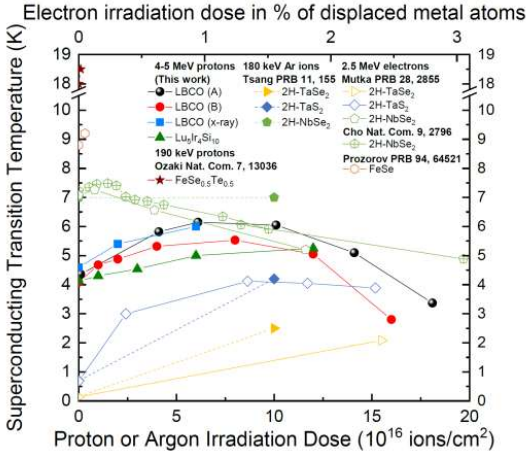
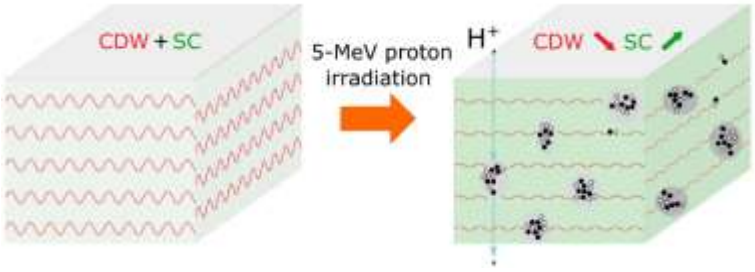




CDW and superconductivity:
T_c "domes" by irradiation induced disorder

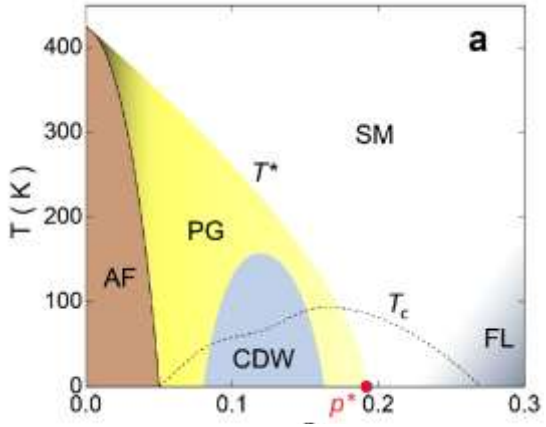
Maxime Leroux

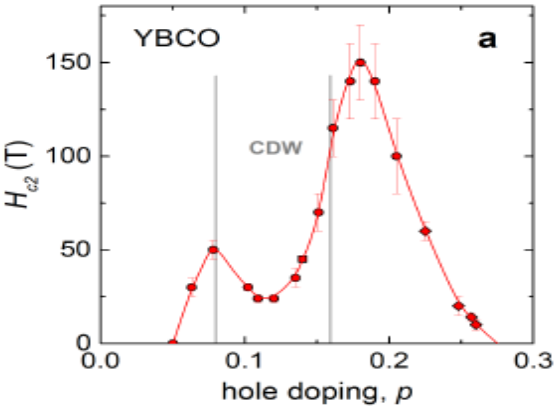
LNCMI Toulouse CNRS

PNAS 116 (22) 10691-10697 (2019)
https://doi.org/10.1073/pnas.1817134116

***Phys. Rev. B* 102, 094519 (2020)**
https://doi.org/10.1103/PhysRevB.102.094519

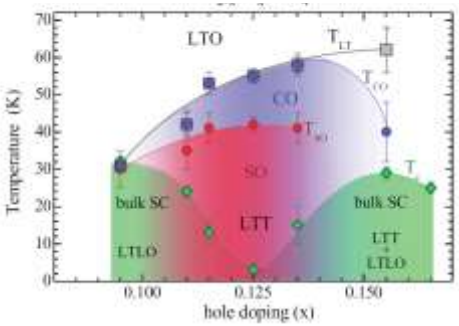
Ubiquitous CDW in T_c dome of cuprates high temperature superconductors



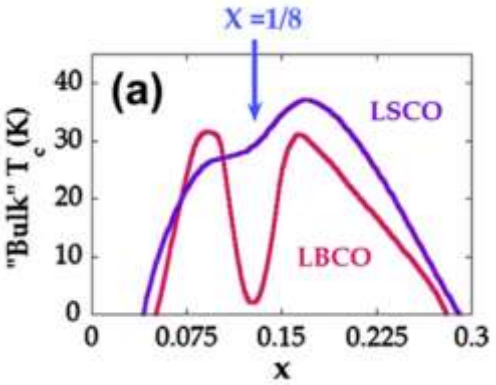


Cuprates, heavy fermions, dichalcogenides, organic…

$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$
$La_{1.875}Ba_{0.125-x}Sr_xCuO_4$
$La_{1.875}Ba_{0.125}CuO_4$



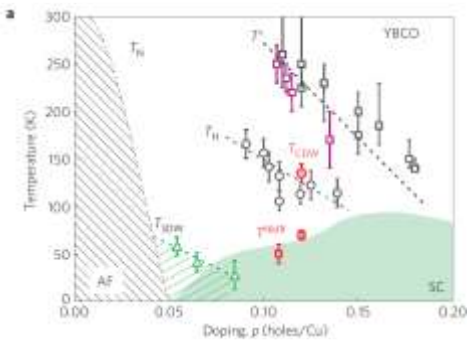
Tranquada et al., Nature 375, 561 (1995)
Hücker, M. et al. PRB 83, 104506 (2011)



$Bi_2Sr_2CaCu_2O_{8+\delta}$
$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

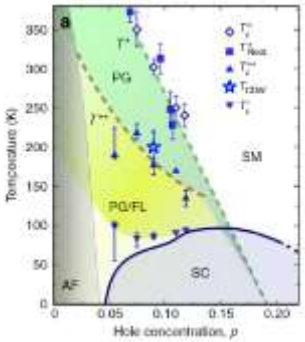
Hoffman, J et al. Science 295, 466-469 (2002)
Comin , R. et al. Science 343, 390-392 (2014)
da Silva Neto, E.H. et al. Science 343, 393-396 (2014)

$YBa_2Cu_3O_{6+x}$
$YNdBa_2Cu_3O_{6+x}$



Doiron-Leyraud N, et al. Nature 447, 565-569 (2007)
Wu, T. […] Julien, M.H. Nature 477, 191–194 (2011)
Gerber, S. Science 350, 949–952 (2015)
Ghiringhelli, G. et al. Science 337, 821–825 (2012)

$HgBa_2CuO_{4+\delta}$
W. Tabis et al. Nature Communications 5, 875 (2014)

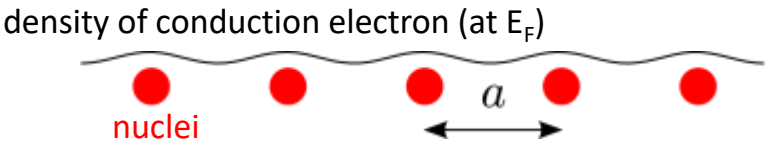


Also electron-doped: $Nd_{2-x}Ce_xCuO_4$
da Silva Neto, E.H. et al. (2015), Science 347, 282-285

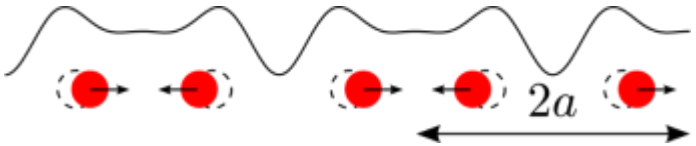
What is the role of the CDW in cuprates ?

