EUCAS 2015

12th EUropean Conference on Applied Superconductivity

6th - 10th September 2015 Lyon - France

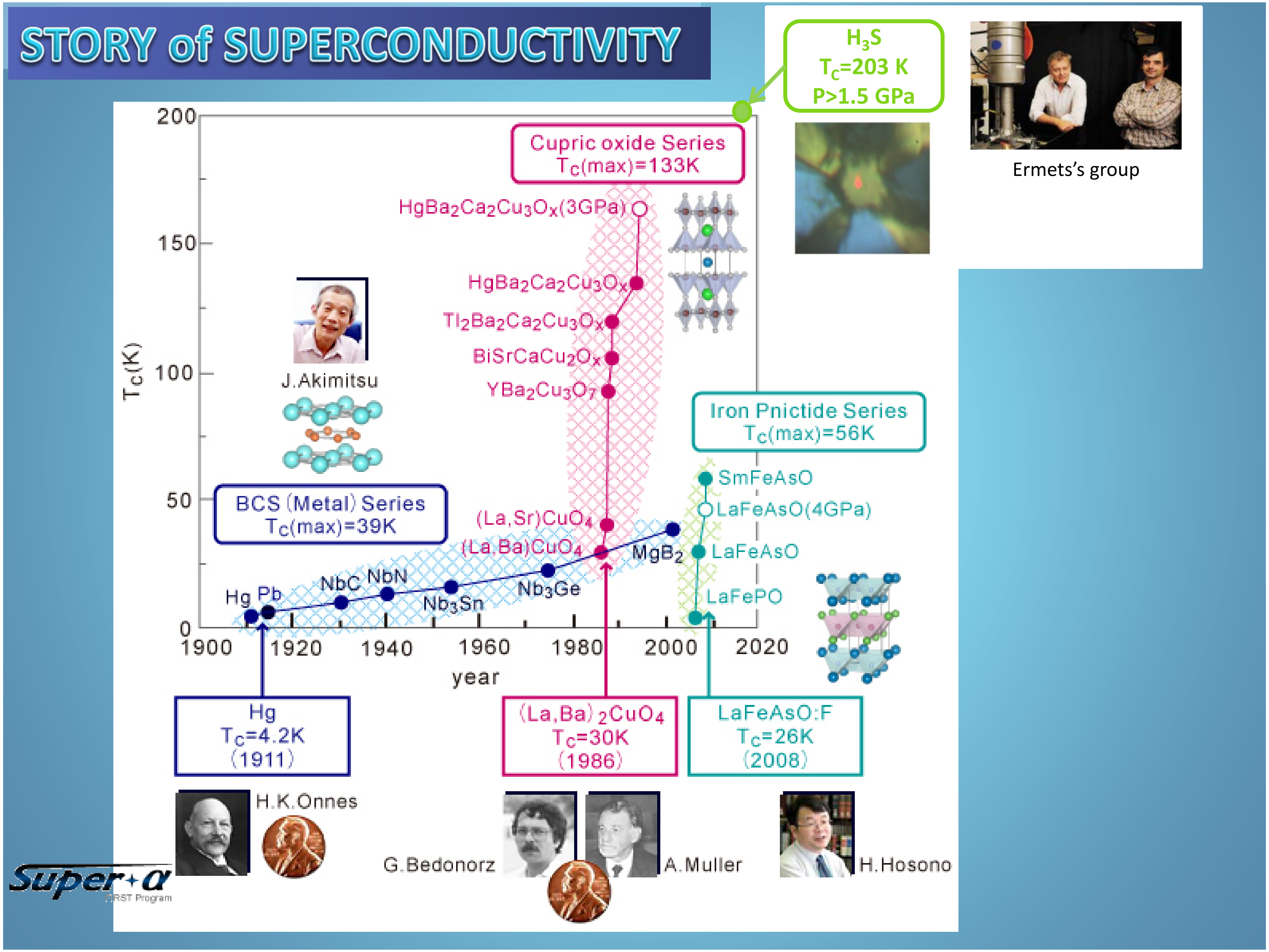
MgB_2 and the Iron-based superconductors

Marina Putti

University of Genova and CNR-SPIN

SPIN

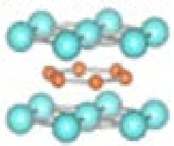
UNIVERSITÀ DEGLI STUDI DI GENOVA


STORY of SUPERCONDUCTIVITY
H_3S
T_C=203 K
P>1.5 GPa
Ermets's group
Cupric oxide Series
T_c(max)=133K
$HgBa_2Ca_2Cu_3O_x$(3GPa)
$HgBa_2Ca_2Cu_3O_x$
$Tl_2Ba_2Ca_2Cu_3O_x$
$BiSrCaCu_2O_x$
$YBa_2Cu_3O_7$
(La,Sr)CuO_4
(La,Ba)CuO_4
MgB_2
Iron Pnictide Series
T_c(max)=56K
SmFeAsO
LaFeAsO(4GPa)
LaFeAsO
LaFePO
BCS (Metal) Series
T_c(max)=39K
Hg
Pb
NbC
NbN
Nb_3Sn
Nb_3Ge
J.Akimitsu
T_c(K)
0
50
100
150
200
1900
1920
1940
1960
1980
2000
2020
year
Hg
T_c=4.2K
(1911)
(La,Ba)$_2CuO_4$
T_c=30K
(1986)
LaFeAsO:F
T_c=26K
(2008)
H.K.Onnes
G.Bedonorz
A.Muller
H.Hosono
Super+α
FIRST Program

THE STORY of LAST 15 YEARS

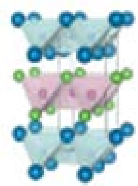
MgB_2

J.Akimitsu



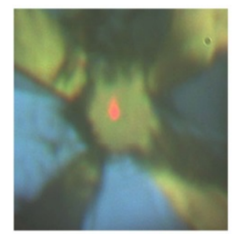
BCS (Metal) Series
T_C(max)=39K

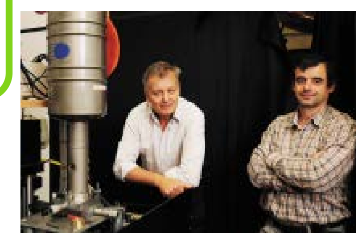
H.Hosono



Iron-based supercoductors
T_C(max)=58 K

H_3S
T_C=203 K
P>1.5 GPa





Ermets's group

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
Plenary presentation PL10 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015.
Not submitted to IEEE Trans. Appl. Supercond.

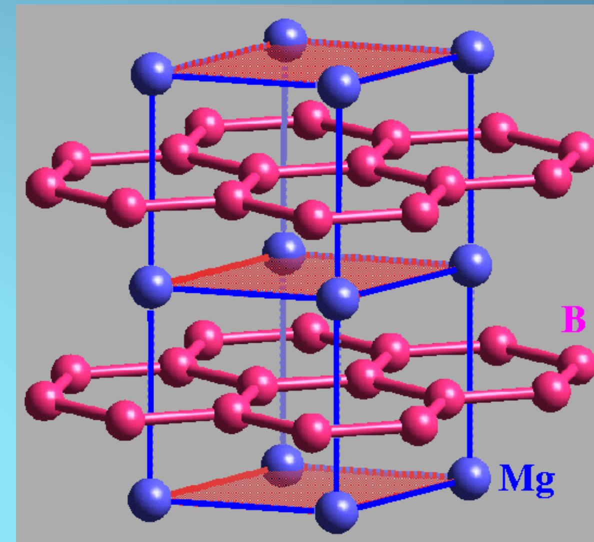
Magnesium diboride

NATURE | VOL 410 | 1 MARCH 2001 |

Superconductivity at 39 K in magnesium diboride

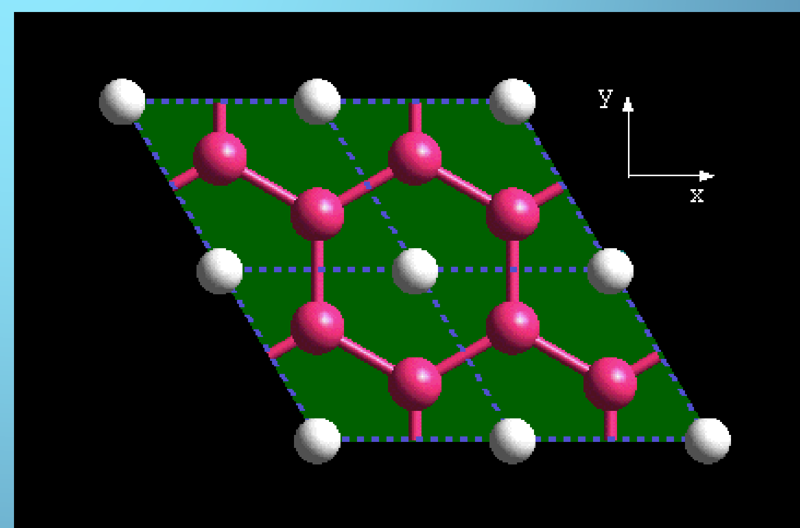
Jun Nagamatsu*, Norimasa Nakagawa*, Takahiro Muranaka*, Yuji Zenitani* & Jun Akimitsu* †

** Department of Physics, Aoyama-Gakuin University, Chitosedai, Setagaya-ku, Tokyo 157-8572, Japan*
† CREST, Japan Science and Technology Corporation, Kawaguchi, Saitama 332-0012, Japan



- Strong covalent bonds between the boron atoms.
- Coupling of electron with the optical vibration mode of boron atoms (mode E_{2g}).

T_c = 39 K, close to the maximum value predicted by BCS theory

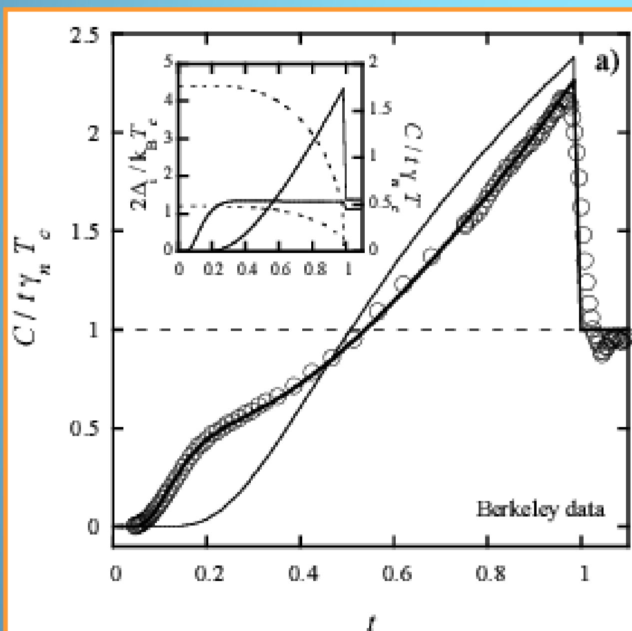


MgB_2 first example of two-gap superconductor

VOLUME 87, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 2001

Specific Heat of $Mg^{11}B_2$: Evidence for a Second Energy Gap

F. Bouquet,[1] R. A. Fisher,[1] N. E. Phillips,[1] D. G. Hinks,[2] and J. D. Jorgensen[2]
[1]*Lawrence Berkeley National Laboratory and Department of Chemistry, University of California, Berkeley, California 94720*
[2]*Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439*
(Received 26 March 2001; published 5 July 2001)

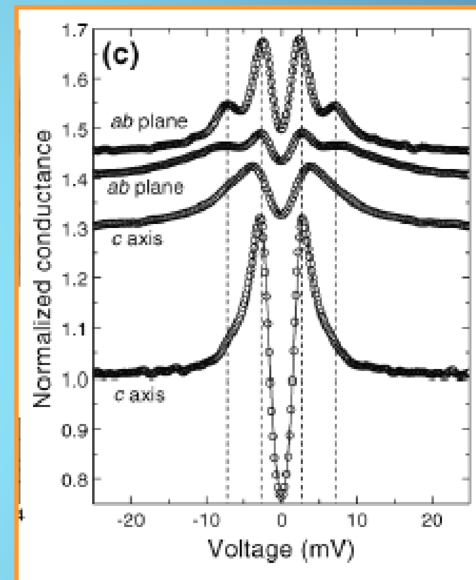


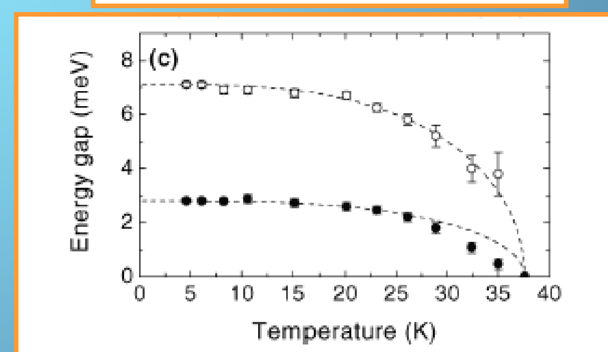
$\Delta_\pi(0) \sim$ 2 meV ; $\Delta_\sigma(0) \sim$ 7 meV

VOLUME 89, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 2002

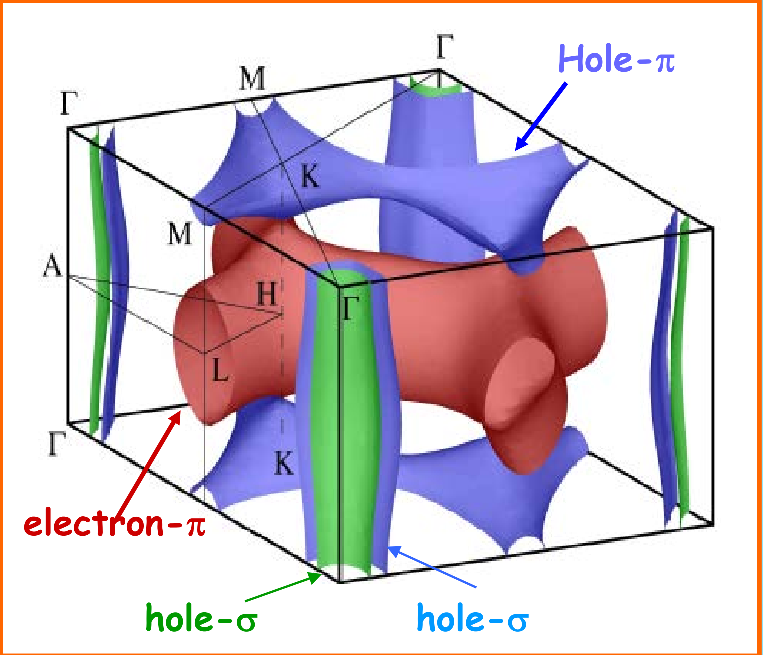
Direct Evidence for Two-Band Superconductivity in MgB_2 Single Crystals from Directional Point-Contact Spectroscopy in Magnetic Fields

R. S. Gonnelli,* D. Daghero, and G. A. Ummarino
INFM-Dipartimento di Fisica, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
V. A. Stepanov
P. N. Lebedev Physical Institute, Russian Academy of Sciences, Leninskiy Prospekt 53, 119991 Moscow, Russia
J. Jun, S. M. Kazakov, and J. Karpinski
Solid State Physics Laboratory, Swiss Federal Institute of Technology (ETH), CH-8093 Zürich, Switzerland
(Received 2 August 2002; published 25 November 2002)





