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Radiation damaged MgB_2: a comparison with A15 superconductors

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TOPICAL REVIEW Supercond. Sci. Technol. 21 (2008) 043001

Radiation effects on MgB_2: a review and a comparison with A15 superconductors

M Putti[1], R Vaglio[2] and J M Rowell[3]

Motivation

➔ Radiation experiments

To investigate superconducting mechanisms

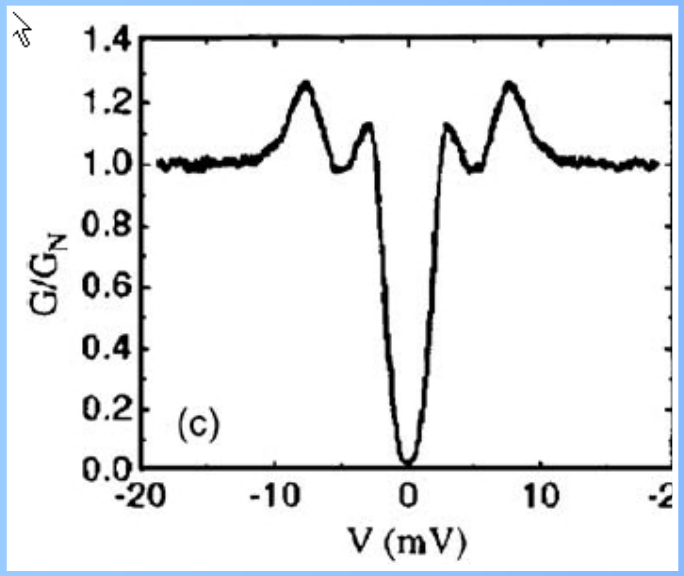
To increase of superconducting properties

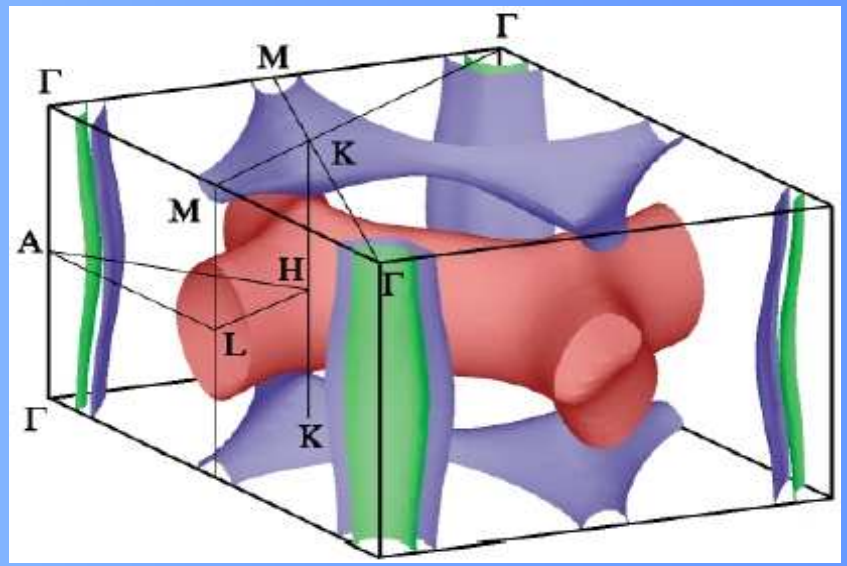
➔ MgB_2 vs A15

High Tc superconductors with conventional e-ph coupling

	T_{c0} (K)	N(0) (states/eV cell)	λ
V_3Si	17	15	1.1
Nb_3Sn	18	12	1.44
Nb_3Ge	22	8	1.8
Nb_3Al	18.6	15	1.6
MgB_2	39	0.71	0.7

Brief Remarks on MgB_2





M. Iavarone *et al.* PRL **89**, 187002 (2002)

σ bands	**π bands**
2D , hole-like	3D, one electron, one hole-like
strongly coupled with ph: λ_σ ~1	weakly coupled with ph: λ_π ~0.3
Large energy gap: Δ_σ~ 7 meV	Large energy gap: Δ_π~ 2 meV

The existence of more parameters (N_i , λ_{ij}) allows a larger T_c in respect to the isotropic system

Role of disorder

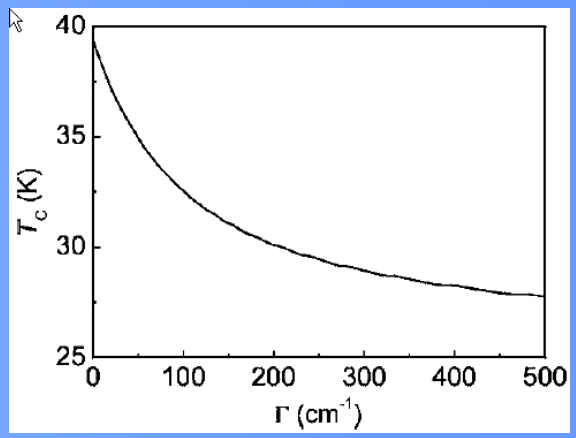
In a two-band s/c interband scattering mixes strong σ-pairs with weak π-pairs and causes pair breaking.

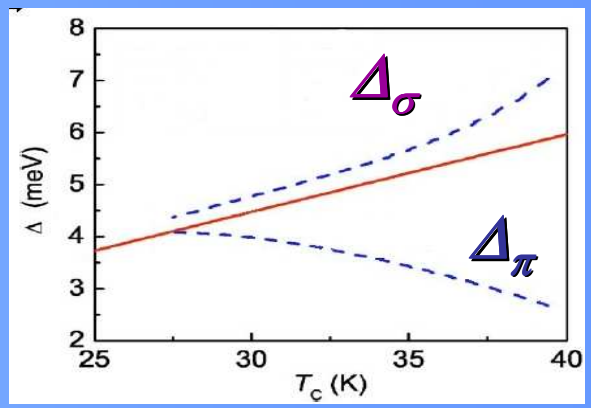
A.A.Golubov and I.I.Mazin, PRB 55 (1977)

σ and π bands have different parity → Interband scattering is suppressed

In the strong scattering limit

- The critical temperature is expected to decrease down to a saturation value 19-25 K
- The energy gaps should merge to the BCS value 3.56





Interband scattering affects T_c and two-gap nature of superconductivity

O.V. Dolgov *et al.* PRB 72, 024504 (2005)

Outline

1. Irradiation Experiments
2. Tc vs residual resistivity behaviour
3. Upper critical field
4. Specific heat
5. Temperature dependence of resistivity
6. Energy Gap
7. Theoretical model for the degradation of superconducting properties
8. Conclusions
9. Acknowledgments

All the results are systematically compared with similar experiments performed in the past on A15 superconductors.

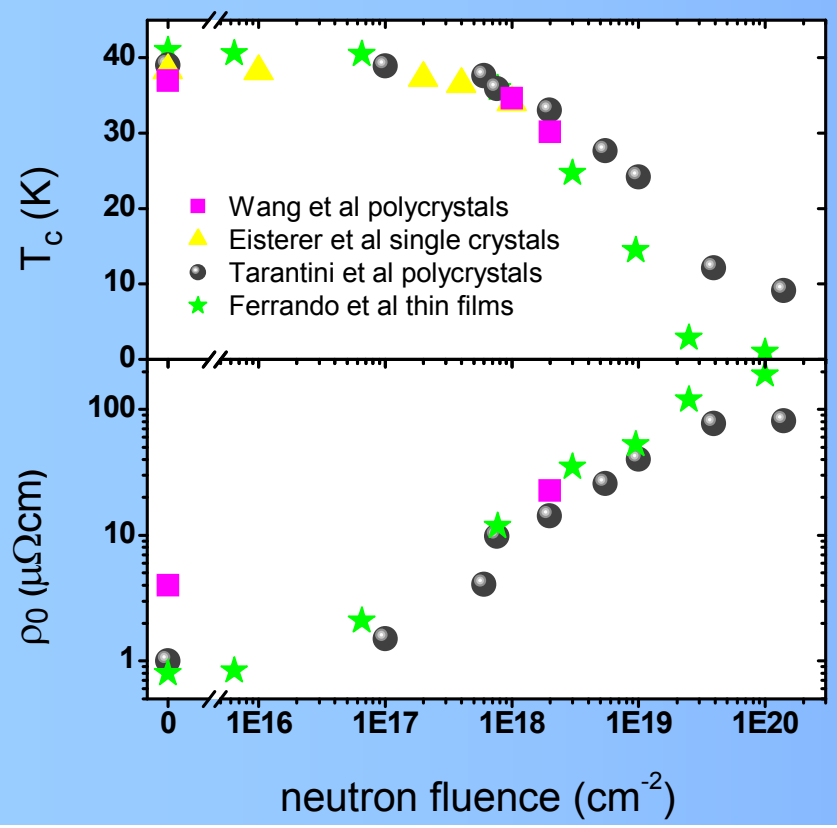
1. Irradiation Experiments

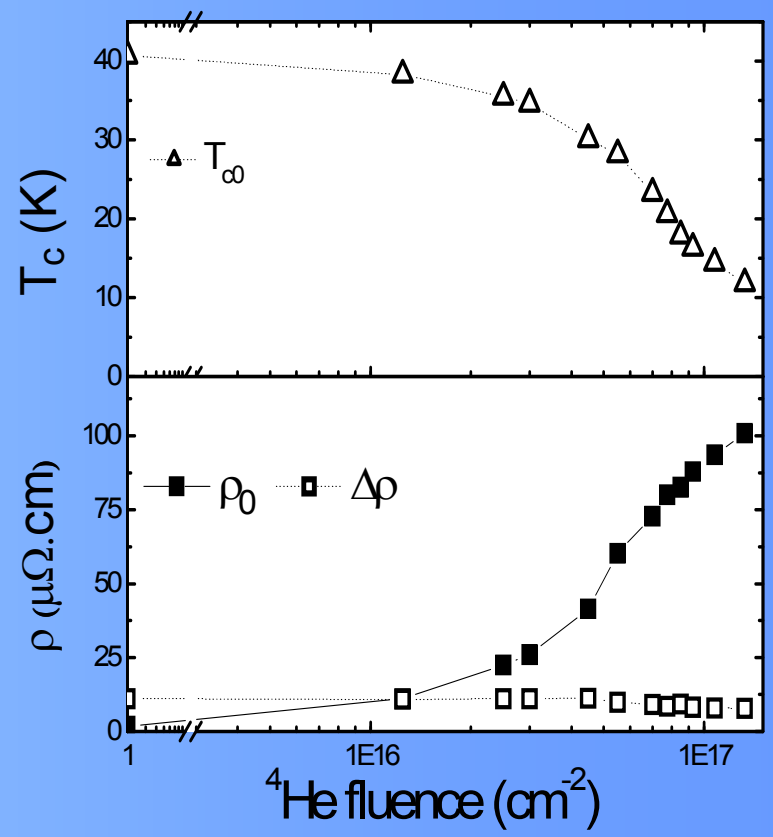
Neutron irradiation experiments:

Kar'kin *et al* 2001 JETP Lett. 73 570
Eisterer *et al* 2002 Supercond. Sci. Technol. 15 L9
Wang *et al* 2003 J. Phys. Condens. Matter 15 883
Zehetmayer *et al* 2004 Phys. Rev. B 69 054510
Putti *et al* 2005 Appl. Phys. Lett. 86 112503
Tarantini *et al* 2006 Phys. Rev. B 73 134518
Wilke *et al* 2006 Phys. Rev. B 73 134512
Ferrando *et al* 2007 J. Appl. Phys. 101, 043903

2 MeV ^{4}He irradiation experiments:

Gandikota R *et al* 2005 *Appl. Phys. Lett.* **86** 012508
Gandikota R *et al* 2005 Appl. Phys. Lett. **87** 072507