Charge Density Wave (CDW)

Metal : “Bloch states”



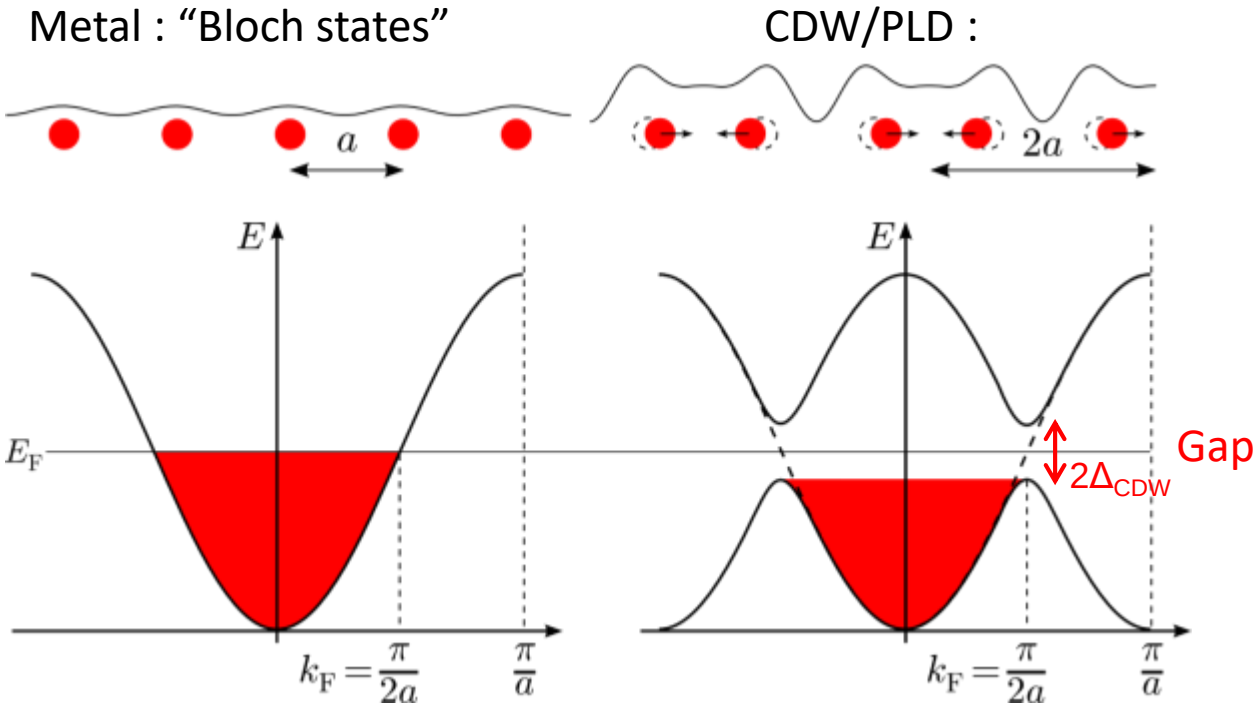
CDW/PLD :



Charge Density Wave (CDW) = static, real space, oscillation of e- density at E_F

Periodic Lattice Distorsion (PLD) = static oscillation of the crystal lattice

Charge Density Wave gap : Δ_{CDW}



CDW gap at the Fermi level

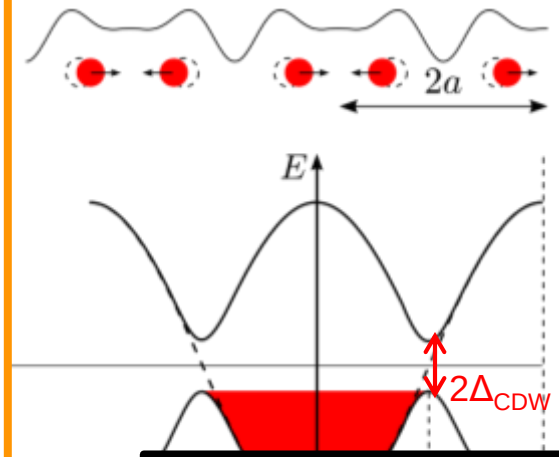
“textbook” picture:
SC and CDW simply compete for the same electrons at E_F

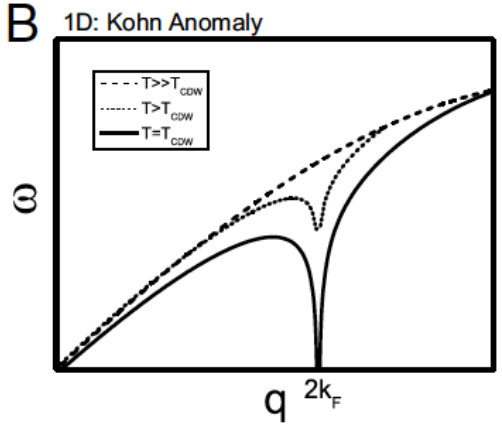
Three « types » of CDW

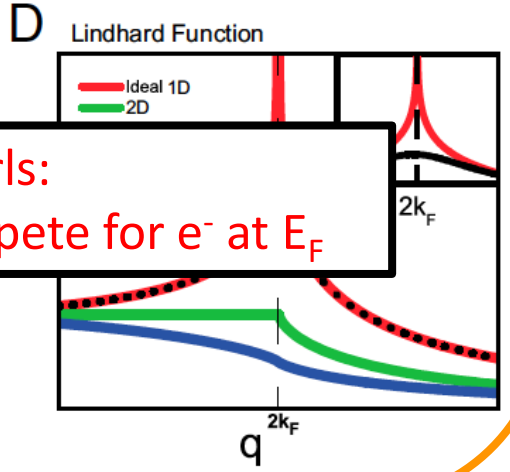
Xuetao Zhu et al. PNAS 112 (8) 2367-2371 (2015)

