Marie Sklodowska-Curie Action (MSCA)
Innovative Training Networks (ITN)
H2020 FP grant agreement no. 764879

EASITrain

Iron-based and MgB_2 classes of superconductors Part II - IBS

Marina Putti

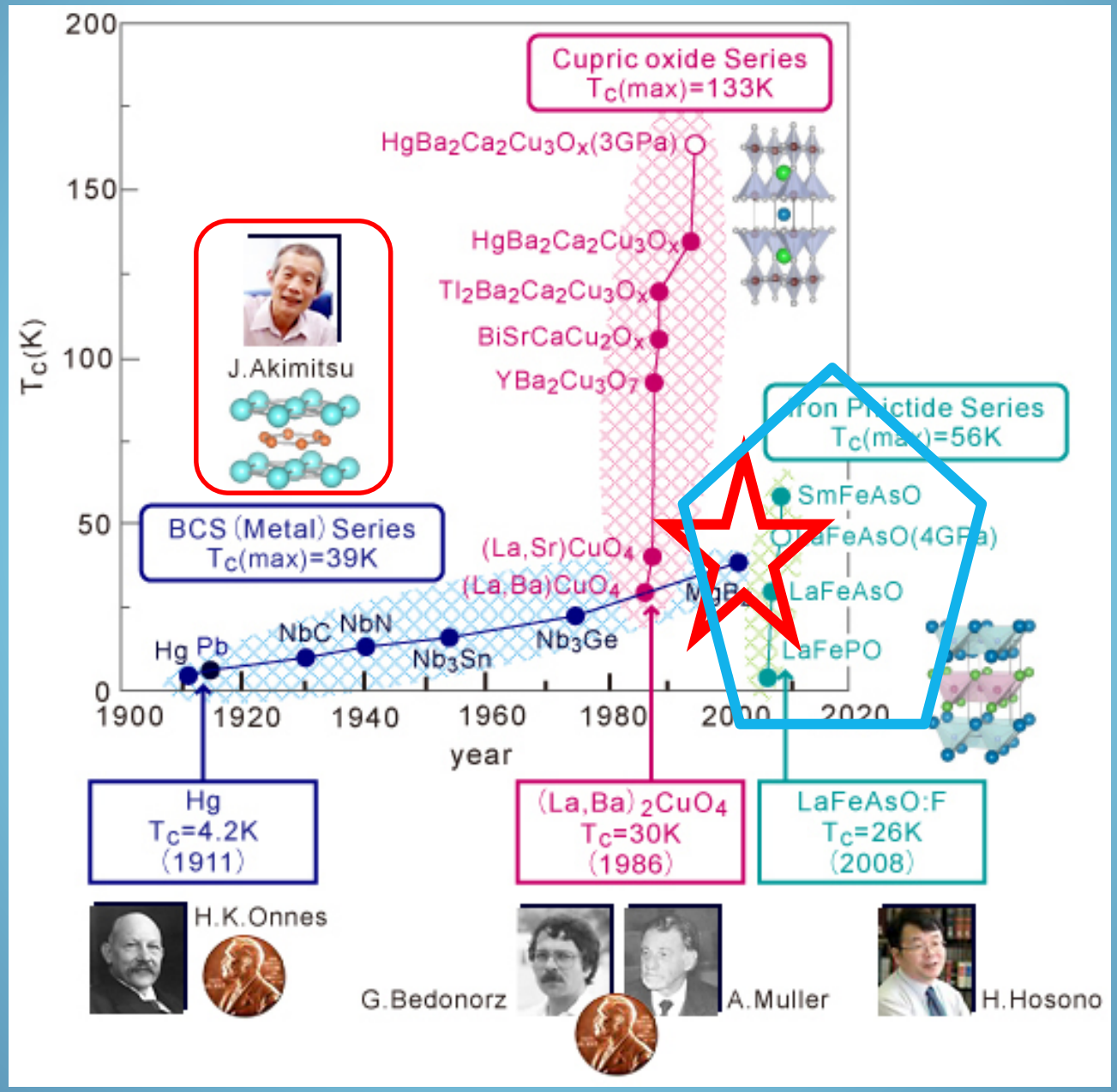
University of Genova and CNR-SPIN

UNIVERSITÀ DEGLI STUDI DI GENOVA

SPIN

3rd-14th September 2018 *EASIschool in Vienna*

STORY of SUPERCONDUCTIVITY



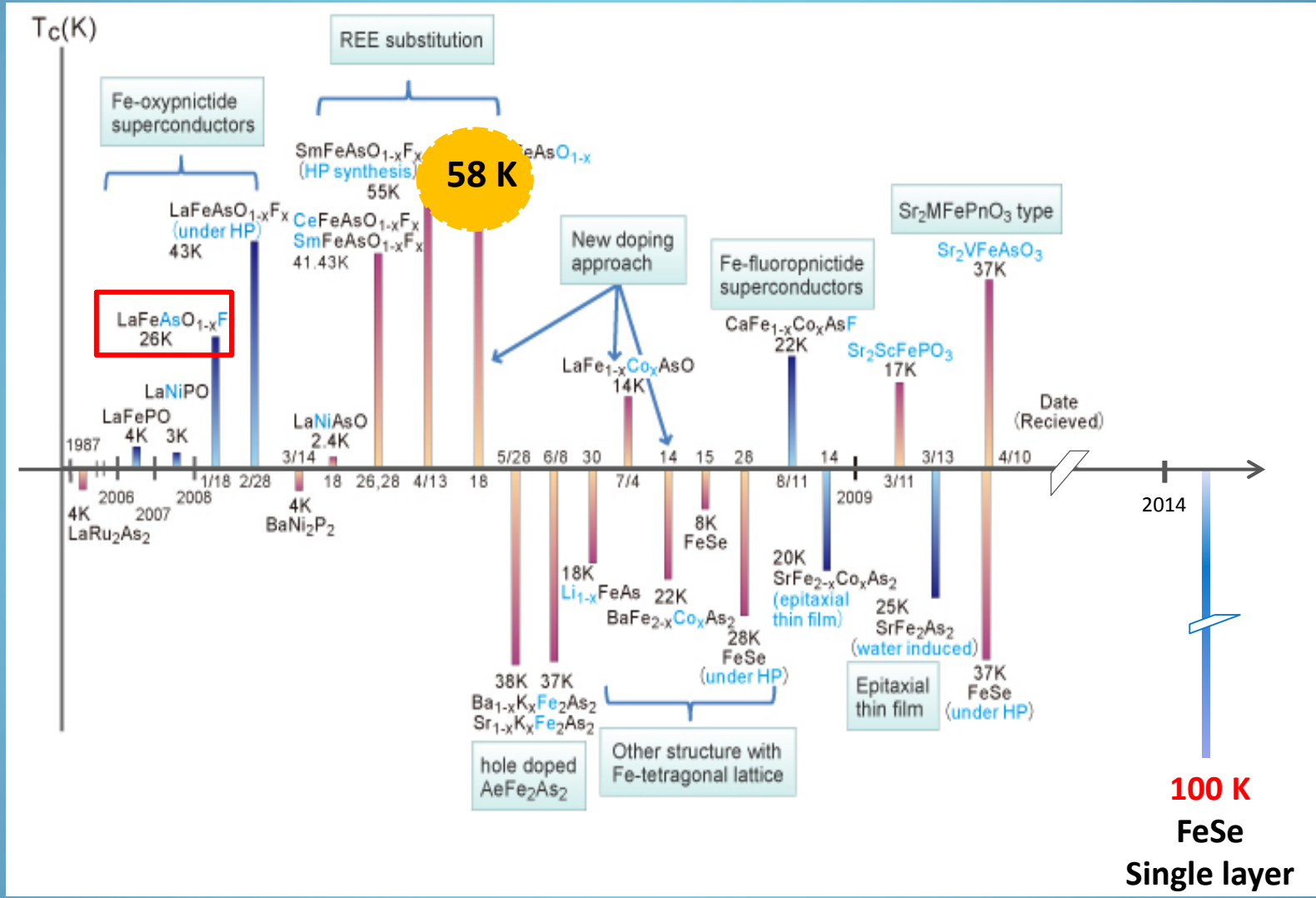
Super+α

OUTLINE

The lecture will **review**:

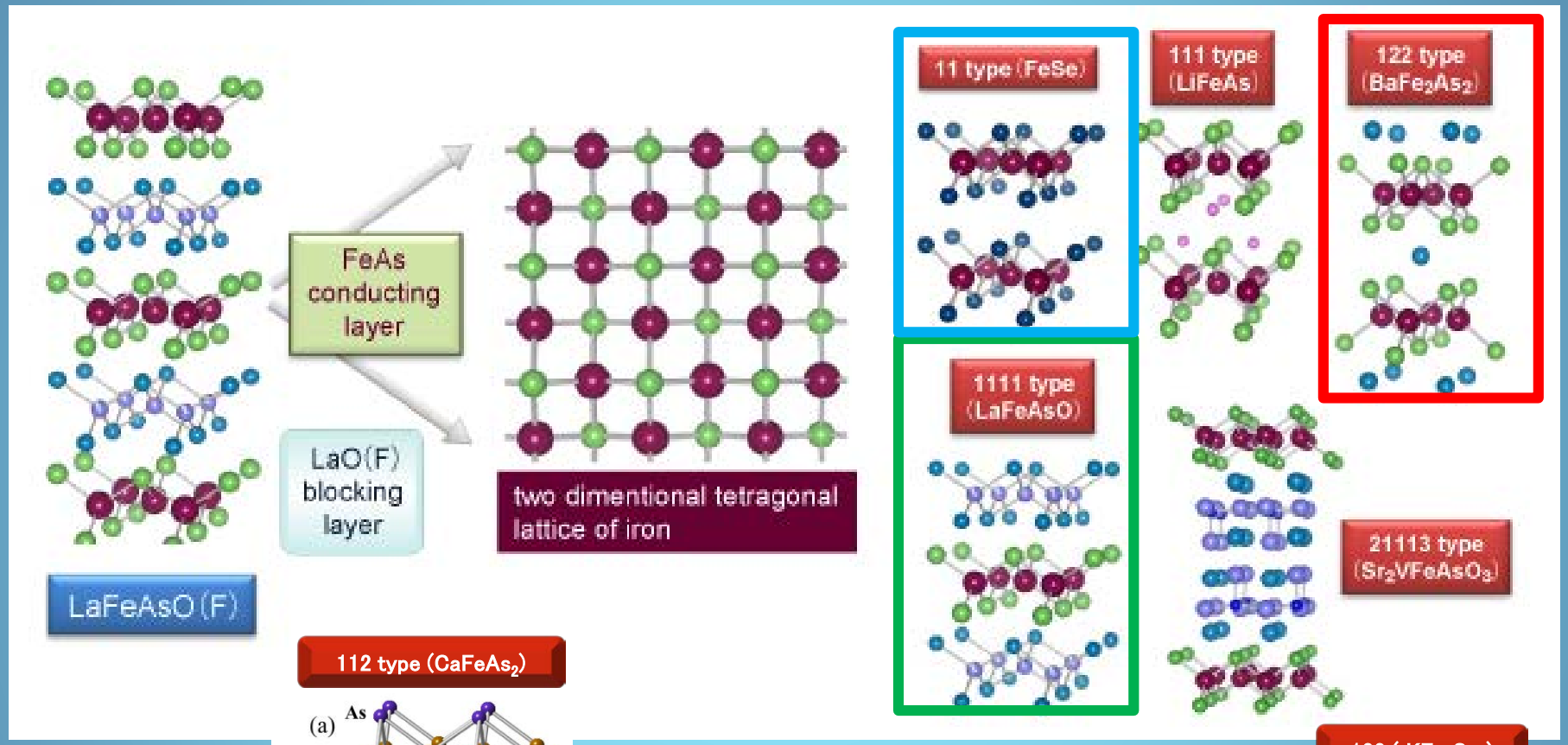
1) **the basic properties of IBS , including the interplay between superconductivity and AFM, unconventional pairing;**
2) the **superconducting properties,** including the upper critical field H_{c2} , critical current density J_c **and critical parameters;**
3) the development and fabrication of **wires** and **tapes.**

Iron based superconductors (IBS)

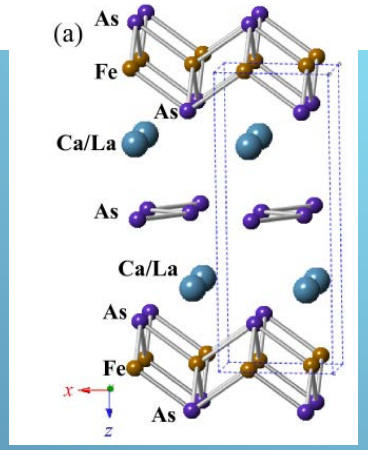


Super+α

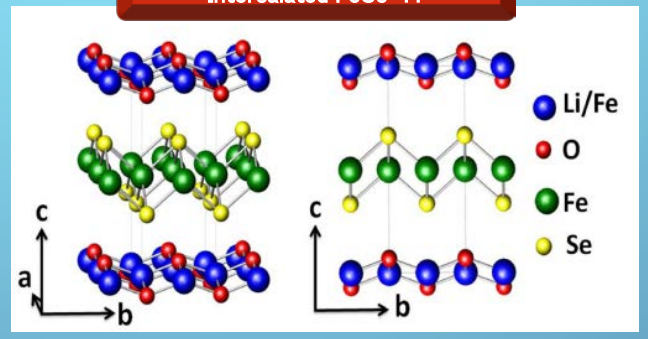
IBS families



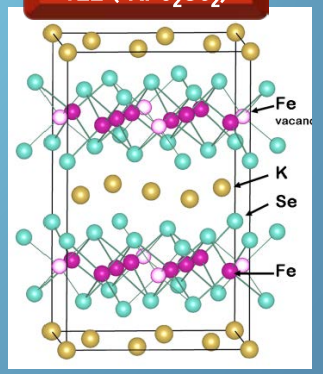
112 type ($CaFeAs_2$)



Intercalated FeSe-11

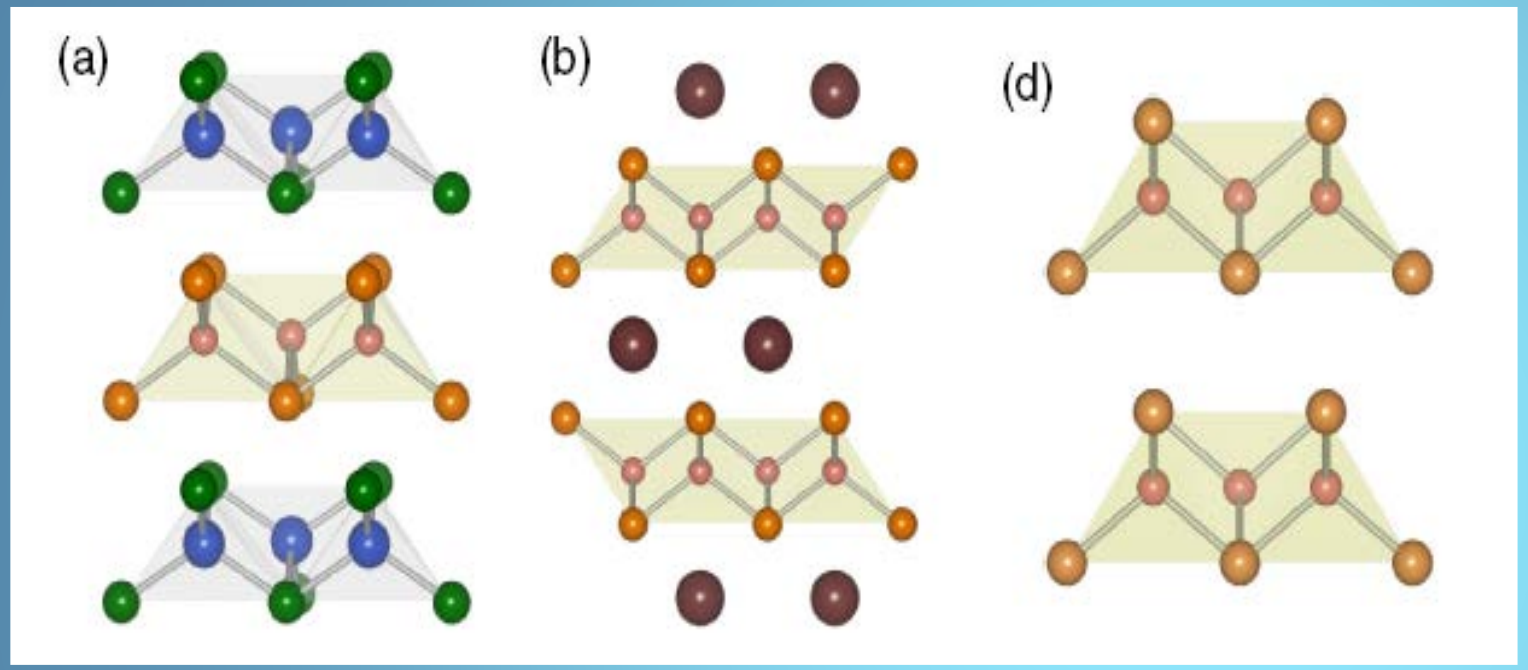


122 (KFe_2Se_2)