Comparison with A15s

Sweedler et al 1974 Phys. Rev. Lett. 33 168
Sweedler et al 1978 J. Nucl. Mater. 72 50
Poate et al 1976 Phys. Rev. Lett. 37 168
Ghosh A K and Myron Strongin 1980 Superconductivity in d- and f-Band Metals 305
Wiesman et al 1978 J. Low Temp. Phys. 30 513
Rowell J M and Dynes R C "Bad metals, good Superconductors"
Alterovitz et al 1981 Phys. Rev. B 24 90
Noolandi J and Testardi L R 1977 Phys. Rev. B 15 5462
Sweedler A R and Cox D E 1975 Phys. Rev. B 12 147
Cox D E and Tarvin J A 1978 Phys. Rev. B 18 22
Burbank R D, Dynes R C and Poate J M 1979 J. Low Temp. Phys. 36 573
Testardi et al 1977 Phys. Rev. Lett. 39 716
Flukiger R 17th International Conference on Low Temperature Physics-LT-17, Ref. 4, 609
Nolscher C and Saemann-Ischenko G 1985 Phys. Rev. B 32 1519
Bett R 1974 Cryogenics 14 361
Vonzovski S V, Izyumov Yu A and Kurmaev E K 1982 Superconductivity of Transition Metals (Berlin: Springer)
Alterovitz S A, et al., 1981 Phys. Rev. B 24 90
Karkin A E, Mirmelshtein A V, Arkhipov V E and Goshchitskii B N 1980 Phys. Status Solidi a 61 K117
Cort B, Stewart G R, Snead C L Jr, Sweedler A R and Moechlecke S 1981 Phys. Rev. B 24 3794
Phys. Rev. Lett. 37 168
Ghosh A K, Gurvitch M, Wiesmann H and Strongin M 1978 Phys. Rev. B 18 6116
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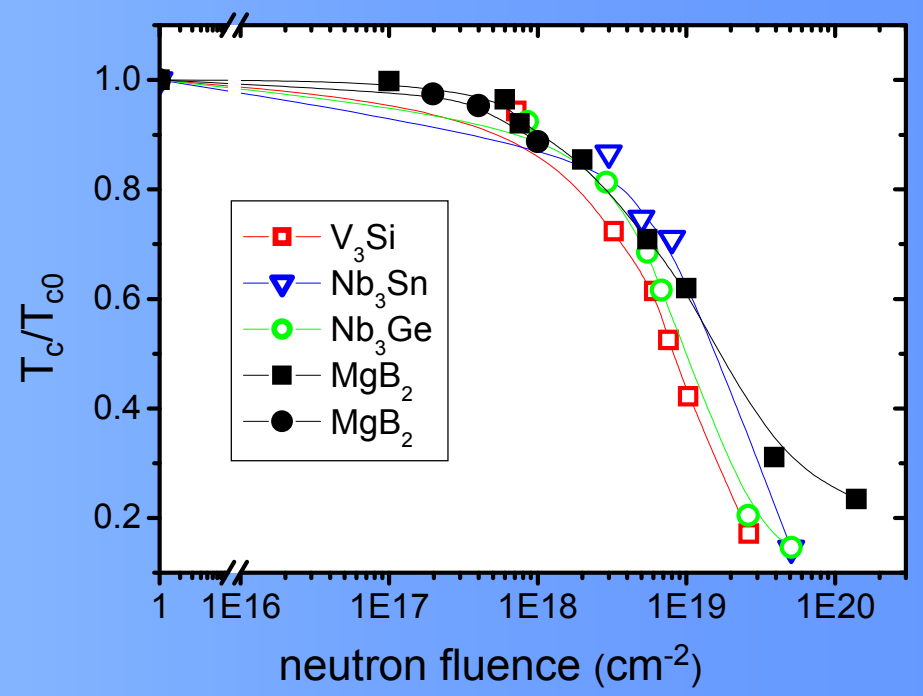
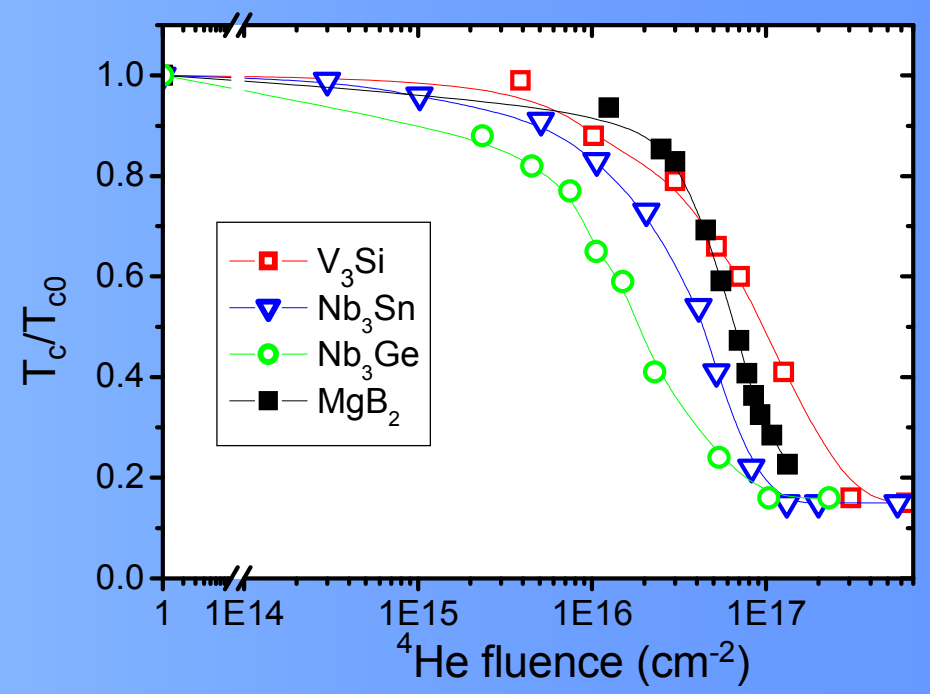
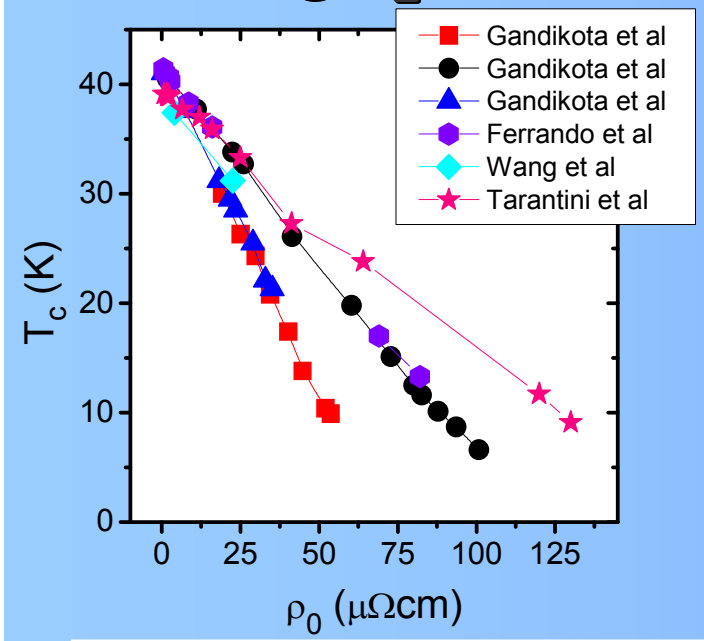
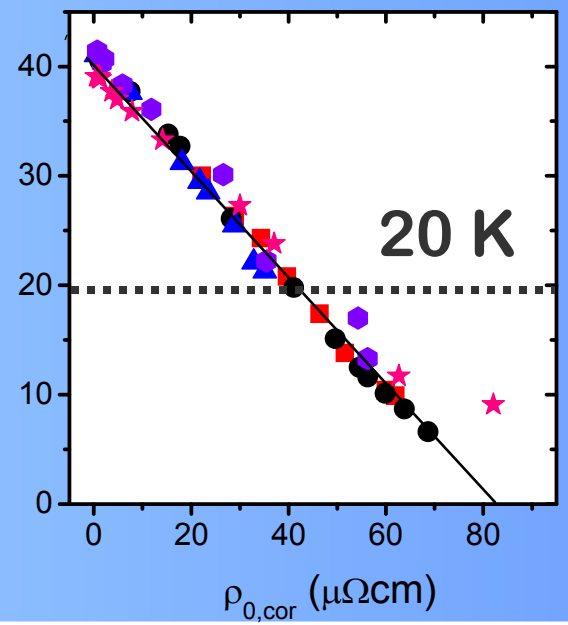




3. T_c vs residual resistivity behaviour

MgB_2



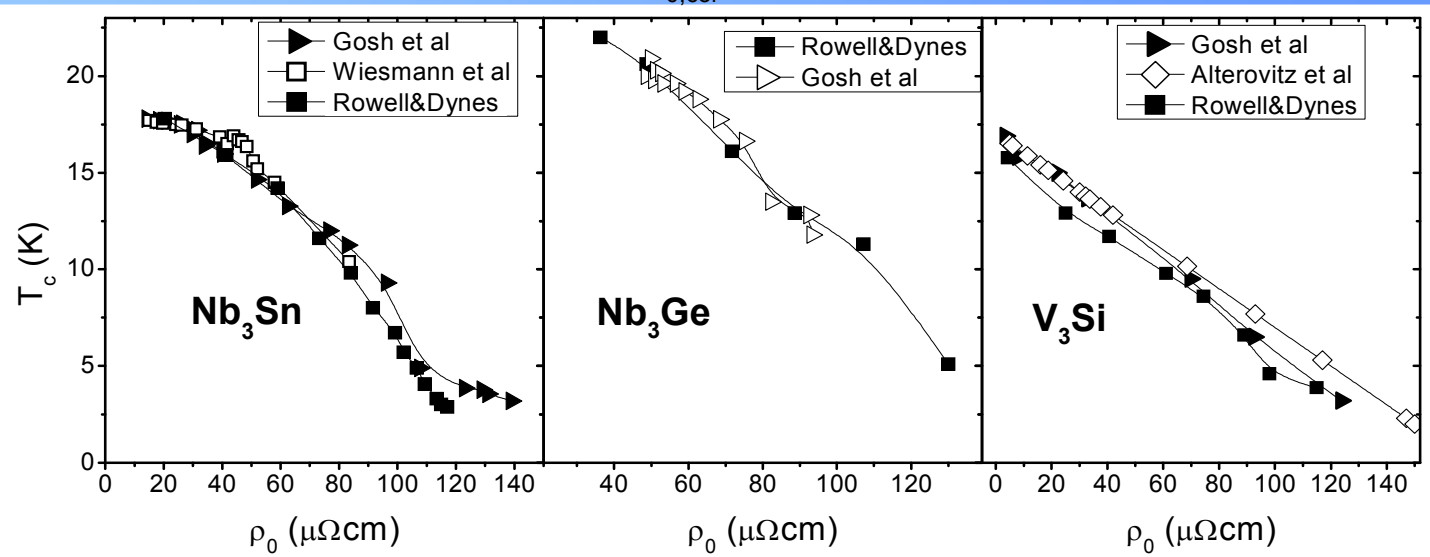


Rowell criterion

$$\rho_{0,cor} = \frac{\rho(40K)}{\rho(300K) - \rho(40K)} \Delta\rho_g$$

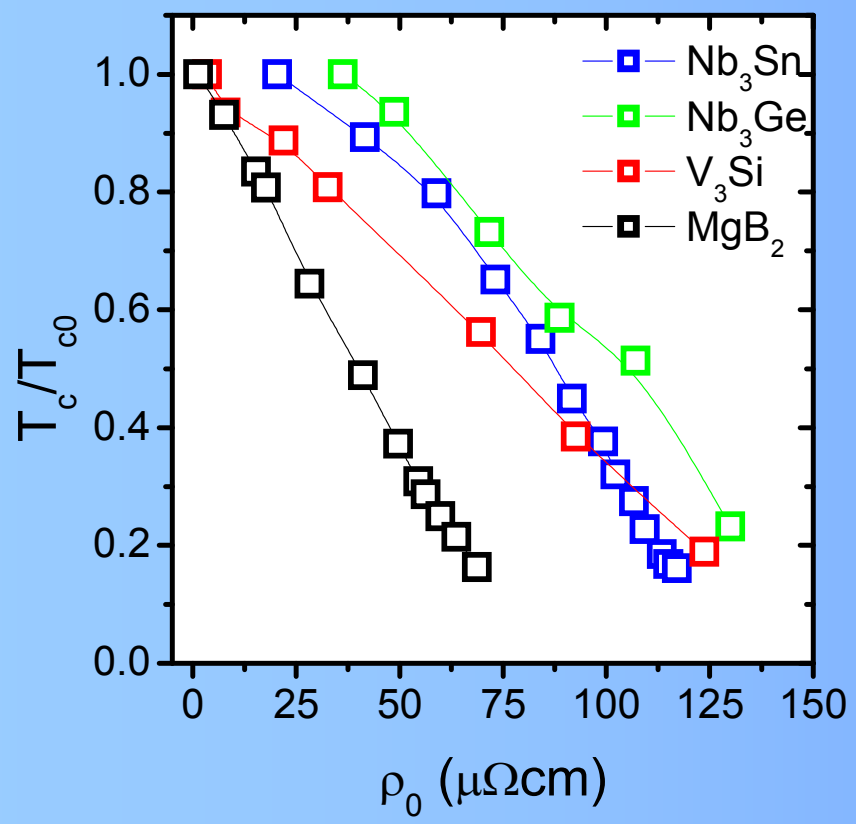
$$\Delta\rho_g \equiv 7.5\ \mu\Omega cm$$