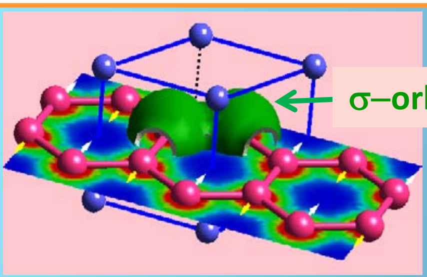
MgB_2 two-band superconductor



σ bands	π bands
2D	3D
hole-like	nearly electron-like
strongly coupled with E_{2g} mode	weakly coupled with E_{2g} mode

Different parity

Interband scattering is negligible



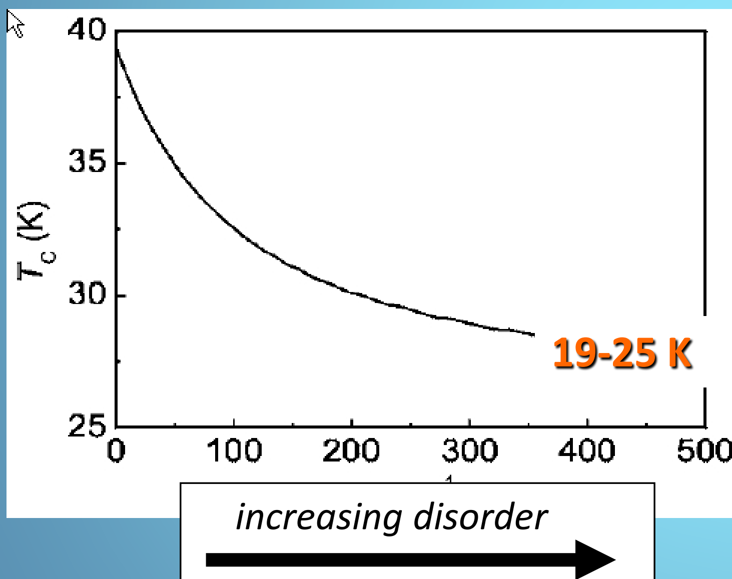
	Δ(0), meV	v_{Fab} (m/s)	v_{Fab}/v_{Fc}	$\xi_{ab}(0)$ (nm)	$\lambda_{ab}(0)$ (nm)	$\kappa = \lambda/\xi$	
σ	7	4.40×10^5	5–6	13	49	4	Type II
π	2.2	5.35×10^5	~1	51	34	0.7	Type I

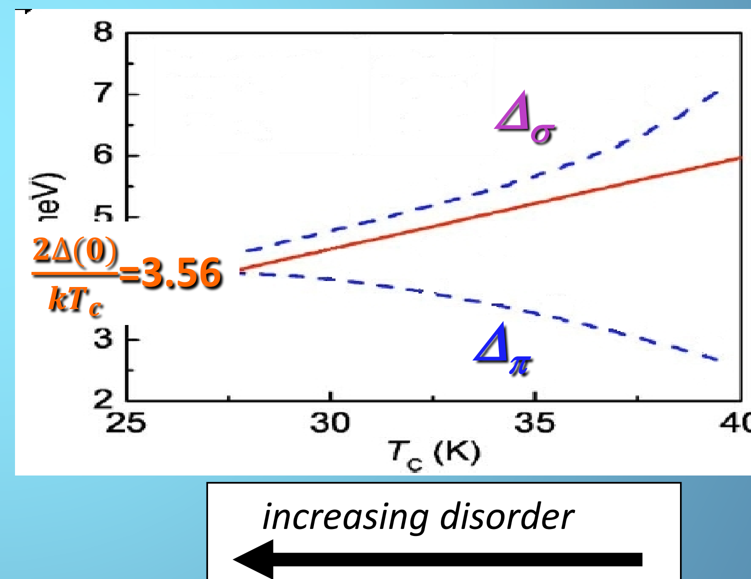
T_c is amplified (by a factor 2) by the occurnce of two **decoupled bands**

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)



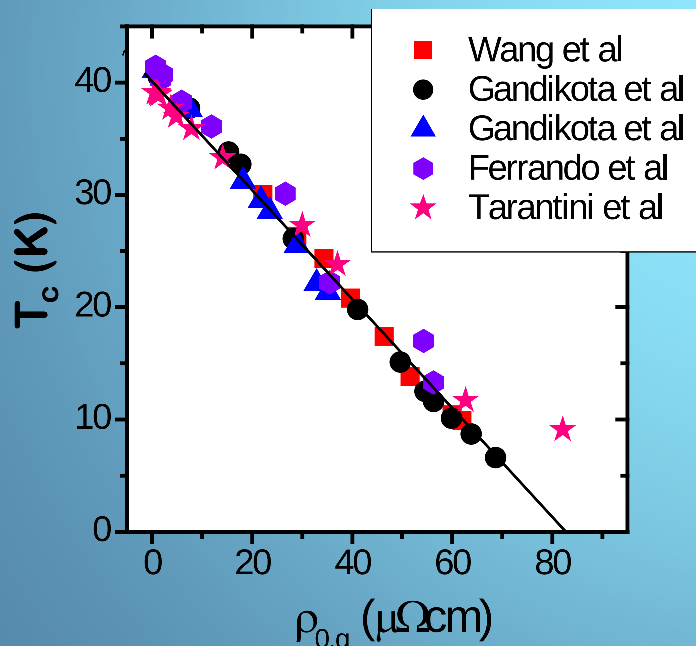


O.V. Dolgov *et al.* PRB 72, 024504 (2005)

Substitutional impurities:

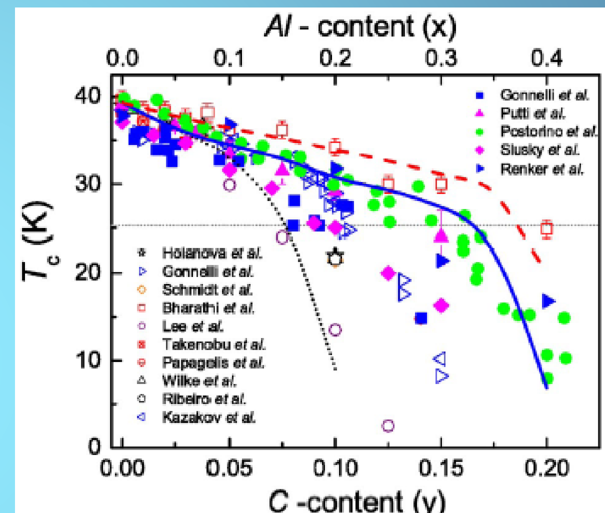
Artificial defects:

- Neutron irradiation
- α-particle irradiation



Putti et al SUST **21** (2008) 043001

- C in the B site: $Mg(B_{1-y}C_y)_2$
- Al in the Mg site: $Mg_{1-x}Al_xB_2$



J. Kortus *et al.* PRL 94, 027002 (2005)

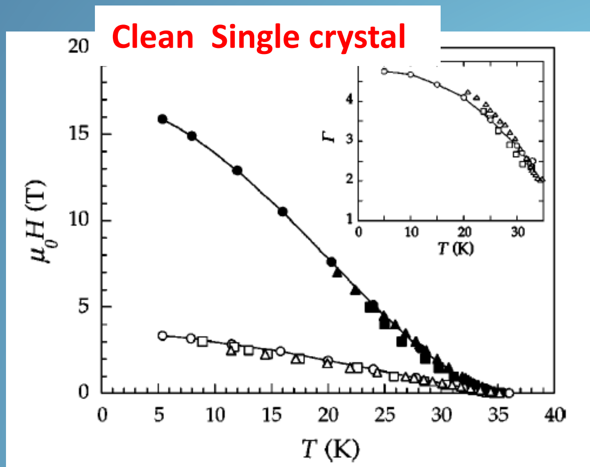
$T_c \rightarrow 0$

Electron doping
⇨ emptying of the σ–bands

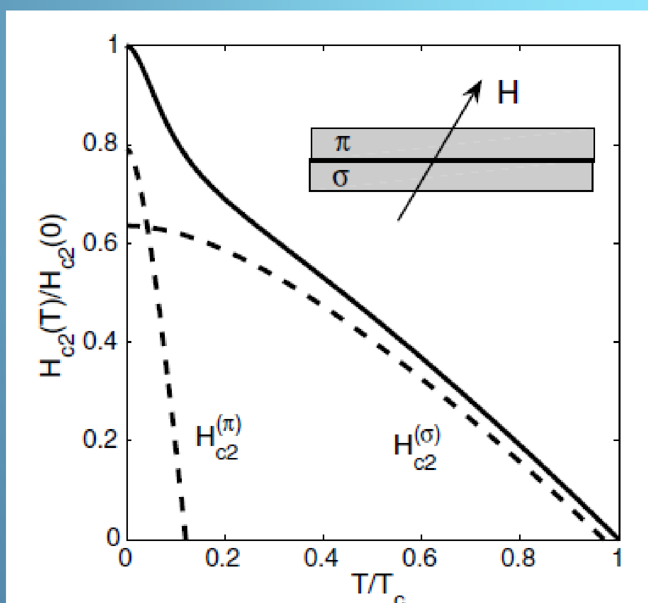
Interband scattering
⇨ merging of the gaps

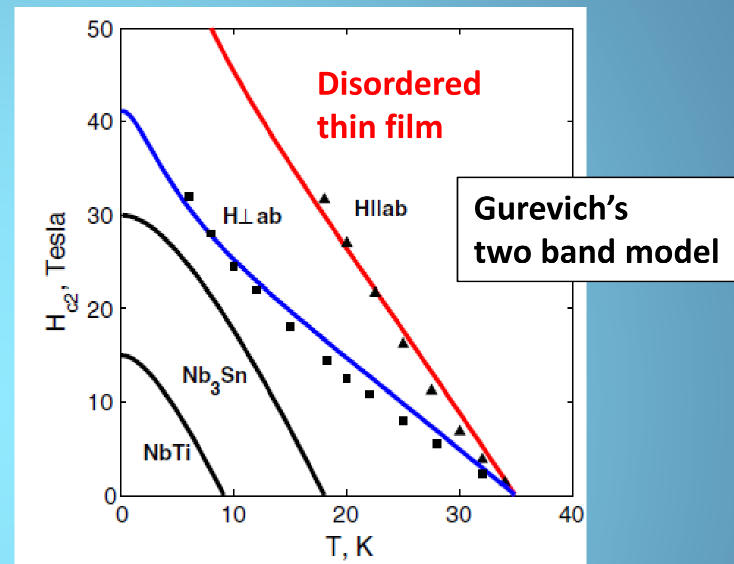
Intraband scattering
⇨ smearing of the DOSs

Upper critical field

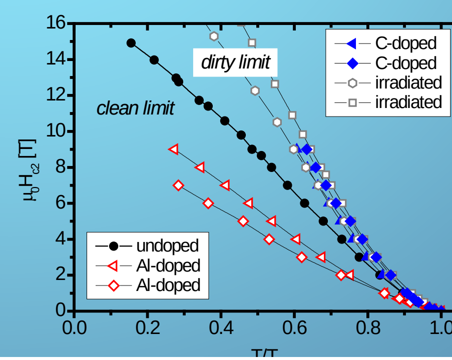


Lyard et al., PRB **66**, 180502(R) 2002

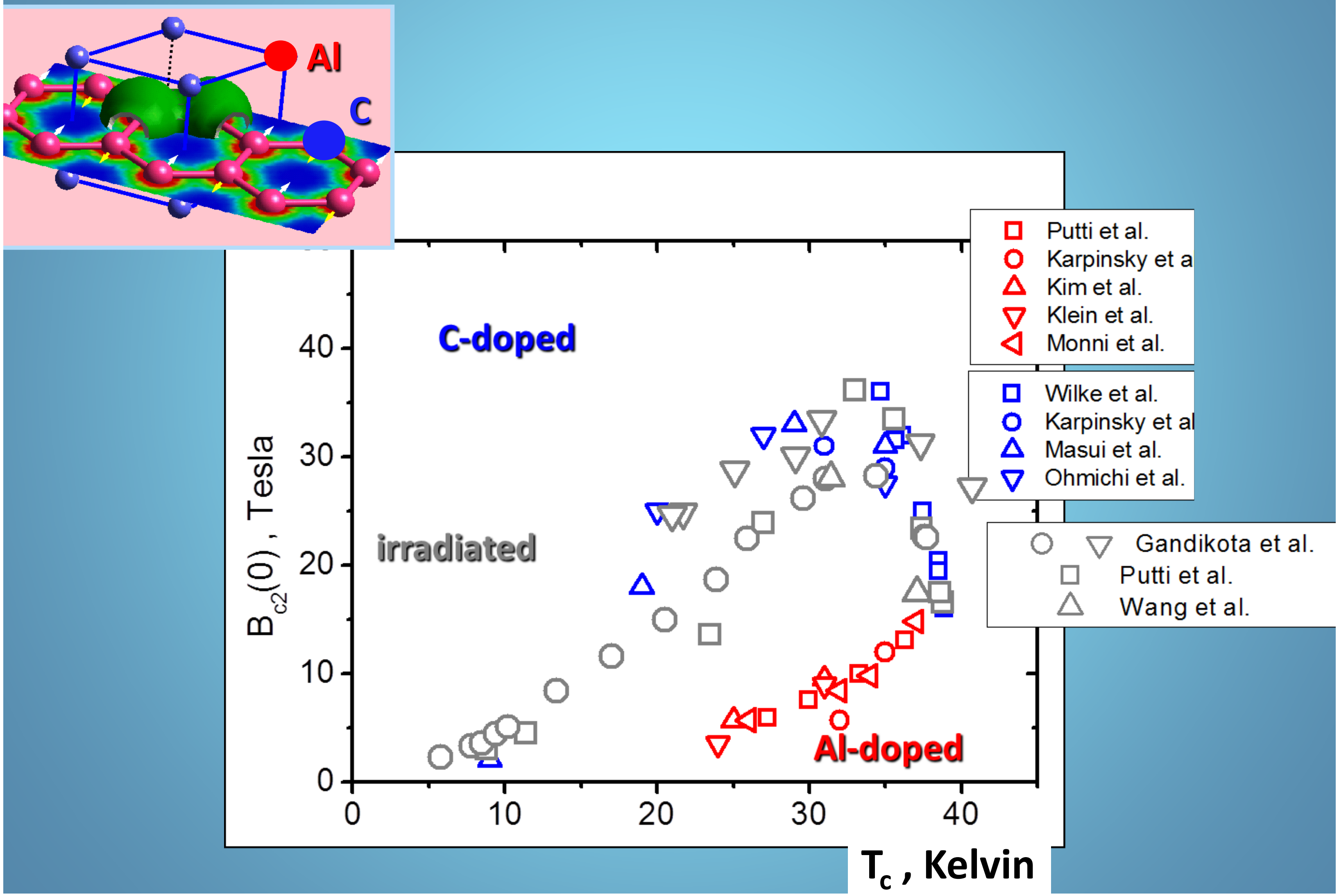




A. Gurevich Physica C 456 (2007) 160–169



Upper critical field



Upper critical field

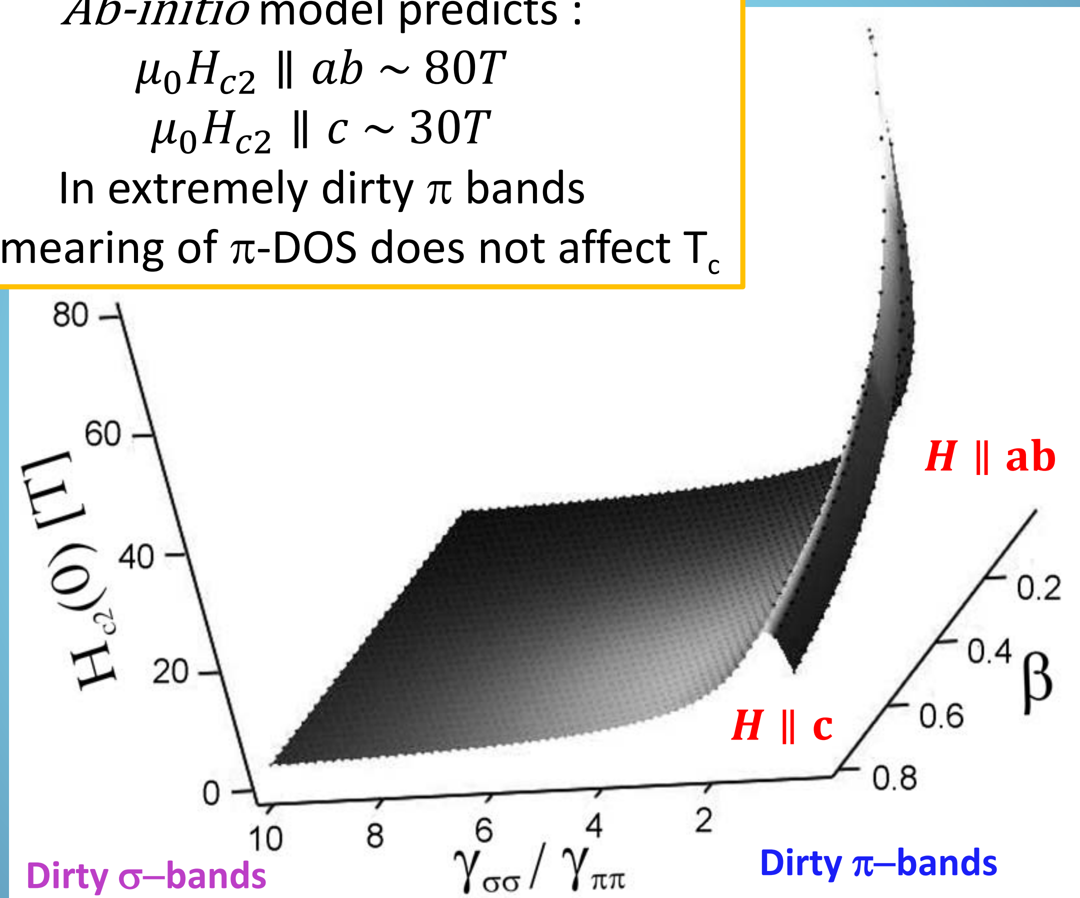
Ab-initio model predicts :

