# First-Order Transition in the magnetic vortex matter in $MgB_2$ tuned by disorder


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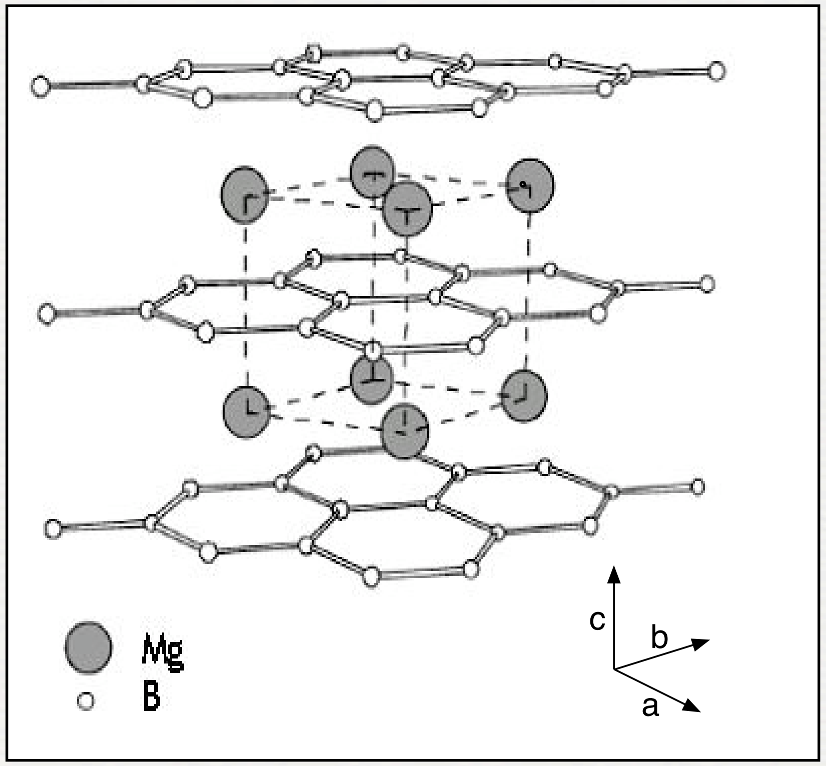
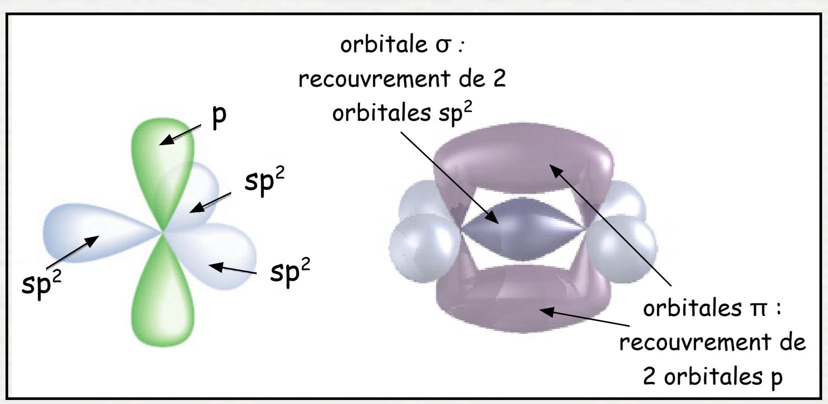


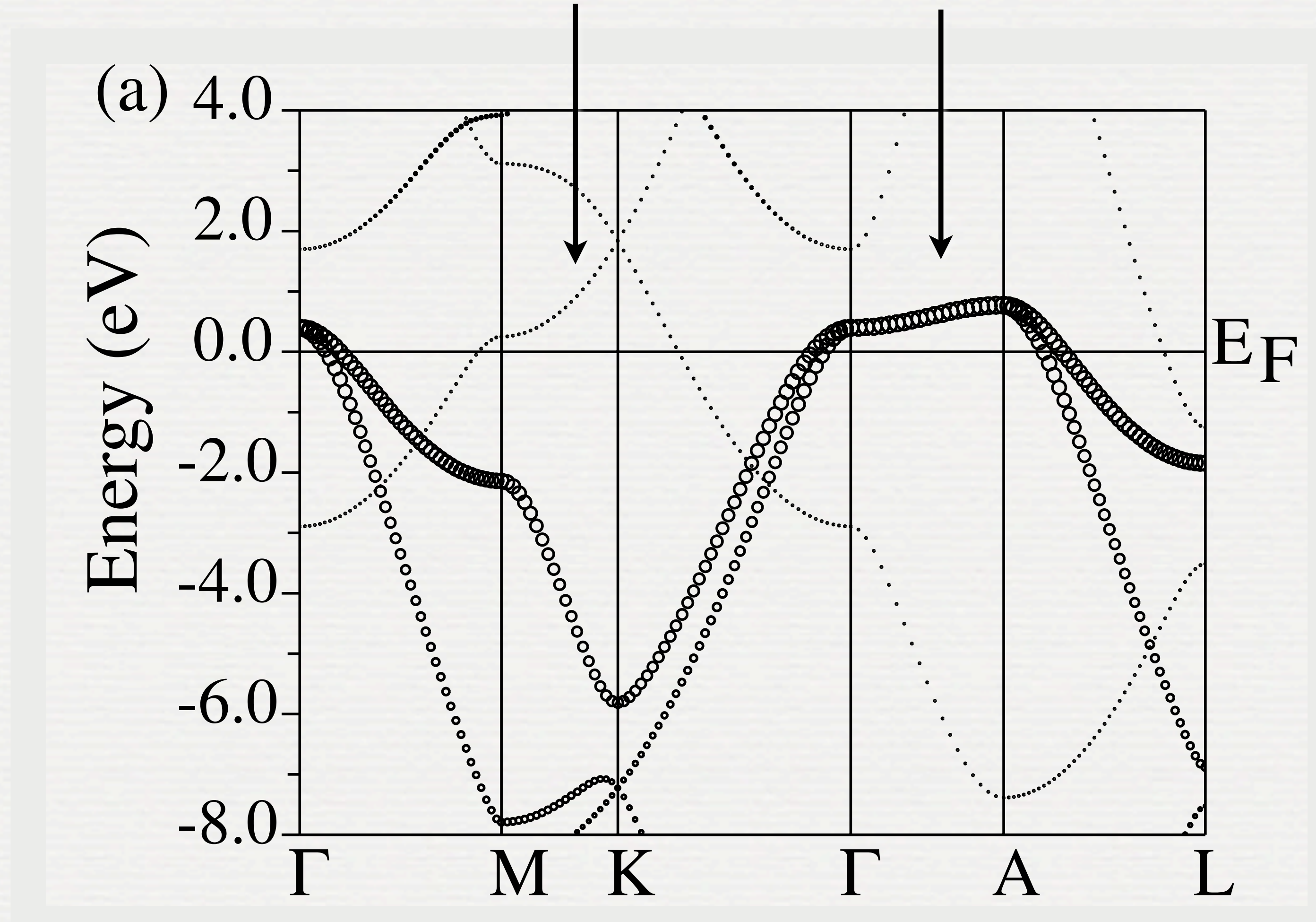

Hexagonale structure

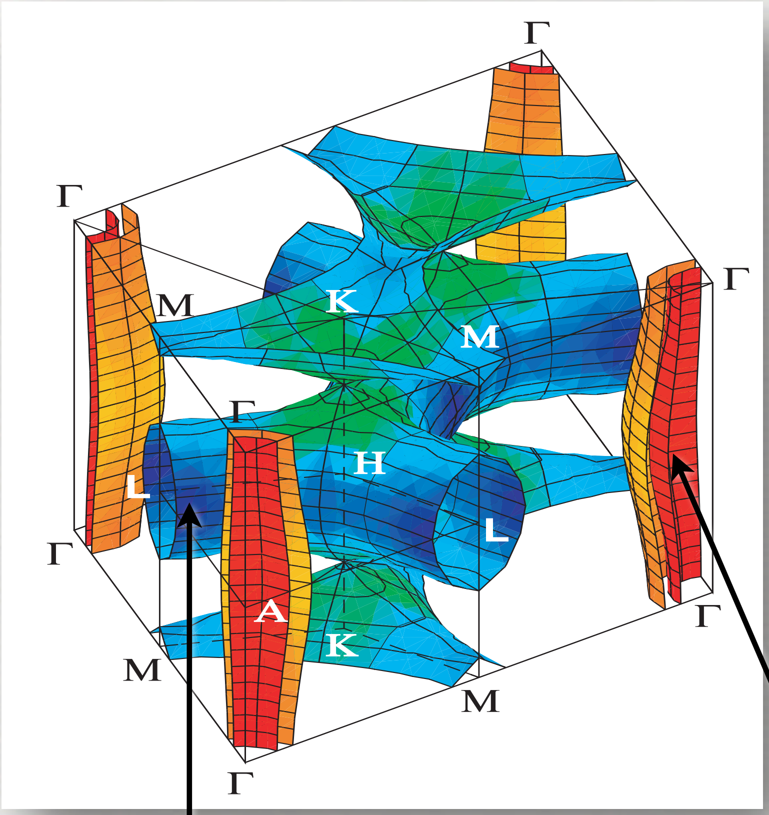



**2 Fermi surface sheets :**

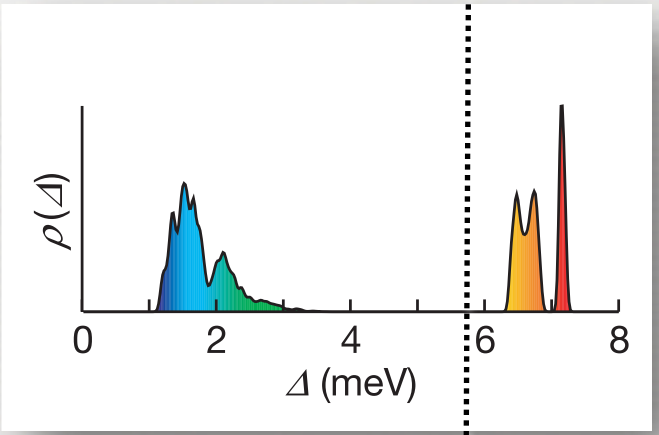
**π sheets**
**(similar to graphite, although larger)**