Type 1: Fermi surface nesting

Gap at E_F



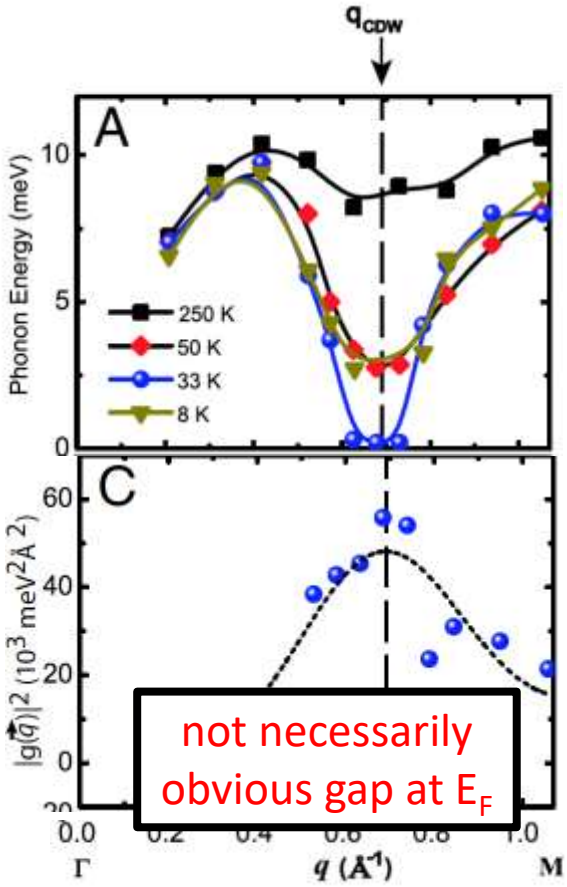




Peierls:
SC and CDW compete for e^- at E_F

$NbSe_3$
$Lu_5Ir_4Si_{10}$

Type 2: max in electron-phonon coupling

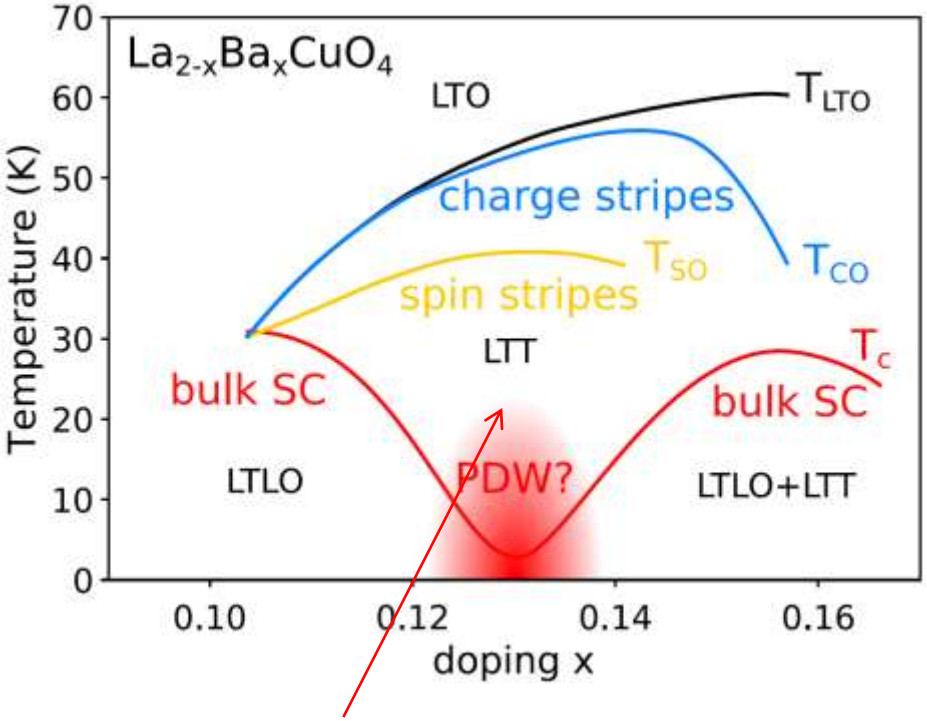


not necessarily obvious gap at E_F

$NbSe_2$

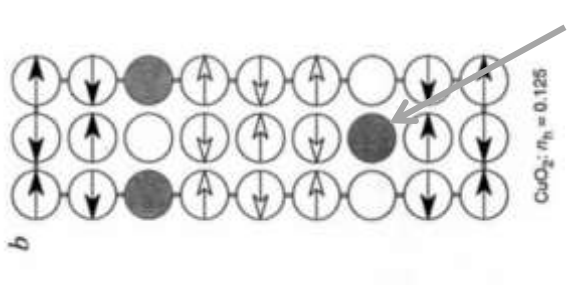
Type 3: CDW in cuprates?

Stripe order in the CuO_2 planes of $La_{2-x}Ba_xCuO_4$ x=0.125 (1/8 doping)

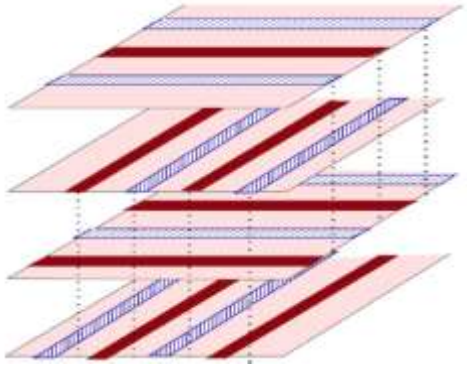


Dynamical layer decoupling ?
2D superconductivity ?
BKT transition ?

J. M. Tranquada et al., Nature 375, 561 (1995)



Stripes = spatial correlations between spins and holes
PDW = **intertwined** spin, charge and SC orders ?



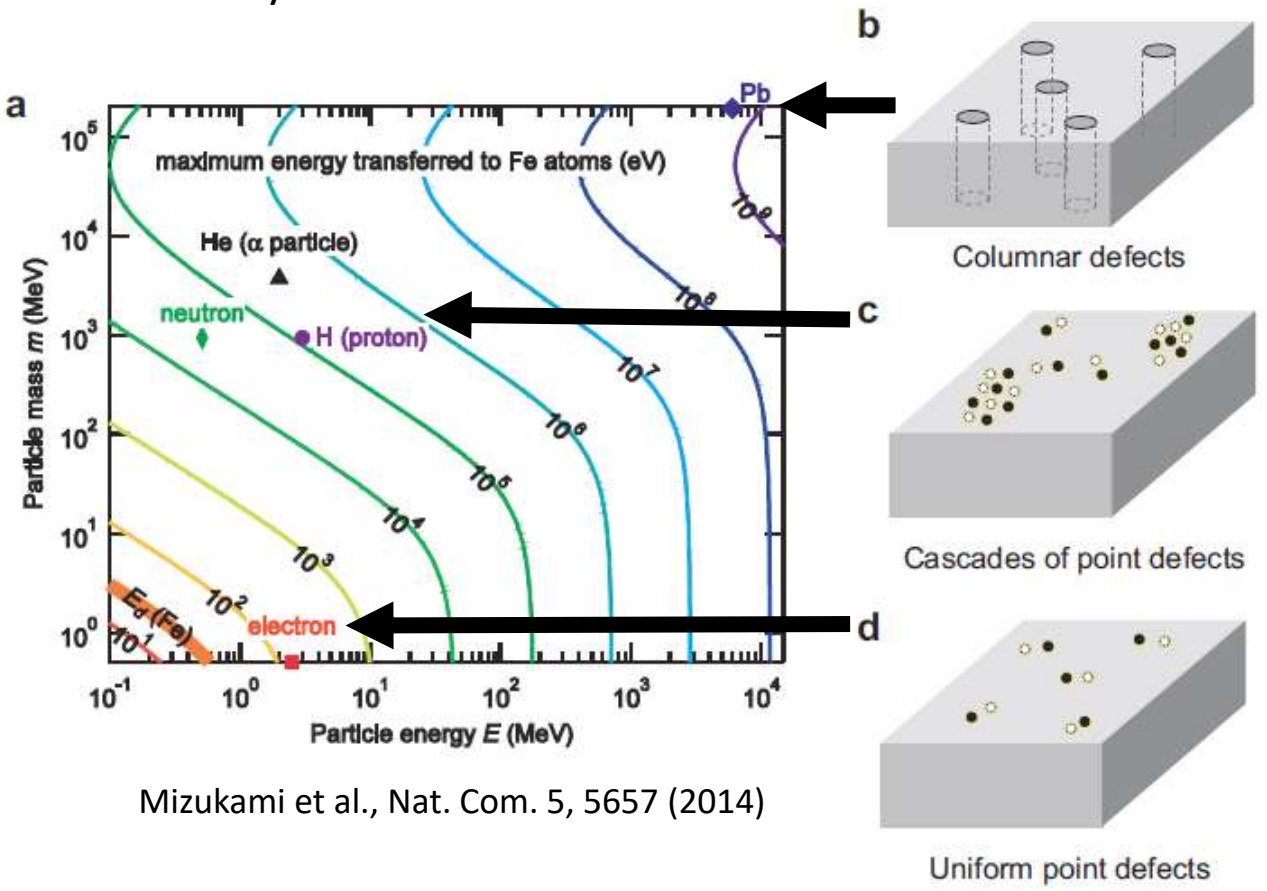
Alternating
3D structure

Stripe order

Tuning parameter: shaping the defects structure using irradiations to suppress CDW

Irradiation offer independent control of:

- Defects geometry
- Defects density



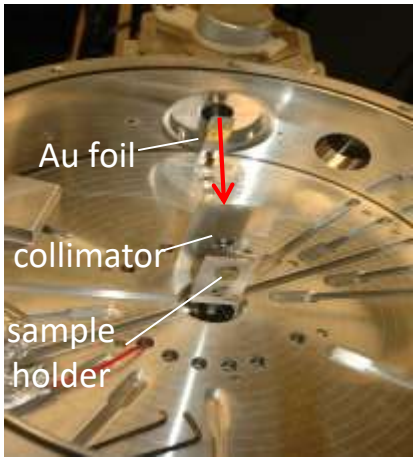
Mizukami et al., Nat. Com. 5, 5657 (2014)

Heavy ion at high energies (100 MeV-GeV)

Particles at a few MeV

Electrons with low recoil energy

Van der Graaf 6MV Tandem Accelerator at Western Michigan University (Prof. A. Kayani)



E.g. : proton-irradiation induced defects in YBCO crystals:

- **point defects (Cu, O)**
- **small clusters with anisotropic strain fields, 2-4 nm**
- **cascade defects (amorphous regions), 2-5 nm**