$\mu_0 H_{c2} \parallel ab \sim 80T$

$\mu_0 H_{c2} \parallel c \sim 30T$

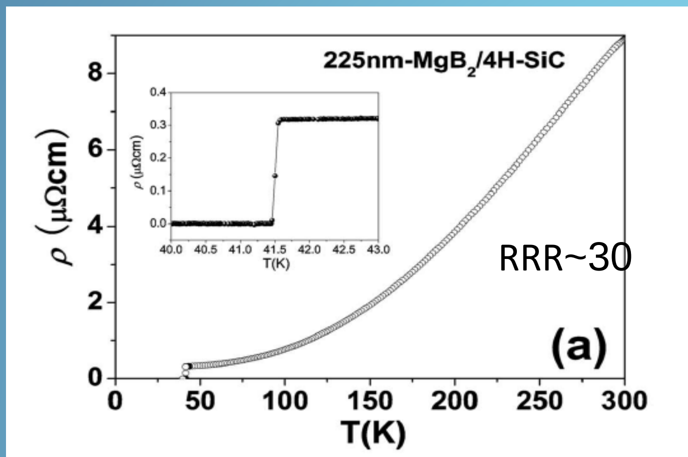
In extremely dirty π bands

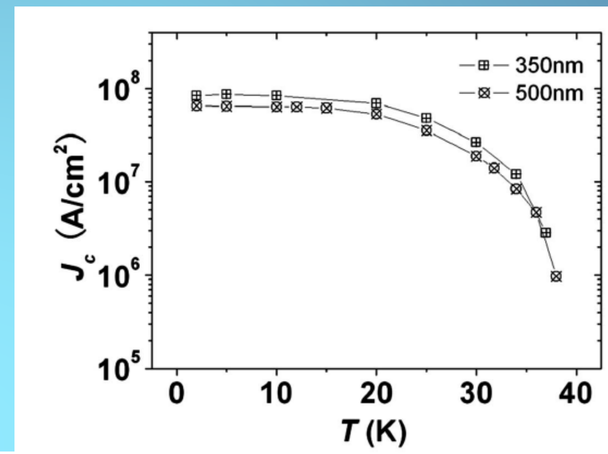
⇨ smearing of π-DOS does not affect T_c



Brotto et al., PRB **82**, 134512 (2010)

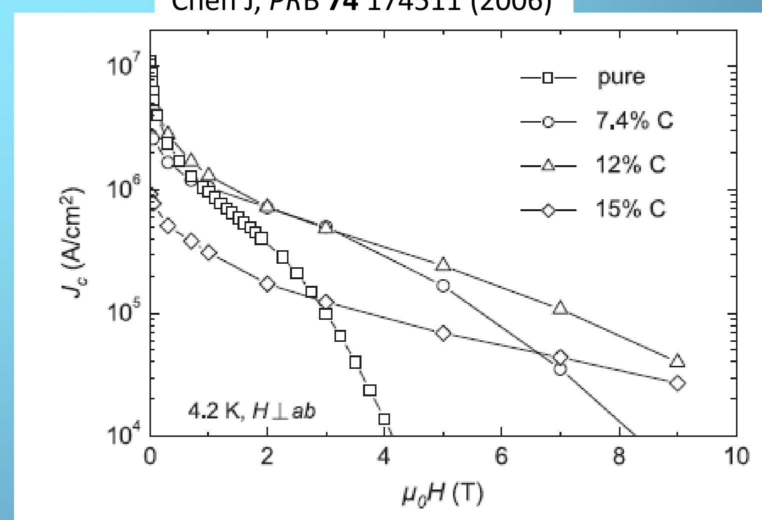
Jc of thin films





J. Appl. Phys. **104**, 013924 (2008)

Chen J, *PRB* **74** 174511 (2006)

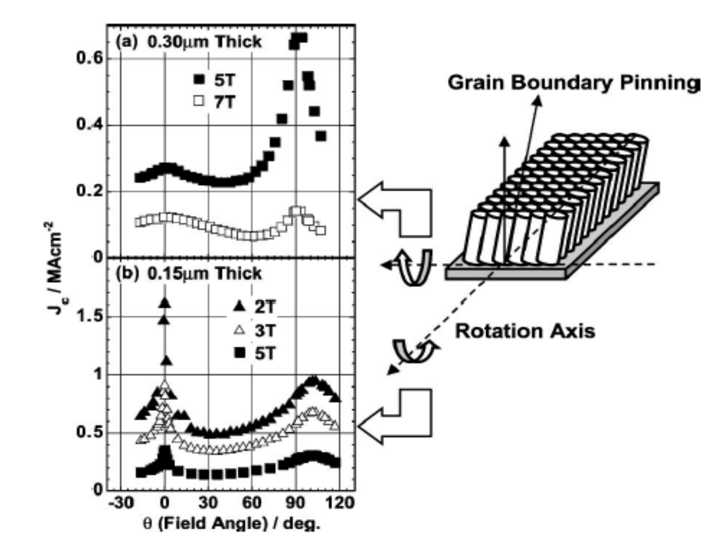


Thin films produced by hybrid physical–chemical vapor deposition (HPCVD) (X X Xi group)

- Extremely clean ($\rho_0 < 1\ \mu\Omega cm$)
- Enhanced T_c ($T_c > 40\ K$)
- Huge $J_c(0)$ ($\sim 10^8 A/cm^2$)
- C-doping substantially improves $J_c(H)$

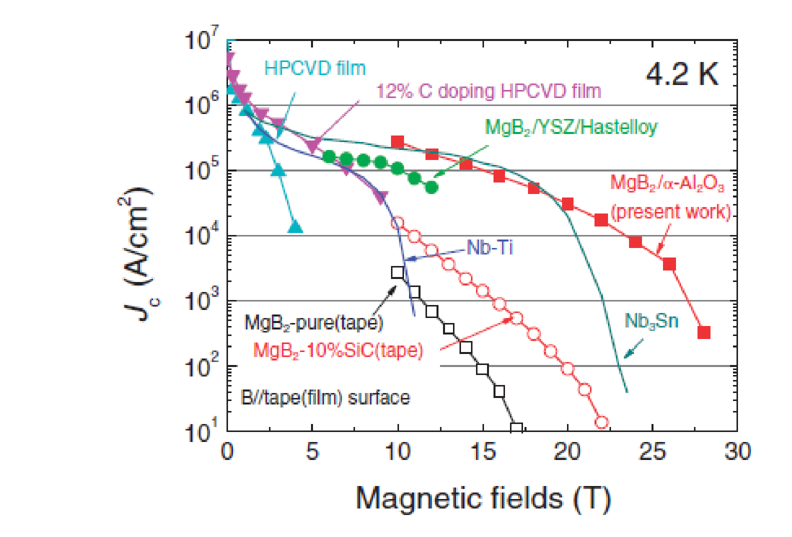
Jc of thin films

Electron Beam evaporation



Kitaguchi et a l APL 85, 2842 (2004)

PLD + post-annealing process



A. Matsumoto: APEX 1, 021702 (2008)

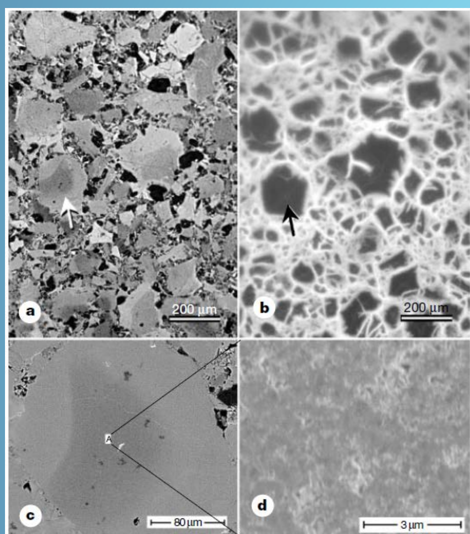
Nanometer-sized columnar-grain structure can produce J_c *(B)* exeeding 10^6 A/cm²

J_c enhancements in fields up to 26 T above Nb_3Sn performance in nanostractured thin films

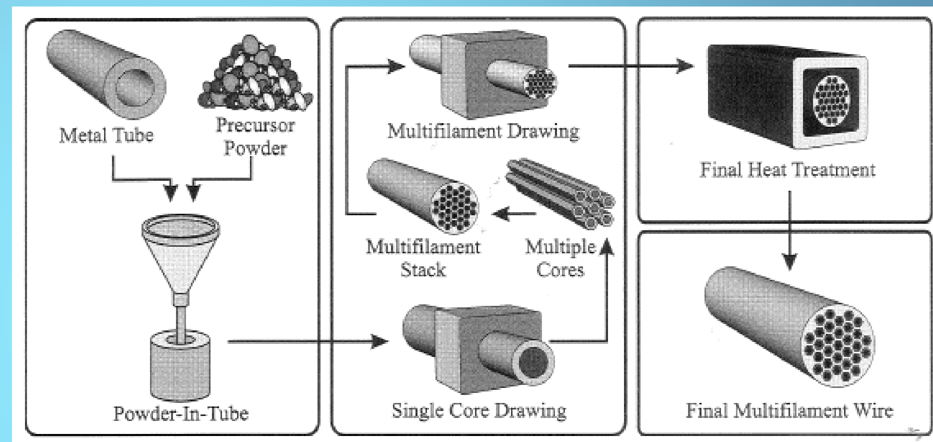
In thin films Jc is enhanced by grain boundary pinning

- High T_c, B_{c2} and J_c
- No evidence of "weak link"

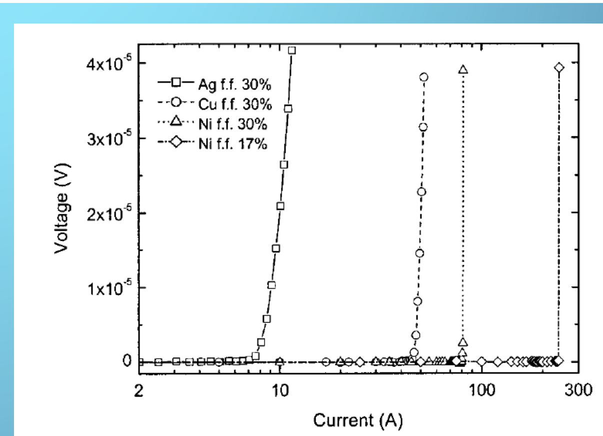
Fast development of Powder in Tube (PIT) technique



D.C.Larbalestier et al., *Nature* **410**, 186 (2001)



Coherence length
$\xi \sim 10$ nm



G.Grasso et .al. 2001 APL 72, number 9

Role of anisotropies in Polycrystals

Current Percolation and B_{c2} Anisotropy.

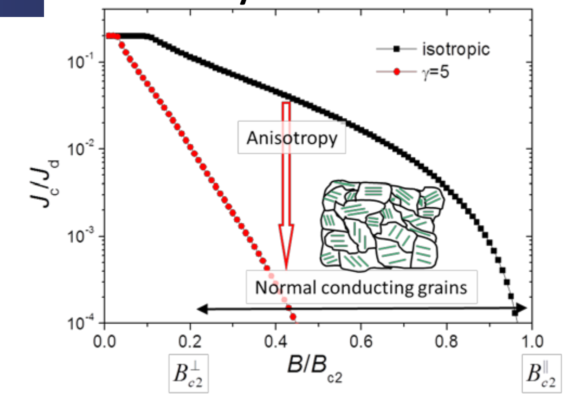
Eisterer, et al.,PRL **90**,247002 2003

⇨ $J_c(B)$ is function of the B_{c2} anisotropy

$$B_{c2}(\theta) = \frac{B_{c2}^{\parallel}}{\sqrt{\gamma^2 \cos(\theta)^2 + \sin(\theta)^2}}$$

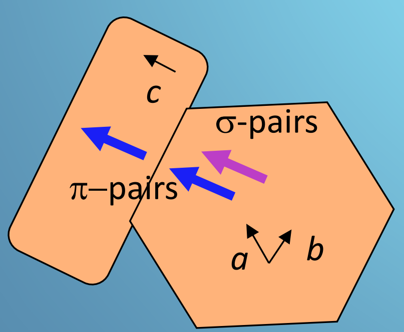
$$\gamma = \frac{B_{c2}^{\parallel}}{B_{c2}^{\perp}} \sim 5-6 \text{ (clean limit)}$$