Super+α

The most famous families



*RE*FeAsO	$AEFe_2As_2$	Fe(Se,Te)
1111	122	11
$T_{c,max}$ = 58 K	$T_{c,max}$ = 40 K	$T_{c,max}$ = 21 K

Superconductivity occurs upon

substituting O with F, H

Deficency of O

heterovalent RE

Fe with Co

heterovalent *AE* metal

external pressure

internal pressure

substitution of Te with Se, S

external pressure

122

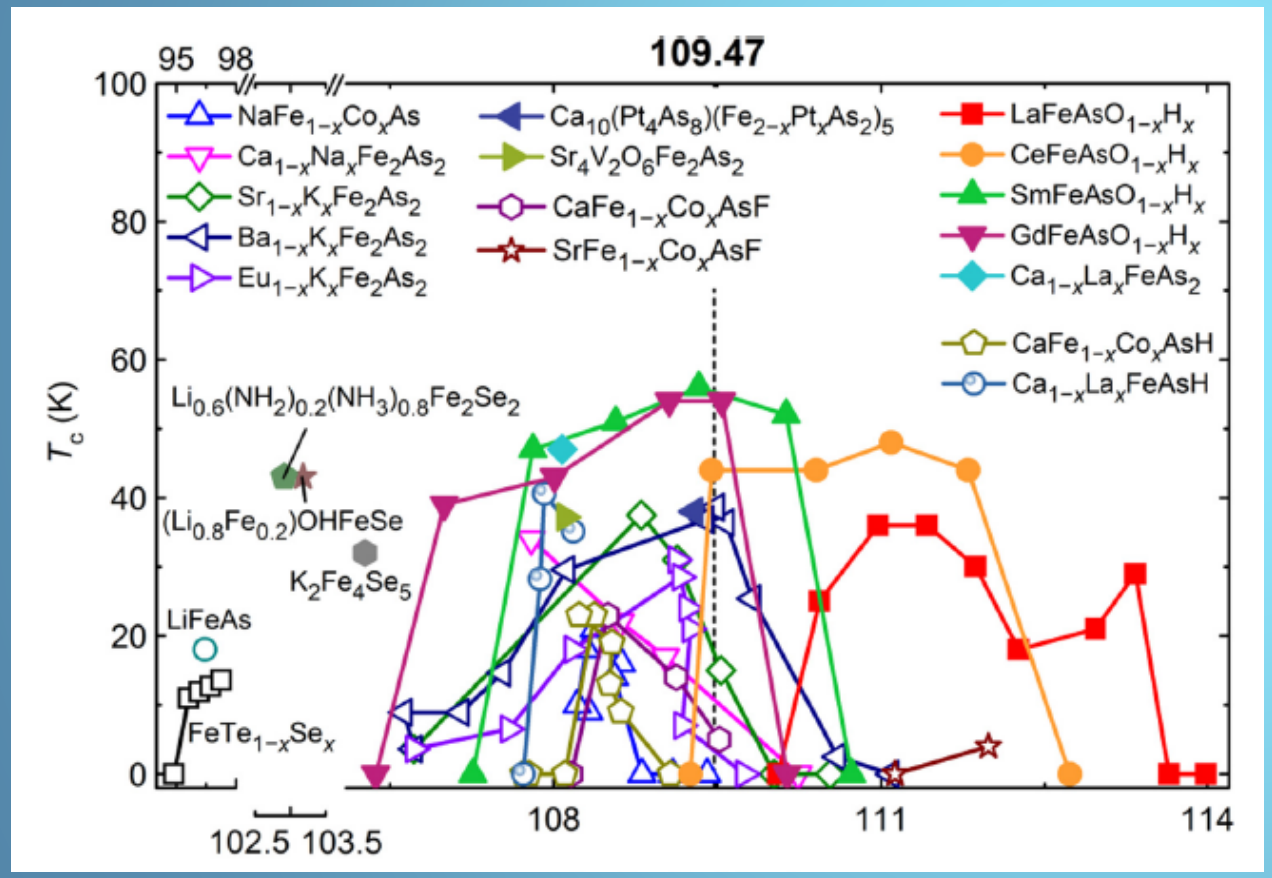
$M_{1-x}AE_xFe_{2-y}TM_yAs_{2-z}P_z$

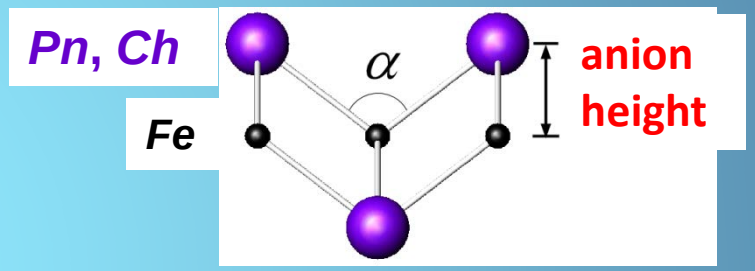
Material	M-site dopant	T_c (K) vs x, $y = z = 0$	Fe-site dopant	T_c (K) vs y, $x = z = 0$	As-site dopant	T_c (K) vs z, $x = y = 0$
$BaFe_2As_2$	K	38/0.4	Co	22/0.2	P	30/0.7
	Rb	23/0.1	Ni	20.5/0.1		
			Pd	19/0.11		
			Rh	24/0.11		
			Ru	21/0.9		
			Pt	25/0.1		
$SrFe_2As_2$	K	36.5/0.5	Co	20/0.2	P	27/0.7
	Na	35/0.5	Ni	10/0.15		
	Cs	37/0.5	Pd	9/0.15		
	La	22/0.4	Rh	22/0.25		
			Ru	13.5/0.7		
			Ir	22/0.5		
			Pt	16/0.16		
$CaFe_2As_2$	Na	33/0.66	Co	17/0.06	P	13/0.3
			Ni	15/0.06		
			Rh	18/0.1		
$EuFe_2As_2$	K	32/0.5			P	26/0.6
	Na	35/0.3				

RE=La, Ce, Pr 40 -46

Correlation between T_c and local structure

T_c is higher in the order **1111** > **122** > **11**.
Does interlayer spacing of FeAs layers enhance optimal T_c ?