A15s

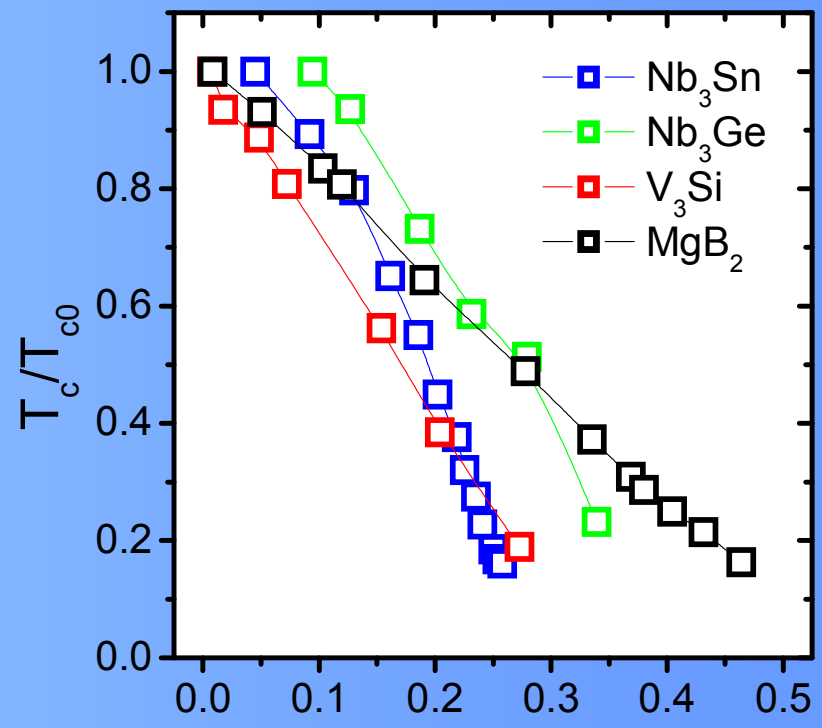


Comparison with A15s

T_c/T_{c0} vs ρ_0



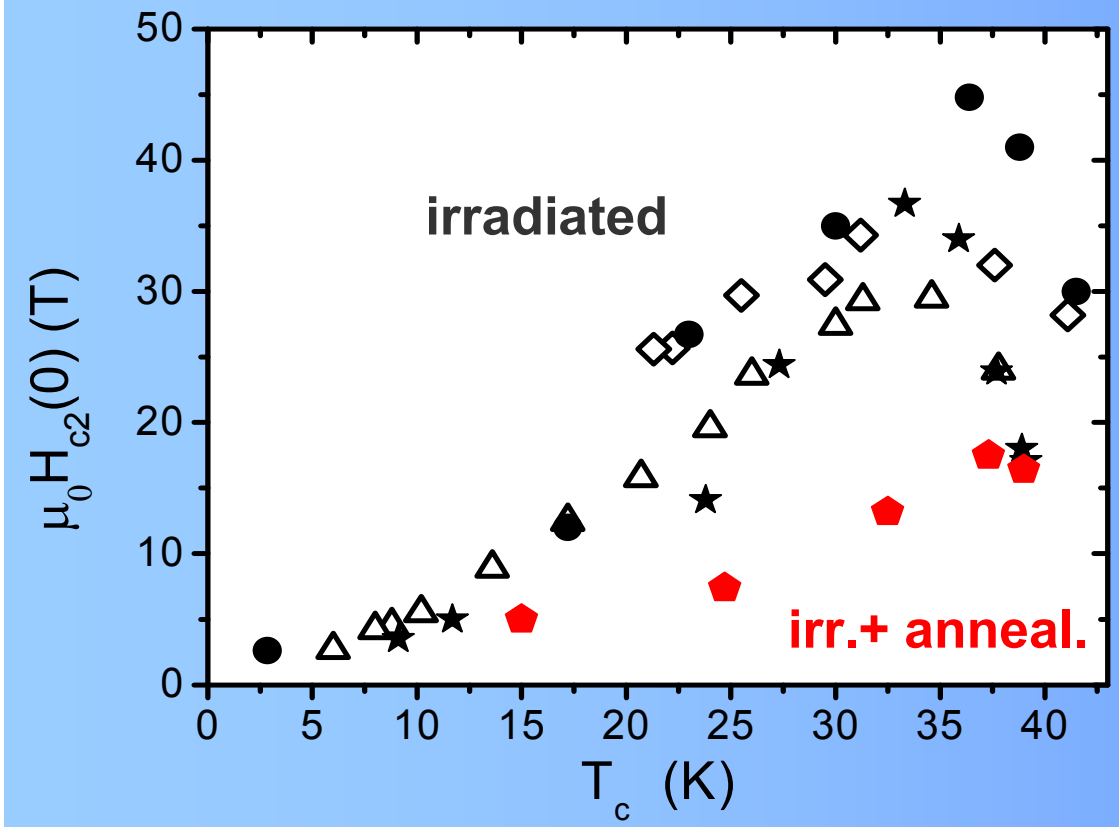
T_c/T_{c0} vs Γ

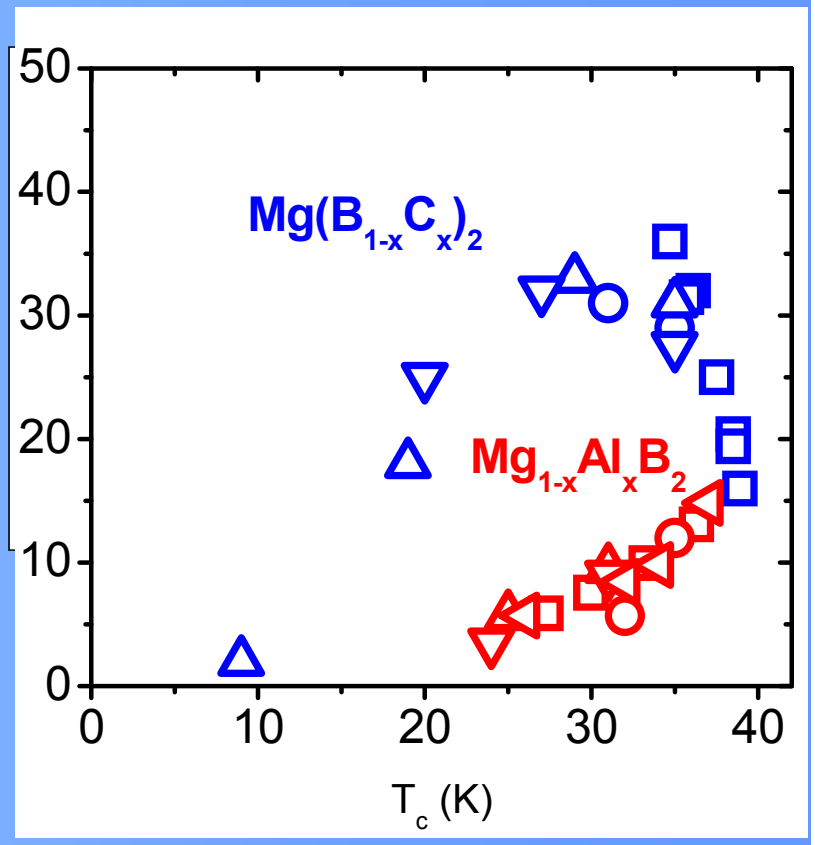


$\propto \rho_0 \Omega_p^2$

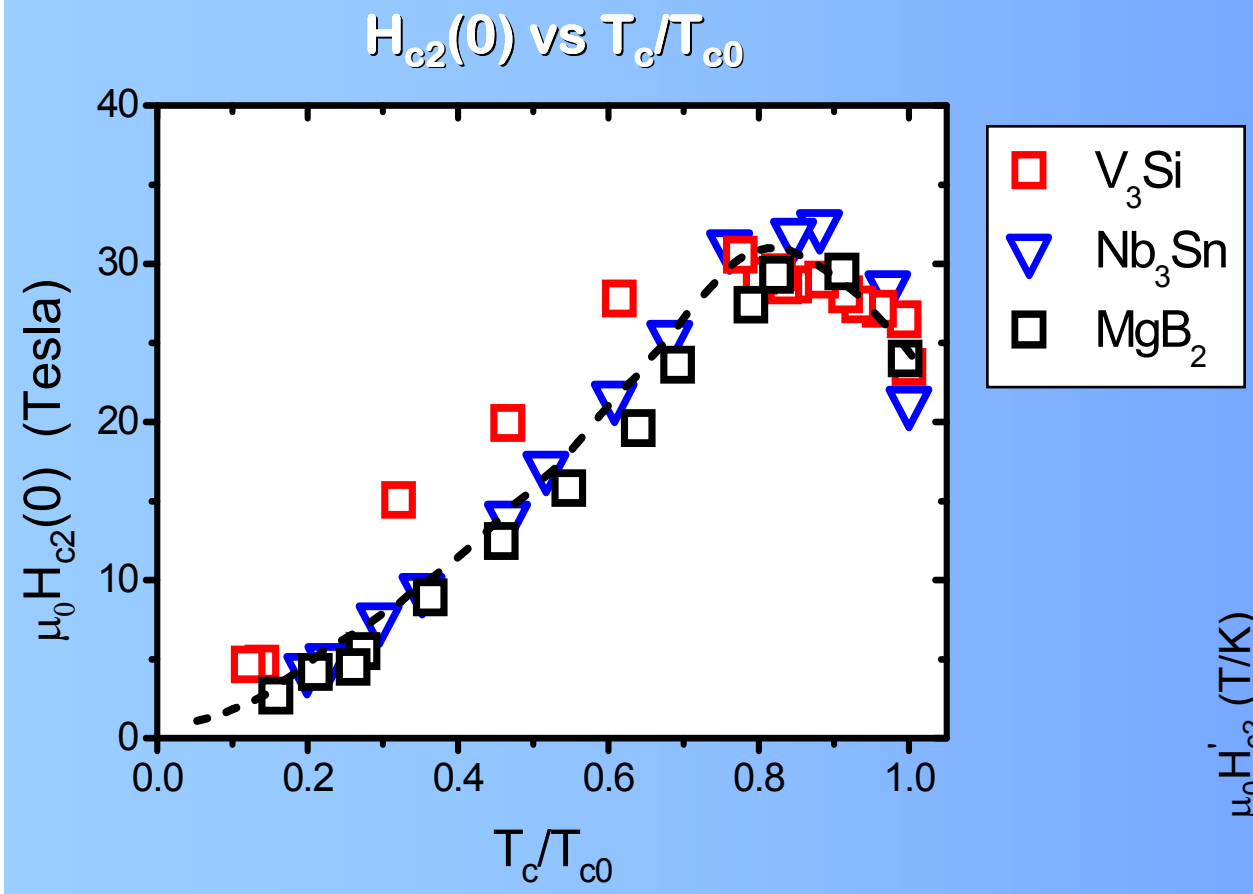
	T_{c0} (K)	$N(0)$ (states/eV cell)	Ω_p (eV)
MgB_2	39	0.71	7.0
Nb_3Sn	18	12	4.0
Nb_3Ge	22	8.0	4.4
V_3Si	17	15	4.0

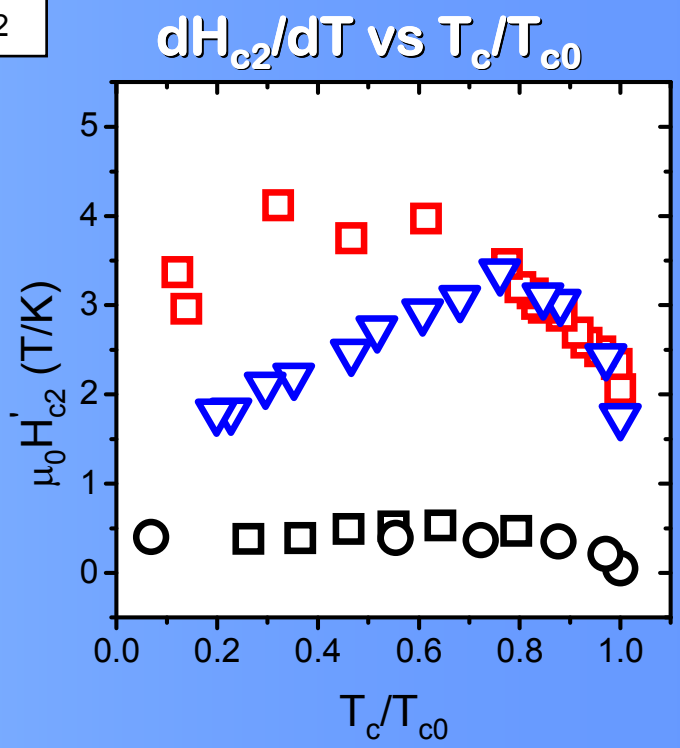
4.1 Upper critical field of MgB_2 : $H_{c2}(0)$ vs T_c





Comparison with A15s



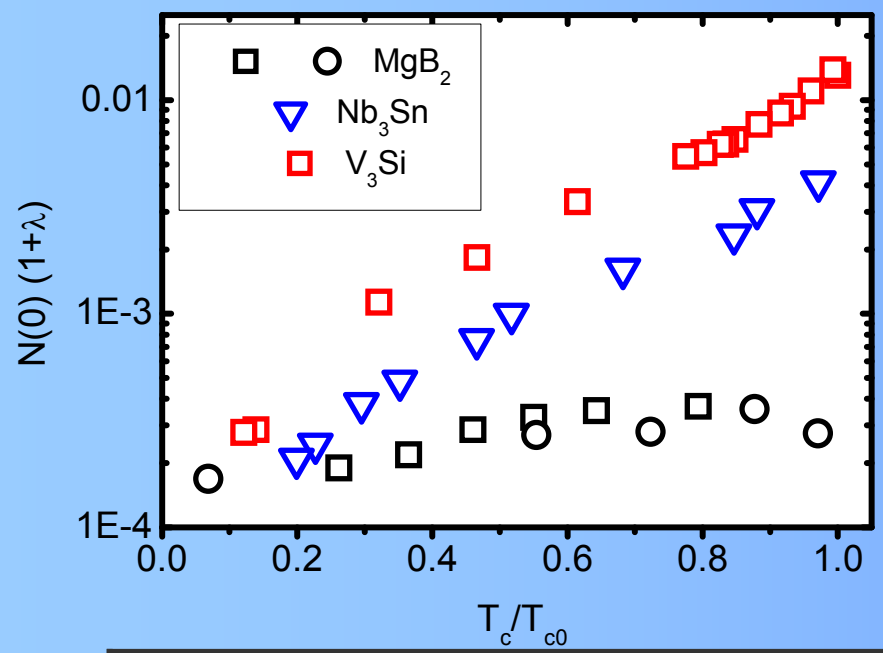


$$\left.\frac{dH_{c2}}{dT}\right| \propto \rho_0 N(0)(1+\lambda)$$

DOS dependence on disorder

Slope of H_{c2}

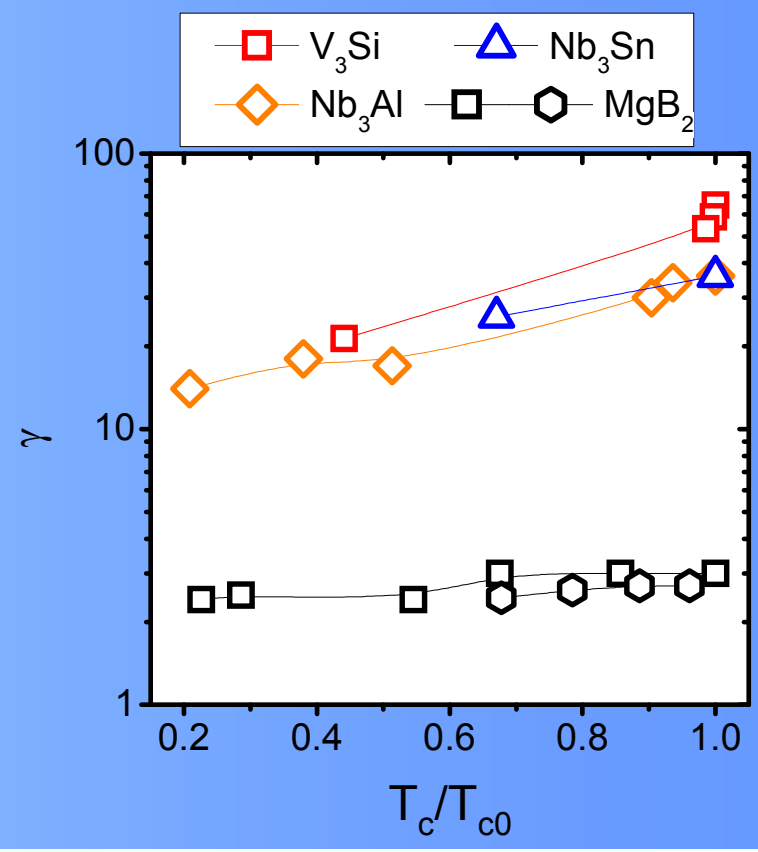
$$N(0)(1+\lambda) \propto \frac{dH_{c2}}{dT} \Big/ \rho_0$$



	T_{c0} (K)	N(0) (states/eV cell)
MgB_2	39	0.71
Nb_3Sn	18	12
Nb_3Al	18.6	15
V_3Si	17	15