M. A. Kirk, Y. Yan, Micron **30**, 507 (1999)

Tuning parameter: irradiation induced disorder

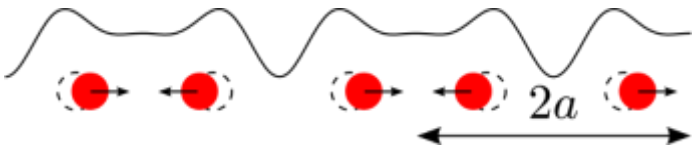
Distinct effects on CDW and SC

Mutka H., *Ph.D. thesis* rep. no. CEA-R–5209

Irradiation

➢ CDW

e⁻ real space modulation



Periodic Lattice Distortion

phase fluctuations

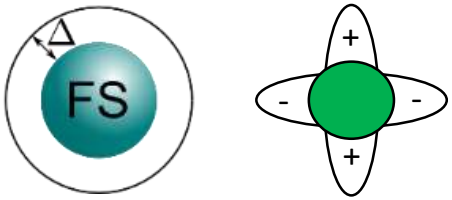
- frustration of modulation
- formation of CDW domains

pair-breaking

- e⁻ mean free path reduced
- electronic susceptibility reduced
- global CDW suppression

➢ Superconductivity

- real space: uniform Cooper pairs density
  - ↳ no phase fluctuations
- momentum-space: k-dependent gap



s-wave

Anderson's theorem
Non magnetic: no effect (isotropization)
Magnetic: pair-breaking

s^{+-} d-wave

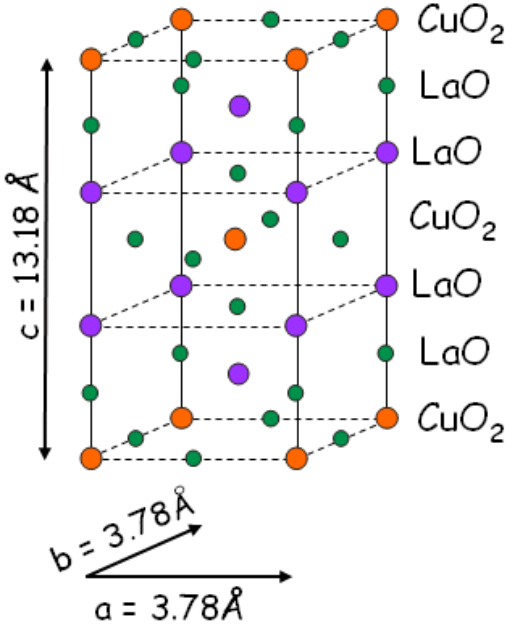
detrimental (pair-breaking)

? Real space modulated SC ?
Pair-Density Wave, FFLO

detrimental
(some analogy to CDW)

Outline

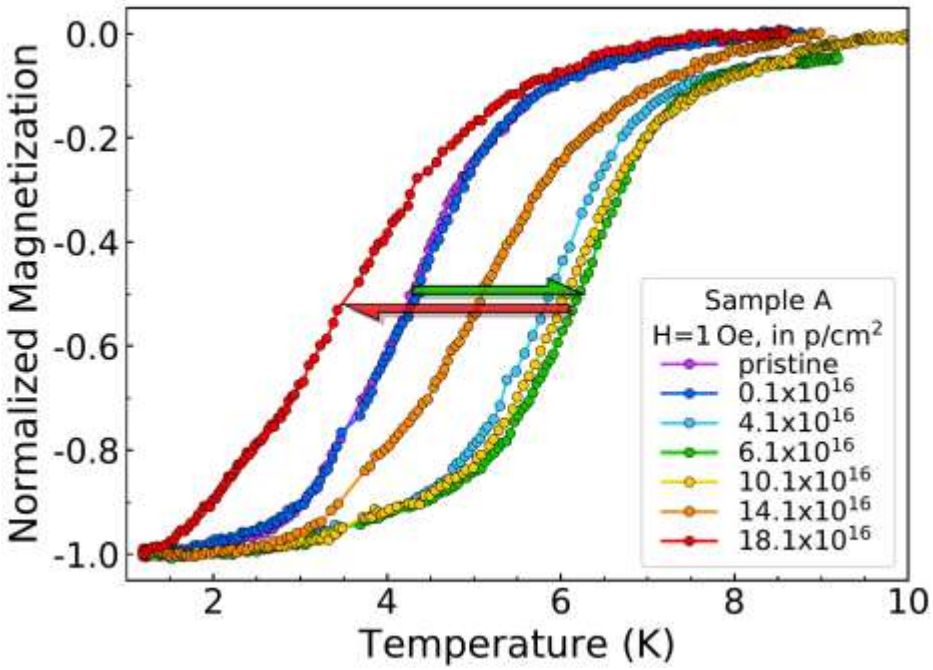
- **Type-3 CDW: strong competition in LBCO**
- Type-1 CDW: strong competition in $Lu_5Ir_4Si_{10}$
- Type-2 CDW: marginal competition and synergy in $NbSe_2$



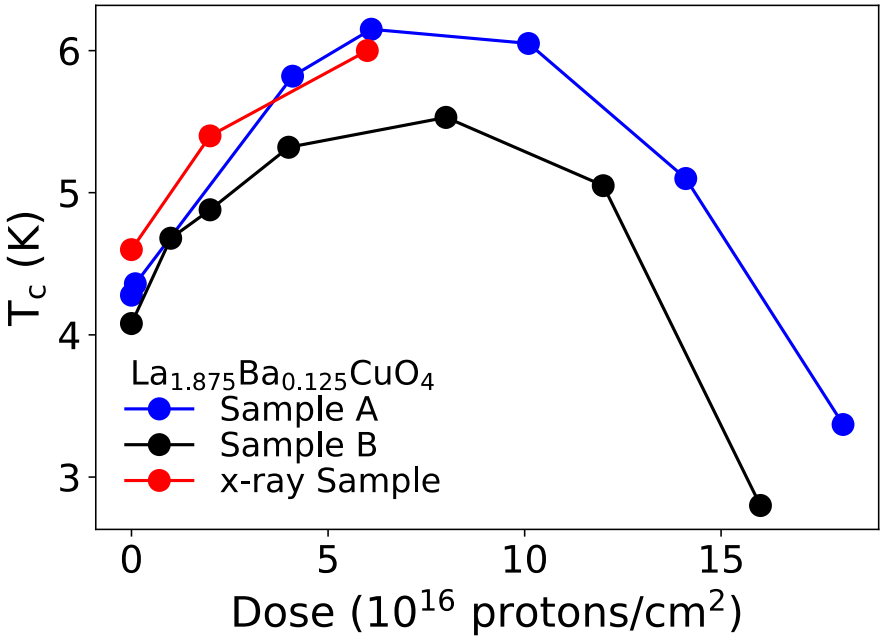
LBCO

Superconductivity T_c increase after proton irradiation in $La_{1.875}Ba_{0.125}CuO_4$

Meissner effect in 5 MeV proton irradiated crystal



No transition broadening until T_c starts to decrease



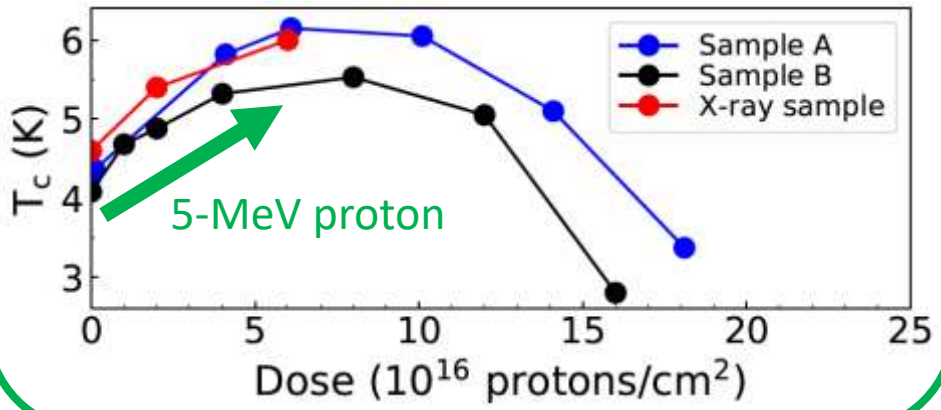
50% increase of T_c with irradiation in a d-wave superconductor !