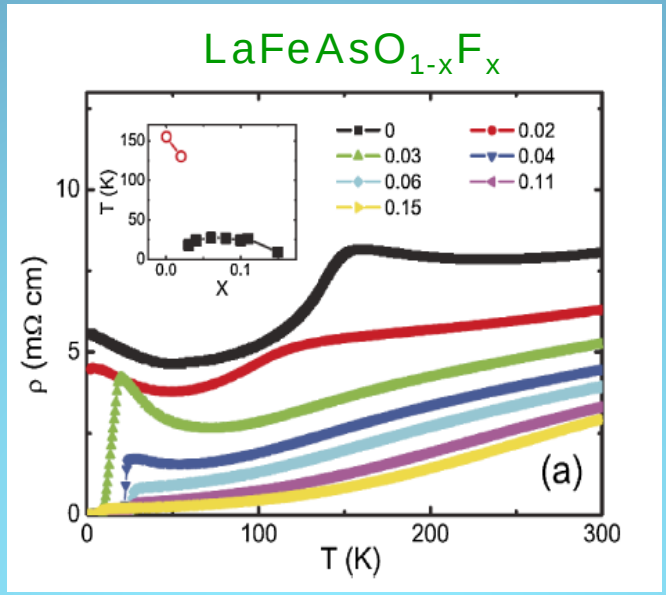


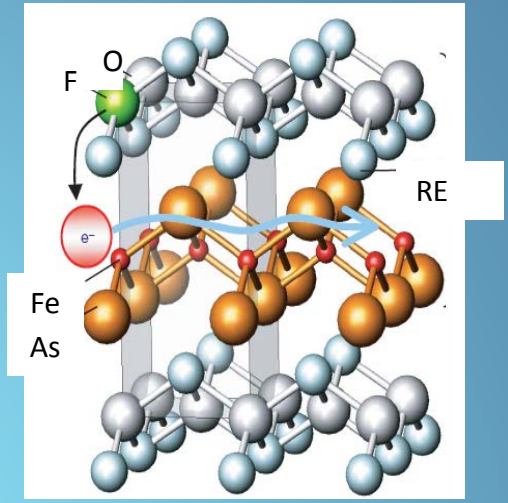
- Phenomenological correlation of T_c with the tethraedron angle and with the anion hight
- Anion hight is a structural parameter associated with strength of spin fluctuation

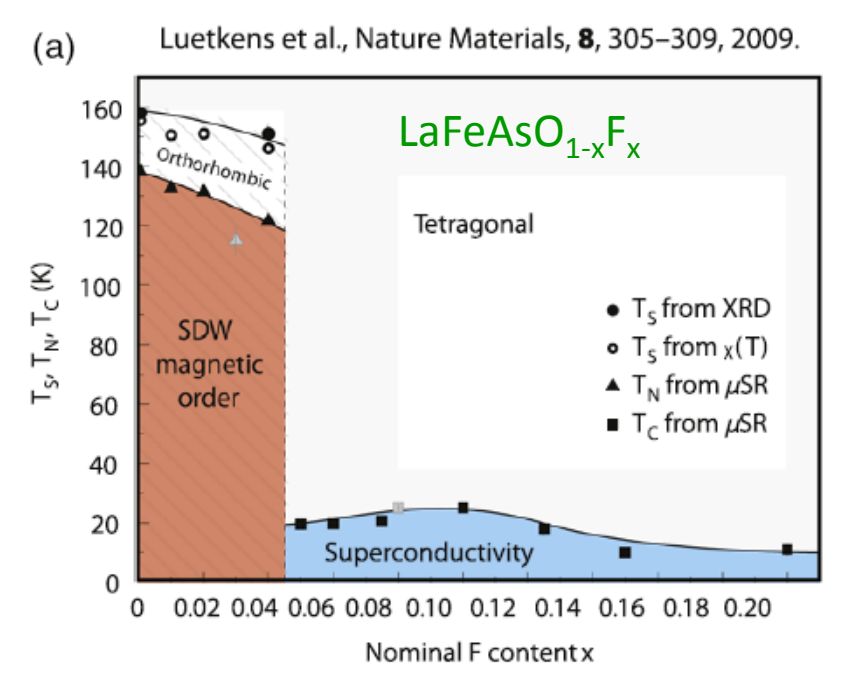
H.Hosono, et al., Mater. Today 21 (2018) 278.

Phase diagrams:

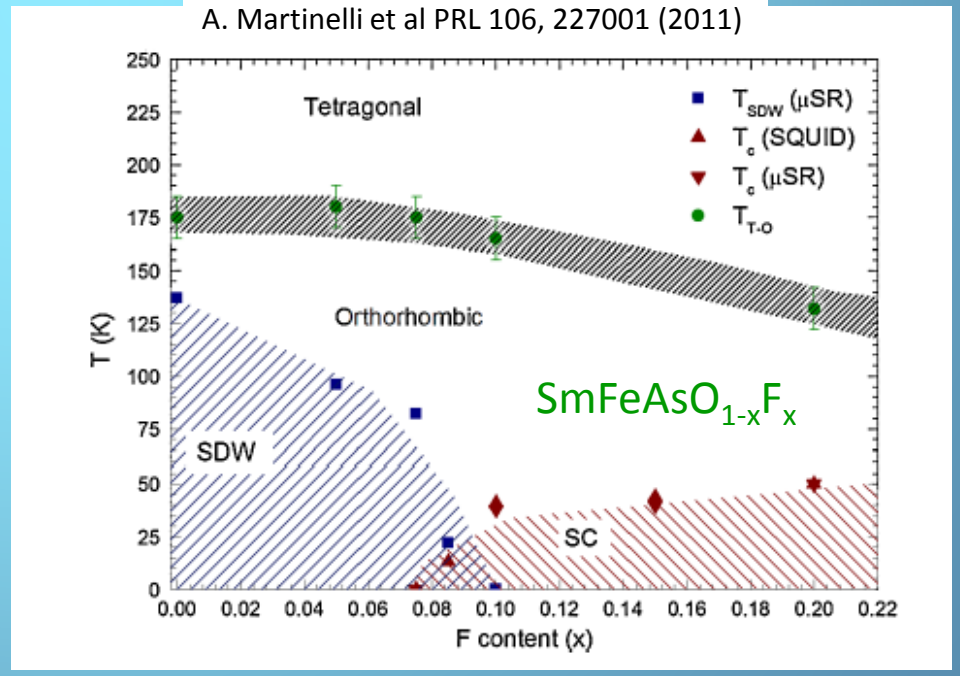
1111



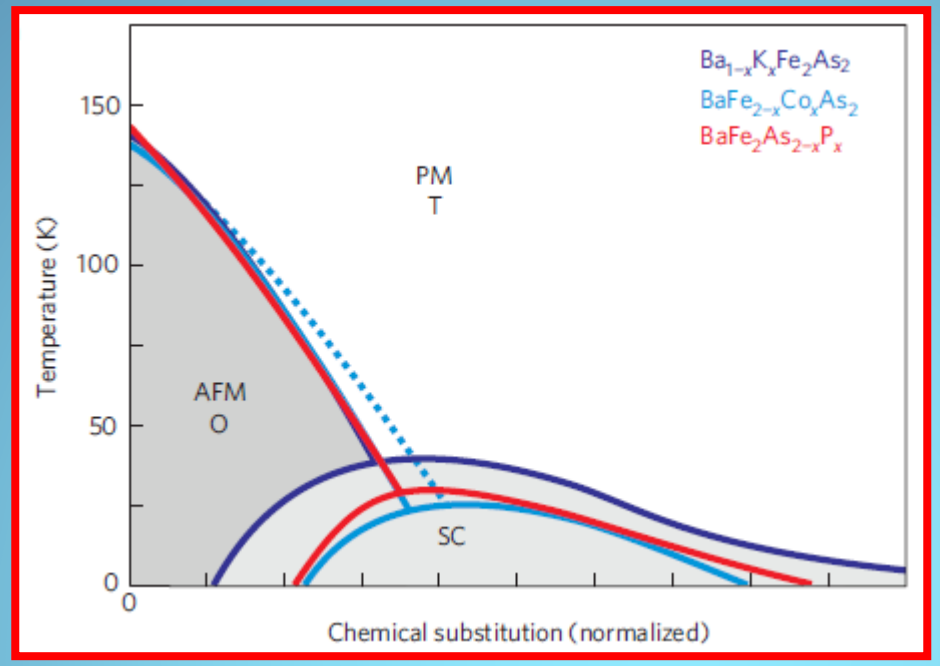




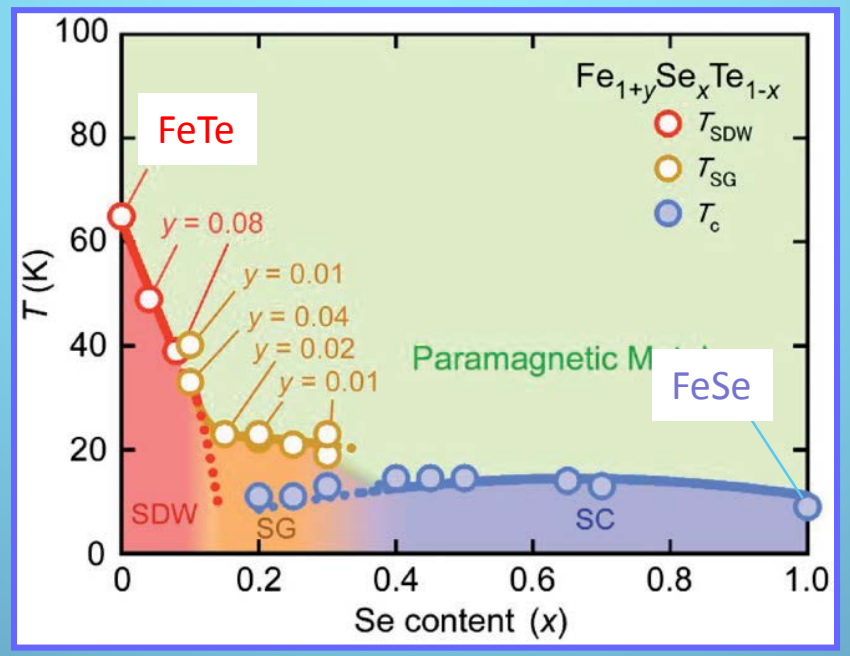
S. Sanna et al., PRB 80, 052503 (2009).
A. Martinelli et al PRL 106, 227001 (2011)



