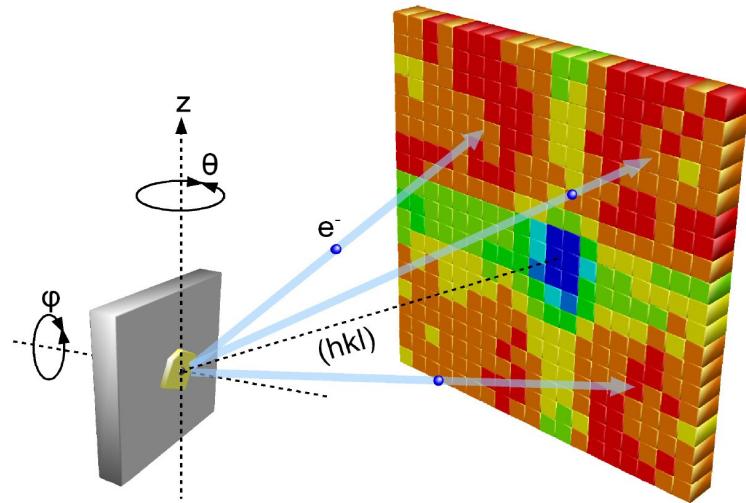
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- Formation of Co-dimers in n-type Si on **near-T** sites ( $T_A = 475\text{-}650^\circ\text{C}$ ), by comparing with [1]?
- near-T** is the prevailing fraction in p<sup>+</sup>-type Si, in the whole annealing temperature range (CoB pairs).



[1] G. Langouche, M. D. Potter, and D. Schroyen, Phys. Rev. Lett. 53, 1364 (1984)