σ sheets
(covalent sp2 bounds)






**2 FS sheets** ⟶ **2 gaps**




BCS value

**π sheets**
**(similar to graphite, although larger)**

↓

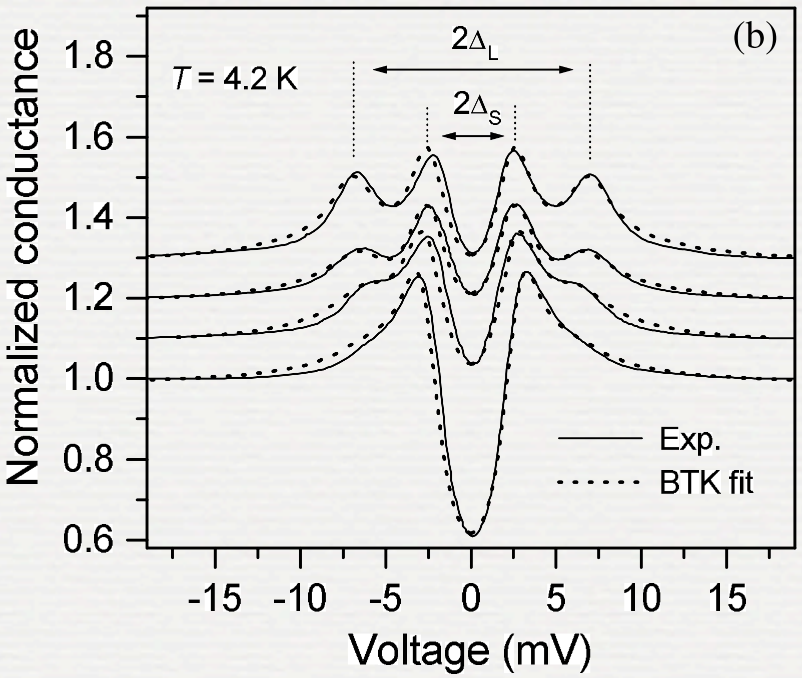
moderate coupling
**-> $T_c < 10K$**

**σ sheets**
(covalent sp2 bounds)

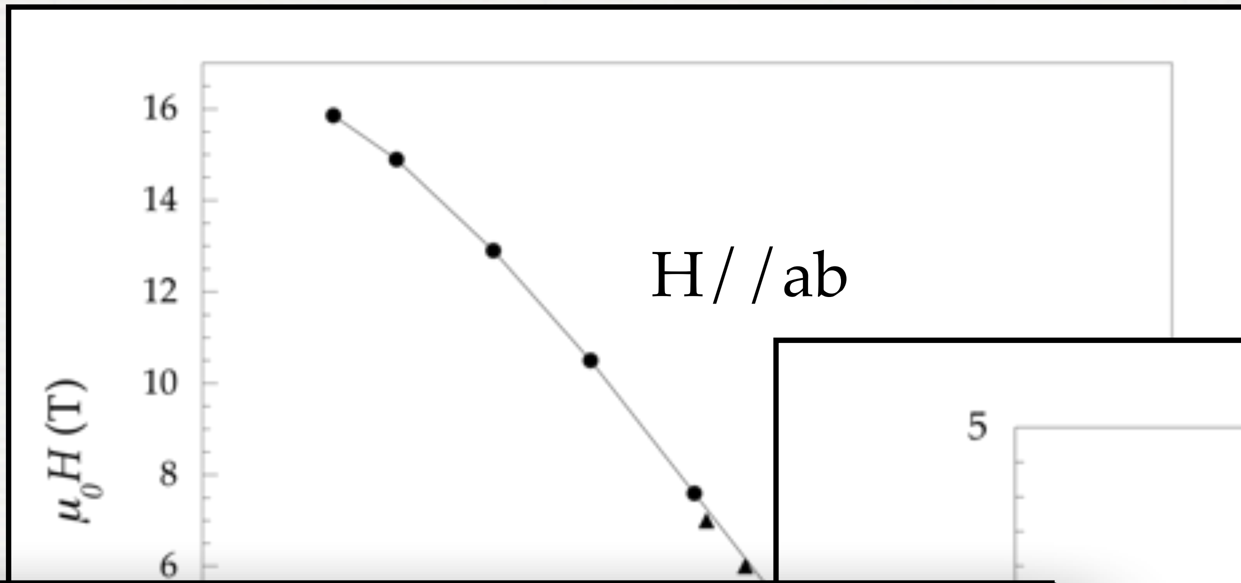
↓

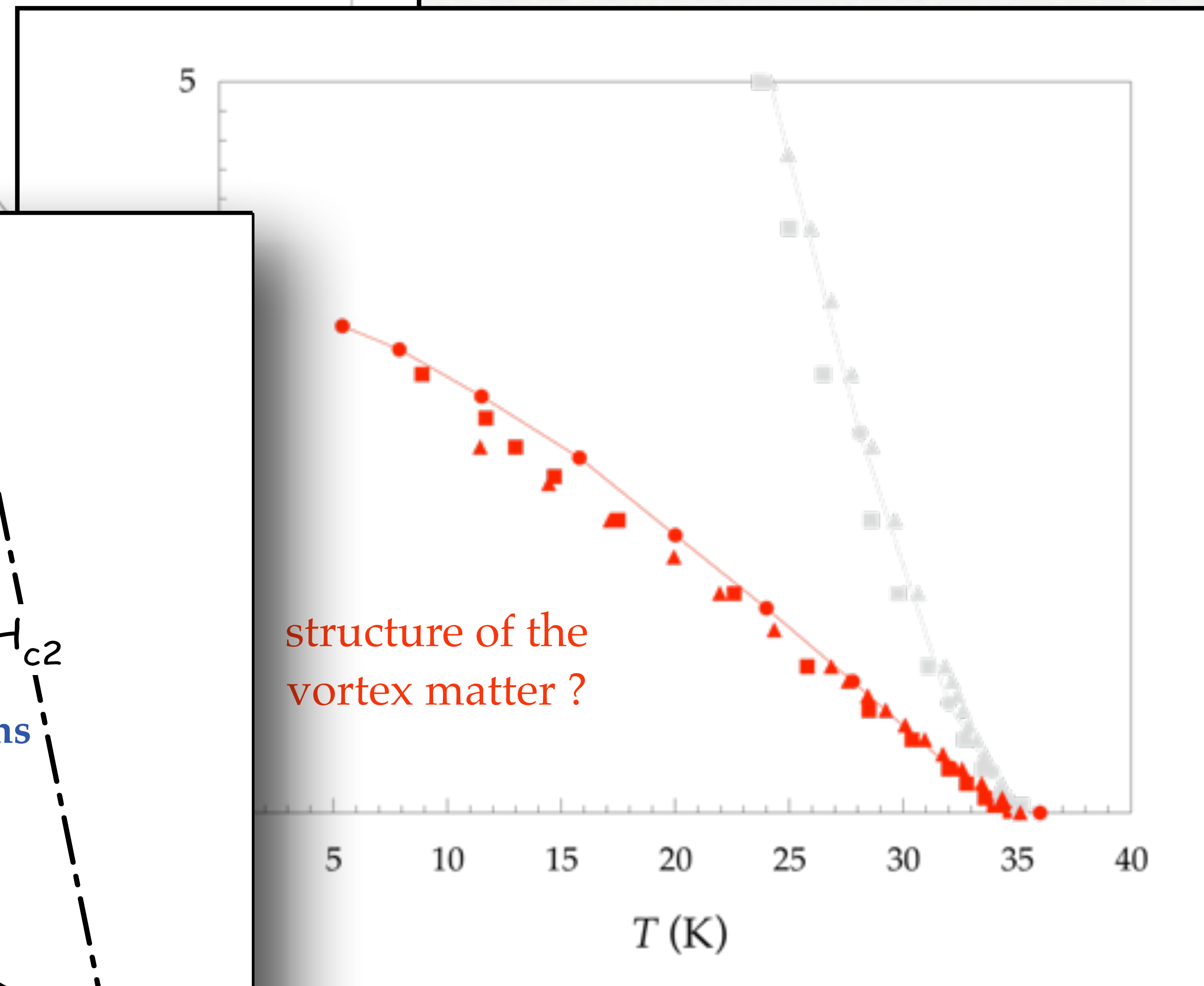
Excellent coupling with
$E_{2g}$ breathing modes
**-> $T_c \sim 40K$**