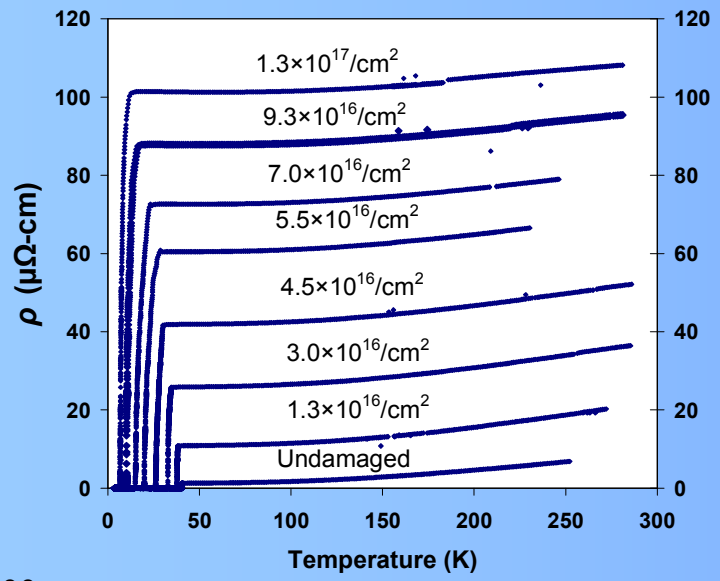
Sommerfeld coefficient

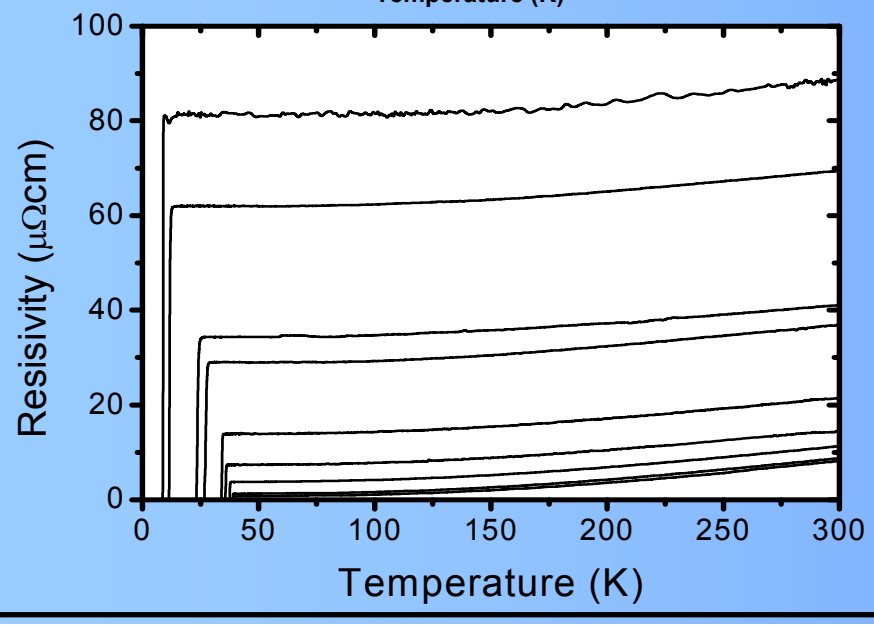
$$\gamma \propto N(0)(1+\lambda)$$

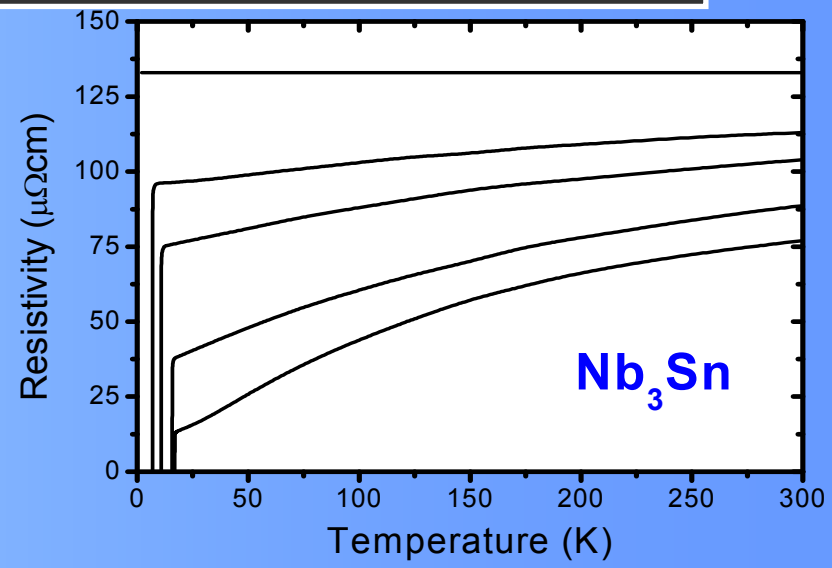


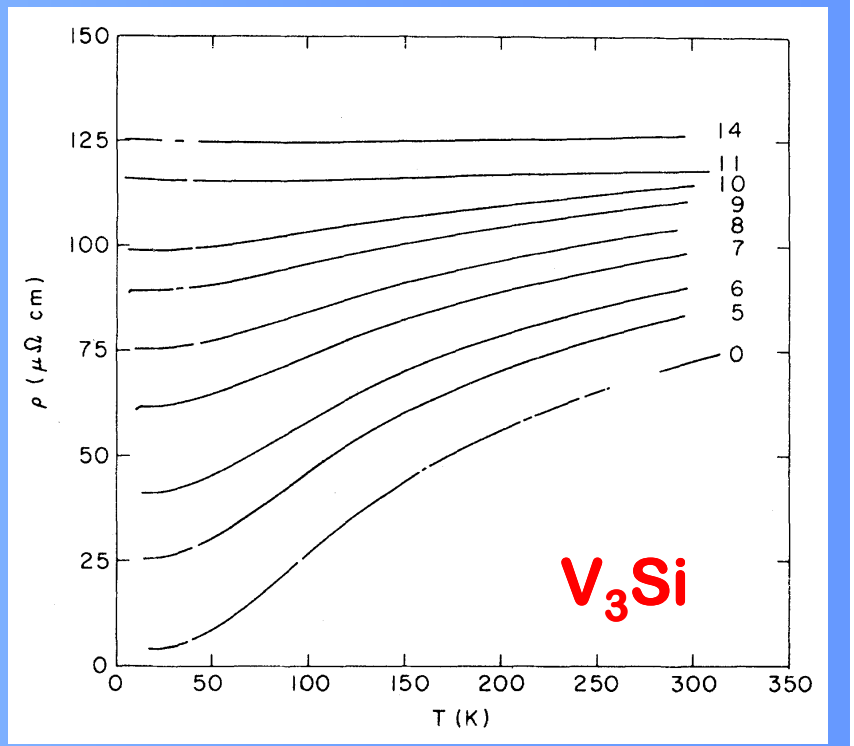
6.1 Temperature dependence of Resistivity

MgB_2









Parallel resistor model

Fisk Z, Webb G 1976 *Phys. Rev. Lett.* **36** 1084
Gurvitch M 1981 *Phys. Rev. B* **24** 7404

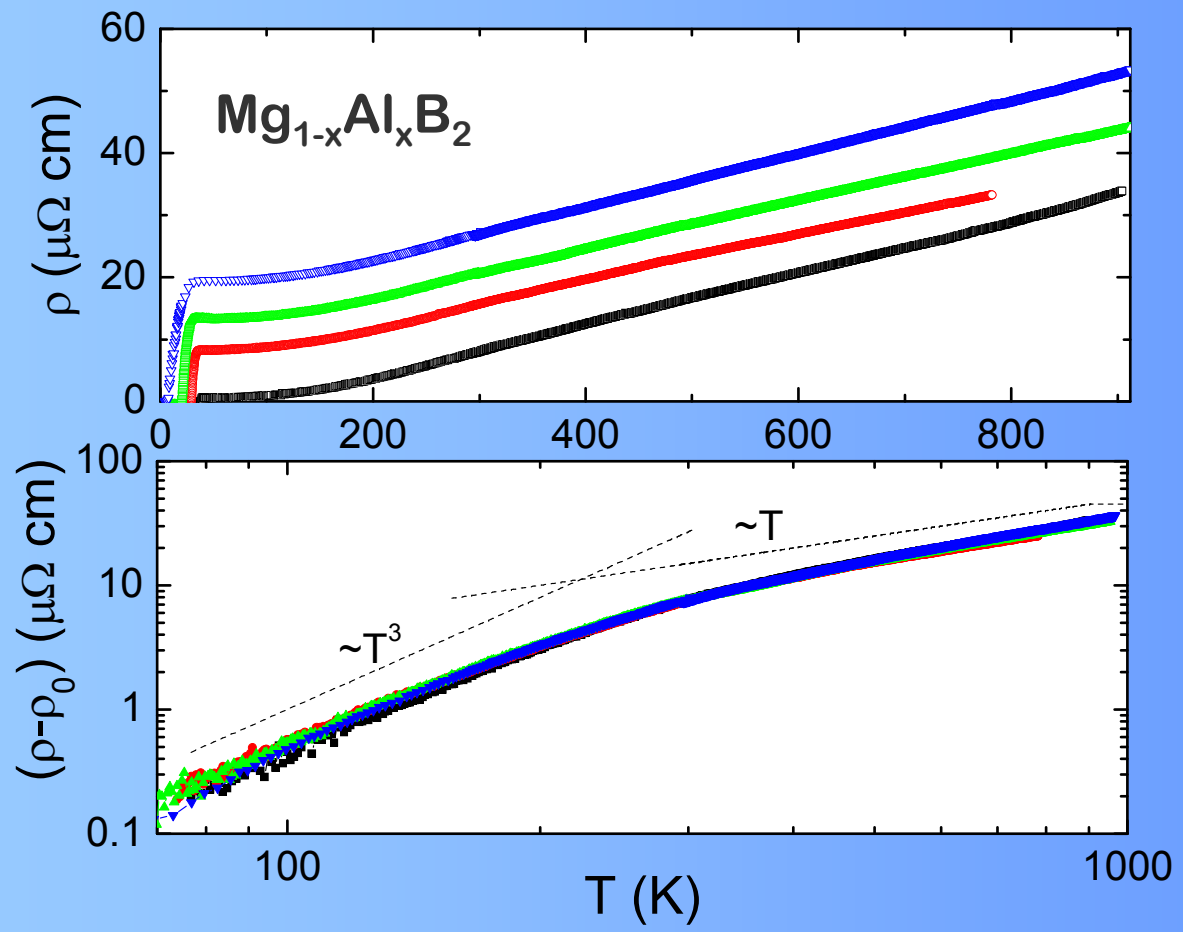
$$\frac{1}{\rho(T)} = \frac{1}{\rho_{ideal}(T)} + \frac{1}{\rho_{sat}} \quad \text{where} \quad \rho_{sat} \propto \frac{v_F}{\Omega_p^2}\frac{1}{a}$$

$$\rho_{ph}(T) = \rho(T) - \rho_0 \propto \frac{\lambda}{\Omega_p^2}$$

If $\rho_{ph} \sim \rho_{sat}$ saturation is expected also without disorder

		Ω_p (eV)	v_F (cm/s)	*a* (Å)	λ	ρ_{sat} ($\mu\Omega$cm)	ρ_{ph}(300K) ($\mu\Omega$cm)	ρ_{ph}(300K) /ρ_{sat}
Nb_3Sn		4	3×10^7	5.3	1.8	**175**	**137**	**0.78**
MgB_2	σ	4	4.4×10^7	3	0.93	**450**	**71**	**0.16**
	π	5.9	5.4×10^7		0.43	**260**	**15**	**0.06**

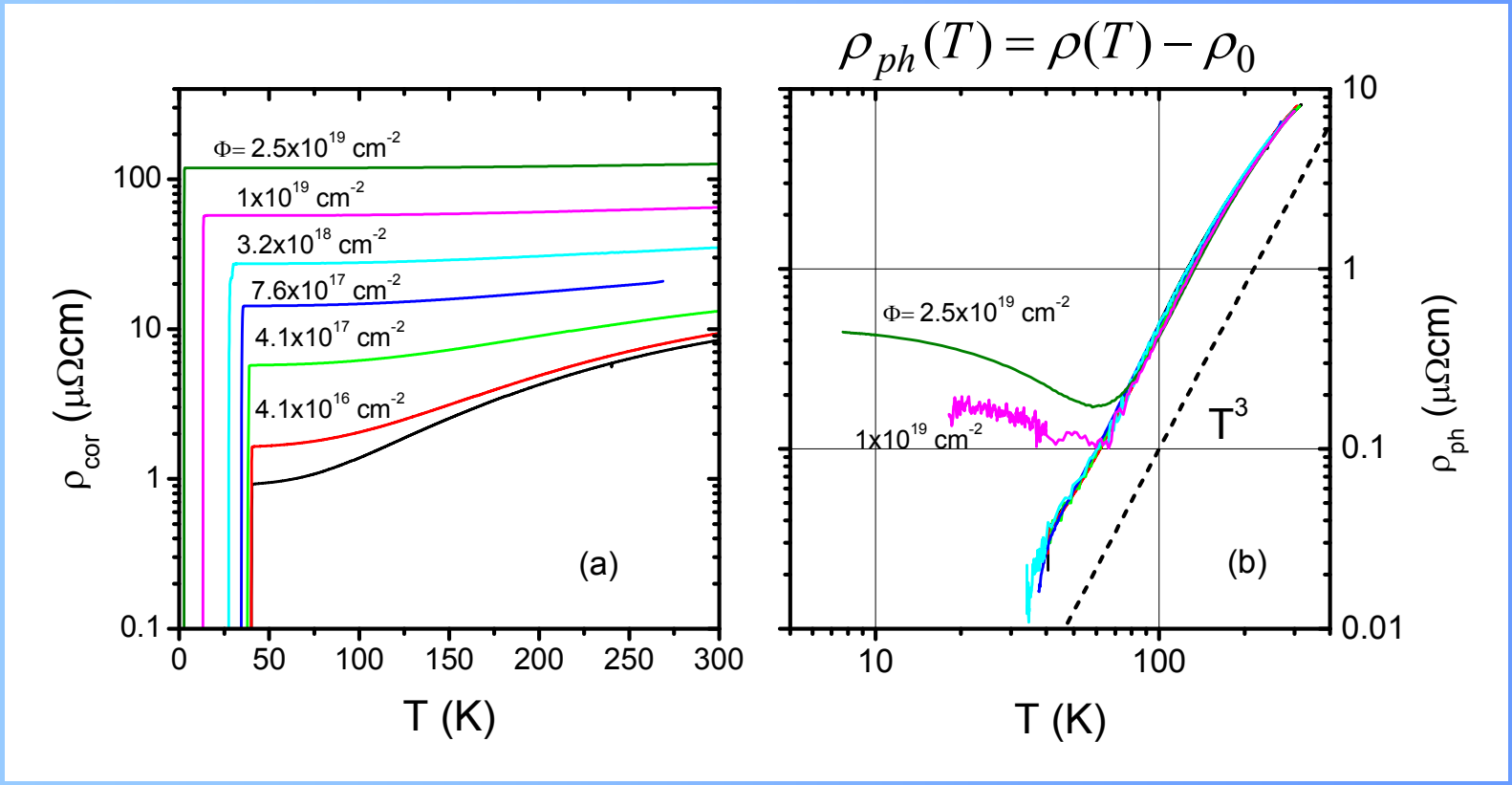
6.2 Looking for saturation in MgB_2



- Resisivity does not saturate up to 1000 K
- Same temperature dependence ➲ Only π – band conduction