Samples: G.D. Gu & J. Tranquada, BNL

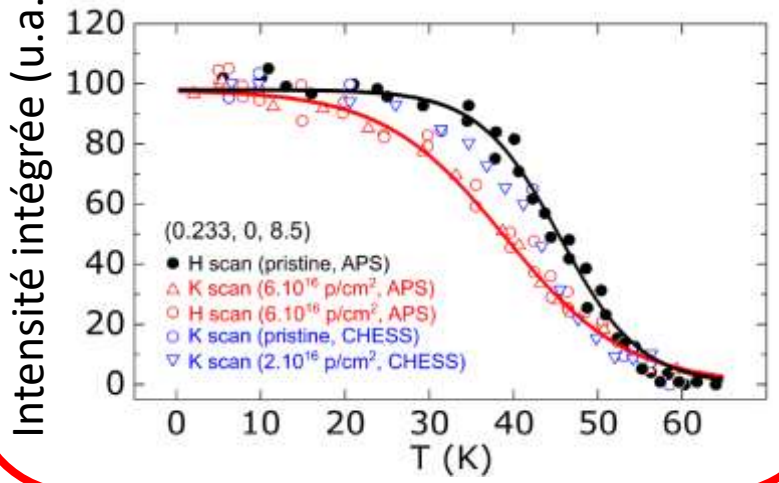
CDW ↔ SC in $La_{1.875}Ba_{0.125}CuO_4$ (1/8 doping)

Effect of disorder induced by <u>proton</u> irradiation

A « new » dome of T_c in cuprates superconductors



X-ray diffraction
low T / pulsed B field



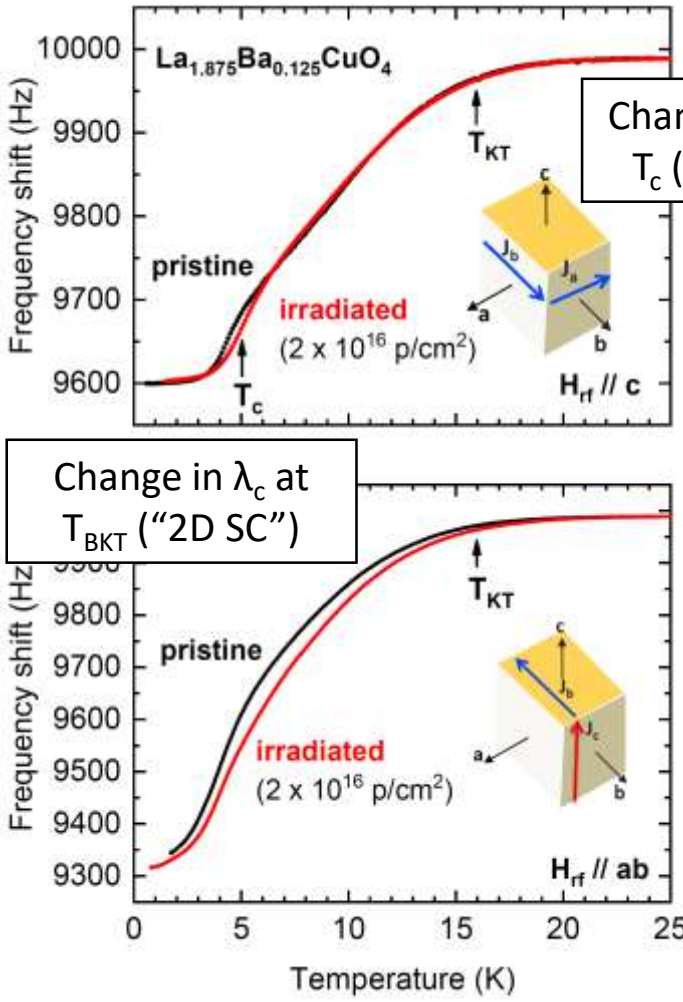
T_c ↗
With disorder!
(in a d-wave!)

T_{CO} ↘
Suppression of CDW

<u>Strong</u> competition
SC ↔ CDW

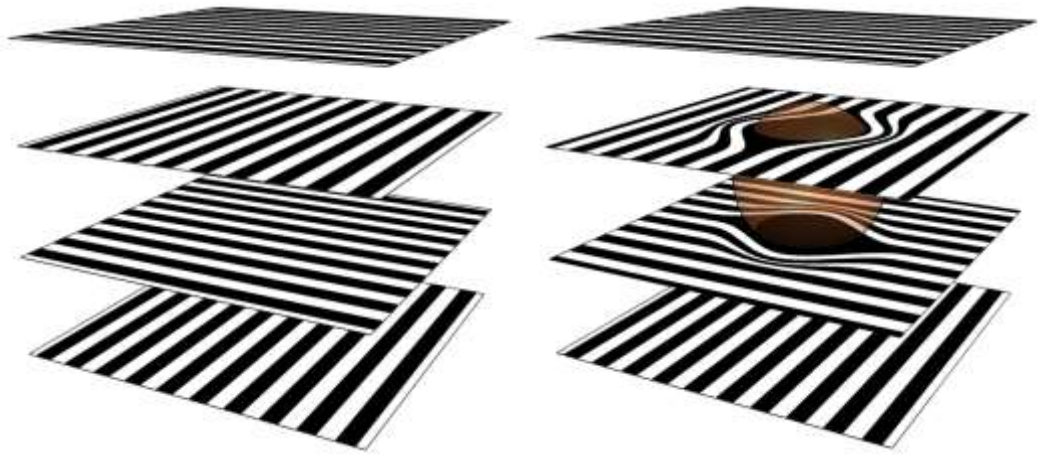
<u>M. Leroux</u> et al. **PNAS** 116 (22), 10691 **(2019)**

Some speculation: suggestion of dynamical layer decoupling from Pair-Density-Wave (PDW) in $La_{1.875}Ba_{0.125}CuO_4$



Magnetic penetration depth

(Tunnel Diode Oscillator Measurements M. Smylie, ANL)



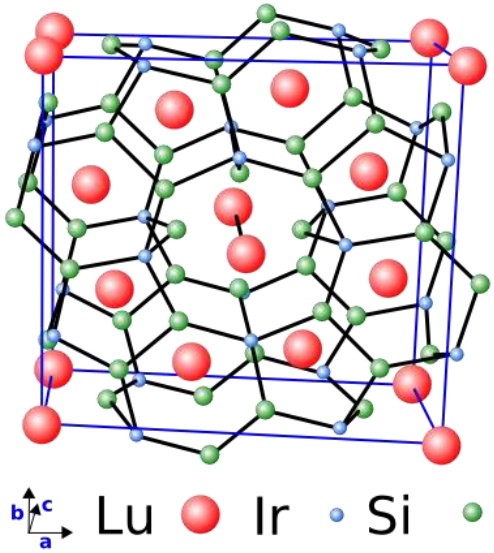
Zero Josephson coupling between layers induced by orthogonal PDW

Defects reintroduce Josephson coupling between layers ?

M. Leroux, V. Mishra,…, Z. Islam and U. Welp, **PNAS, 2019, 116 (22) 10691-10697**

Outline

- Type-3 CDW: strong competition in LBCO
- **Type-1 CDW: strong competition in $Lu_5Ir_4Si_{10}$**
- Type-2 CDW: marginal competition and synergy in $NbSe_2$