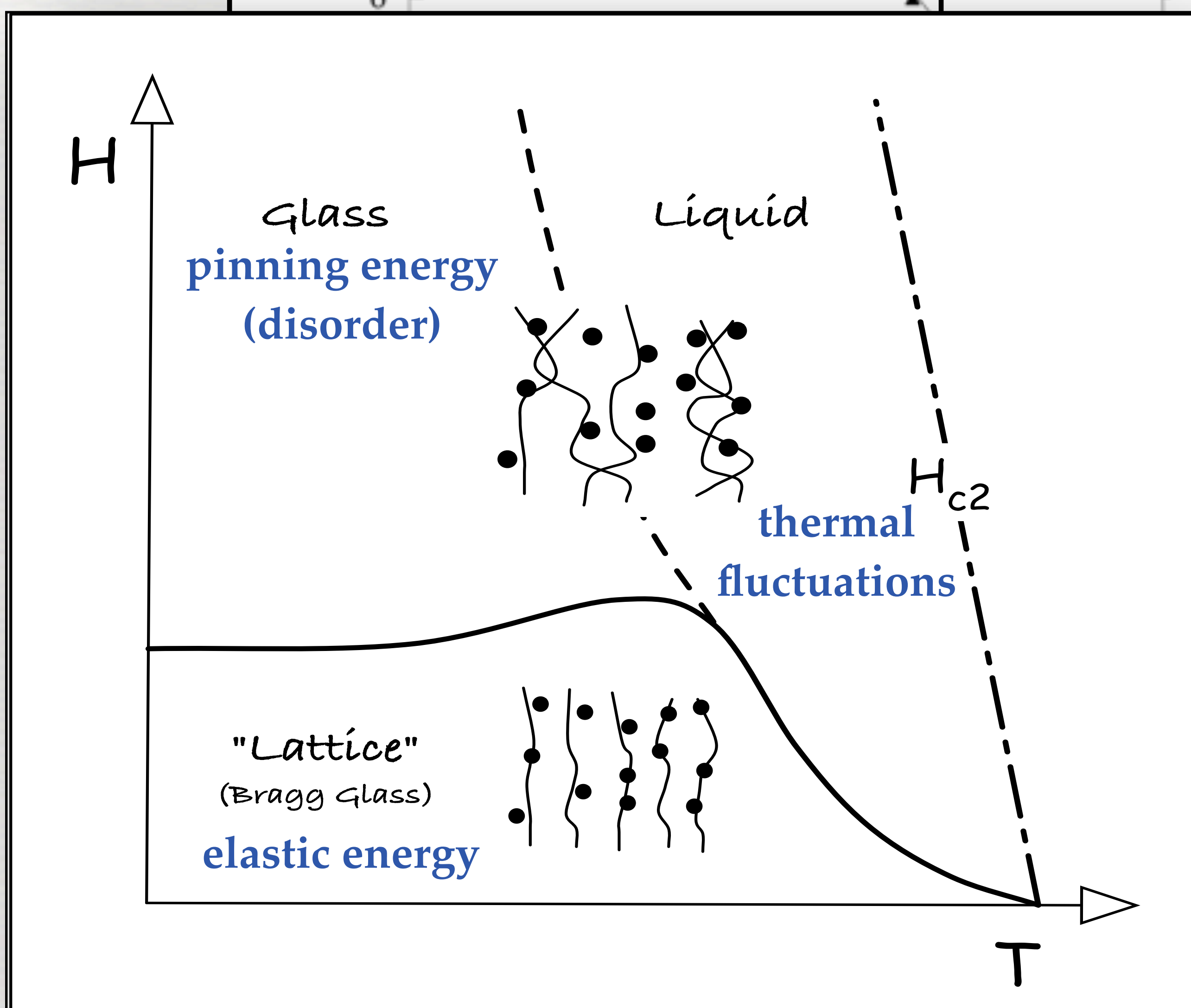
**P.Szabo et al. PRL 01**



H-T phase diagram
($H_{c2}$ line)




Possible T or H induced melting
of the ordered vortex matter

The influence of thermal fluctuations can be quantified by the Ginzburg number :

$$Gi = \frac{1}{2}\left[\frac{k_B T_c}{\epsilon_0 \xi_c}\right]^2 = \left[\frac{\text{thermal energy}}{\text{elastic energy}}\right]^2$$

$$\epsilon_0 = (\Phi_0/4\pi\lambda_{ab})^2$$

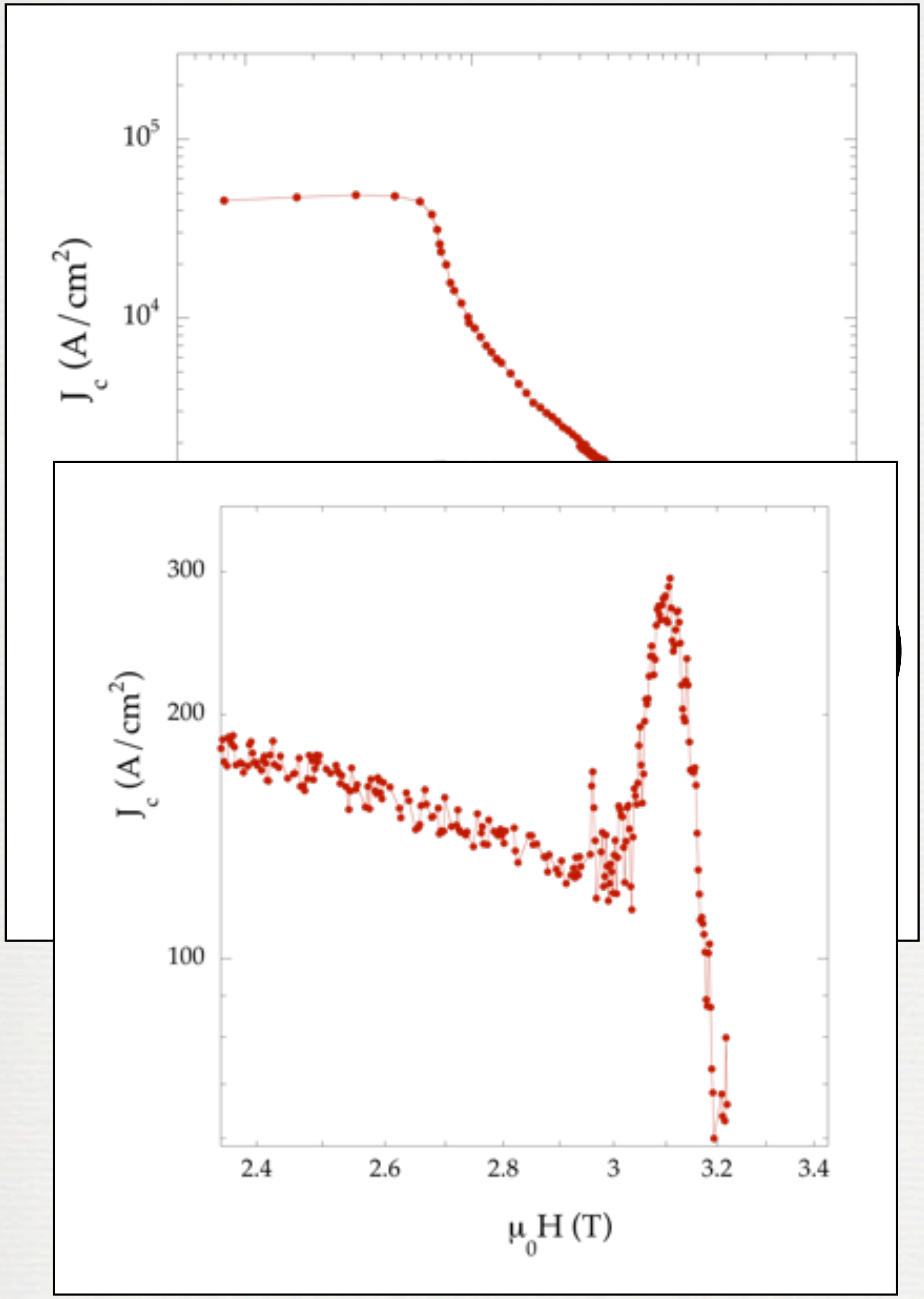
| | $\lambda_{ab}$ (nm) | $\xi_{ab}$ (nm) | $\Gamma$ | $T_c$ (K) | $\varepsilon_0\xi_c$ (K) | $G_i$ |
|---|---|---|---|---|---|---|
| YBaCuO | 160 | 1.5 | 6 | 92 | 200 | $3\ 10^{-2}$ |
| Nd(O,F)FeAs | 270 | 3 | 5 | 35 | 200 | $4\ 10^{-3}$ |
| (K,Ba)$BiO_3$ | 280 | 3 | 1 | 32 | 800 | $2\ 10^{-4}$ |
| $MgB_2$ | 50 | 10 | 5 | 39 | 16000 | **$10^{-6}$** |

| $J_c$ ($A/cm^2$) |
|---|
| $1\text{-}10\ 10^5$ |
| $1\text{-}10\ 10^5$ |
| $1\text{-}10\ 10^5$ |
| **a few $10^4$** |

thermal fluctuations are fully **negligible** in $MgB_2$

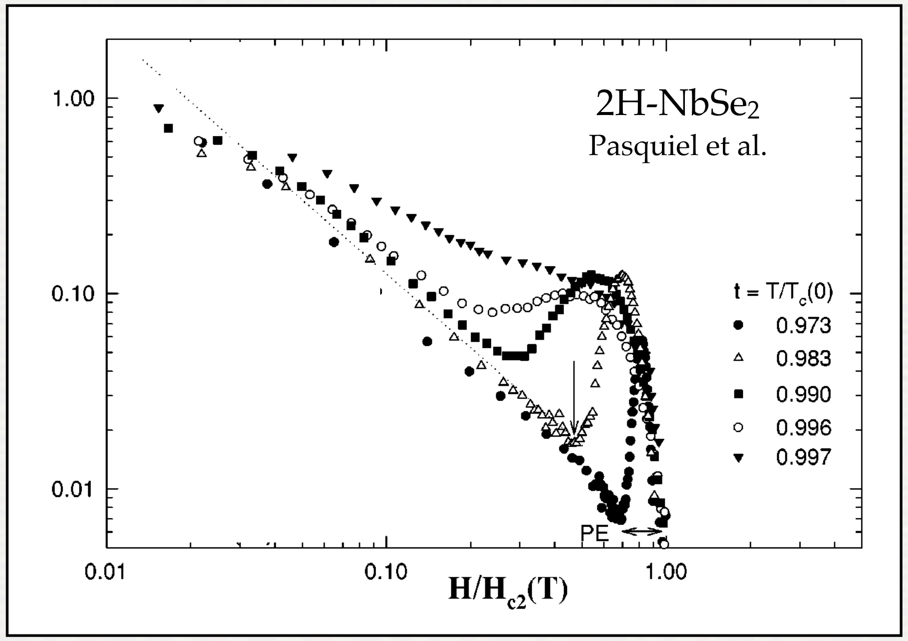
small critical current density (low amount of disorder)

The ordered (Bragg glass) phase is expected to occupy the lagest part of the H-T phase diagram