I.Pallecchi et al., PRB 79, 134508 (2009)

6.3 Temperature dependence of $\rho_{ph}(T)$



$$\rho_{ph}(T) \propto T^3$$

↓

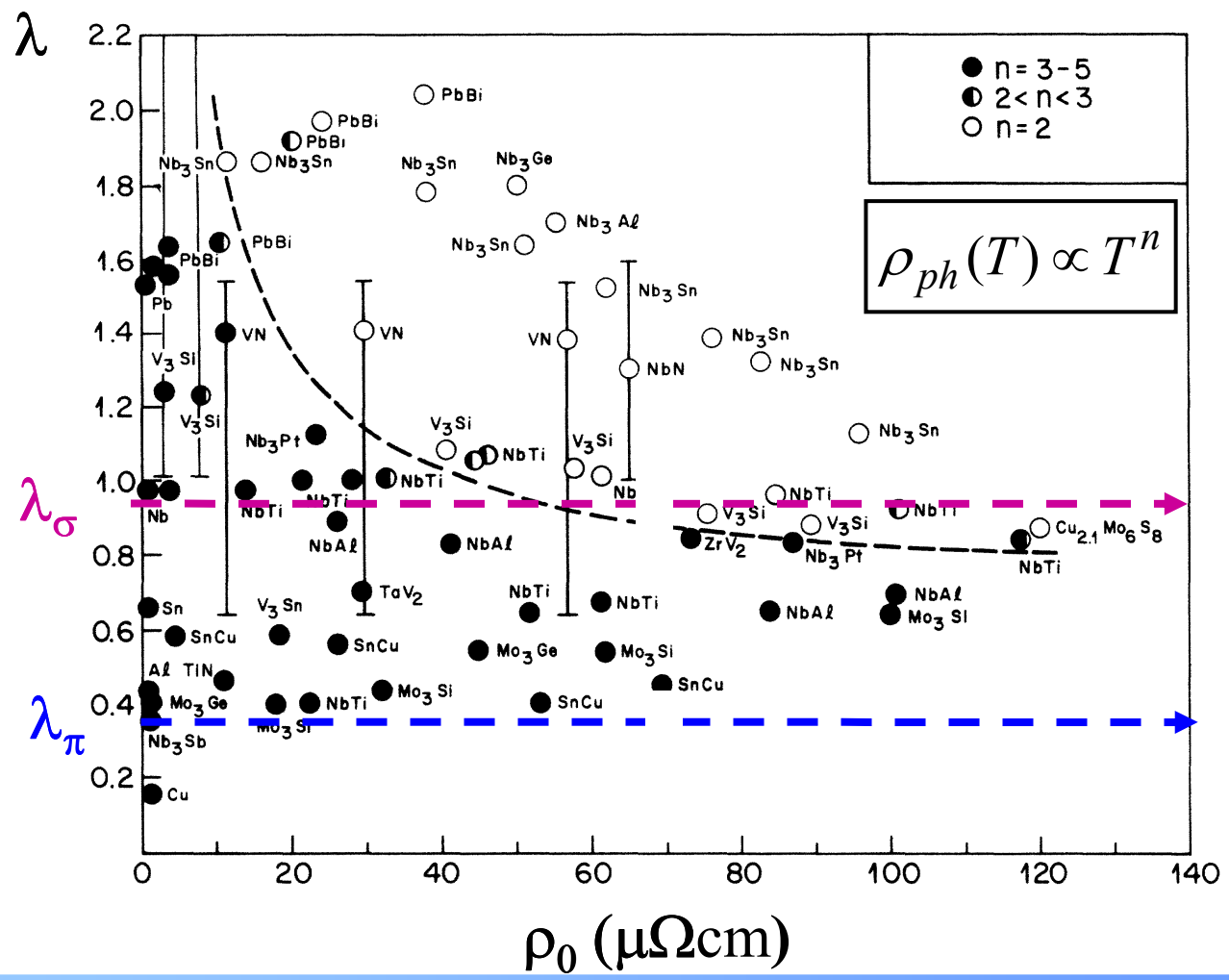
Only π carriers contribute to resistivity

6.3 The Gurvitch plot

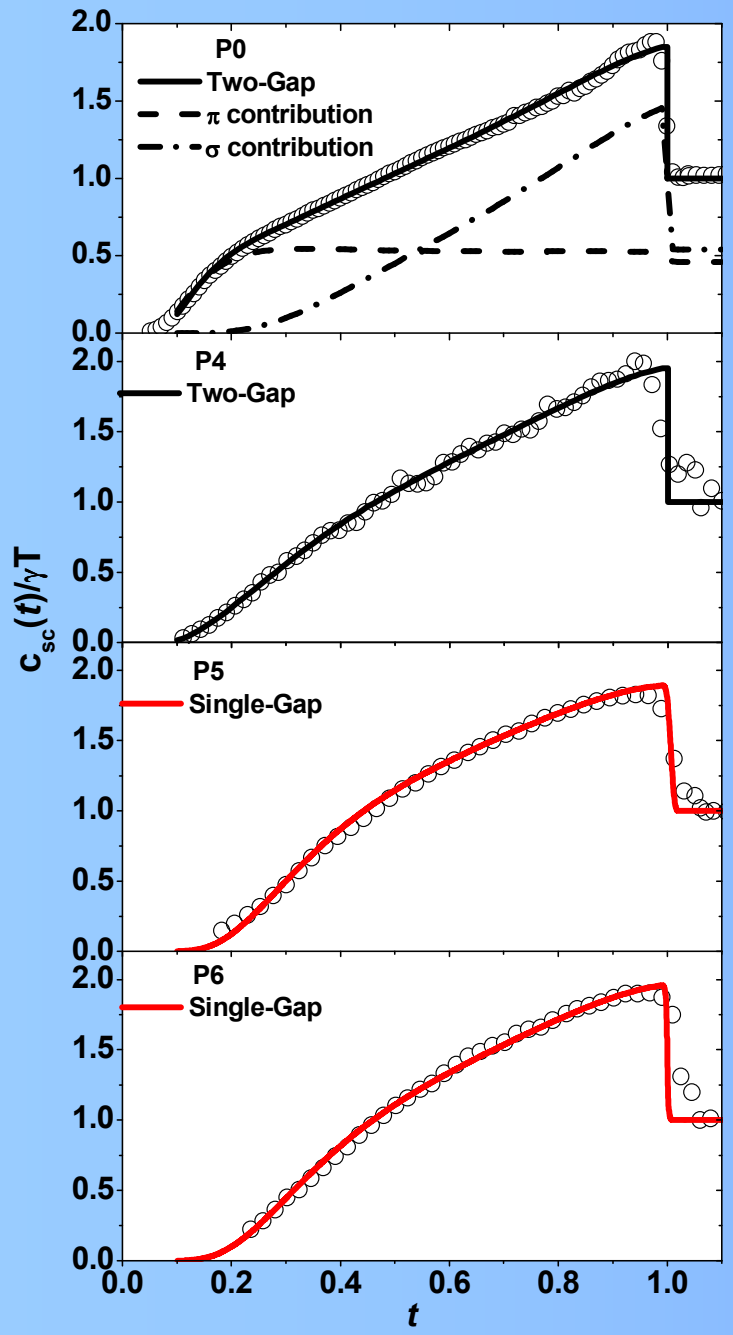
VOLUME 56, NUMBER 6 PHYSICAL REVIEW LETTERS 10 FEBRUARY 1986

Universal Disorder-Induced Transition in the Resistivity Behavior of Strongly Coupled Metals

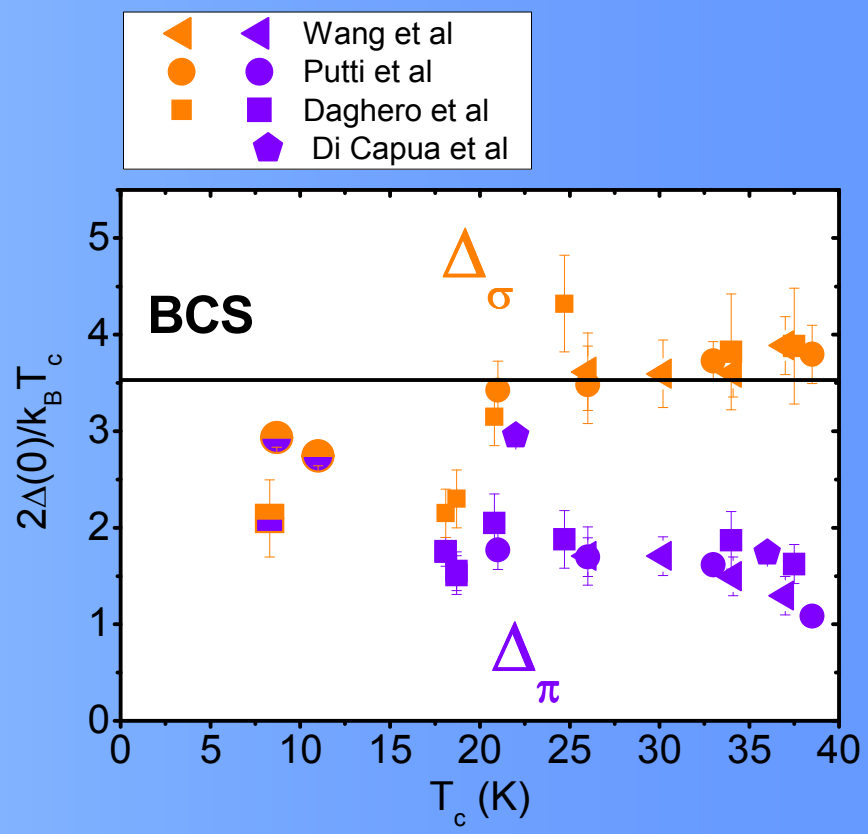
M. Gurvitch



7.1 Energy gaps in MgB_2

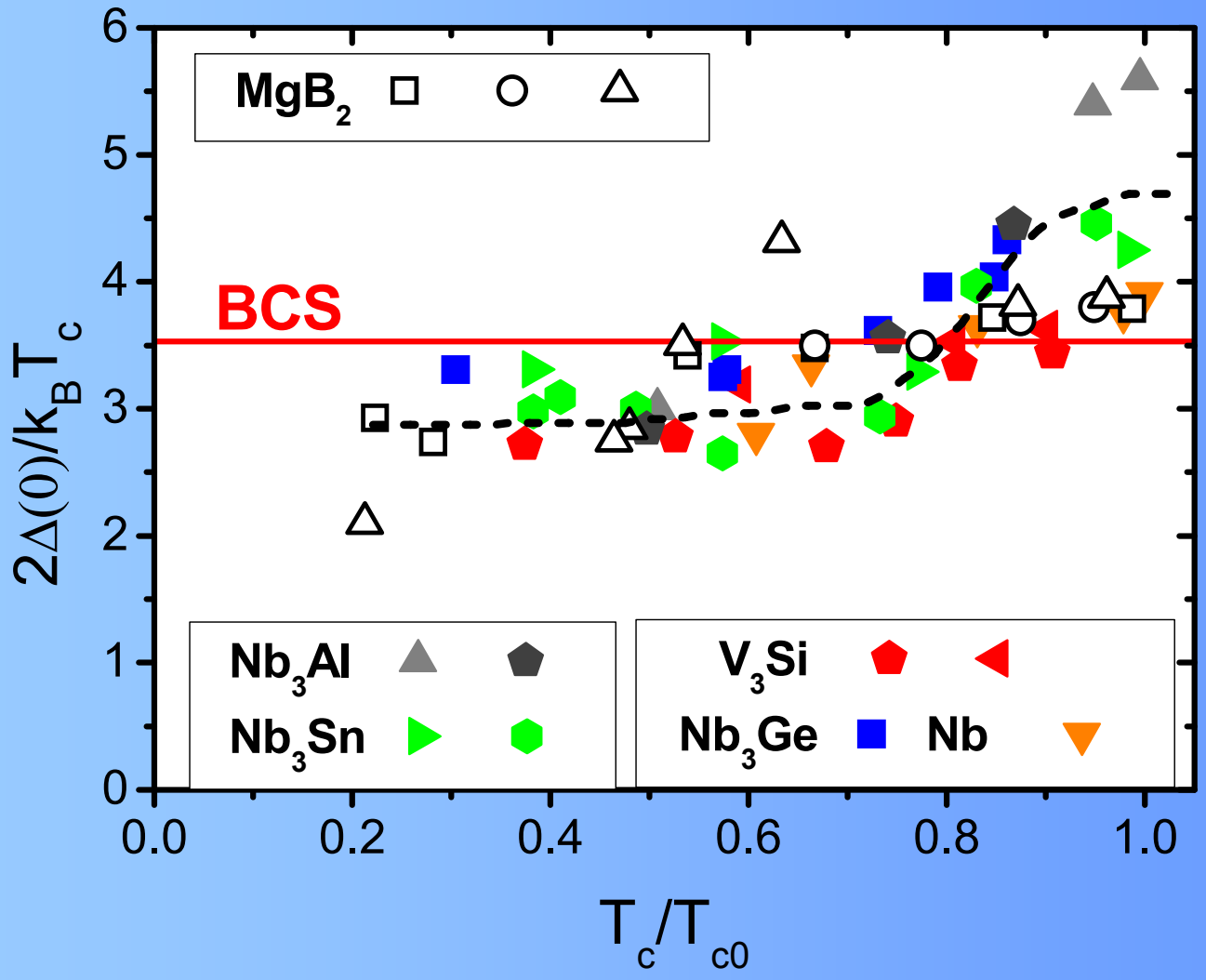


Increasing irradiation



- Definitive evidence of merging of the two gaps
- The merging takes place at a lower temperature than the 20 K