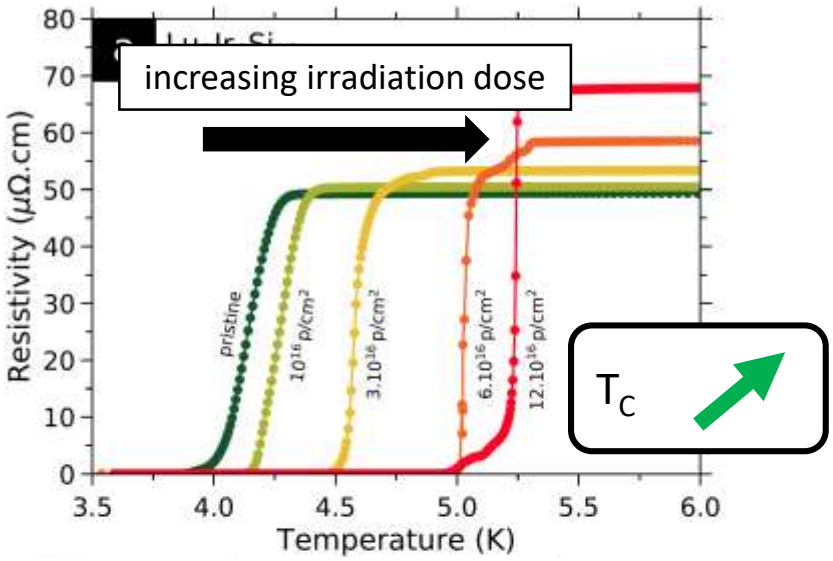


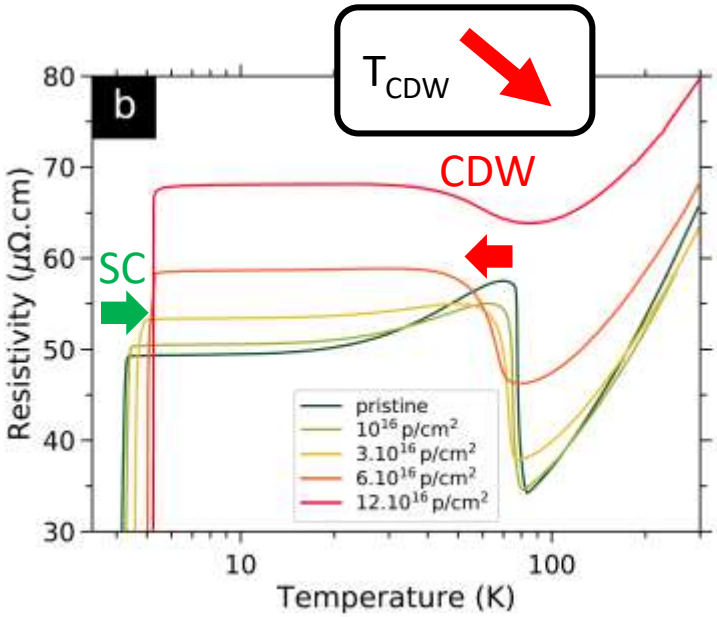
1D CDW along Lu chains (c-axis)

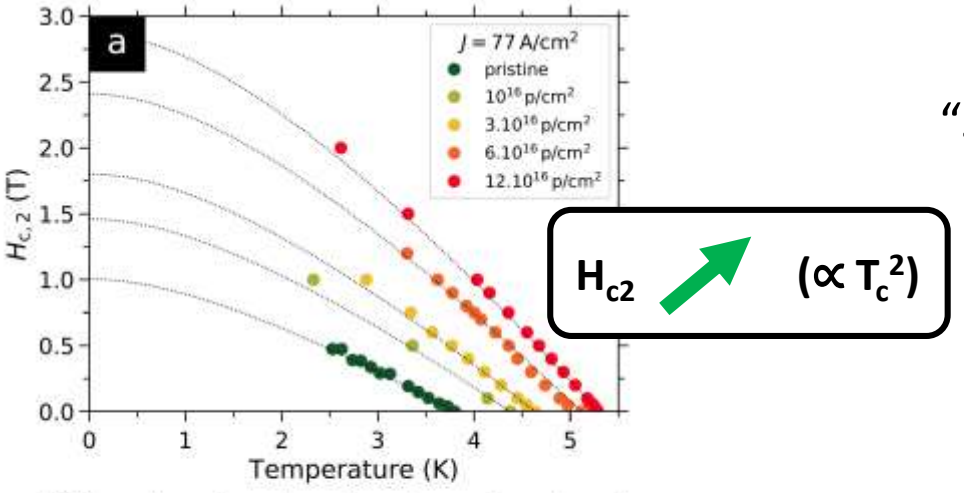
T_{CDW} = 77 K

T_{SC} = 4.0 K

Type-1 CDW (quasi-1D, Peierls) with s-wave SC: $Lu_5Ir_4Si_{10}$ Proton irradiation study



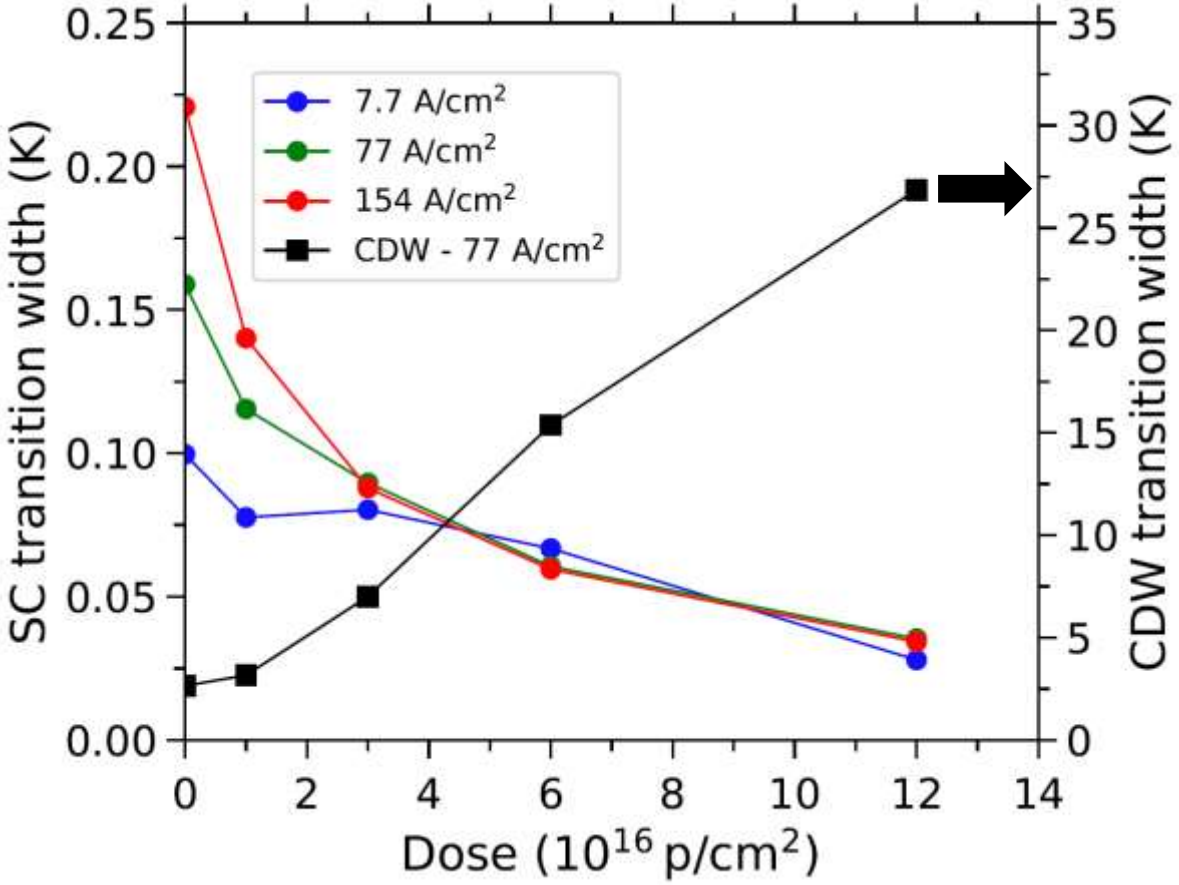




"Standard" CDW ↔ SC competition for e^- at E_F

M. Leroux, et al., PRB 102, 094519 (2020)

$Lu_5Ir_4Si_{10}$: SC vs CDW transition width



CDW transition width ↗ with irradiation
(**real-space phase fluctuations** i.e. CDW broken into domains)

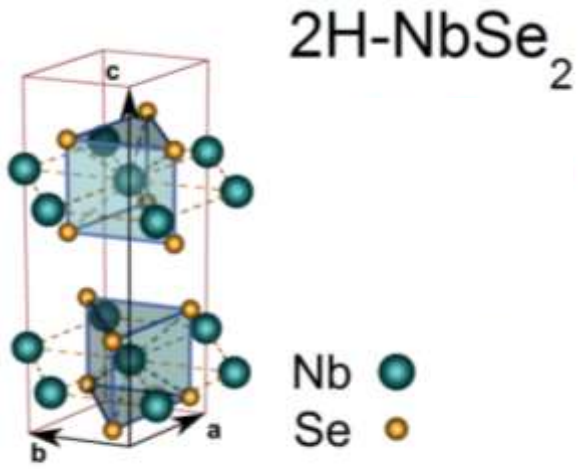
SC transition width ↘ with irradiation
(real-space homogenization)