Courtesy of M. Eisterer

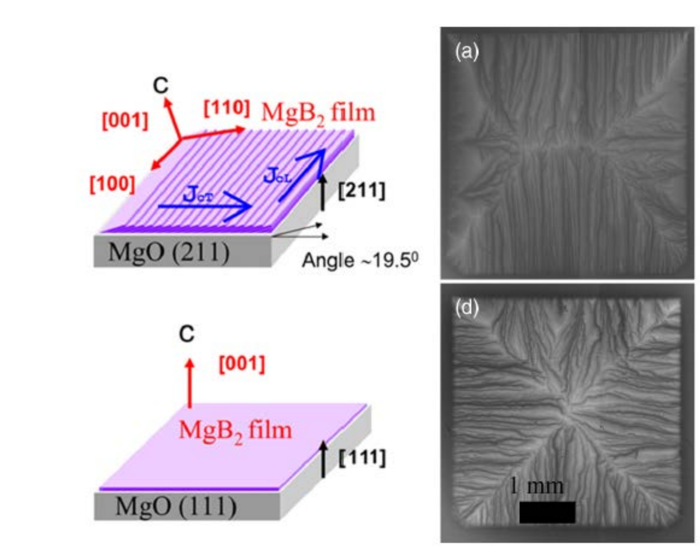


λ anisotropy and pairbreaking effects

⇨ $J_c(B=0)$ is function of the λ anisotropy



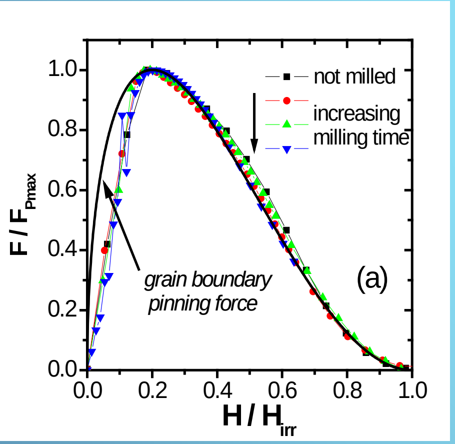
Polyanskii et al., PRB **90**, 214509 (2014)



How to enhance pinning strength in polycrystals

- Incresing H_{c2} with C doping
- Introducing pinning centers with nanoparticle addiction

Carbon in elemental form (microspheres, nanotubes, nanodiamond, graphene)
C-containing compounds such as SiC, TiC, B_4C,
Organic compounds: -malic acid , toluene, benzene, naphthalene , thiophene, pyrene

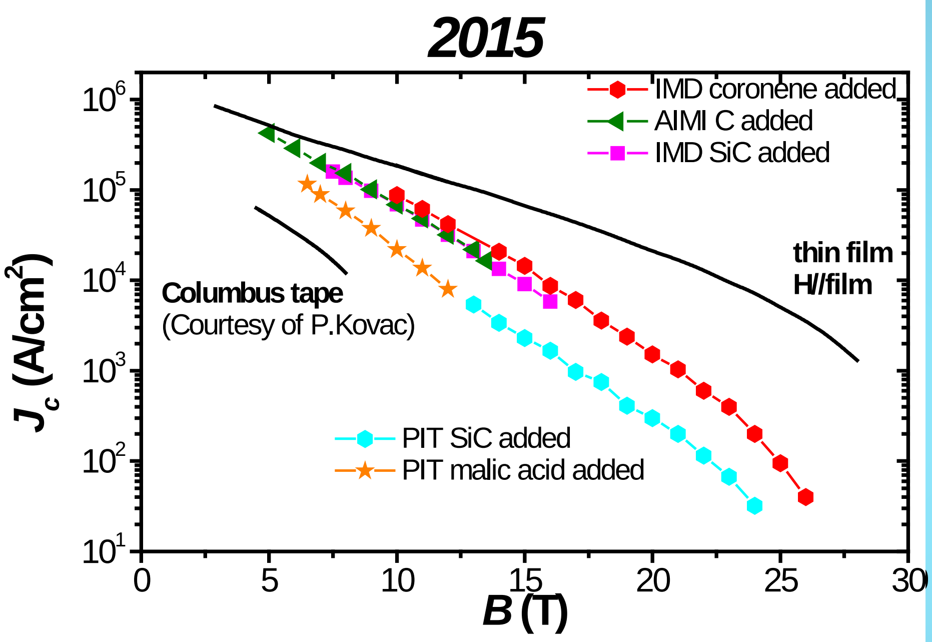


V Braccini, INFM, Italy
E W Collings, The Ohio State University, US
S X Dou, University of University of Wollongong, Australia
R Flukiger, DPMC, University of Geneve; Switzerland
W Goldaker, KIT, Germany
H Kumakura, NIMS, Japan
Y Ma, et al Chinese Academy of Sciences, China
……

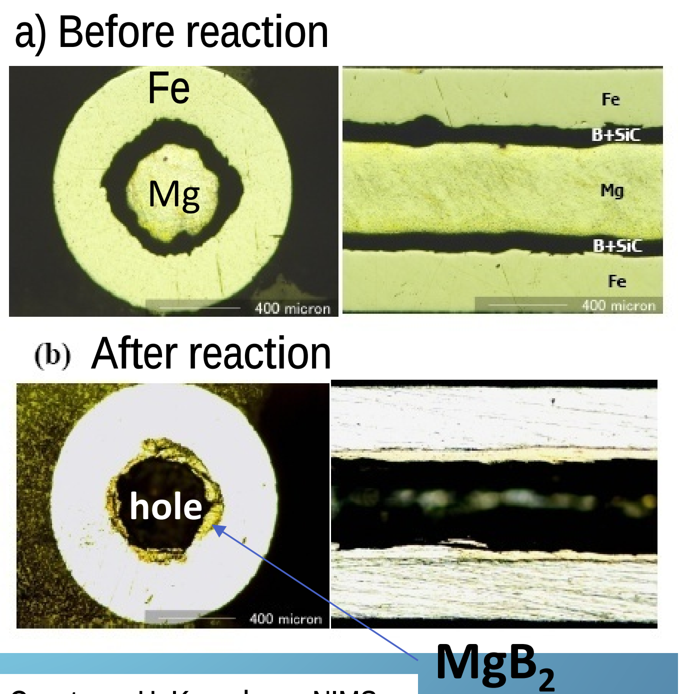
Despite many attempts at nanoparticle additions, the principal pinning defects in MgB_2 are grain boundaries.

Fine grains in C additioned MgB_2

Critical current density



Moving from 1stG (PIT) to 2° G (IMD) wires
(Giunchi G, et.al 2003 SUST 16 285)

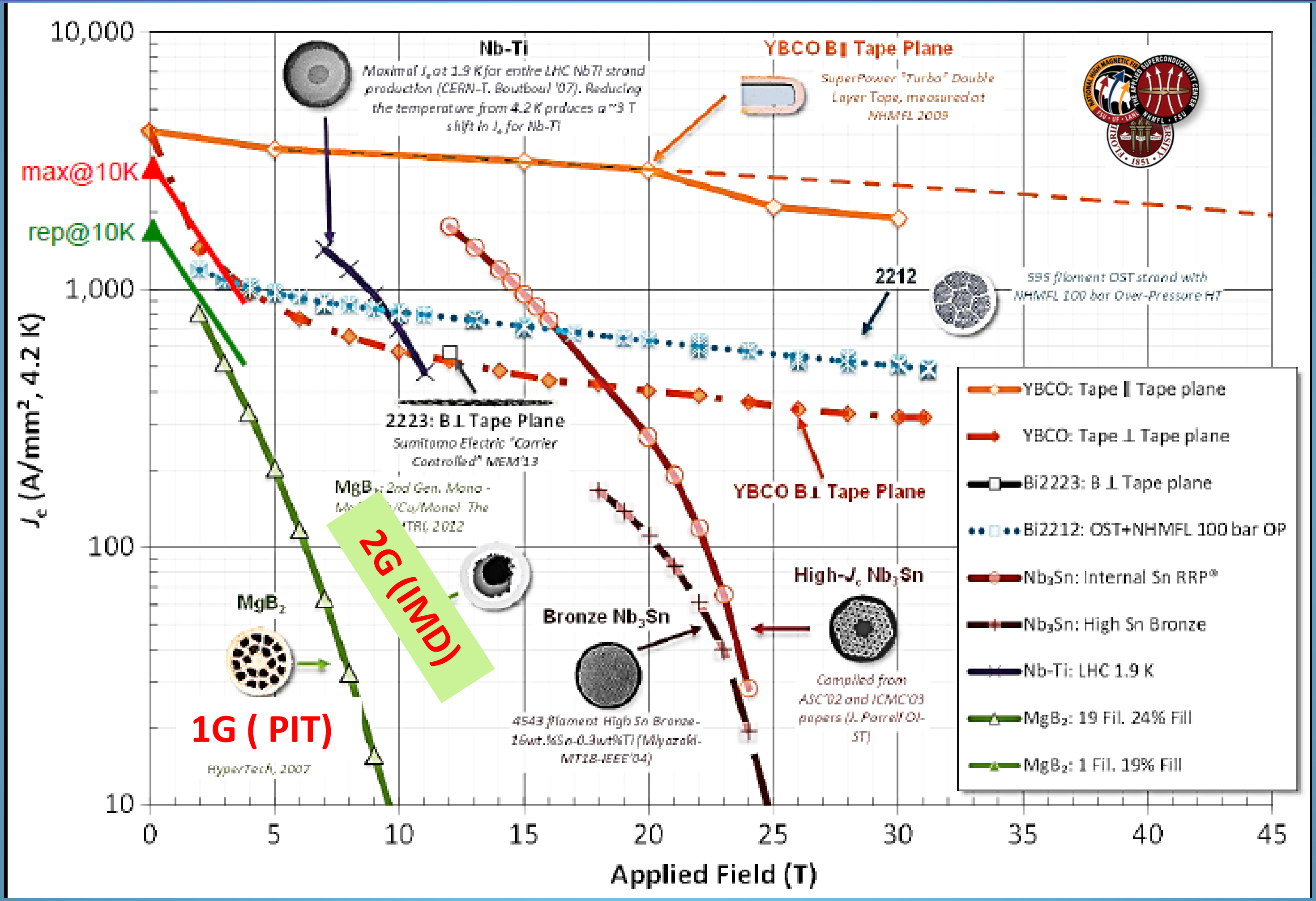


Courtesy: H. Kumakura, NIMS

K Togano, et al., SUST **22** (2009) 015003
J.H. Kim , et al., SUST 23 (2010) 075014
G Z Li et al.SUST 26 (2013) 095007
Shu Jun Ye, et al., SUST 27 (2014) 085012

M. Putti and G.Grasso MRS BULLETIN 36 , 608

Engineering critical current



Wire manufacturing companies

Hyper Tech Research, Inc.

Columbus Superconductors

Ready for industrial production
2 different manufacturing process
ex-situ and in-situ technique

EPOCH WIRES – infinite superconductivity

Cutting Edge Superconductors Inc.

Interested in commercial production
of wires or wires+magnet

Early stage New York based company,
granted as SME partner by UK for R&D activities on MgB_2
They plan to start commercial production in early 2014.

MgB_2 wires for Cryo-free MRI
Summer 2015 for MRI magnet 1.5T-3T magnet

Interested in the MgB_2 technology

BRUKER **Bruker BEST**

HITACHI

SUPERCON INC

1000 m of MgB2 wire
already demonstrated
in collaboration with IFW Dresden

Patents on MgB2 wires
Several R&D activities

Western Superconducting Technologies Co., Ltd.

Courtesy of Columbus Superconductors

MgB_2 on the market: MRI application

Columbus Superconductors

ASG Superconductors

PARAmed MEDICAL SYSTEMS

First commercial systems using MgB_2 installed in hospital in EU and North America