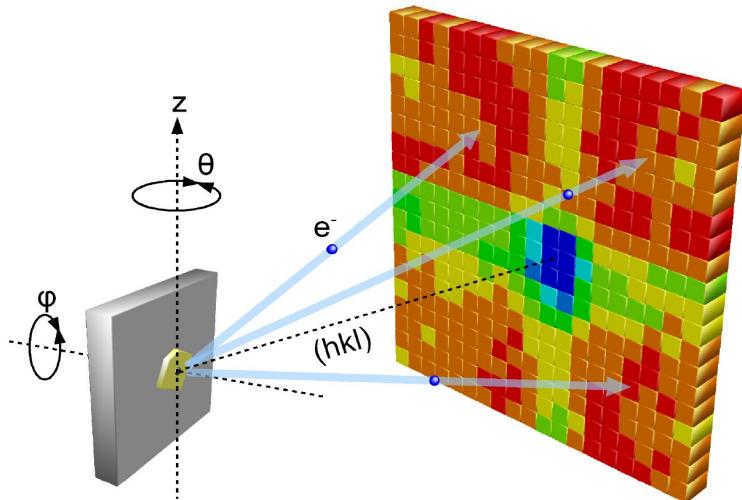
# Conclusion



**Emission channeling** is used to investigate the lattice sites of Ni, Co and Fe in Si.

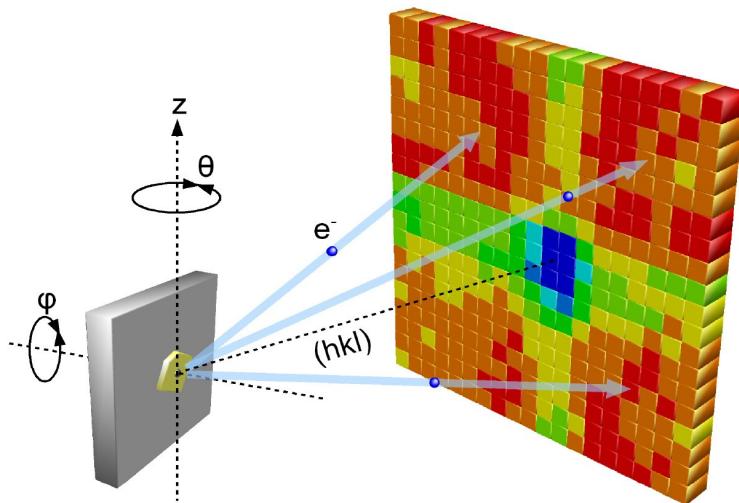
# Conclusion

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# Conclusion



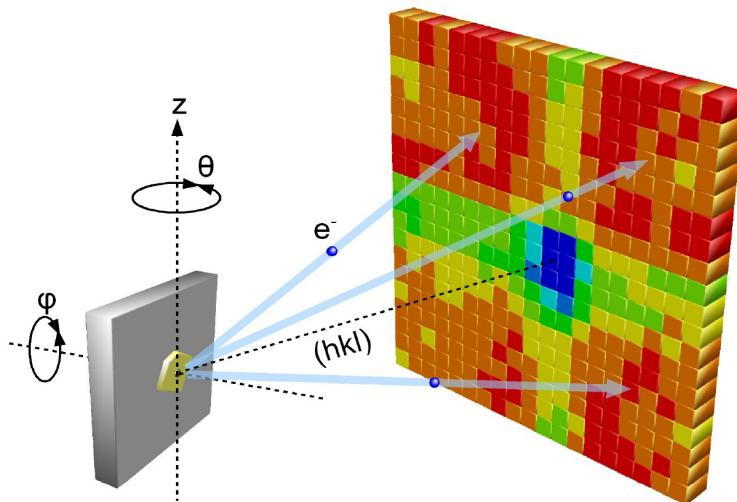
Three lattice sites were found:

**Ideal S**

Single  
vacancies.

**Emission channeling** is used to investigate the lattice sites of Ni, Co and Fe in Si.

# Conclusion



**Emission channeling** is used to investigate the lattice sites of Ni, Co and Fe in Si.

Three lattice sites were found:

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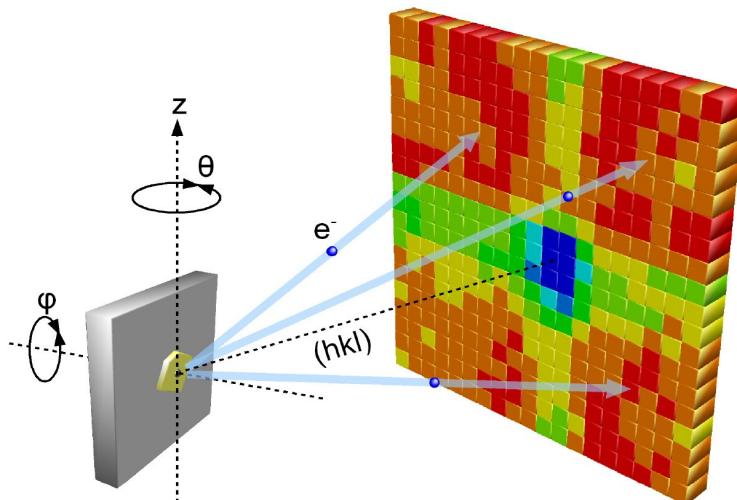
Single vacancies.

**Near-BC**

Multivacancies such as divacancies and hexavacancies.

More stable in  $n^+$ -Si

# Conclusion



**Emission channeling** is used to investigate the lattice sites of Ni, Co and Fe in Si.

Three lattice sites were found:

**Ideal S**

Single vacancies.

**Near-T**

Multivacancies, FeB and CoB pairs in  $p^+$ -Si and Co-dimers in  $n$ -Si.

**Near-BC**

Multivacancies such as divacancies and hexavacancies.

More stable in  $n^+$ -Si

# Thank you for your attention

**Acknowledgments:** This work was performed within the ISOLDE proposal IS453 and supported by FCT-Portugal, project CERN-FP-123585-2011, and by the European Union FP7-through ENSAR, contract 262010. D.J. Silva is thankful for FCT Grant SFRH/BD/69/435/2010.



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