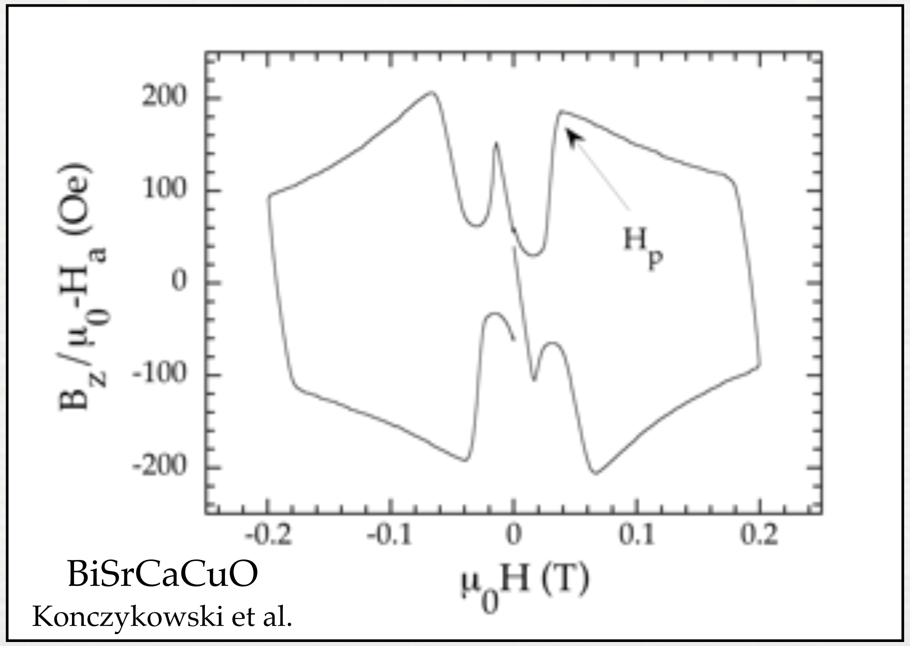



# peak effect in $J_c$ close to $H_{c2}$

Commonly observed in low $T_c$ materials




«fishtail» effect in high HTSC



softening of the vortex lattice close to $H_{c2}$
(elastic constants decreasing more rapidly than pinning)

OR

crossover from (weak) collective pinning
to strong pinning

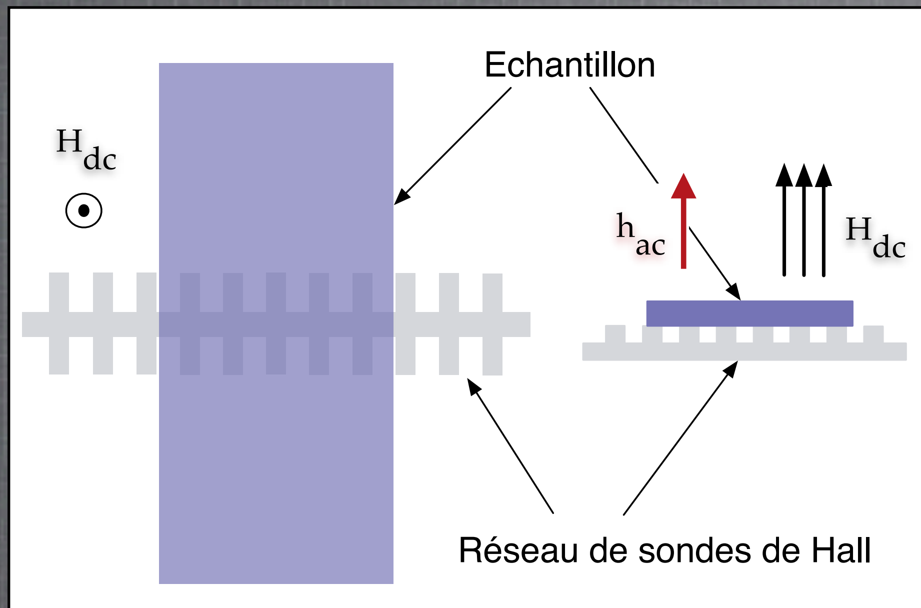
OR

proliferation of dislocation ***at field induced***
order - disorder transition

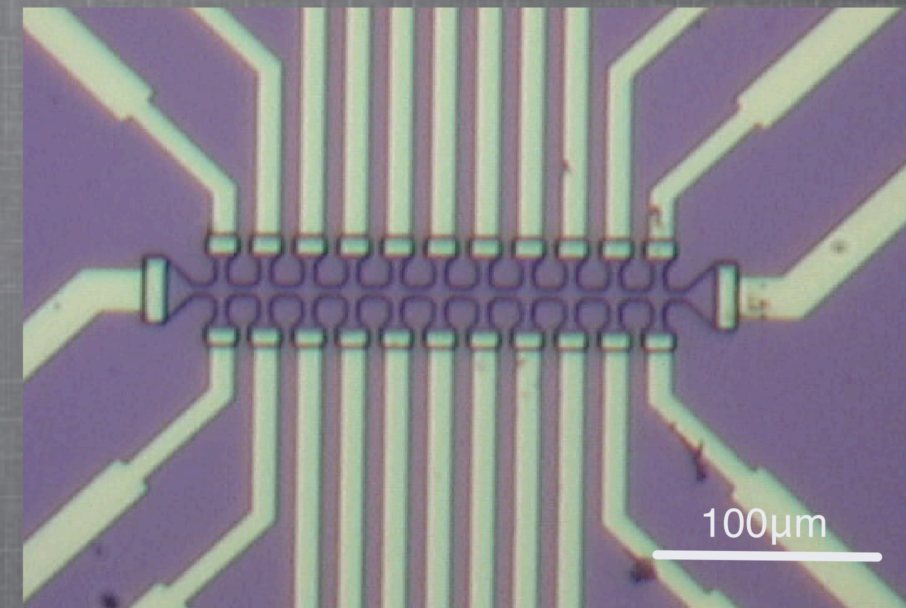
influence of point disorder ?

here introduced by electron irradiation
(Frenkel pairs - cryogenic irradiation prevents
clustering and/or recombinaison)
4 doses from 1.0 to 5.2 $10^{19}$ e/cm$^2$

# Hall probe magnetometry




$R_H = k.B$ with k ~ 700 Ohm/T

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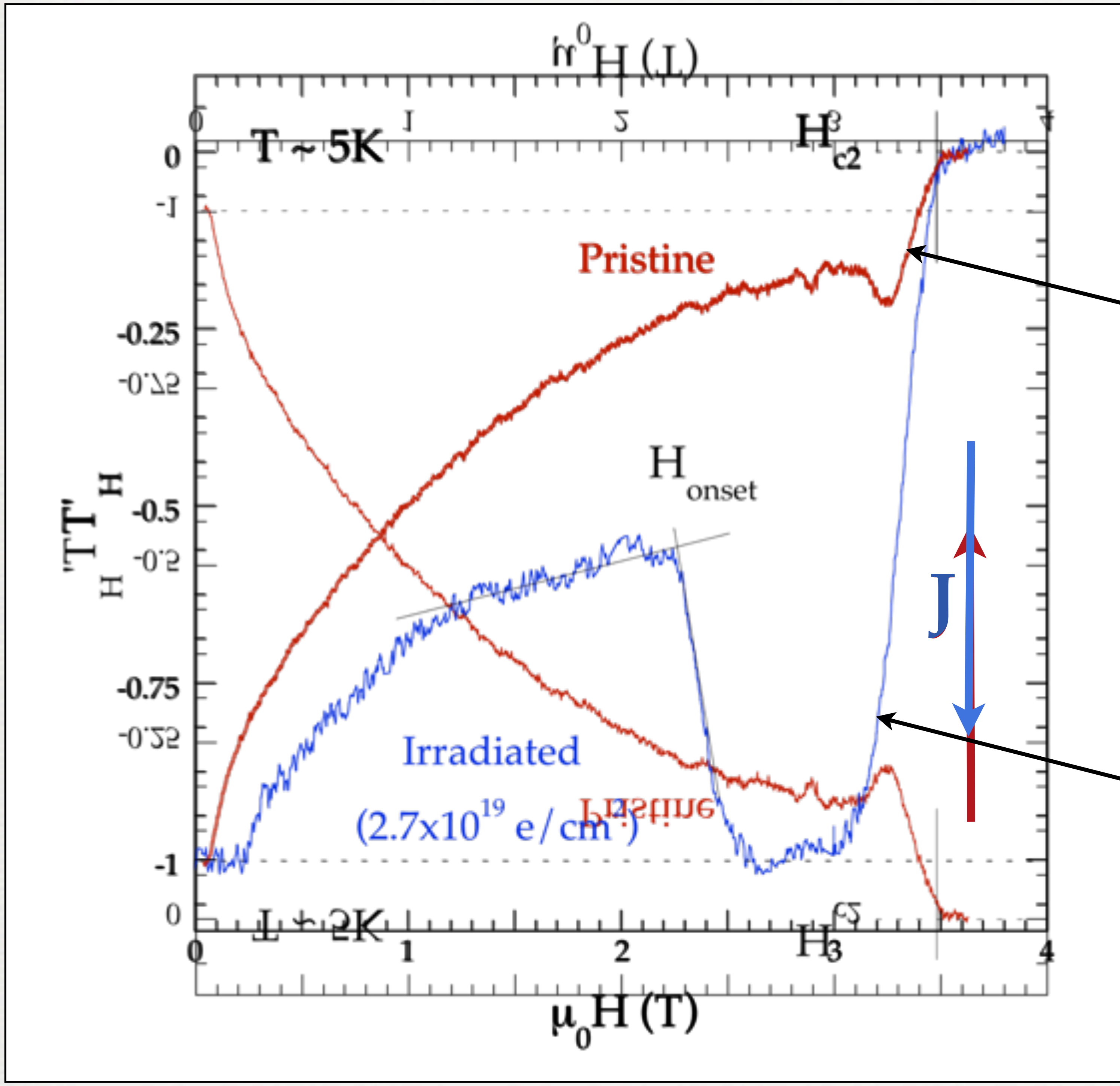
miniature AsGa-based quantum well Hall sensor

Local (DC) field measurements $\longrightarrow J \propto \partial B / \partial x$ <-> width of the magnetization loops