7. 2 Energy gaps: comparison with A15



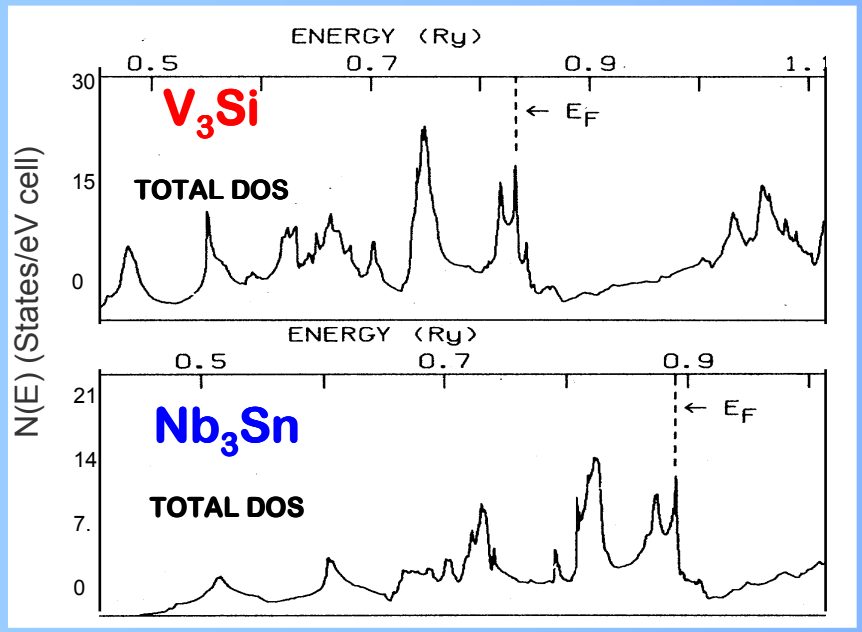
The reduced gap drops systematically below the BCS value with increasing disorder

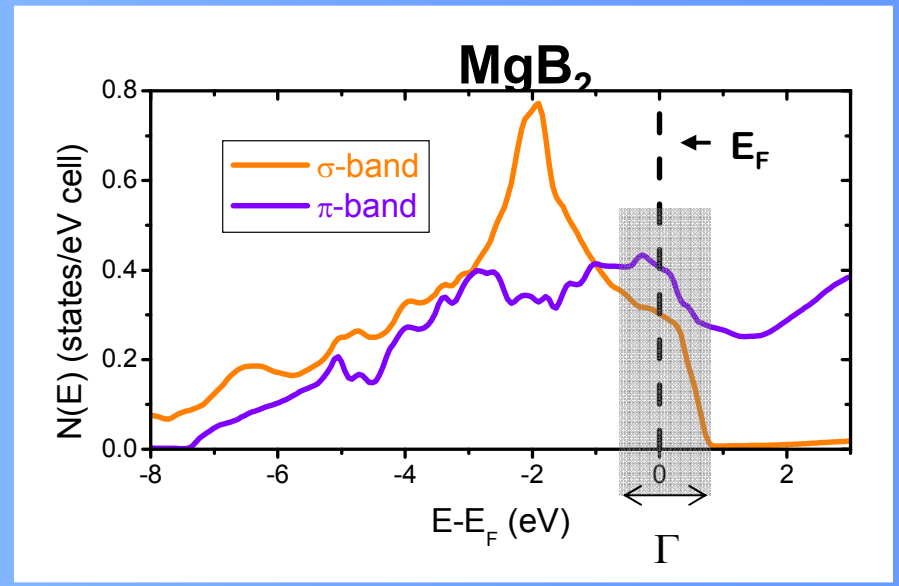
8.1 Theoretical model for the degradation of T_c. Testardi-Matteis model: smearing of the DOS

VOLUME 41, NUMBER 23 PHYSICAL REVIEW LETTERS 4 DECEMBER 1978

Electron Lifetime Effects on Properties of *A*15 and bcc Materials

L. R. Testardi and L. F. Mattheiss
Bell Laboratories, Murray Hill, New Jersey 07974





$$N(E,\Gamma) = \int S(E,E',\Gamma) N(E',\Gamma=0) dE'$$

$$S(E,E',\Gamma) = \frac{1}{\pi} \frac{\Gamma}{(E-E')^2 + \Gamma^2}$$

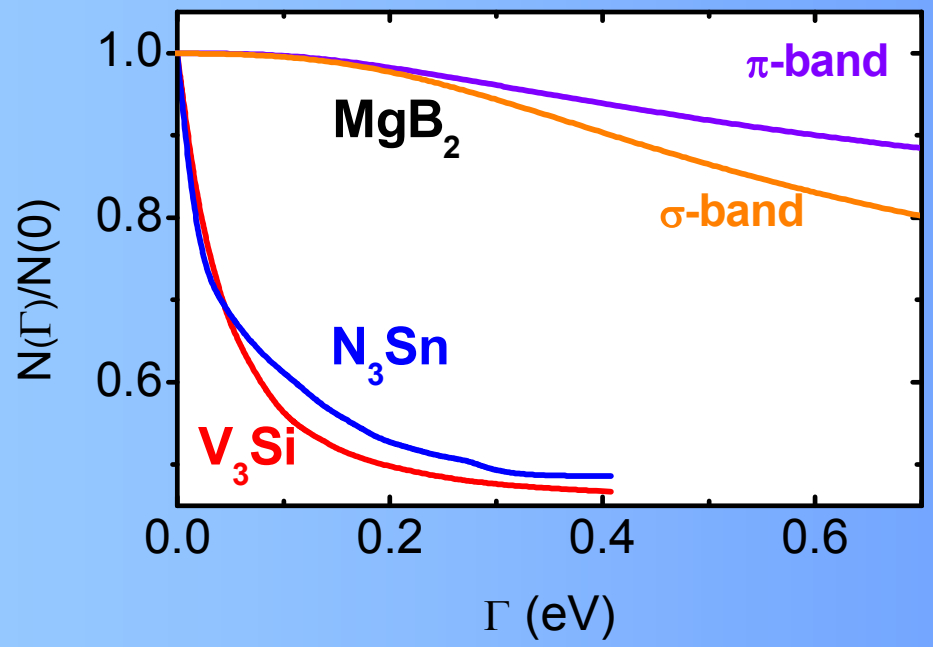
$$\rho_0 \propto \frac{\Gamma}{\Omega_p^2}$$

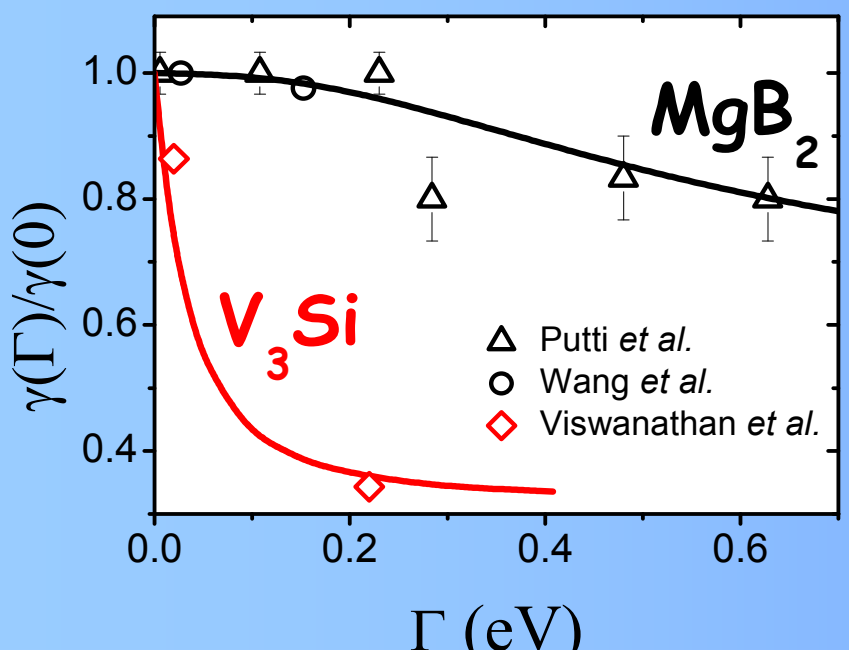
$N(E)$ is the density of states

$S(E,\Gamma)$ is a Lorentian function

Γ is the relaxation rate

N(Γ) vs Γ



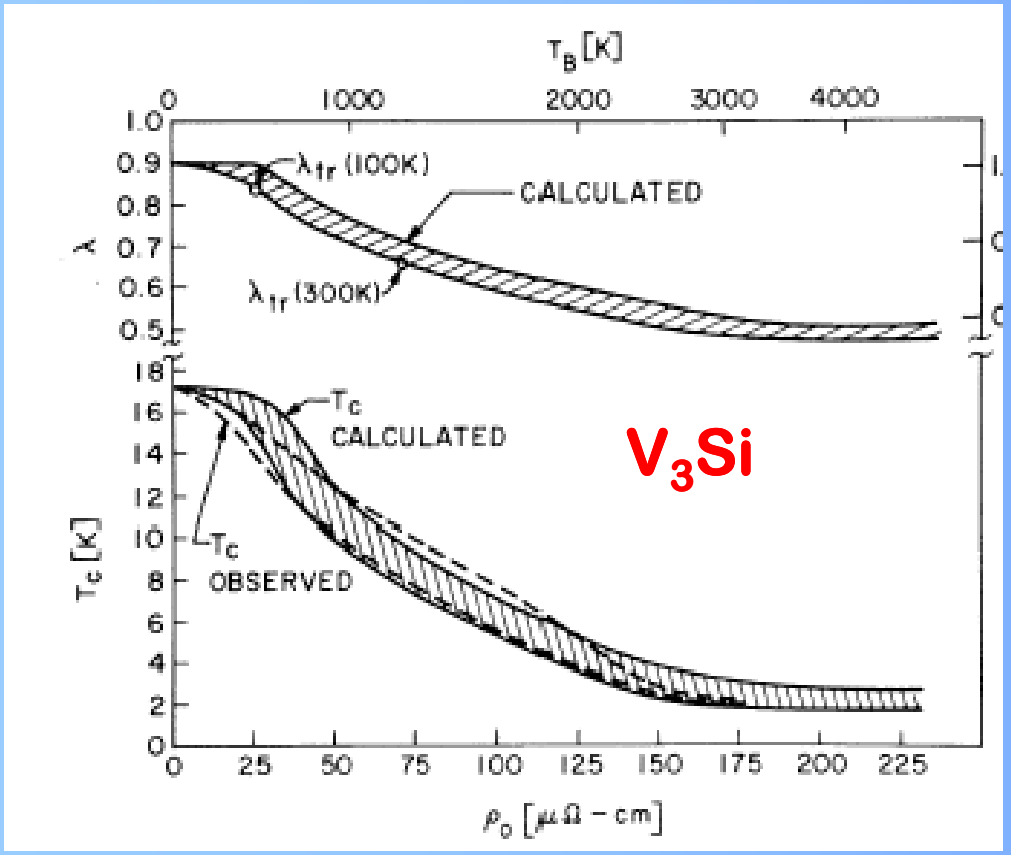


Sommerfeld coefficient vs Γ

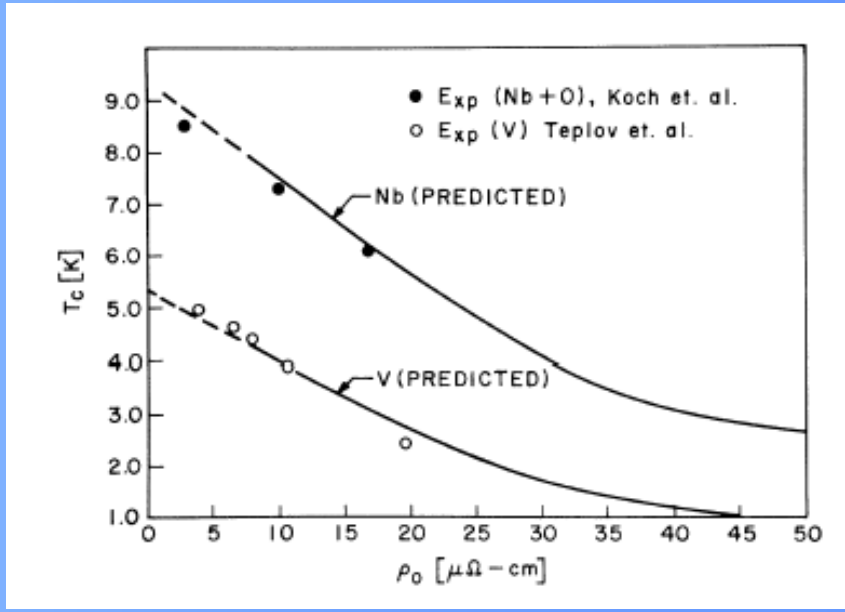
$$\gamma(\Gamma) \propto N(\Gamma)[1+\lambda(\Gamma)]$$