Phase diagrams :



122

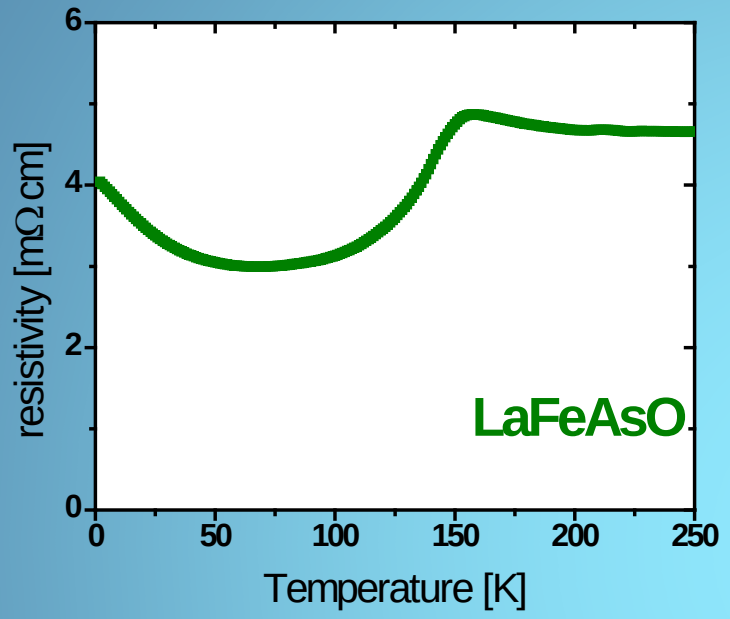


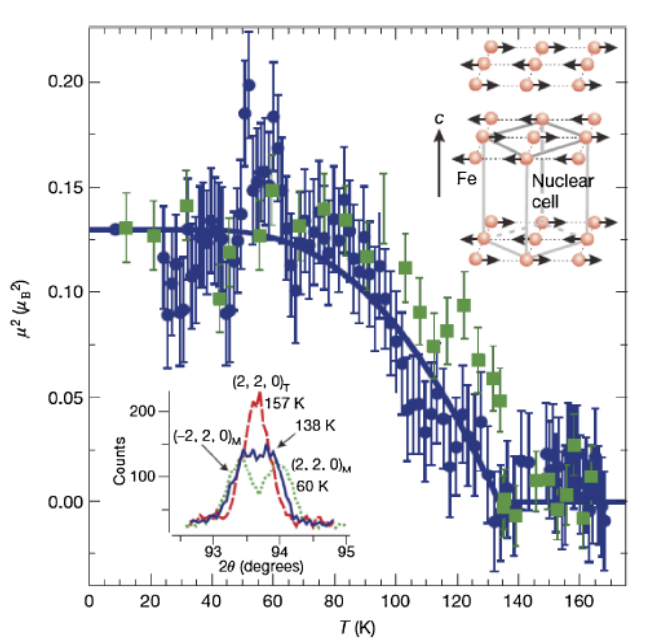
11

Parent compounds:

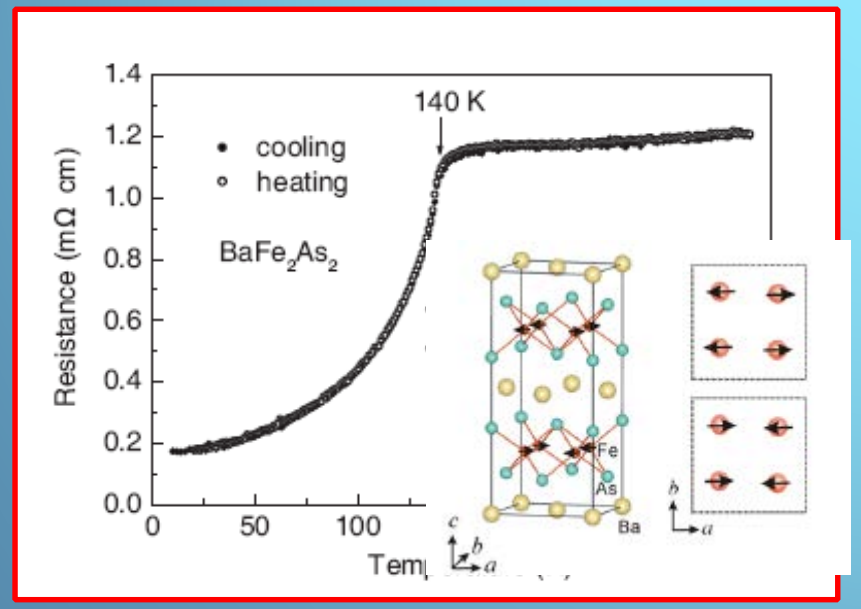
AFM state:

1111





C. de la Cruz et al., 2008 Nature 453 899

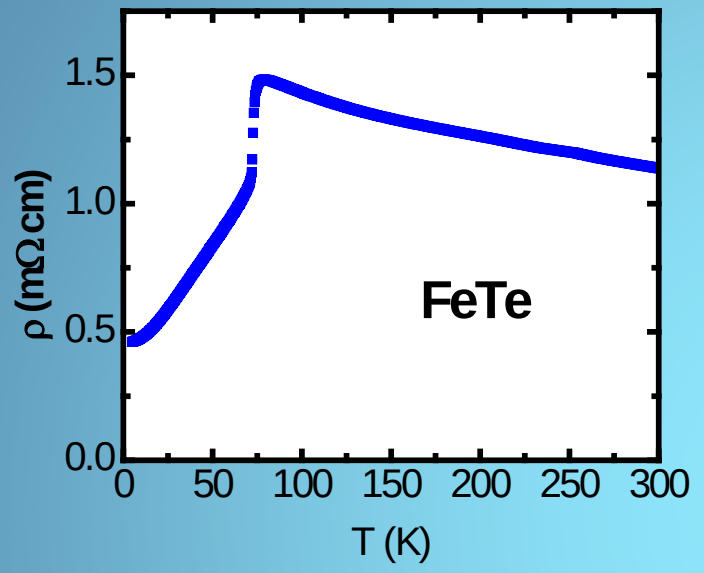


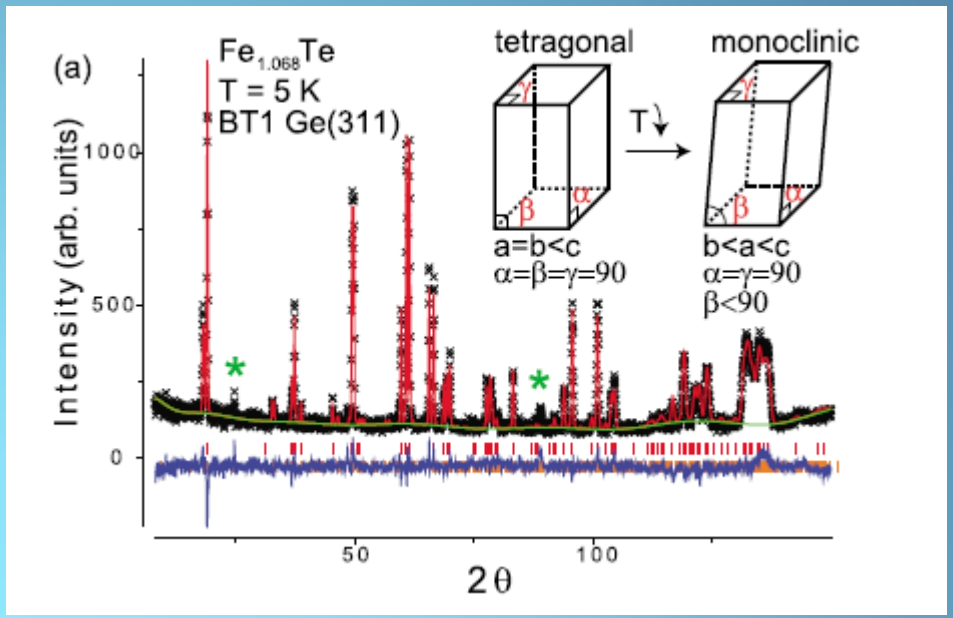
- a SDW ordering of Fe (≈0.4μ_B/Fe)
- associated to a tetragonal-orthorhombic transition