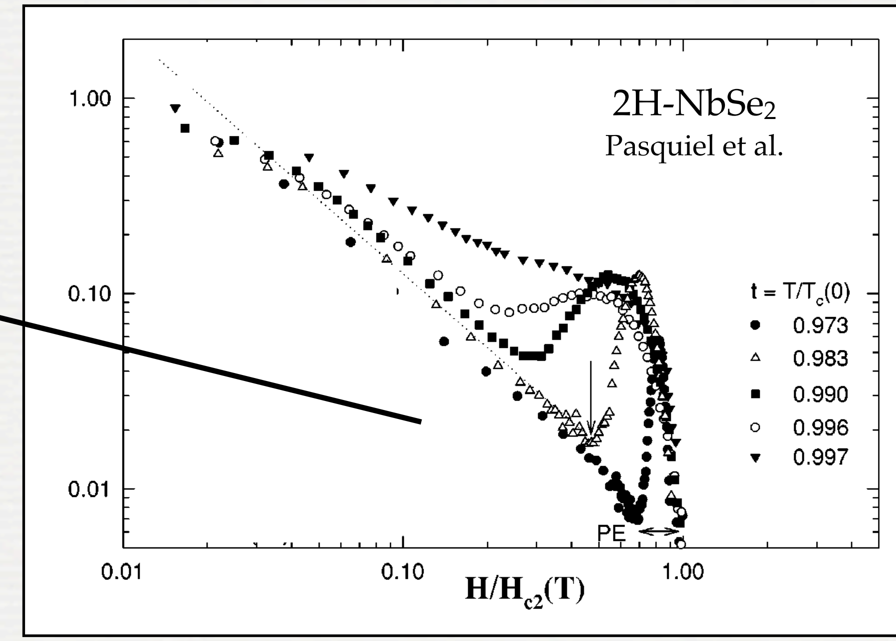
J > ~ 500 A/cm²

AC transmittivity : $T'_H = \dfrac{B_{ac}(T) - B_{ac}(T << T_c)}{B_{ac}(T << T_c) - B_{ac}(T << T_c)} = F(Jd/h_{ac}) \sim 1 - \dfrac{Jd}{h_{ac}}$

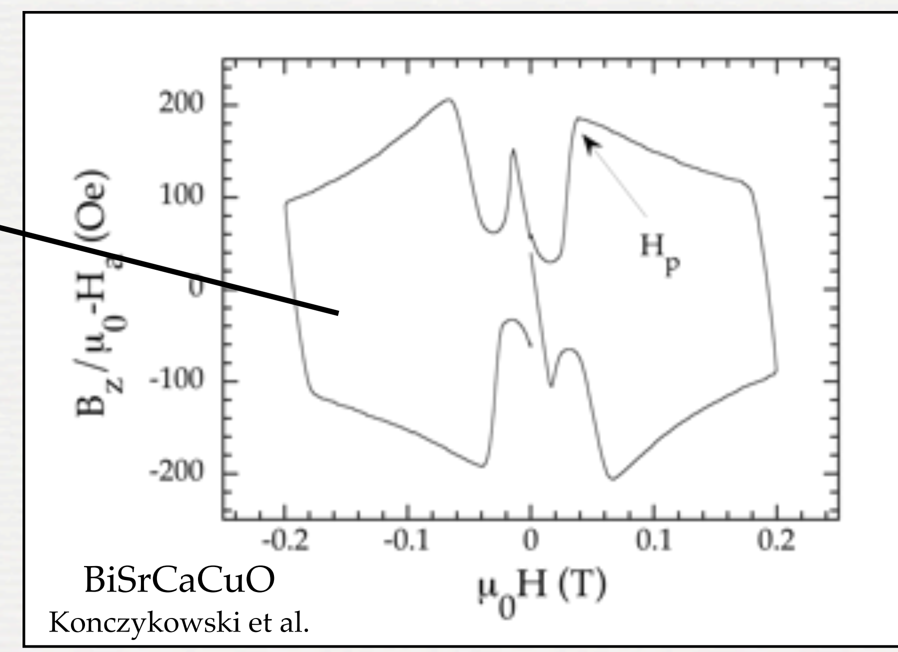
1000 > J > ~ 50 A/cm²



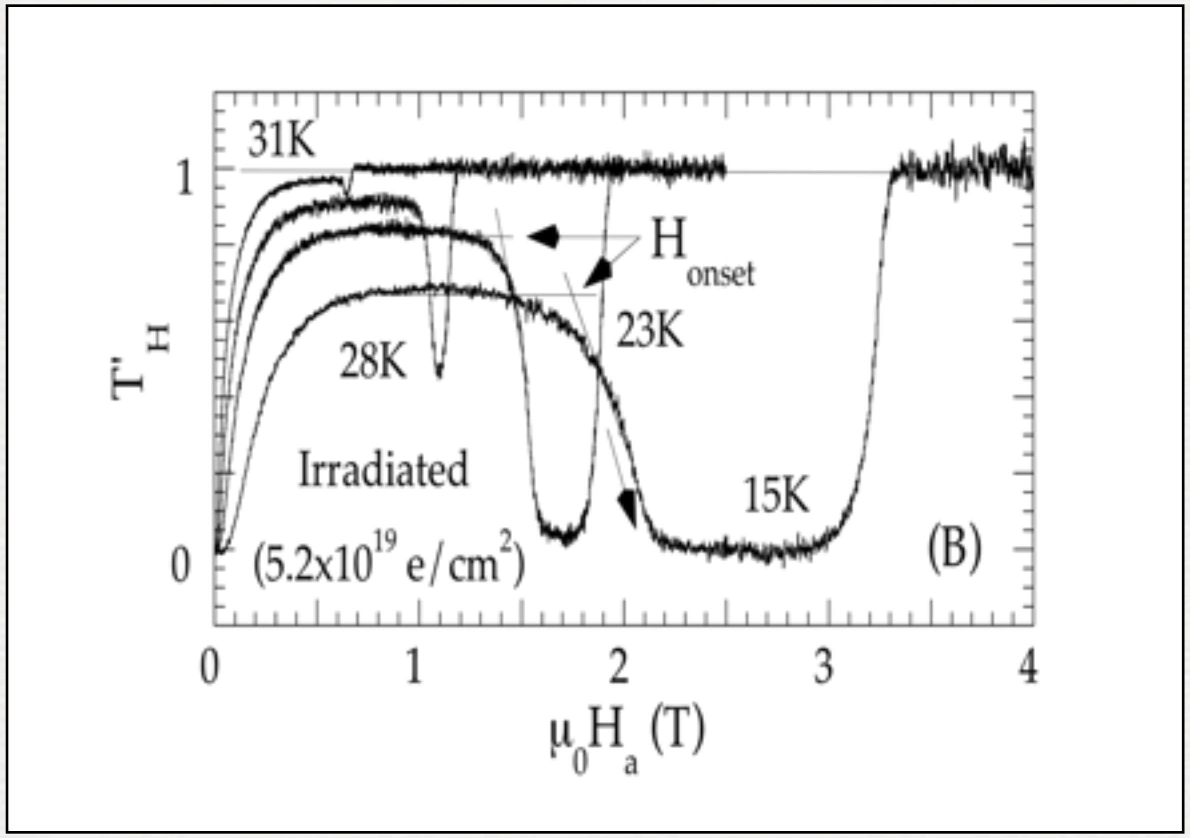
T ~ 5K
$H_{c2}$
Pristine
$H_{onset}$
J
Irradiated
(2.7x10^19 e/cm^2)
0
-0.25
-0.5
-0.75
-1
$H_{TT'}$
0
1
2
3
4
$\mu_0$H (T)

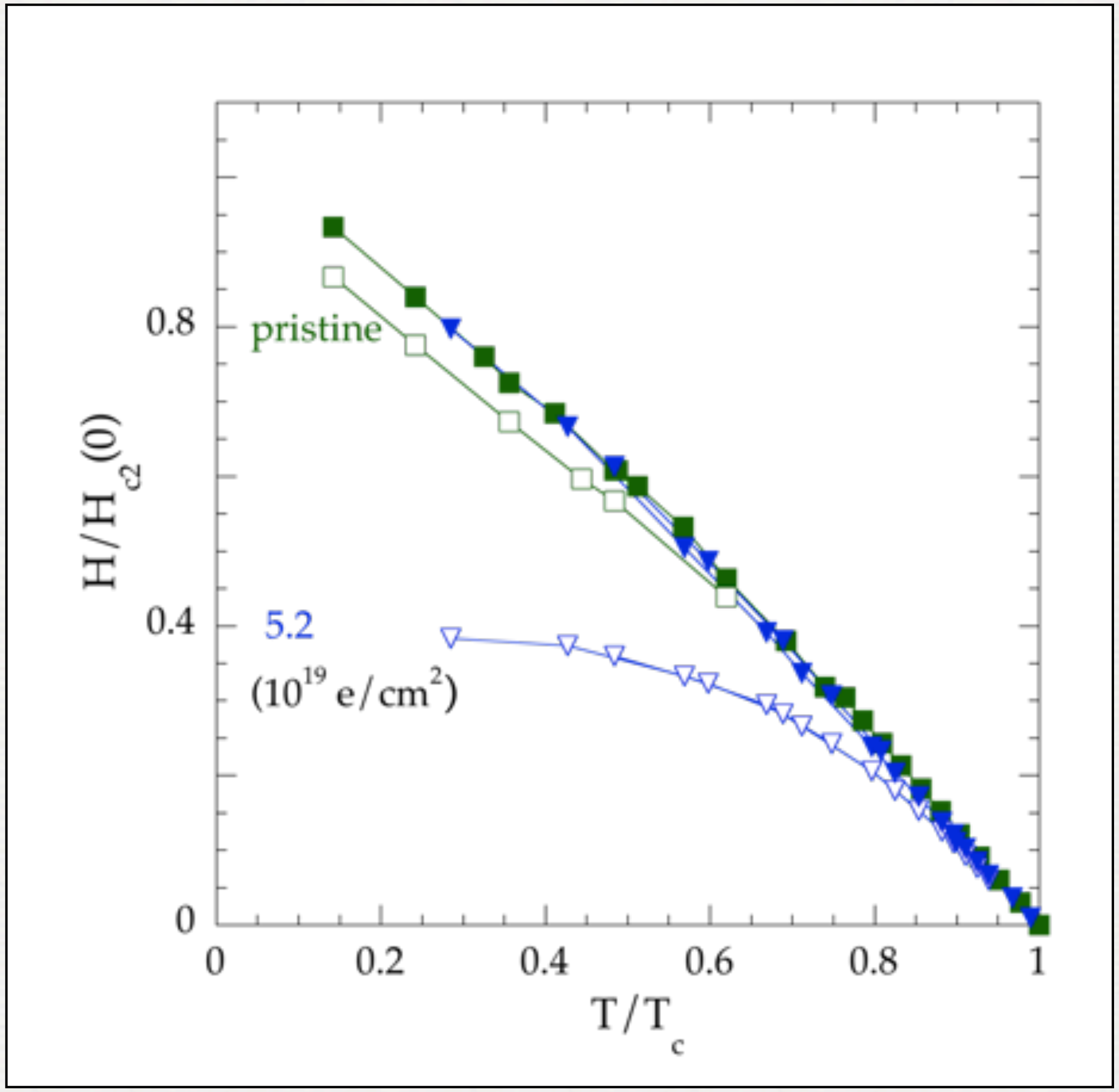
2H-NbSe2
Pasquiel et al.
1.00
0.10
0.01
t = T/Tc(0)
0.973
0.983
0.990
0.996
0.997
PE
0.01
0.10
1.00
H/Hc2(T)

200
100
0
-100
-200
Bz / μ0-Ha (Oe)
Hp
-0.2
-0.1
0
0.1
0.2
μ0H (T)
BiSrCaCuO
Konczykowski et al.