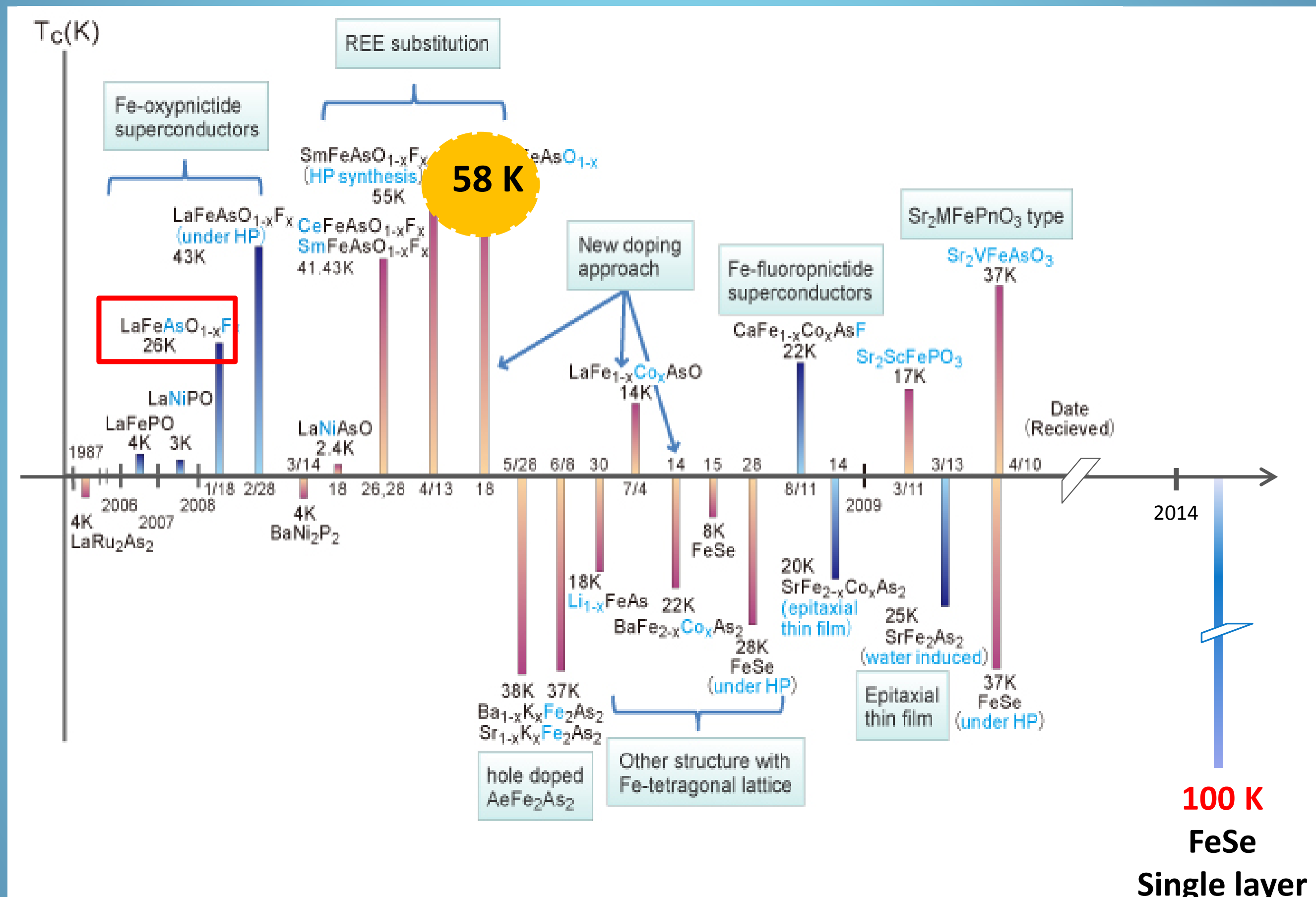
Operating T=20K

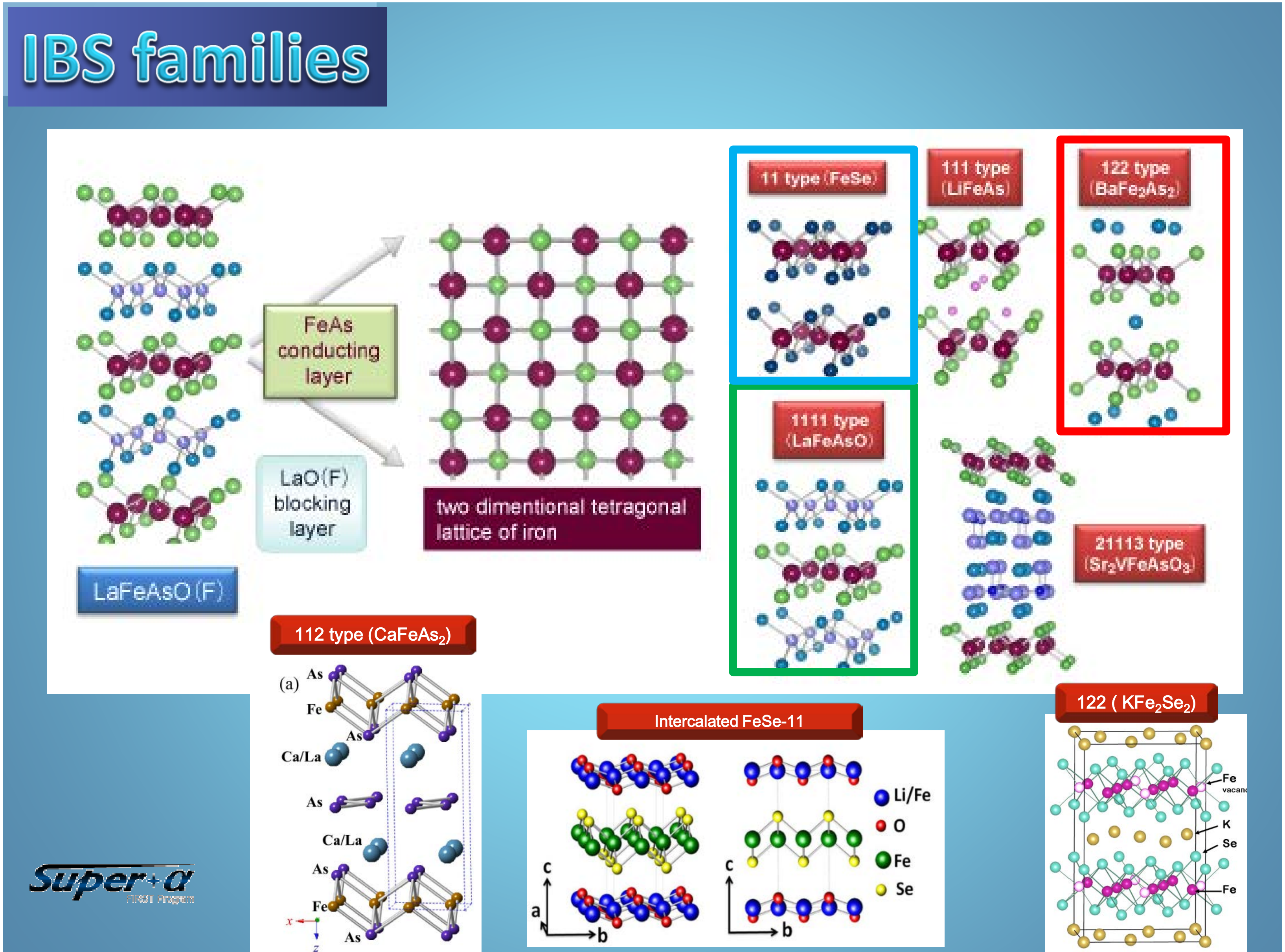
26 magnet systems produced so far

Courtesy of Columbus Superconductors

This demonstrates that 14th years since its discovery MgB_2 is a reality, but it needs a breakthrough to become a high field conductor

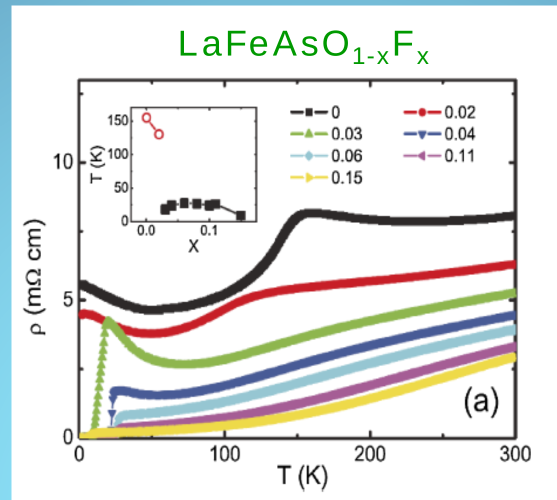
Iron based superconductors (IBS)

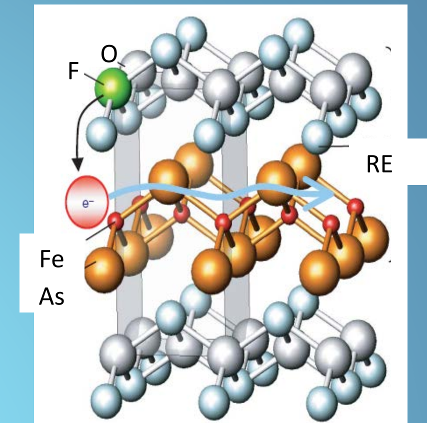


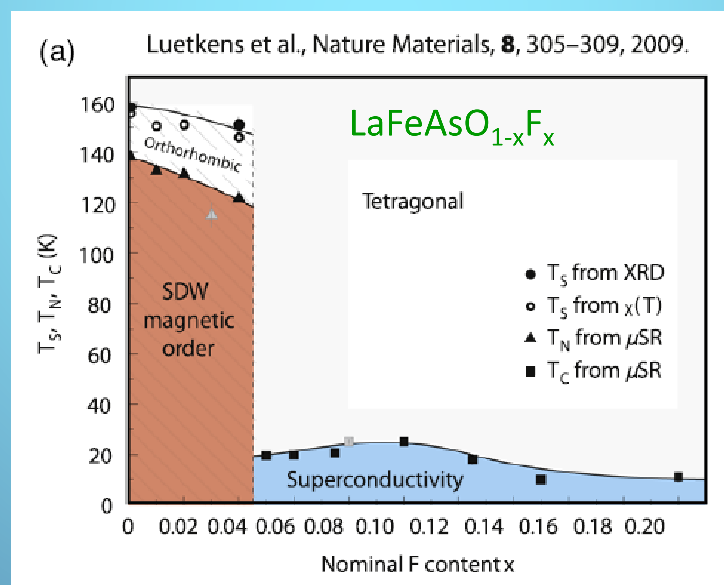

IBS families
FeAs conducting layer
LaO(F) blocking layer
LaFeAsO(F)
two dimentional tetragonal lattice of iron
11 type (FeSe)
111 type (LiFeAs)
122 type ($BaFe_2As_2$)
1111 type (LaFeAsO)
21113 type ($Sr_2VFeAsO_3$)
112 type ($CaFeAs_2$)
(a)
As
Fe
As
Ca/La
As
Ca/La
As
Fe
As
x
z
Intercalated FeSe-11
c
a
b
c
b
Li/Fe
O
Fe
Se
122 (KFe_2Se_2)
Fe
K
Se
Fe
Super-α

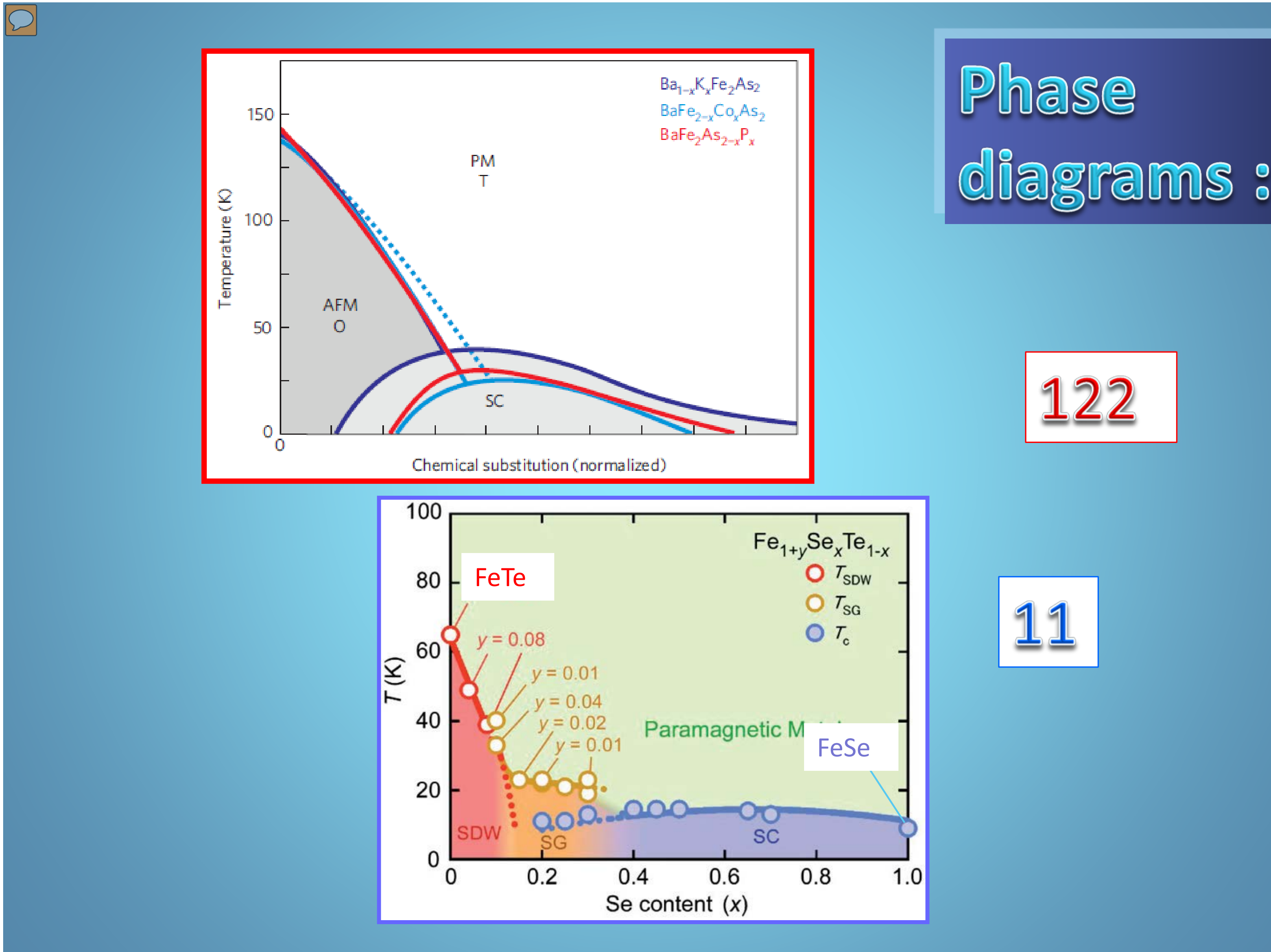
Phase diagrams:

1111

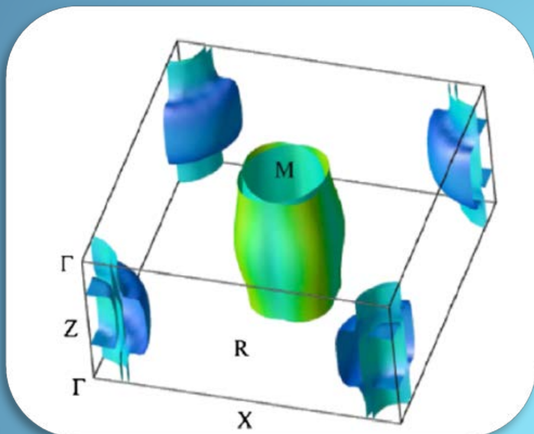




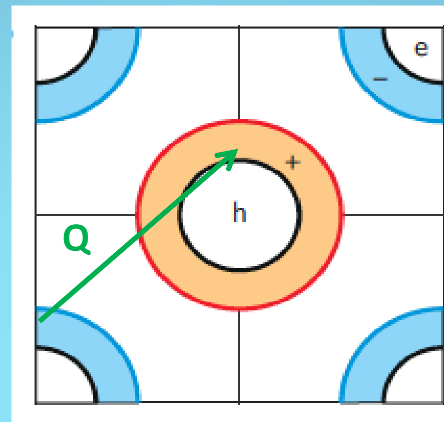



Phase diagrams :
122
11
Ba1−xKxFe2As2
BaFe2−xCoxAs2
BaFe2As2−xPx
PM
T
AFM
O
SC
Temperature (K)
150
100
50
0
0
Chemical substitution (normalized)
Fe1+ySexTe1-x
TSDW
TSG
Tc
FeTe
FeSe
y = 0.08
y = 0.01
y = 0.04
y = 0.02
y = 0.01
Paramagnetic M
SDW
SG
SC
T (K)
100
80
60
40
20
0
0.2
0.4
0.6
0.8
1.0
Se content (x)

Band structure



D. J. Singh and M.-H. Du: Phys. Rev. Lett. 100 (2008)



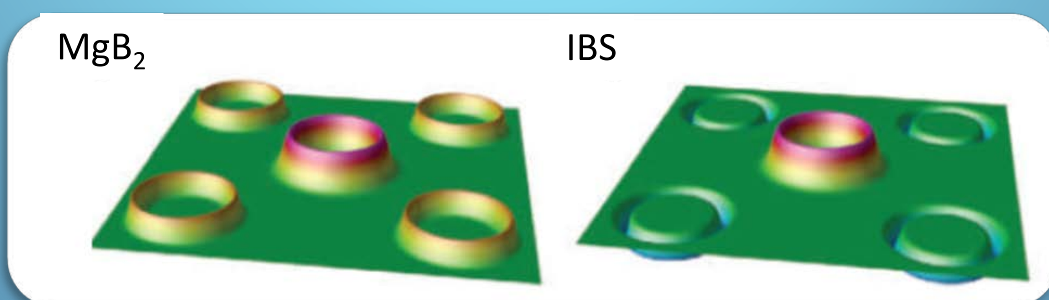
Igor I. Mazin, Nature 464 (2011) 183

Supercontuctivity promoted by AFM fluctuations which couple e- and h- bands

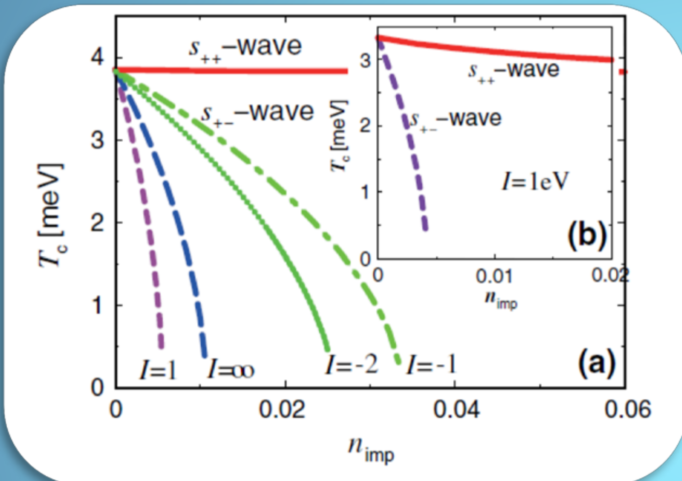
Superconducting order parameter:

⇨ MgB_2 : two-band *s* wave with the same sign

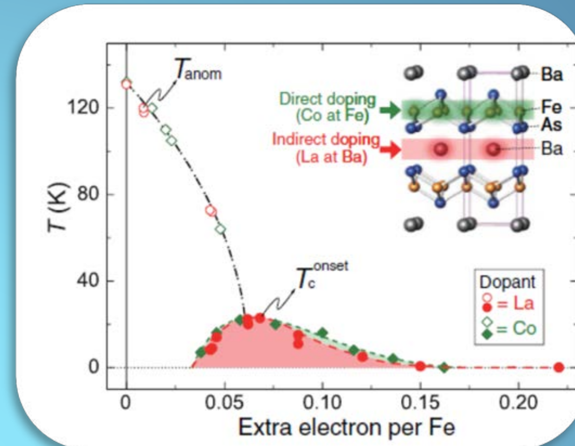
⇨ IBS : two-band *s*± wave



Tc vs impurities

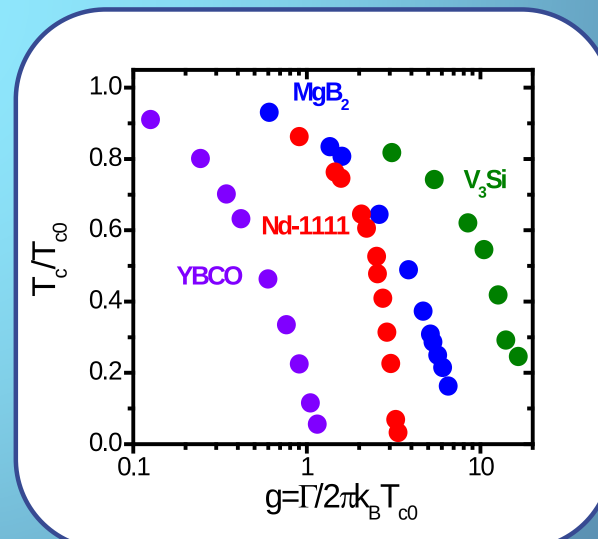


S Onari eta l., PRL 103, 177001 (2009)]



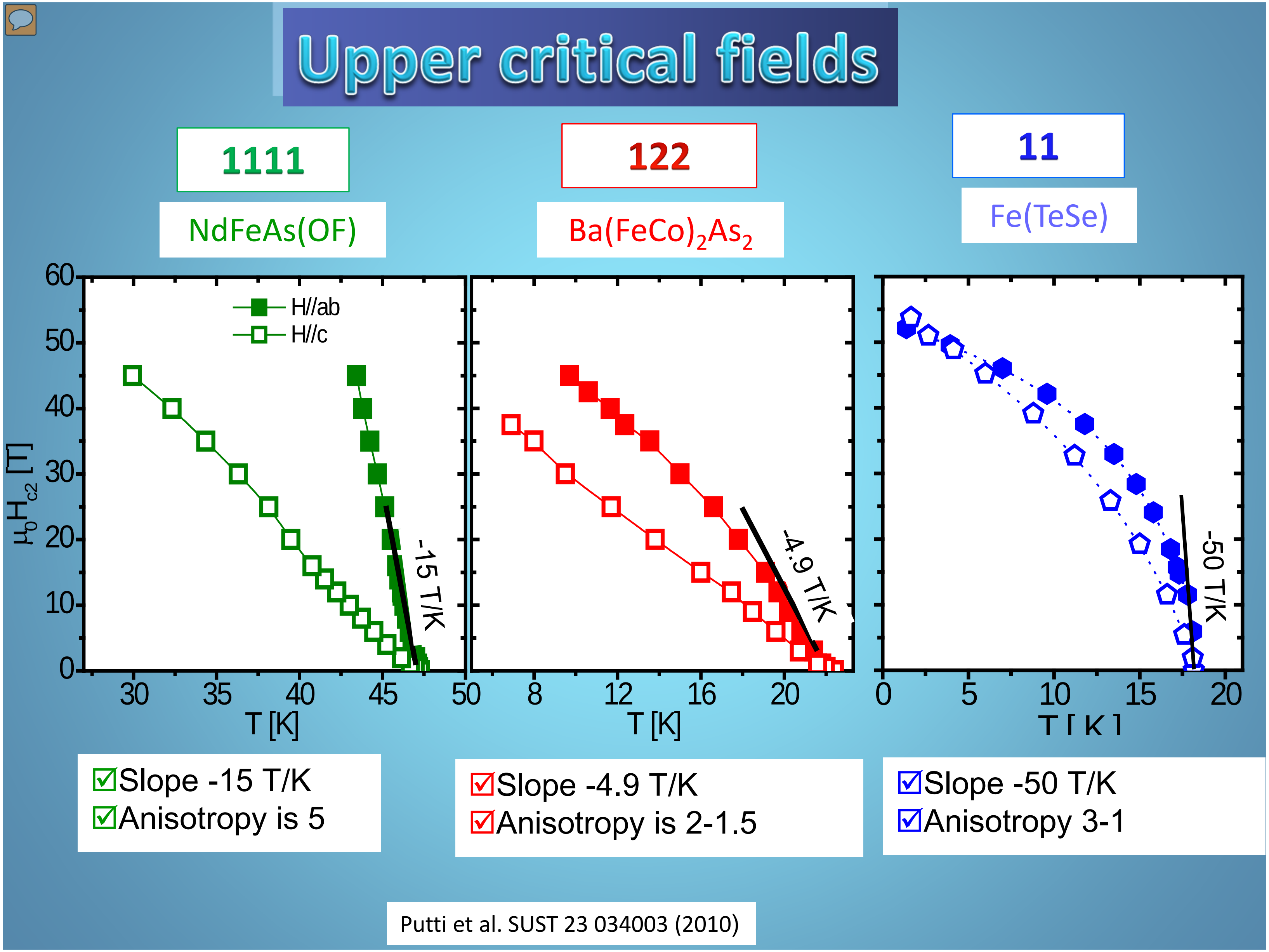
T Katase et al., PRB 85, 140516(R) (2012)

In case of s ± wave pairing a rapid suppression of Tc with impurities has been predicted

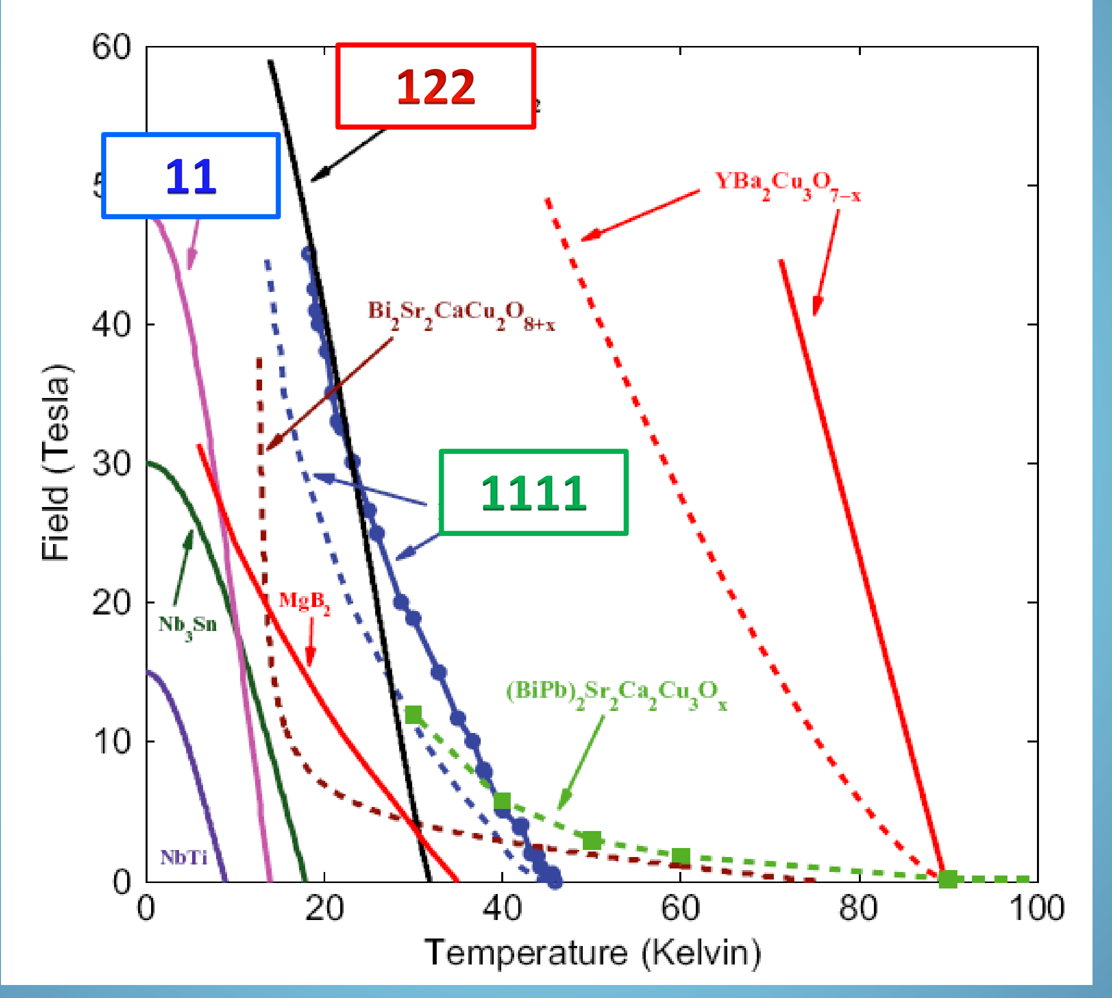


C Tarantini et al.,PRL 104, 087002 (2010)

Superconductivity in IBS is quite robust agains disorder


Upper critical fields
1111
NdFeAs(OF)
122
Ba(FeCo)$_2$As$_2$
11
Fe(TeSe)
H//ab
H//c
$\mu_0 H_{c2}$ [T]
T [K]
-15 T/K
-4.9 T/K
-50 T/K
☑Slope -15 T/K
☑Anisotropy is 5
☑Slope -4.9 T/K
☑Anisotropy is 2-1.5
☑Slope -50 T/K
☑Anisotropy 3-1
Putti et al. SUST 23 034003 (2010)

Upper critical Fields



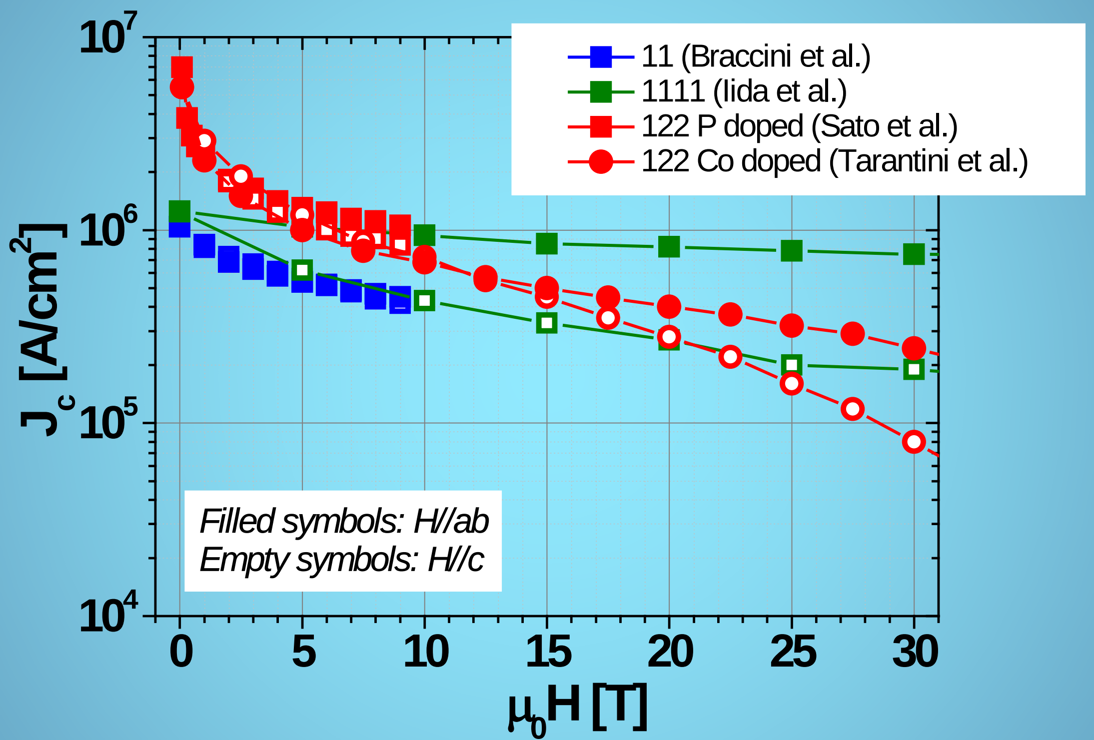
C. Tarantini et al., PRB 84, 184522 (2011)

Superconducting parameters

	1111	122	11	YBCO	MgB_2
T_c [K]	55	38	16	93	39
B_{c2} (0) [T]	>50	60	55	>50	20-30
ξ_{ab} [nm]	2.5	3	1.5	2.2	10
γ_H	5	2	2-3	4-14	3-5
λ_{ab} (nm)	200	200	490	180	50-100
Ginzburg number G_i	$4 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	$>10^{-3}$	$<10^{-5}$
pairing	Not BCS	Not BCS	Not BCS	Not BCS	BCS

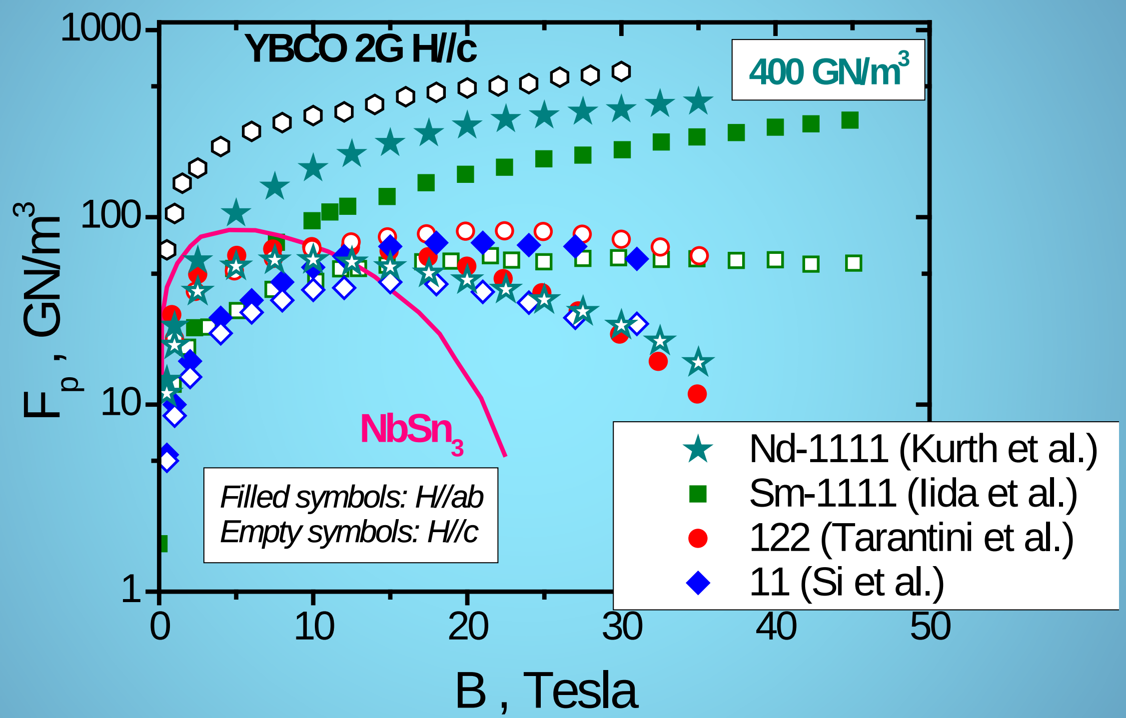
Several similarities with HTS :
High H_{c2}, small coherence length, unconventional pairing
but, *lower anisotropy*