122

AFM state:

FeSe-11

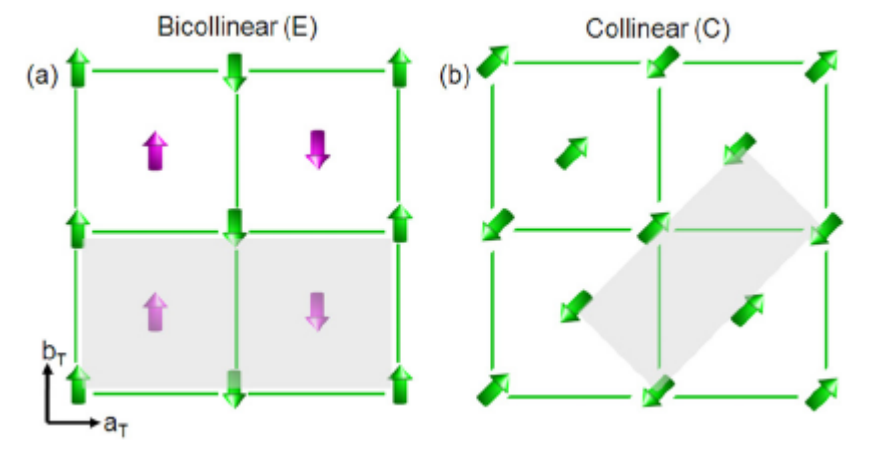




PHYSICAL REVIEW B **79**, 054503 (2009)

FeTe exhibits:

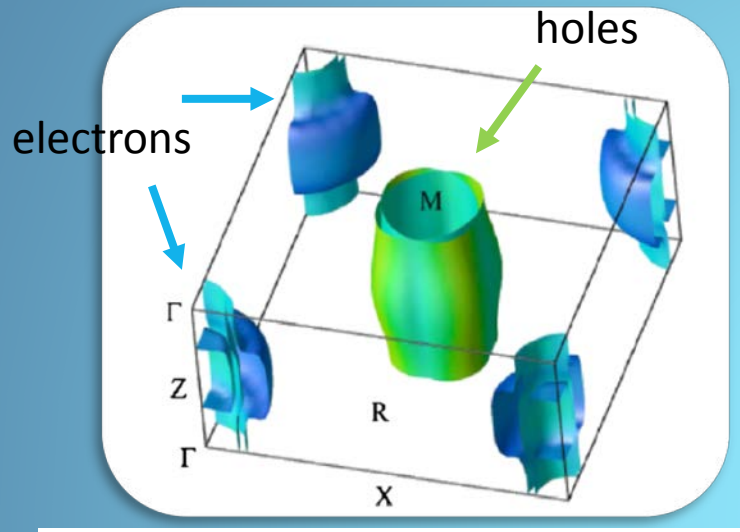
- bicollinear AFM ordering of Fe (≈2.5 μ_B/Fe)
- spin direction 45° rotated in respect to 1111 and 122
- Tetragonal to monoclinic transition



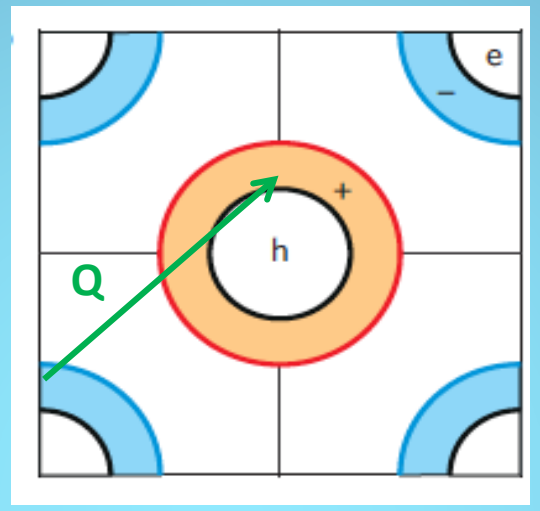
11

1111-**122**

Band structure



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



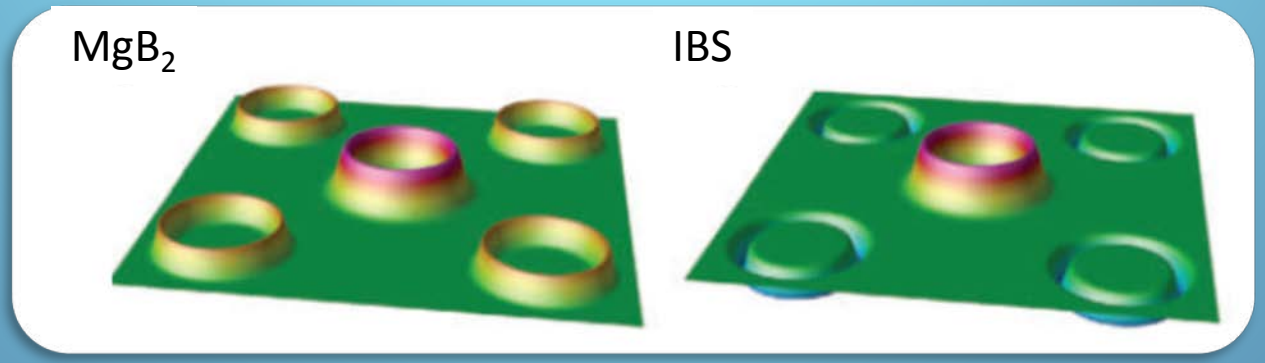
Igor I. Mazin, Nature 464 (2011) 183

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

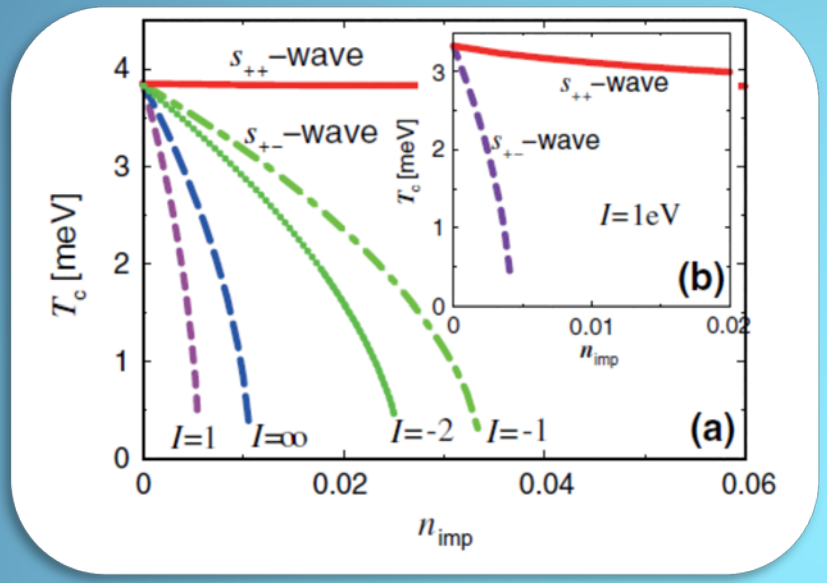
Superconducting order parameter:

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

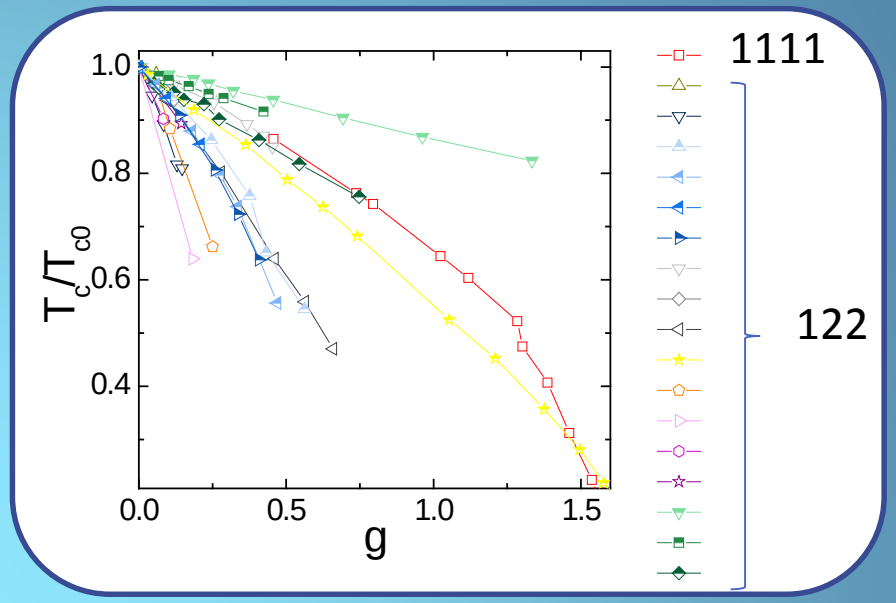
⇨ IBS : two-band *s*± wave



Tc vs impurities

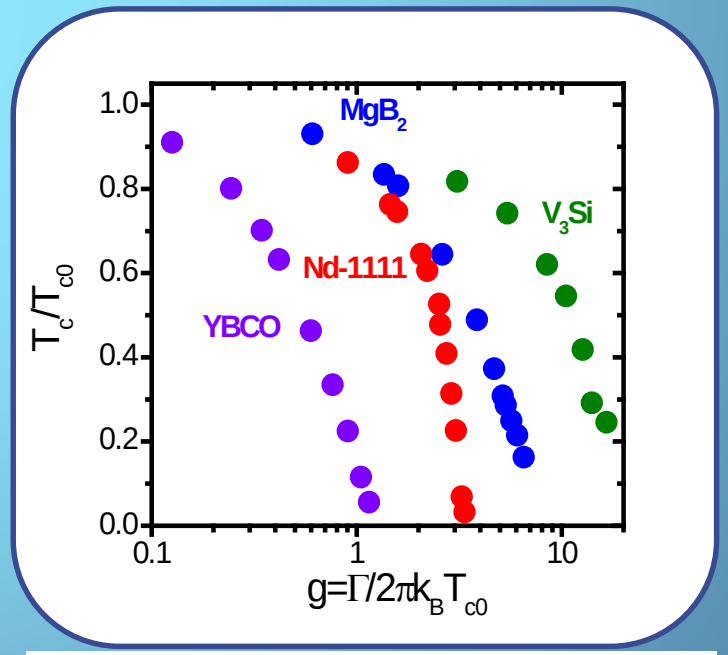


S Onari eta l., PRL 103, 177001 (2009)]



I. Pallecchi et al., SUST 31, 034007 (2018)

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

OUTLINE

The lecture will **review**:

1) the **basic properties** of IBS , including the interplay between superconductivity and AFM, and unconventional pairing;
2) **the superconducting properties, including the upper critical field Hc2 , the critical current density Jc and the critical parameters;**
3) the development and fabrication of **wires** and **tapes.**

Upper critical fields

1111

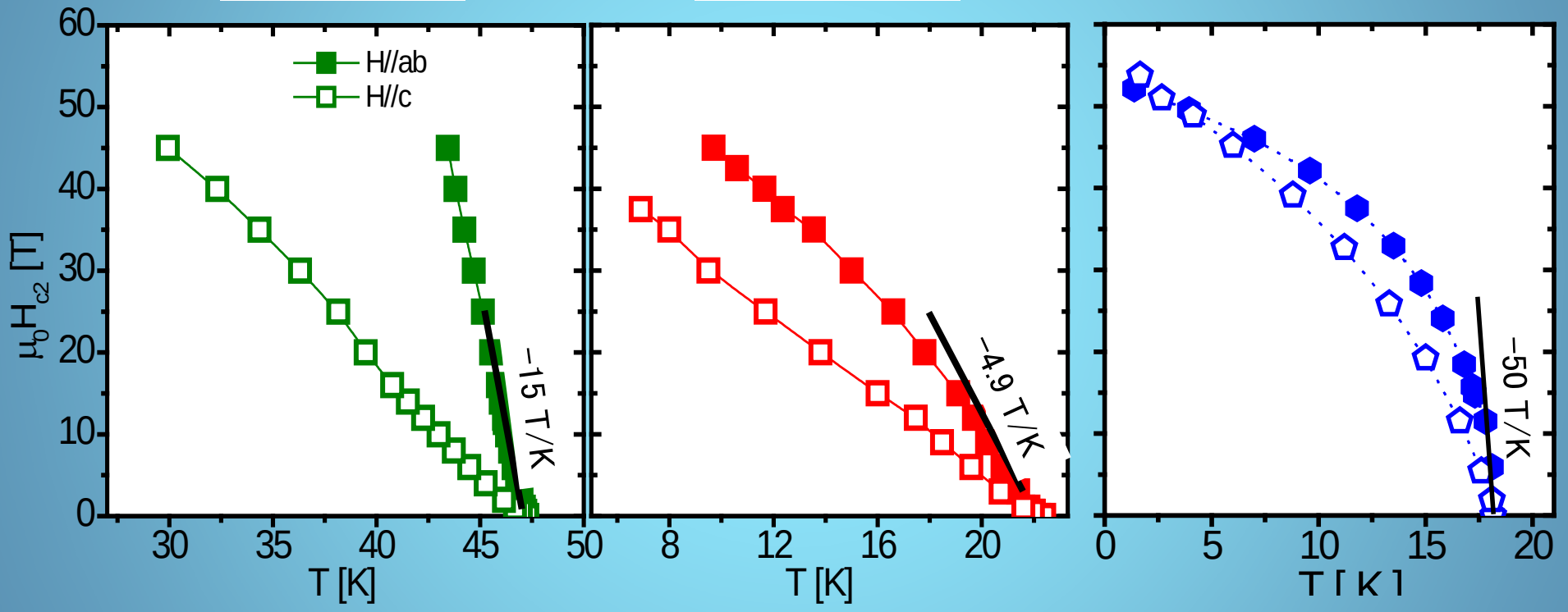
NdFeAs(OF)

122

$Ba(FeCo)_2As_2$

11

Fe(TeSe)