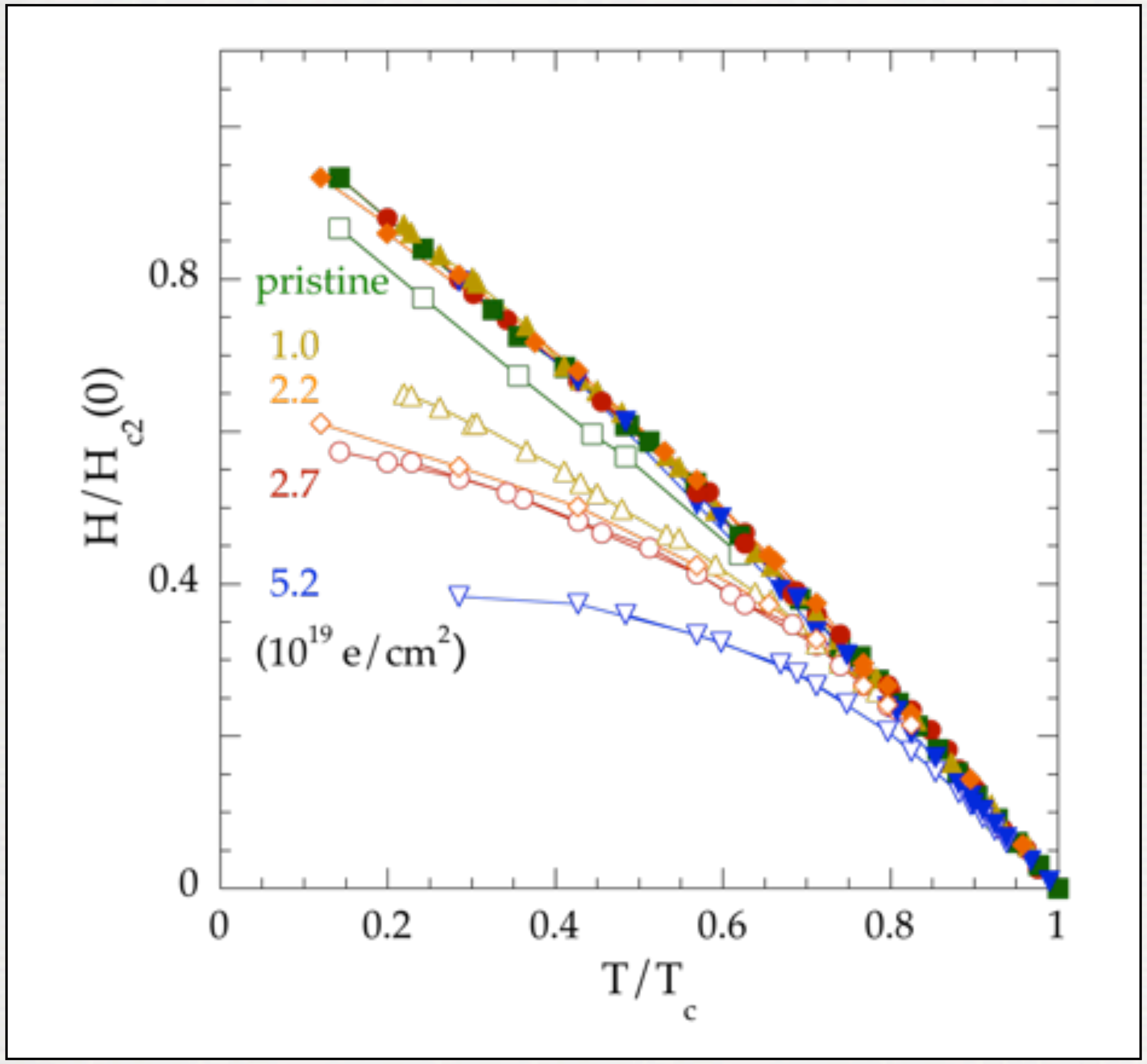


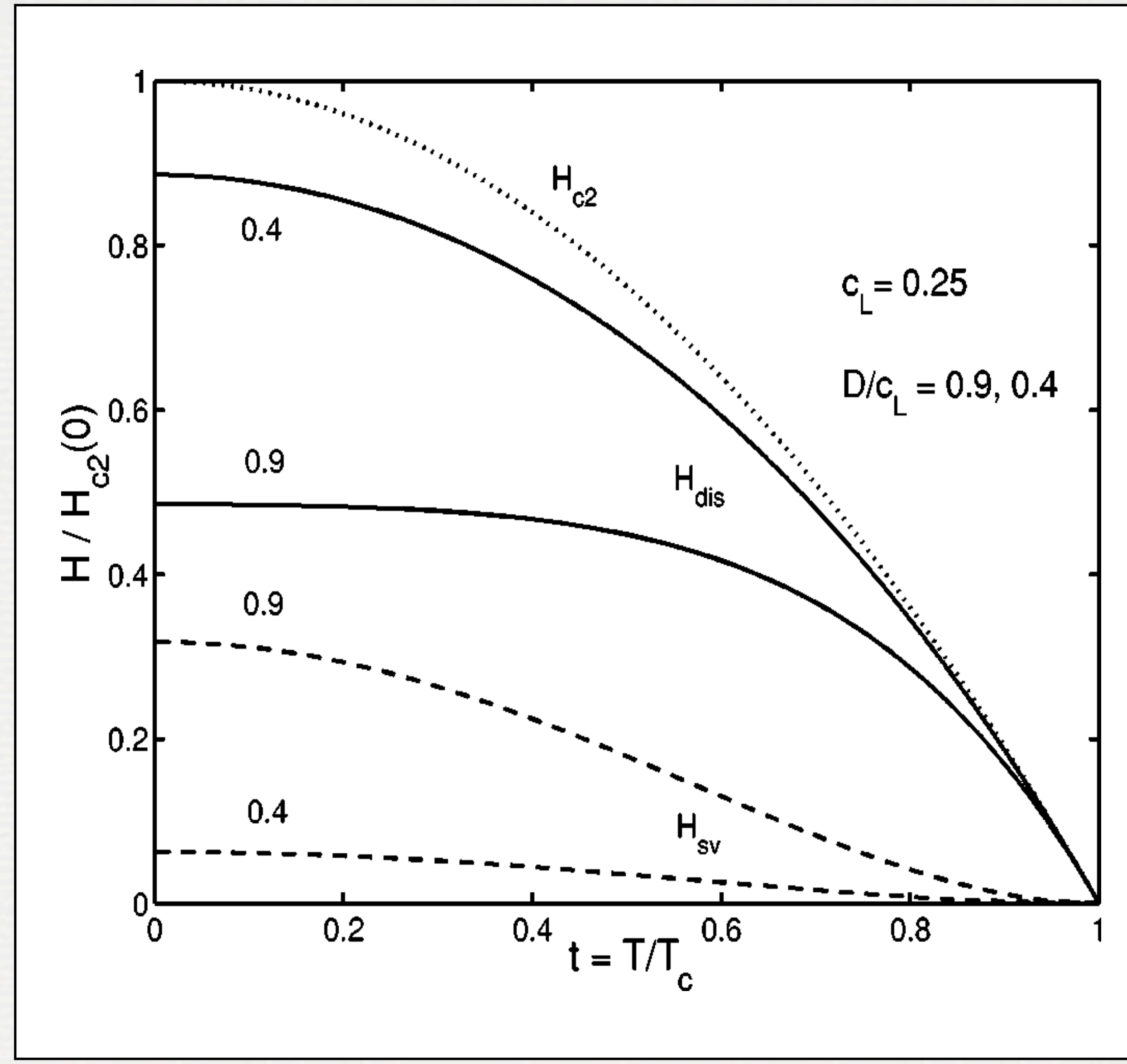
31K
1
$H_{onset}$
28K
23K
$T'_H$
Irradiated
15K
0
$(5.2x10^{19}$ e/cm$^2)$
(B)
0
1
2
3
4
$\mu_0H_a$ (T)

0.8
pristine
$H/H_{c2}(0)$
0.4
5.2
$(10^{19}$ e/cm$^2)$
0
0
0.2
0.4
0.6
0.8
1
$T/T_c$