See poster by **Pierre Rodière**

M. Leroux, et al., PRB 102, 094519 (2020)

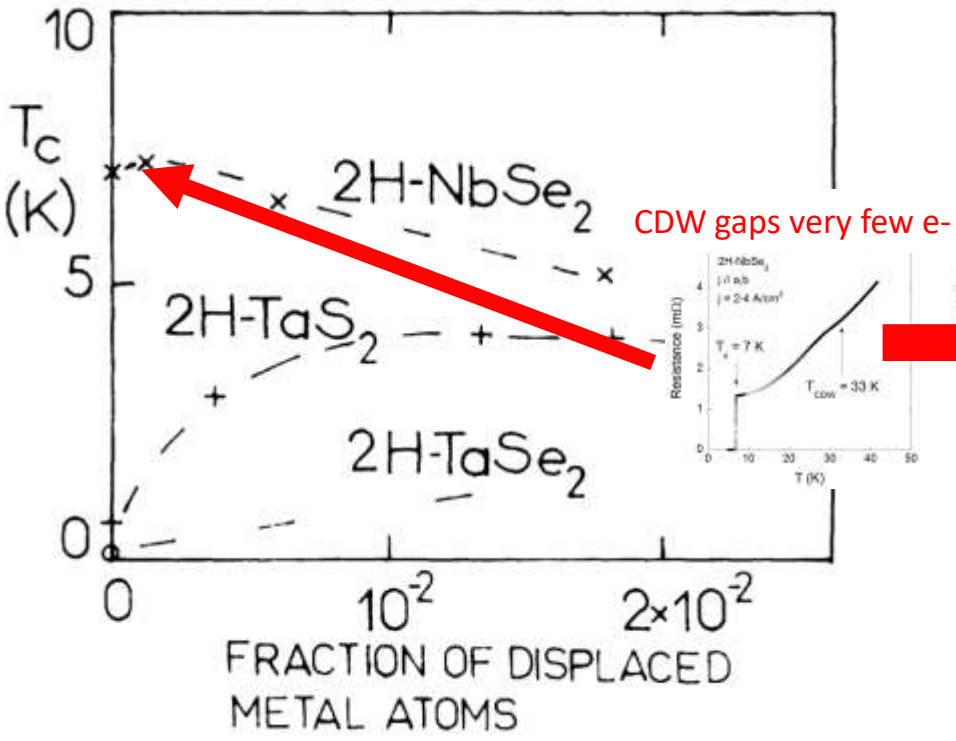
Outline

- Type-3 CDW: strong competition in LBCO
- Type-1 CDW: strong competition in $Lu_5Ir_4Si_{10}$
- **Type-2 CDW: marginal competition and synergy in $NbSe_2$**

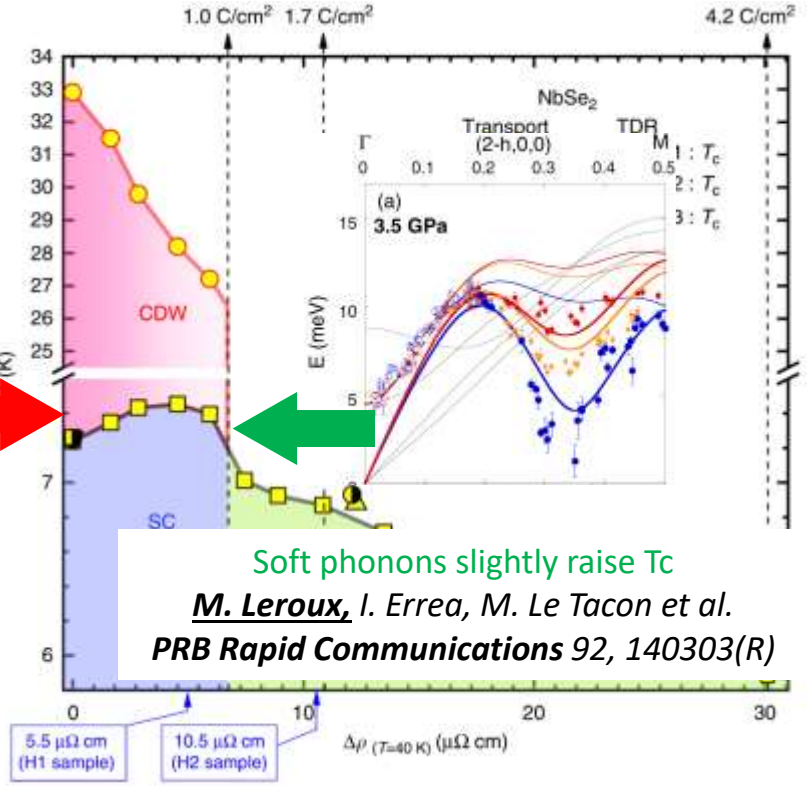


Type-2 CDW with SC: 2H−$NbSe_2$

electron irradiation studies



CDW gaps very few e-



Soft phonons slightly raise Tc

M. Leroux, *I. Errea, M. Le Tacon et al.*

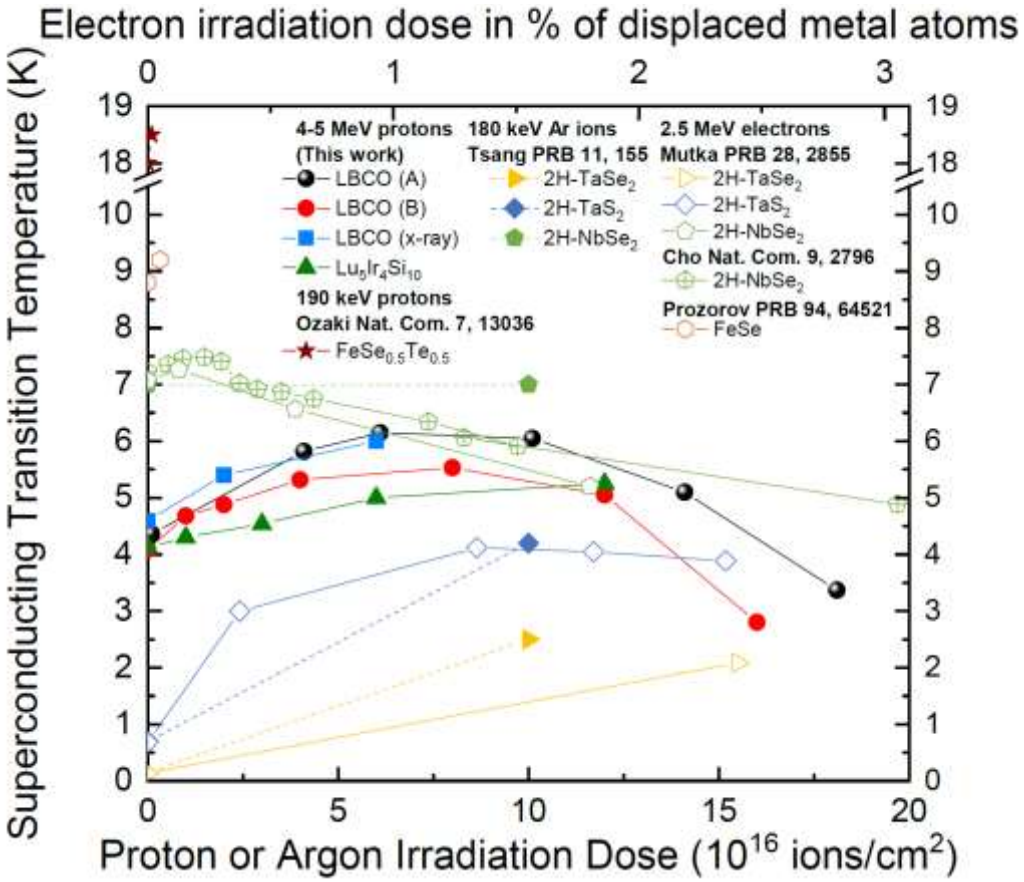
PRB Rapid Communications *92, 140303(R)*