Critical current of thin films



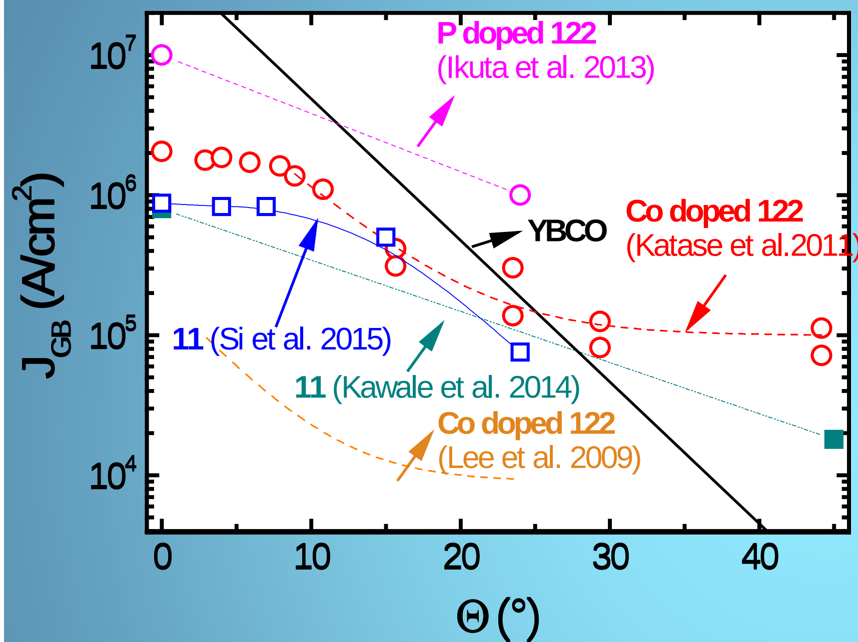
V. Braccini, APL 103, 172601 (2013)
Iida , Sci. Rep. 3:2139 (2013)
Tarantini et al., Sci. Rep. 4, (2014).
Sato et al., Applied Physics Letters **104**, 182603 (2014);

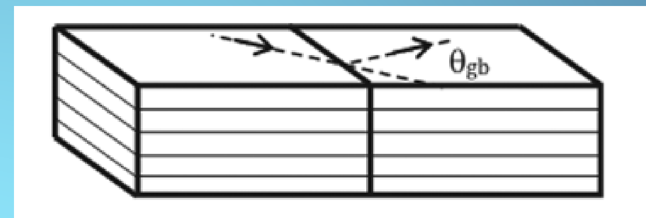
Pinning Force



Kurth et al., EUCAS 2015
Iida , Sci. Rep. 3:2139 (2013)
Tarantini et al., Sci. Rep. 4, (2014).
Sato et al., Applied Physics Letters **104**, 182603 (2014)
Si, W. et al. Nat. Commun. 4:1347 (2013).

Dependence of Jc on the misaglineament angle





122 bicrystals

Lee et al., *Appl. Phys. Lett.* 95, 212505 (2009).
Katase et al., Nat. Commun. 2, 409 (2011)
Sagakami et al.,Physica C 494 (2013) 181–184

11 bicrystals

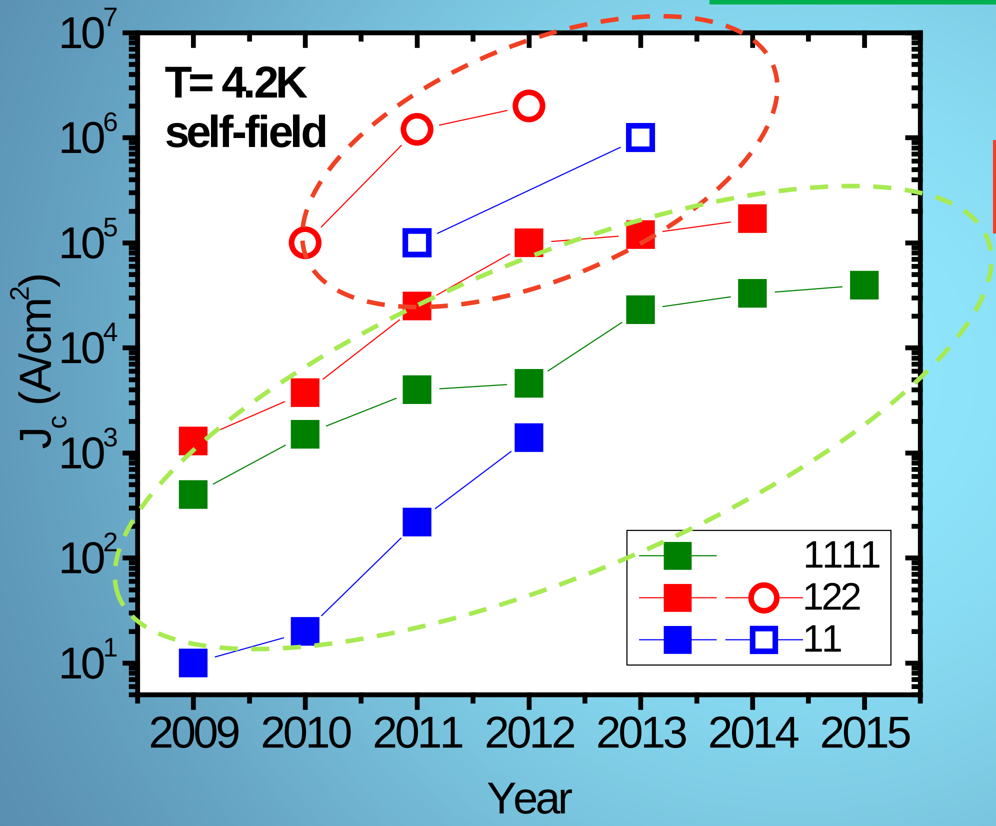
Kawale et al.,ASC 2014
Si *et al*, Appl. Phys. Lett. **106** 032602 **(**2015)

In HTS J_c decreases exponentially with GB angle

IBS Advantageous GB over HTS

J_c of technical conductors

Coated Conductors

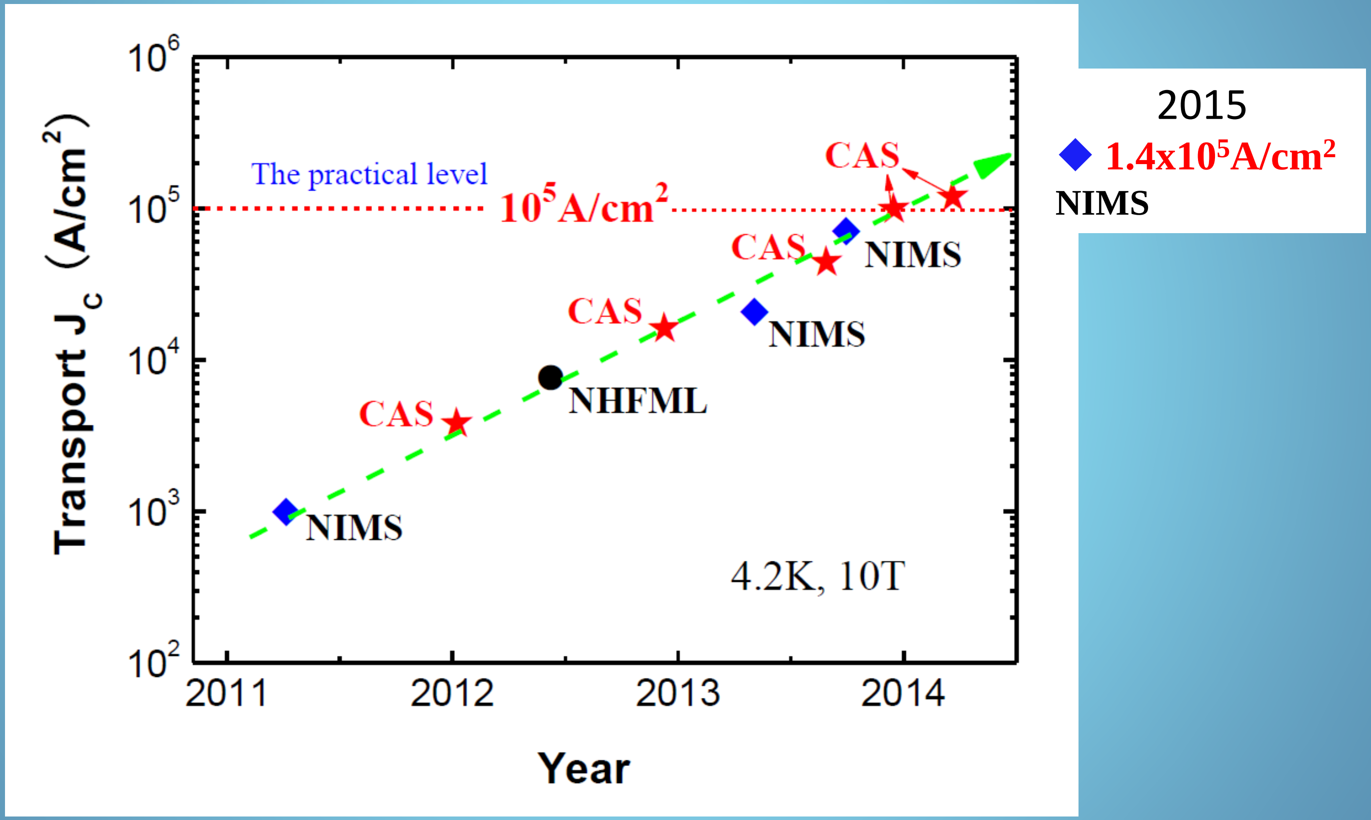


PIT Wires&Tapes

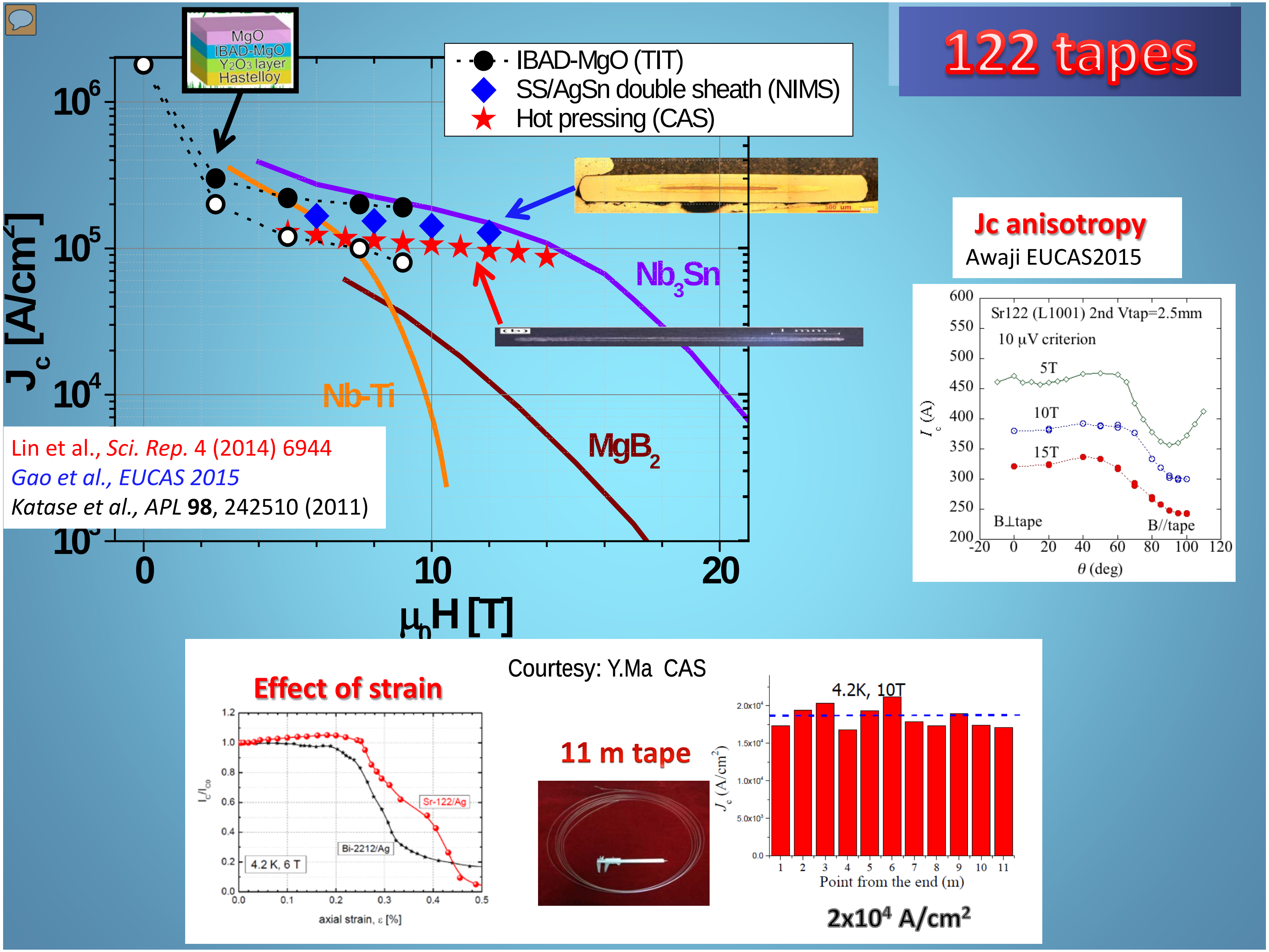
- Improving the phase purity
- Controlling the mechanical processes
- Incresing the density by HP