-> $H_{onset}$ (T)




see also
Mikitik & Brandt
PRB '01, 03' et '05

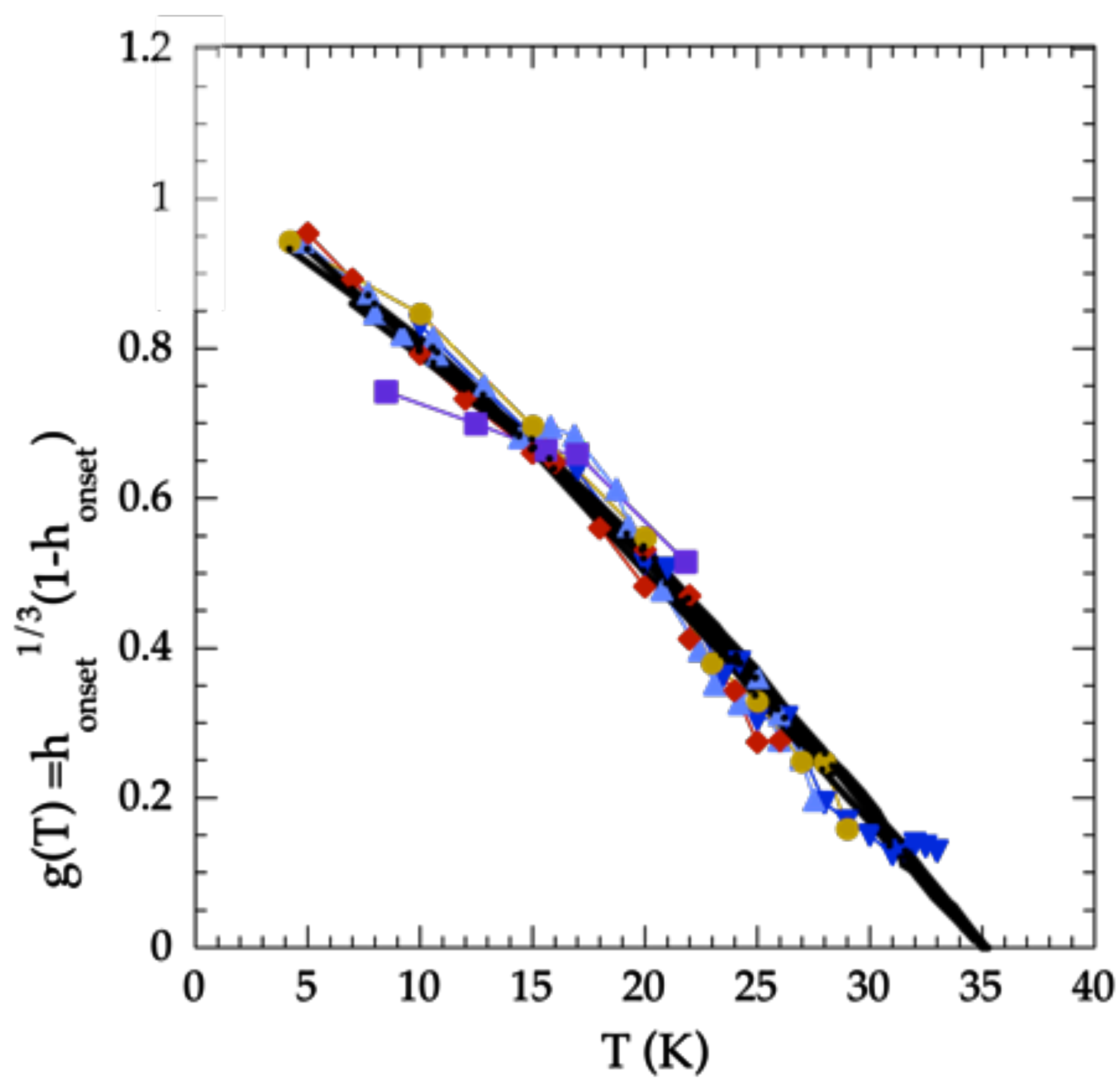
$$E_{el} = E_{pin} \rightarrow \boxed{h_{OD}(1-h_{OD})^3 = \frac{1}{2\pi c_L^8}\left(\frac{g(T) j_c^{SV}(0)}{j_0(0)}\right)^3}$$

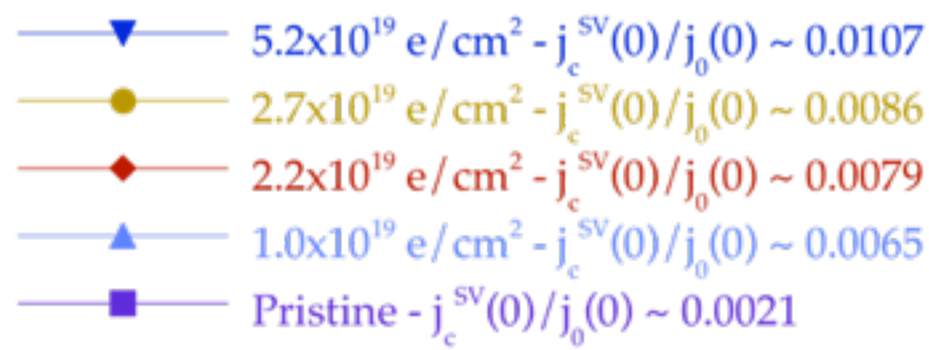
$h_{OD} = H_{OD}(T)/H_{c2}(T)$

pinning strengh rewritten through $J^{sv}$
= (single vortex) critical current and
g(T) depends on pinning mechanism

pinning induced by fluctuations in

- the electronic mean free path : $g(T) = H_{c2}(T)/H_{c2}(0)$
- ~~the critical temparature : $g(T) = [H_{c2}(T)/H_{c2}(0)]^{-1/3}$~~