Mutka, H. (1983) PRB, *28* (5), 2855–2858
10.1103/PhysRevB.28.2855

Cho, K. et al. (2018) *Nat. Com.*, *9*(1), 1–9
10.1038/s41467-018-05153-0

SC – CDW marginal competition/synergy

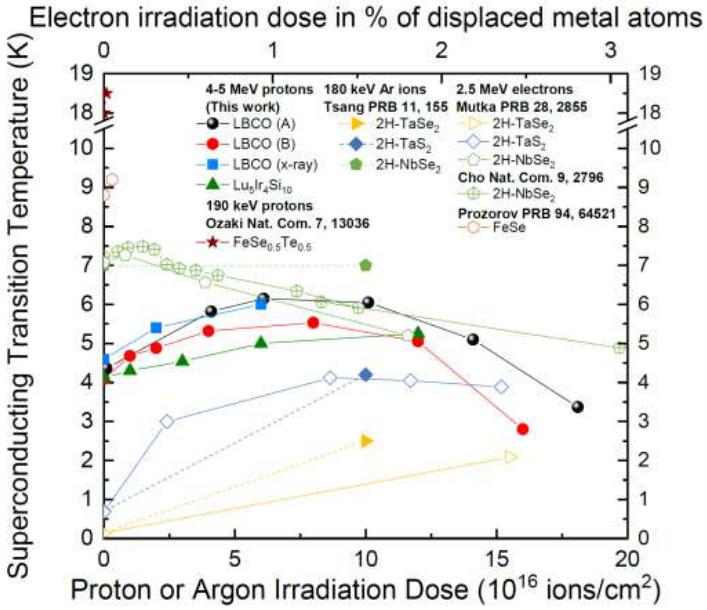
Dome of T_c with irradiation: the complete literature



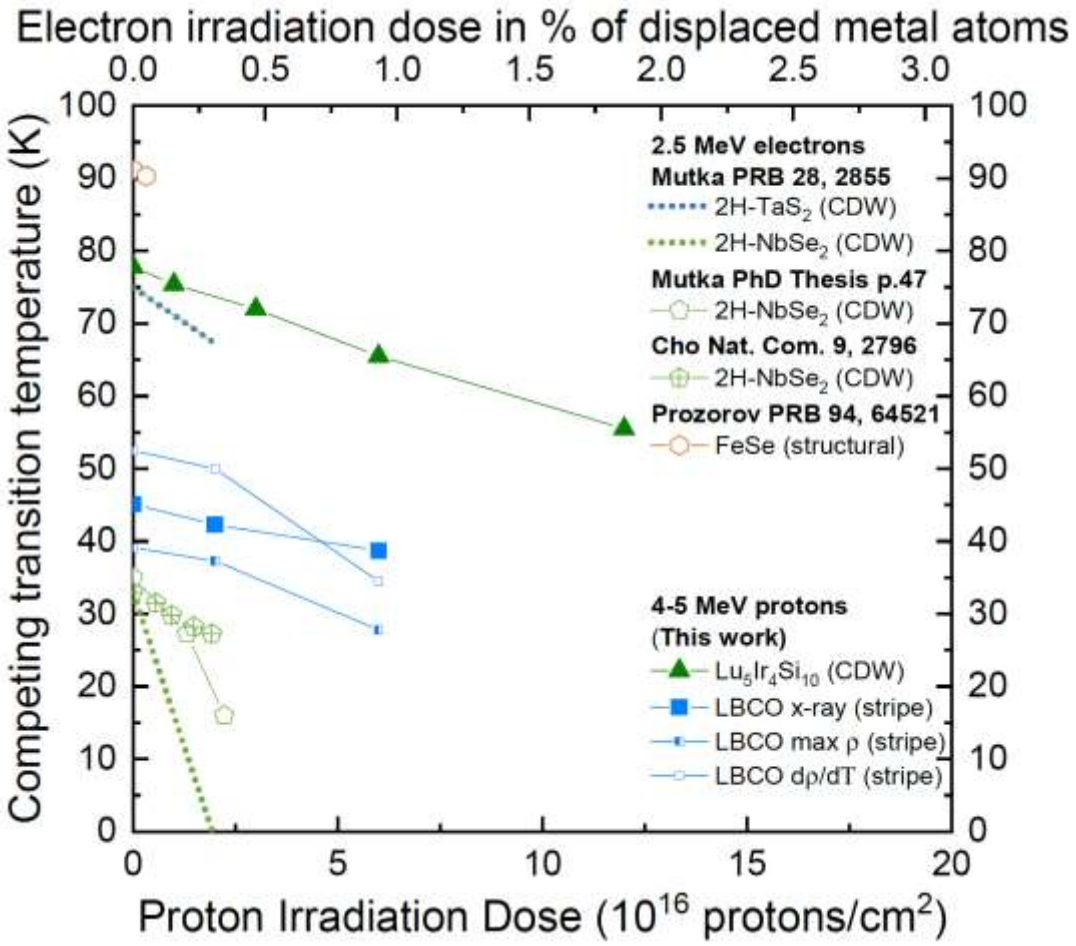
untapped potential of irradiations to study SC vs spatially modulated order

M. Leroux, V. Mishra,…, Z. Islam and U. Welp, **PNAS, 2019, 116 (22) 10691-10697**

Dome from competition with real-space modulated orders



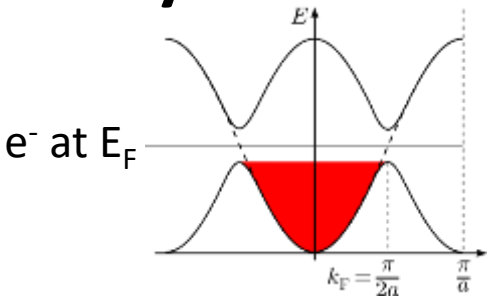
Suppression of CDW by disorder



Charge Density Wave ↔ Superconductivity

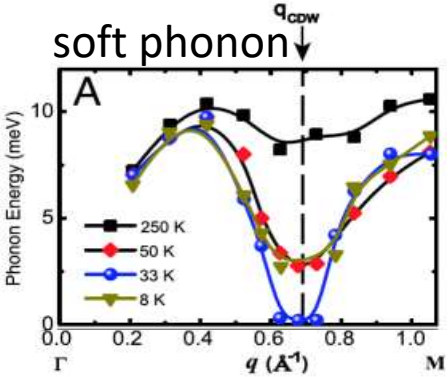
- Type-1: 1D, nesting, Peierls
  - Competition ($Lu_5Ir_4Si_{10}$)

    Leroux et al., PRB 102, 094519 (2020)
    Leroux et al. *J Supercond Nov Magn* 26, 1669–1672 (2013)



- Type-2: 2D, e-ph coupling
  - competition and synergy ($NbSe_2$)

    Cho, K. et al. (2018) *Nat. Com.*, *9*(1), 1–9
    Leroux et al. PRB Rap. Com. 92, 140303(R) (2015)
    Leroux et al. PRB 86, 155125 (2012)

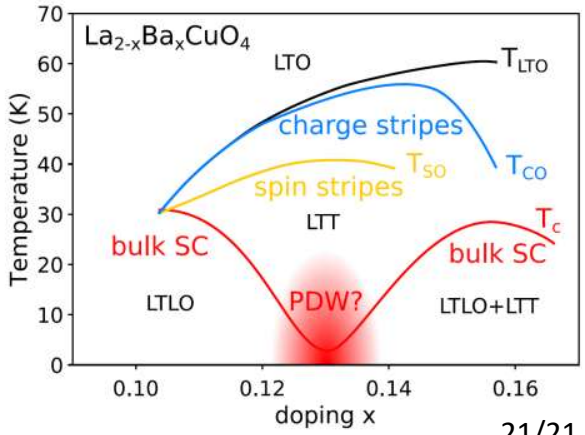


Weber et al. PRL 107, 107403

- Type-3: ODC, stripes, PDW ? (YBCO, LBCO)
  - Competing phenomenon ?
  - Or crucial intertwining ?

Irradiation as an external tuning parameter: strongly suppress real-space modulated orders (CDW, Q ≠ 0)

Leroux et al., PNAS, 2019, 116 (22) 10691-10697



What happens to the Hall effect ?

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