$$where \quad \lambda(\Gamma) \propto \mathrm{N}(\Gamma)$$

T_c vs ρ in A15
Comparison with experiments



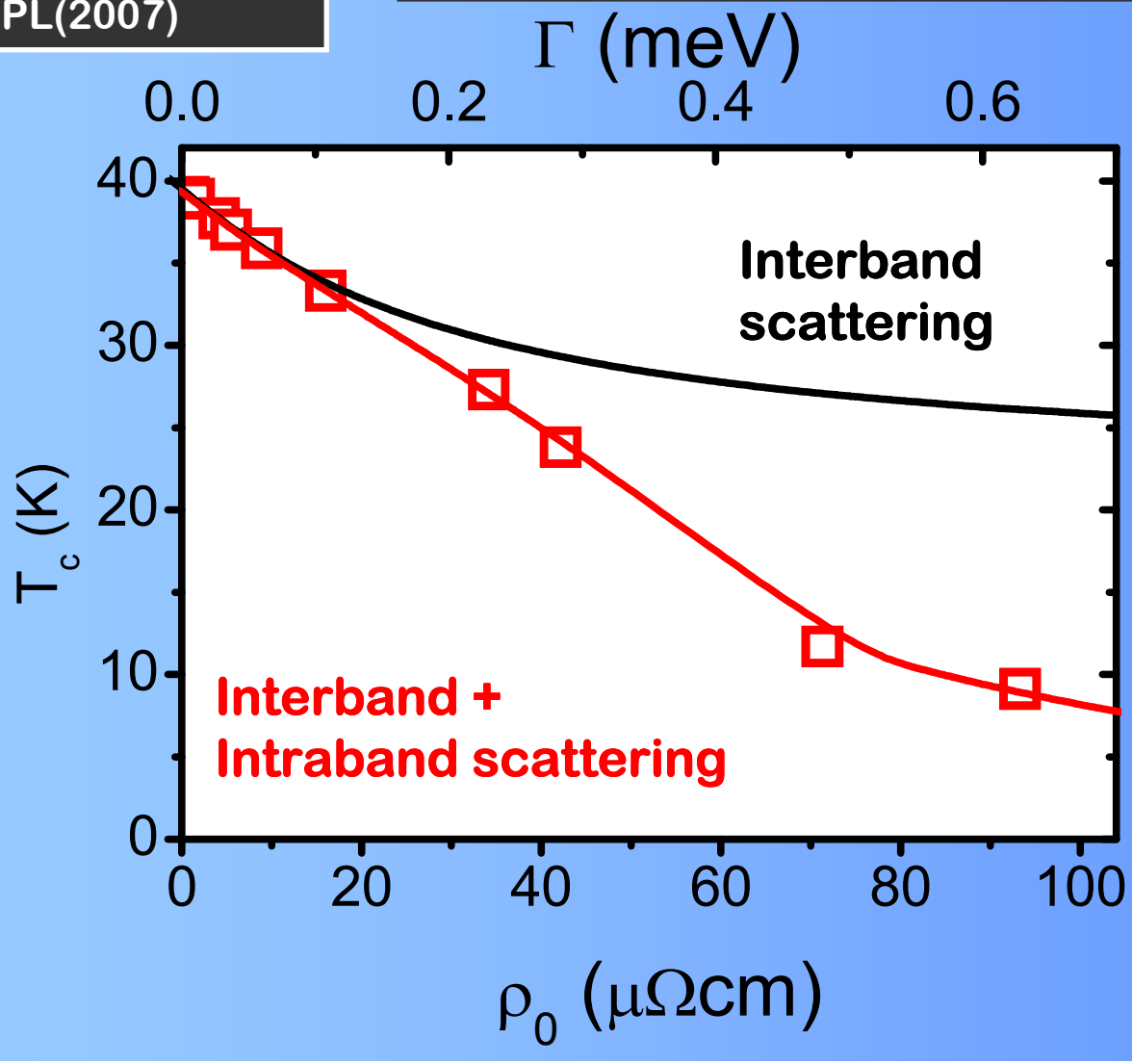
$\lambda(\Gamma) \propto N(\Gamma)$



8.2 A model for suppression of T_c in MgB_2

M.Putti et al EPL(2007)

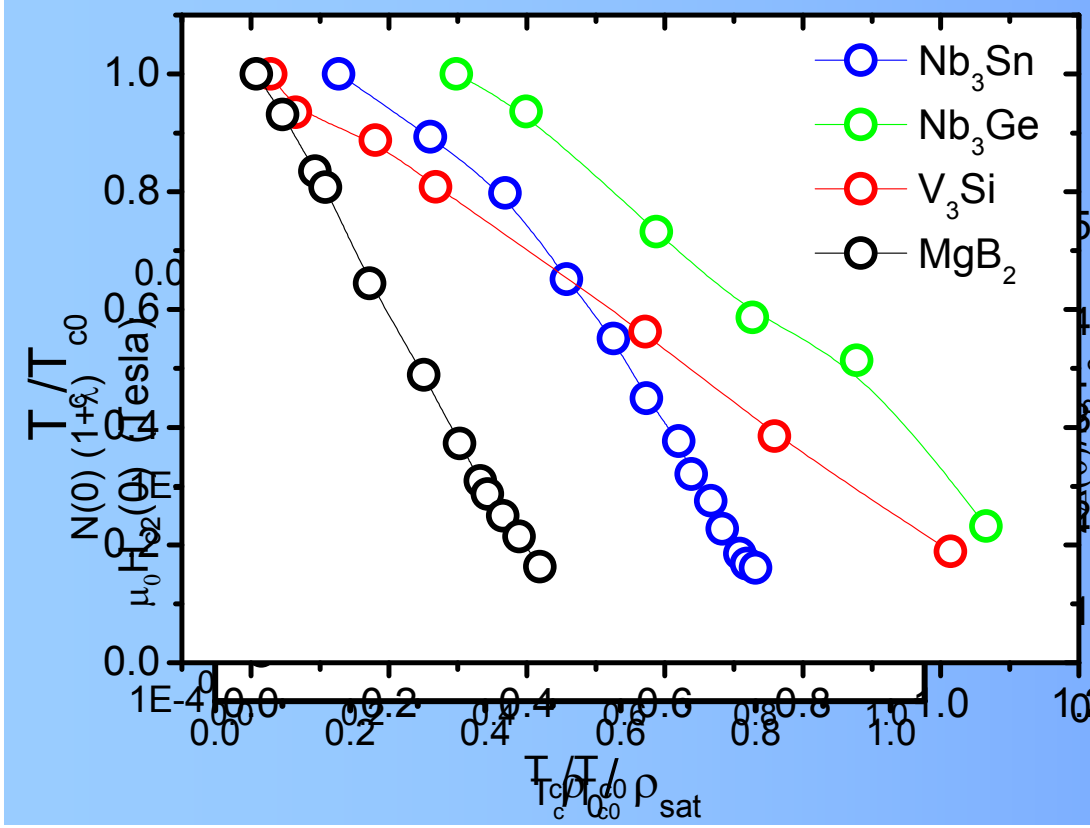
- ➔ **Interband scattering** and two band isotropization
- ➔ **Intraband scattering** and smearing of the DOS

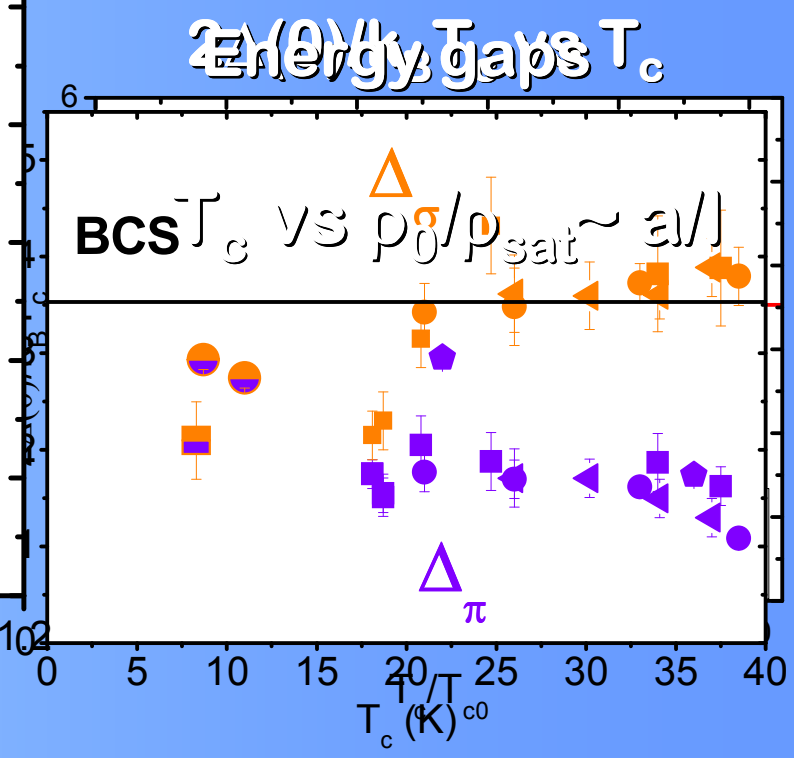


9. Conclusions

The comparison between the behavior of damaged MgB_2 and A15s has emphasized:

- ➔ Some similarities
- ➔ Some differences
- ➔ Some unclear issues:





10.Acknowledgements

P Manfrinetti, A Palenzona, V Ferrando, C Tarantini, I Pallecchi, P.Brotto, M.Tropeano E.Galleani and C Ferdeghini at CNR-INFM-LAMIA

H. U. Aebersold and E. Lehmann at PSI

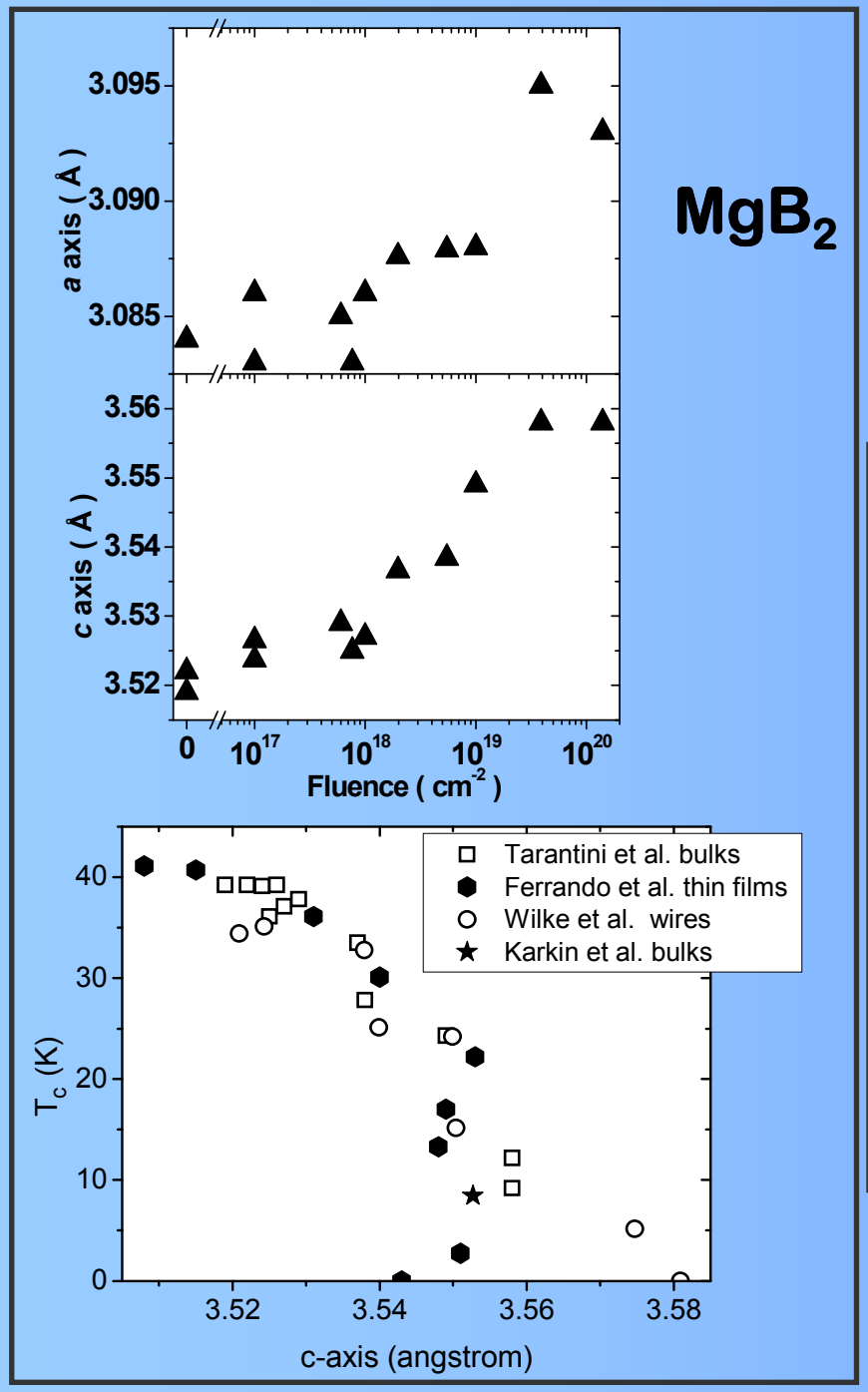
R Di Capua and P Orgiani at CNR-INFM-Coherentia