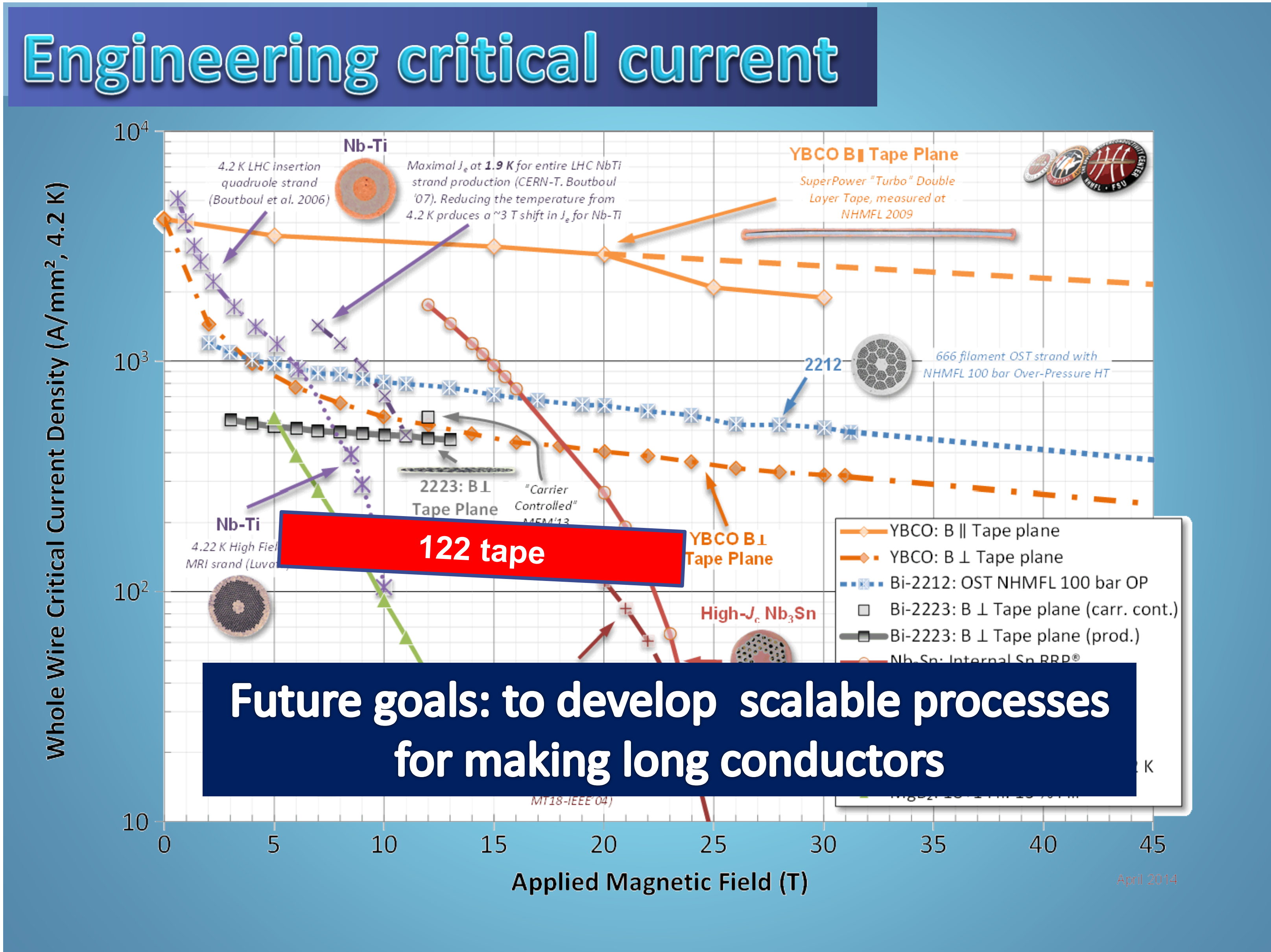
I.Pallecchi et al, SUST (2015) 28

PIT processed 122 wires & tapes



Y. Ma, Physica C 516 (2015) 17-26

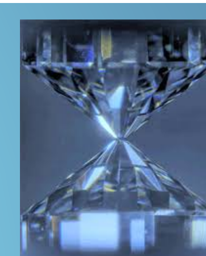

122 tapes
MgO
IBAD-MgO
Y2O3 layer
Hastelloy
IBAD-MgO (TIT)
SS/AgSn double sheath (NIMS)
Hot pressing (CAS)
Nb3Sn
Nb-Ti
MgB2
Jc [A/cm2]
μ0H [T]
0
10
20
Lin et al., Sci. Rep. 4 (2014) 6944
Gao et al., EUCAS 2015
Katase et al., APL 98, 242510 (2011)
Jc anisotropy
Awaji EUCAS2015
Sr122 (L1001) 2nd Vtap=2.5mm
10 μV criterion
5T
10T
15T
B⊥tape
B//tape
Ic (A)
θ (deg)
Courtesy: Y.Ma CAS
Effect of strain
Sr-122/Ag
Bi-2212/Ag
4.2 K, 6 T
Ic/Ic0
axial strain, ε [%]
11 m tape
4.2K, 10T
Jc (A/cm2)
Point from the end (m)
2x10^4 A/cm^2


Engineering critical current
Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
Nb-Ti
4.2 K LHC insertion quadruole strand (Boutboul et al. 2006)
Maximal J_e at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K prduces a ~3 T shift in J_e for Nb-Ti
YBCO B‖ Tape Plane
SuperPower "Turbo" Double Layer Tape, measured at NHMFL 2009
2212
666 filament OST strand with NHMFL 100 bar Over-Pressure HT
2223: B⊥ Tape Plane
"Carrier Controlled"
YBCO B⊥ Tape Plane
High-J_c Nb_3Sn
122 tape
YBCO: B ‖ Tape plane
YBCO: B ⊥ Tape plane
Bi-2212: OST NHMFL 100 bar OP
Bi-2223: B ⊥ Tape plane (carr. cont.)
Bi-2223: B ⊥ Tape plane (prod.)
Future goals: to develop scalable processes for making long conductors

Sulfur hydride systems-brief story

Always Hydrogen has been the best candidate **for room temperature superconductivity** but it need extremely high pressure to become **metallic**.

1) Improvment of diamond anvil cells (DAC) which today allows to reach 600 Gpa exceeding the pressure in the Earth's inner core (360 GPa).



Several new elements superconducting under pressure discovered in the last 15 years: **Sulfur (17 K)**, **Oxygen 0.6 K)** , Iron (1.2 K) , **Boron (11 K), Lithium (20 K)**, Europium (2.5 K).
Dense **hydrogen has been made conductive** at around 300 Gpa.

2) Discovery of MgB_2 which clarifies that high T_c superconductivity is promoted by covalent bonds which assure strong electron–phonon coupling.
These conditions can be fulfilled for covalent compounds dominated by hydrogen
N.W. Ashcroft (Hydrogen Dominant Metallic Alloys: High Temperature Superconductors? *Phys. Rev. Lett.* 92, 187002 (2004).

Ashcroft's idea was supported in numerous calculations predicting high values of T_c for many hydrides. So far only Tc ~17 K has been observed experimentally **in silane under pressure.**

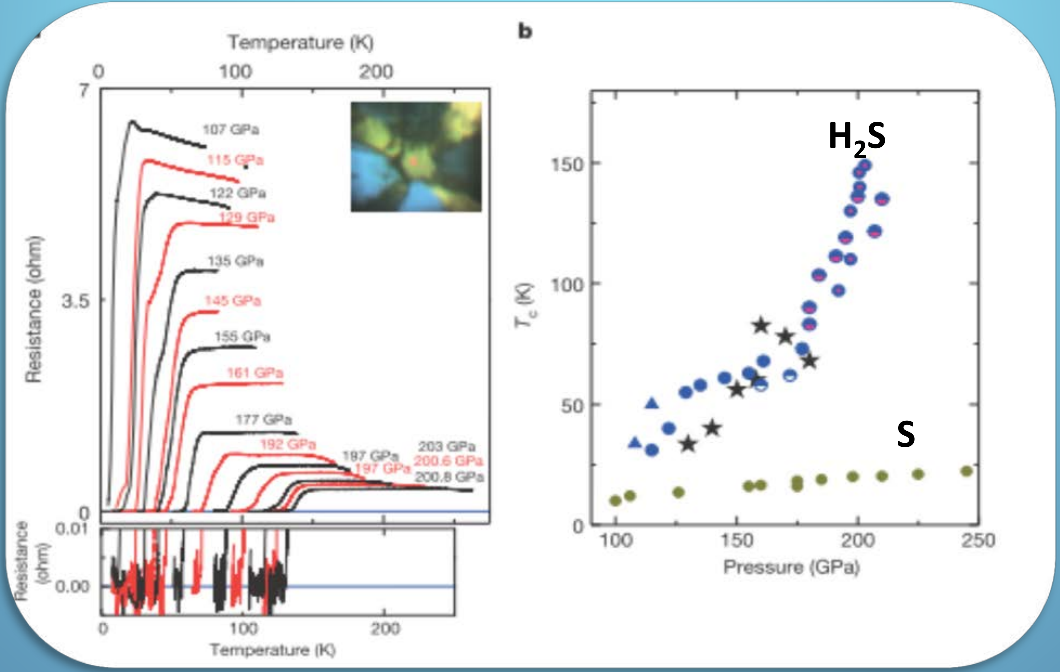
The discovery of superconductivity **190 K in H_2S** has been posted on arXiv.org in December 2014 by the Eremet's group. **They have done the giant leap**.

Conventional superconductivity at 203 Kelvin at high pressure in the sulfur hydride

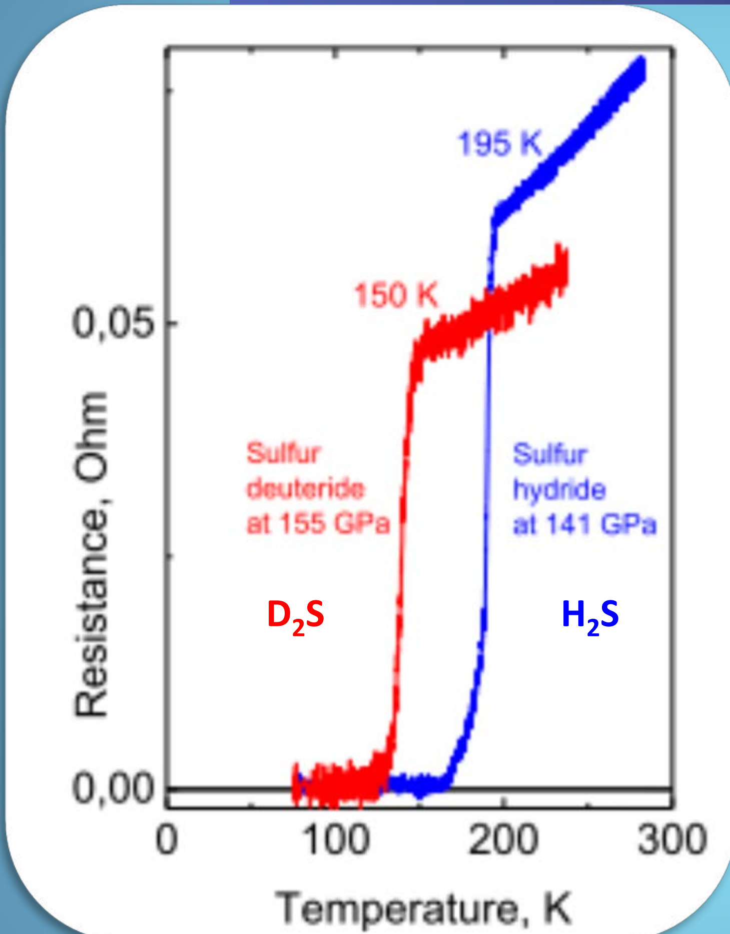
A.P. Drozdov, M.I. Eremets I. A. Troyan, V. Ksenofontov, S. I. Shylin
Nature published 17 August 2015, doi: 10.138/Nature 14964

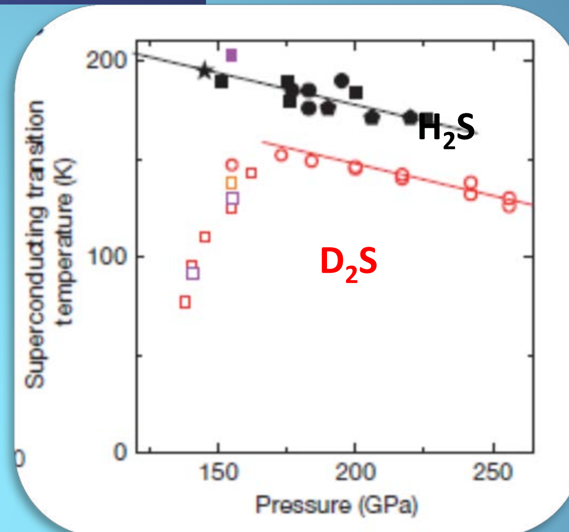
H_2S: relatively easy to handle and predicted to transform to a metal and a superconductor at a low pressure P<100 GPa with a high T_c<80 K Li et al, J. Chem. Phys. 140, 174712 (2014).

Further investigations has indicated that at experimentally relevant pressures H_2S is unstable, decomposing into **H_3S** and **S.** PRB 91, 060511(R) (2015)].



Isotopic effect



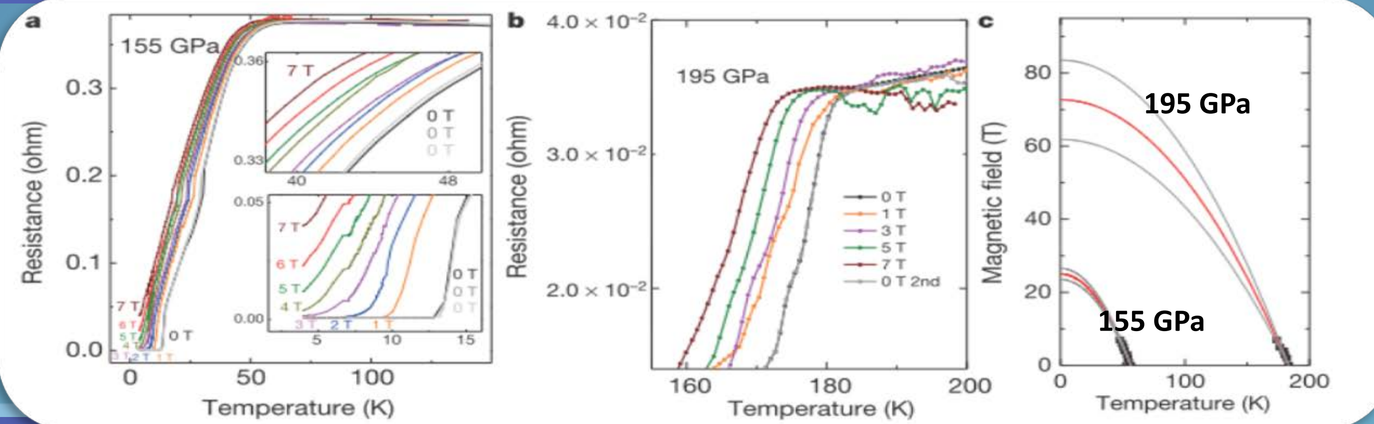


$$T_c \propto M^{-\alpha}$$

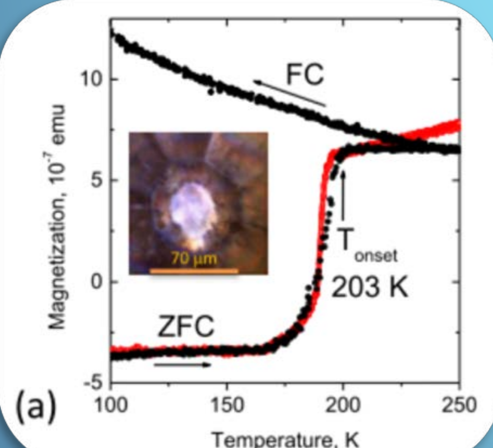
$$\alpha \sim 0.3$$

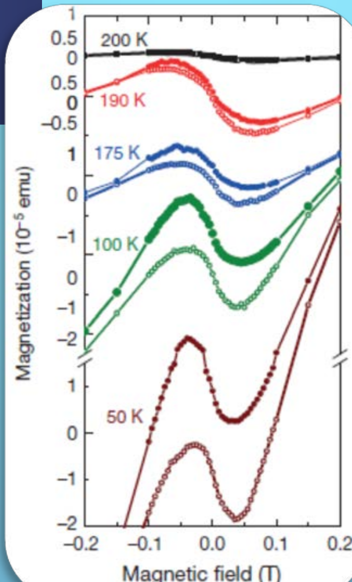
BCS superconductor

Electrical characterization



Magnetic characterization





Type II superconductor

B_{c2} (0) ~ 70 T

B_{c1} (0) ~ 30 mT

Superconducting parameters

	H_3S	IBS-122	YBCO	MgB_2
T_c [K]	200	38	93	39
B_{c2} (0) [T]	70	60	>50	20-30
ξ [nm]	2.5	3	2.2	10
B_{c1} (0) [mT]	30	40	20	100
λ_{ab} (nm)	125	200	180	50-100
Ginzburg number G_i	10^{-3}	$2\cdot10^{-5}$	$>10^{-3}$	$<10^{-5}$
pairing	BCS	Not BCS	Not BCS	BCS

Conclusion

- Another step towards achieving superconductivity at room temperature has been done.
- The myth that BCS superconductors can not be a high temperature superconductor has been debunked.
- There are many hydrogen-containing materials with strong covalent bonding (such as organics) but typically they are insulators.
- In principle, they could be tuned to a metallic state by doping or gating. High power available ab-initio calculation method could facilitate exploration for the desired High Tc materials.

Many thanks to all the colleagues and friends who helped me in the present talk

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EUCAS 2015

12th EUropean Conference on Applied Superconductivity

6th - 10th September 2015 Lyon - France

Thank you for your attention