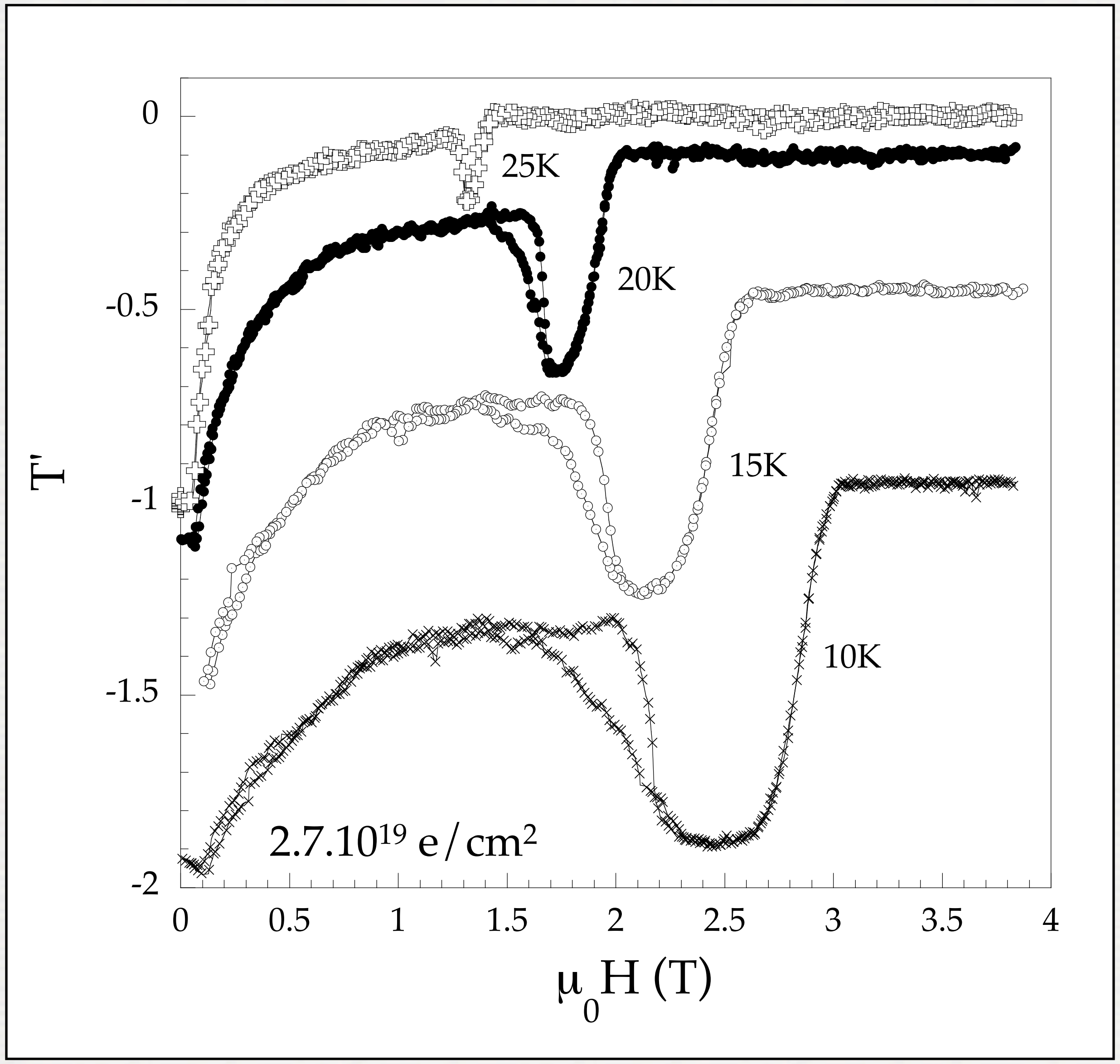

Field induced order - disorder transition

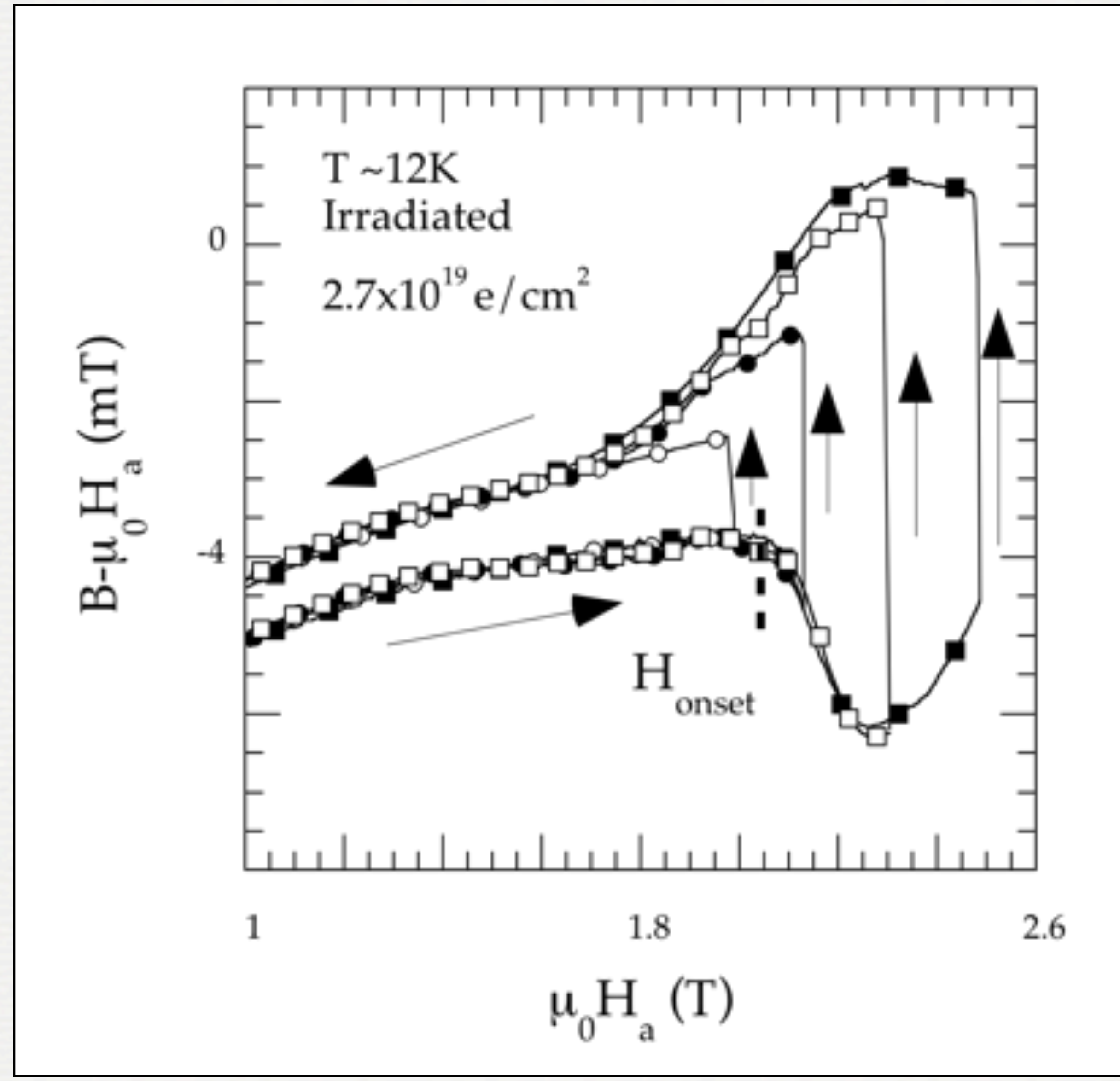
?

equivalent to

T induced melting of vortex solid ($E_{el} \sim kT$)

**First order**



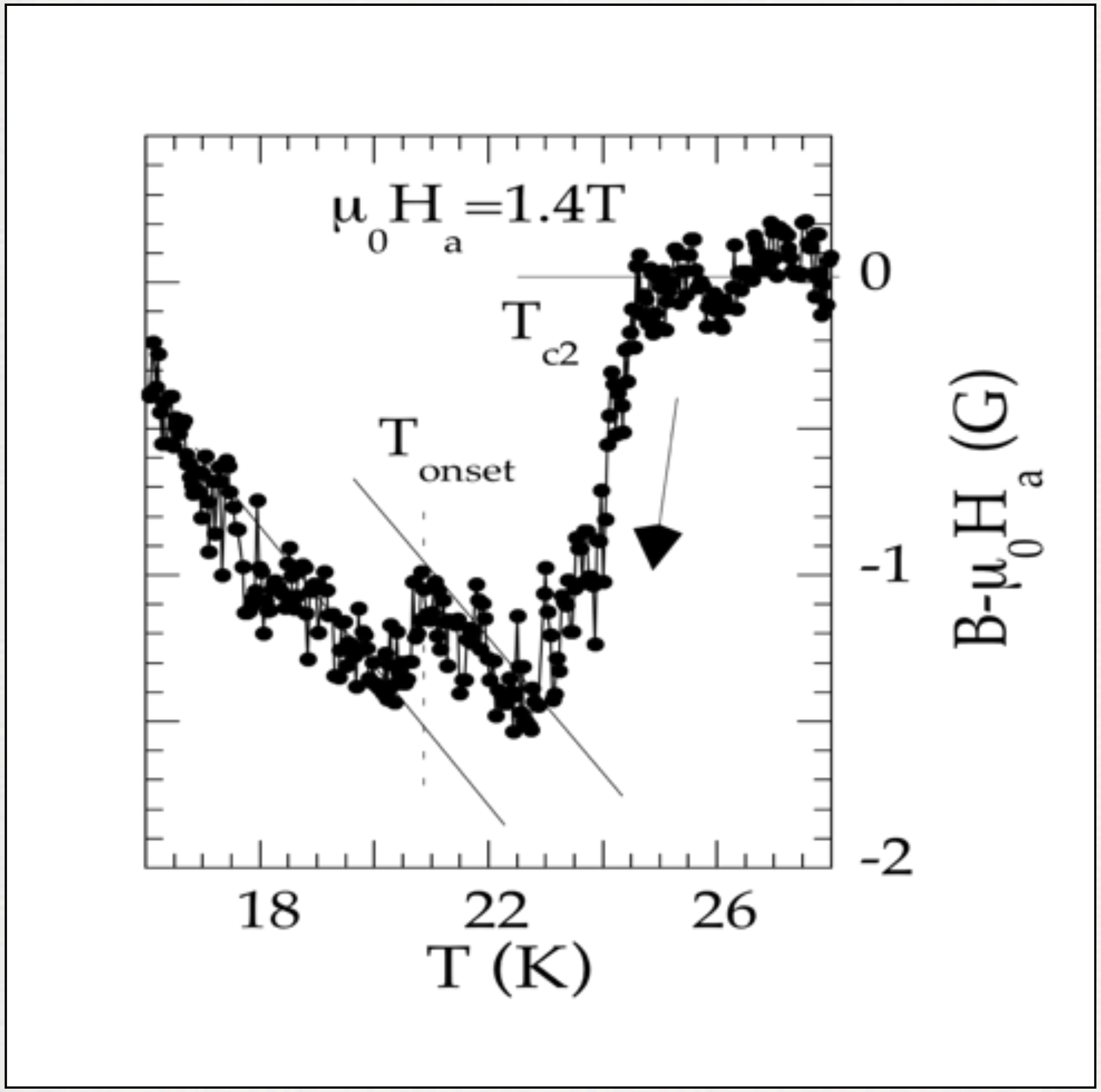




Hysteris on T′(H)
on the descending branch, quenched defects (present in the high field disordered phase) lead to higher J i.e. lower T′

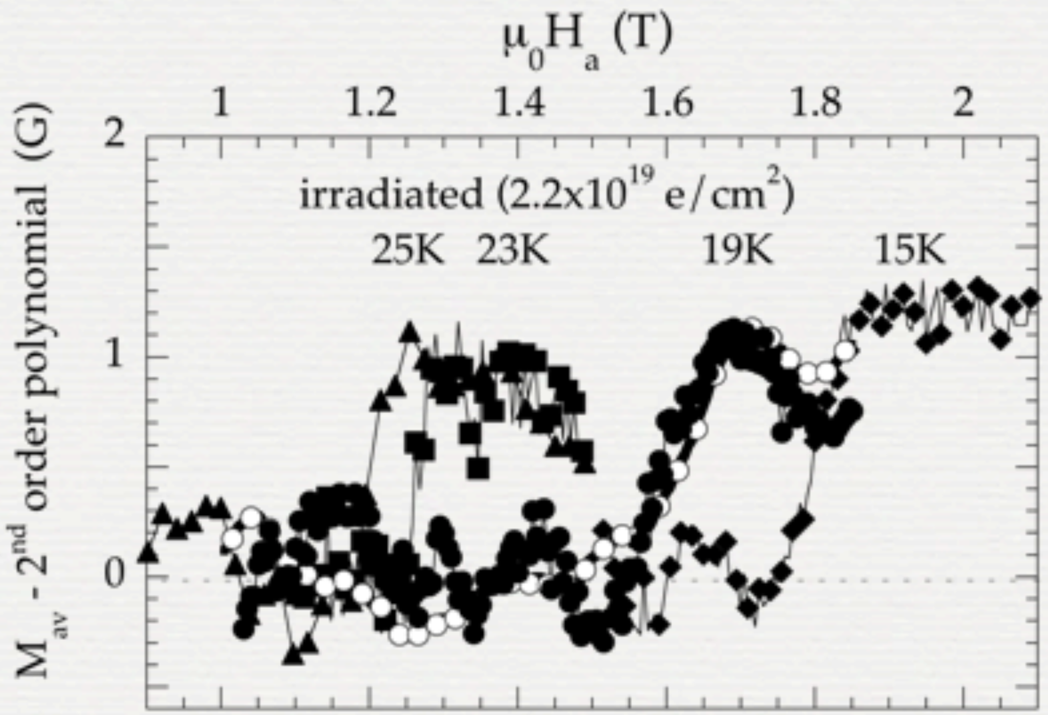
Asymetrical hysteresis loop in DC measurements

on the descending branch M depends on the field value at which the ramp direction has been reversed (amount of dislocations which proliferate above $H_{onset}$)

indications for 1st order transition but
is there discondinuity (JUMP) in the REVERSIBLE (~ average)
magnetization at $H_{onset}$




the width of the irreversibily can be reduced by «shaking» the vortices
= adding a small AC component on the DC field




Note : jump = 1G at 2T=20000G
i.e. $\Delta B/B \sim 5 10^{-5}$

discontinuity also present in M(T)

# CONCLUSION

- The absence of complicating factors such as strong layeredness and thermal fluctuations in $MgB_2$ is used to study the influence of disorder on the the structure of the vortex matter (*field induced* order-disorder transition).

- The temperature and $n_d$ dependence of the transition line testify that this transition is mediated by the proliferation of dislocations.

- The discontinuity in magnetization and the strong magnetic history effects attest to the first order nature of this transition.

- Pinning is mediated by fluctuations in the electronic mean free path in $MgB_2$.

for further information see : T.Klein et al. PRL, 105, 047001 (2010).