X X Xi at PSU

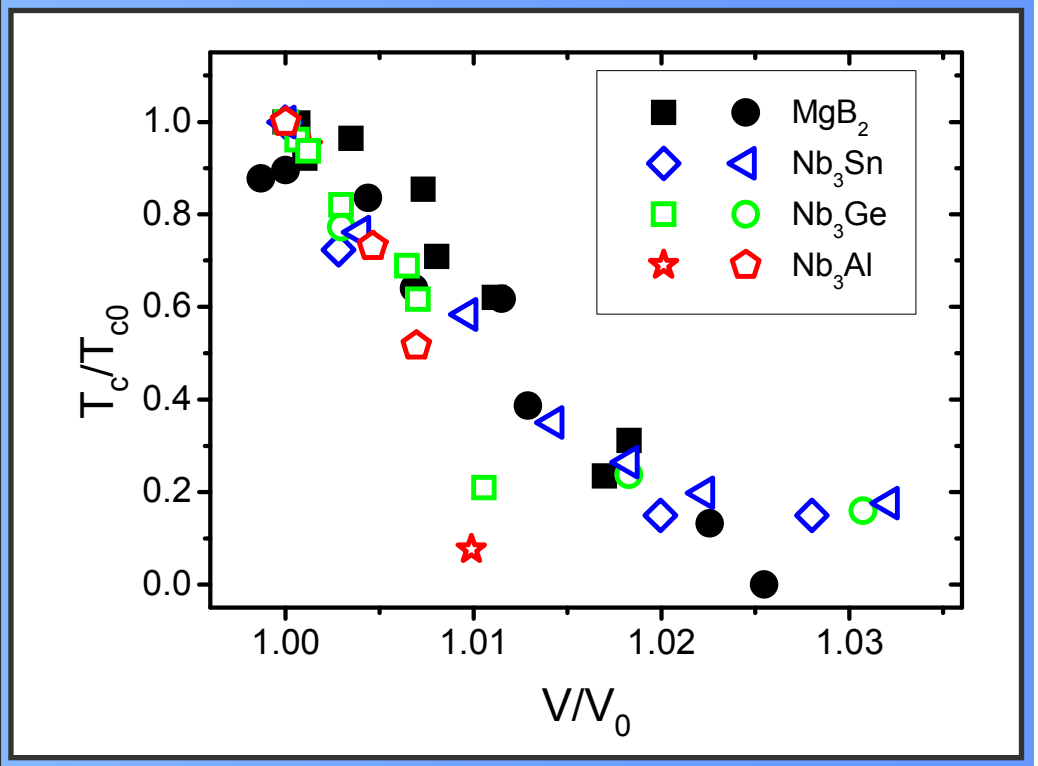
N Newman, R Singh and R Gandikota at ASU

B Moeckly at STI

2.1 Defect structure: Cell parameters vs fluence



Comparison with A15s



2.2 Defect structure: Annealing experiment

Defects in A15 (A_3B)

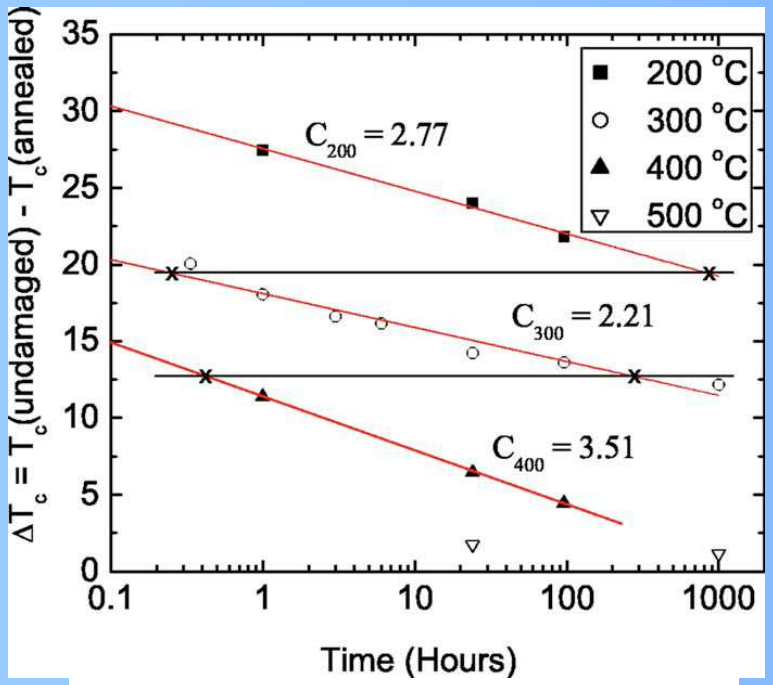
☑ displacements of A and B atoms

☑ antisite defects (A in place of B and vice versa)

Defects in MgB_2

☑ displacements of Mg and B atoms

❑ antisite defects are energetically unfavorable



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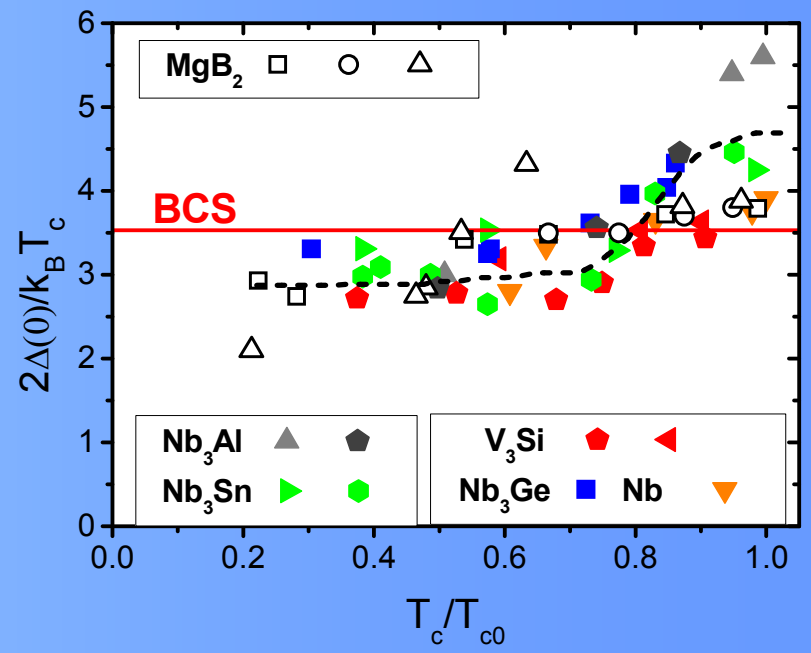
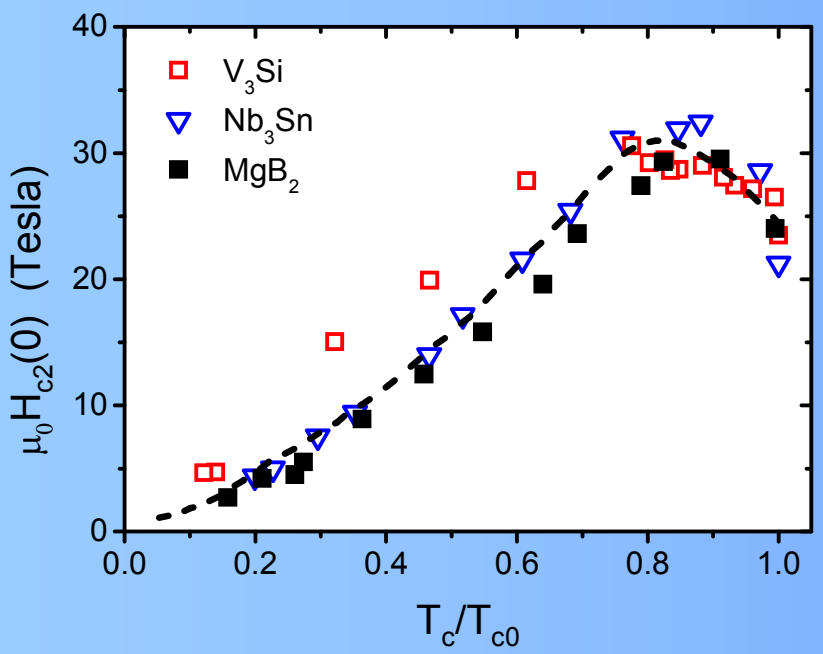
	T_{an} (°C)	E_a (eV)
Nb_3Sn	450	1.7
	750	2
MgB_2	200	1
	400	1.5

Main similarities:

- ➔ Linear ρ_0 vs T_c behaviour
- ➔ $H_{c2}(0)$ vs T_c
- ➔ reduced gap vs T_c

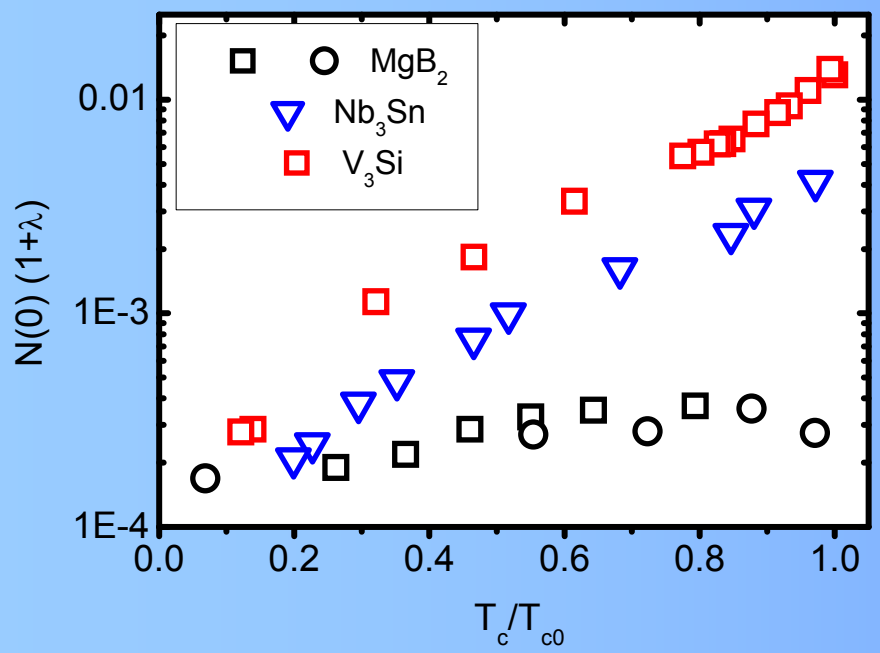




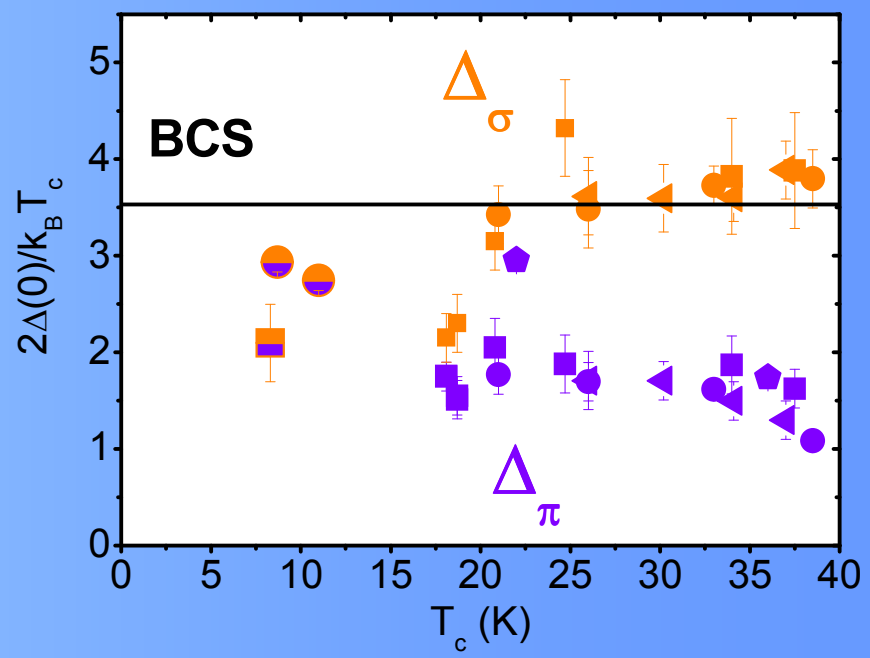
Main differences:

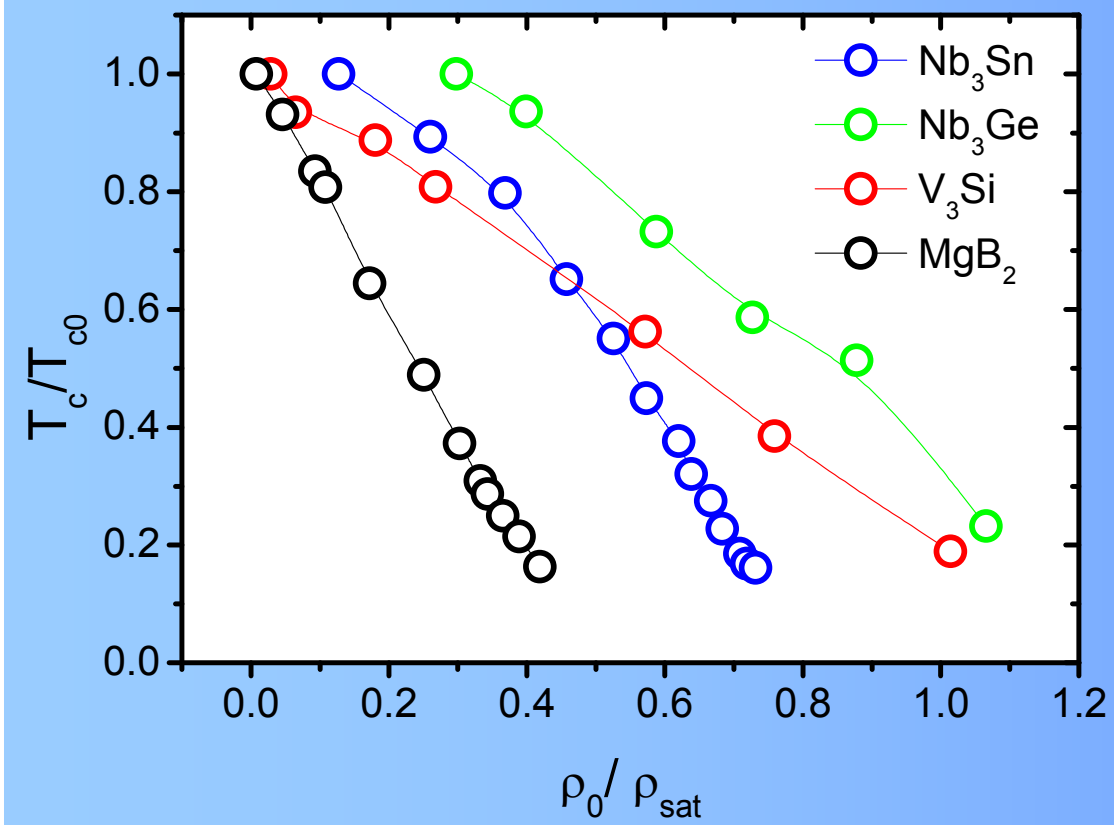
- ➔ DOS and its dependence on disorder
- ➔ Two gap feature

N (1+λ)



Energy gaps





T_c vs ρ_0/ρ_{sat}