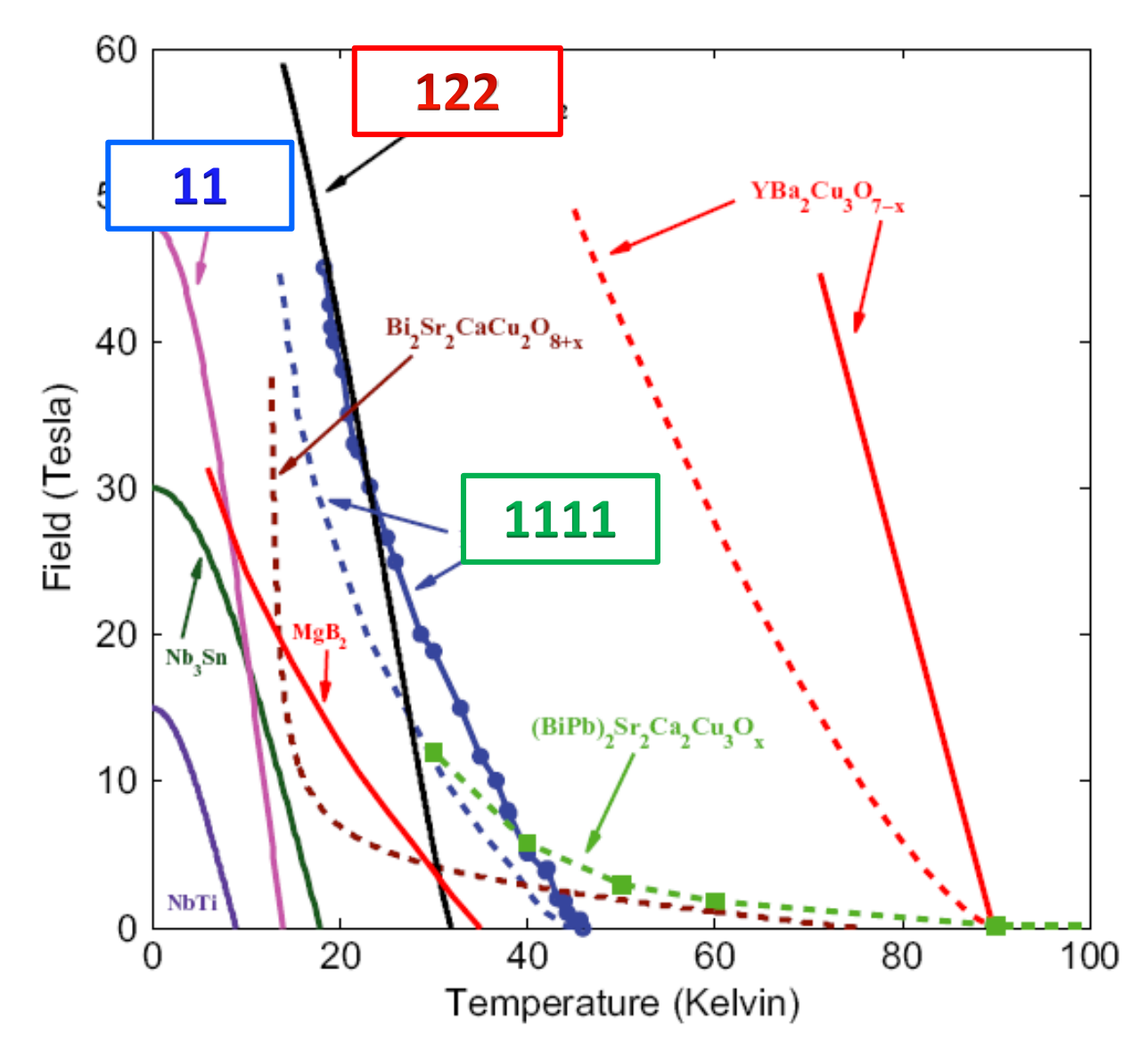
☑Slope −15 T/K
☑Anisotropy is 5

☑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	$4\cdot10^{-4}$	$2\cdot10^{-5}$	$1\cdot10^{-3}$	$>10^{-3}$	$<10^{-5}$
pairing	Not BCS	Not BCS	Not BCS	Not BCS	BCS

$$G_i = \sim \frac{\Delta T}{T_c}$$

Width of the critical regime around T_c

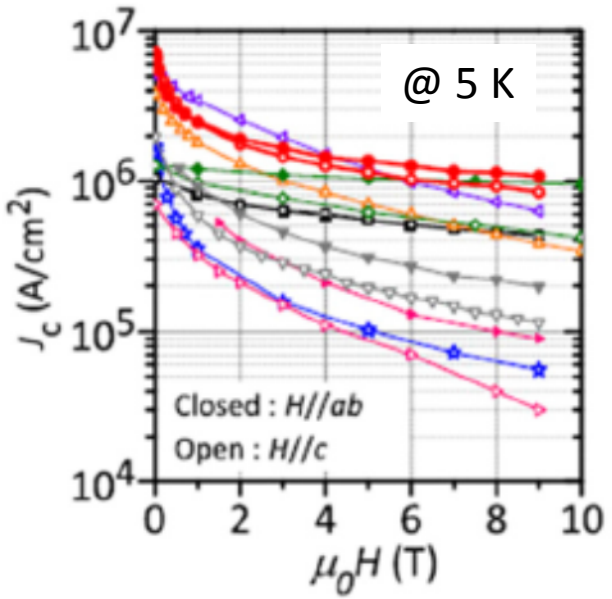
$$Gi = \left[\frac{\gamma \cdot kT_c}{H_c^2(0)\xi^3(0)}\right]^2 \propto \gamma^2 \cdot T_c^4$$

anisotropy

Several similarities with HTS :

High H_{c2}, small coherence length, unconventional pairing but, *lower anisotropy*

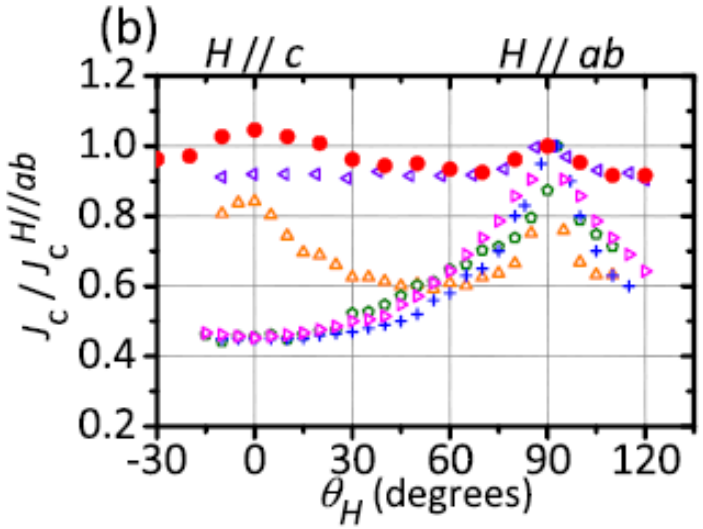
Critical current density of thin films



- 122:P (Sato et al., 2014)
- 122+BZO (Miura et al.,2013)
- 1111 (Iida et al.,2013)
- 122 SL (Lee et al., 2013)
- 122:Co/Fe (Iida et al., 2010)
- 122:Co/IBAD (Trommler et al.,2012)
- 11 (Braccini et al.,2013)
- 122:Co (Hiramatsu et al.,2012)

J_c @ low temperature is:

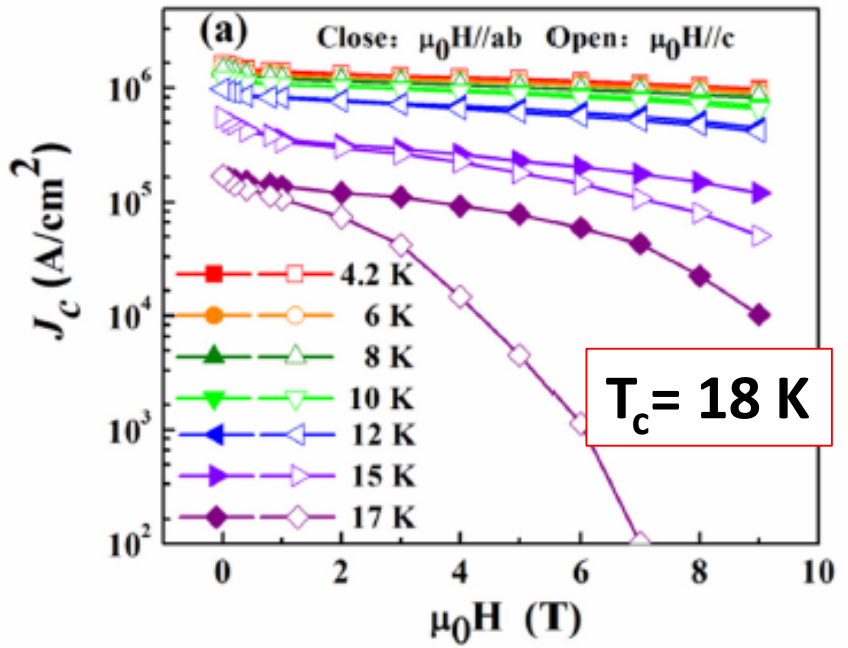
- Large (above 10^6 A/cm^2 in self-field)
- Almost field independent
- Nearly isotropic

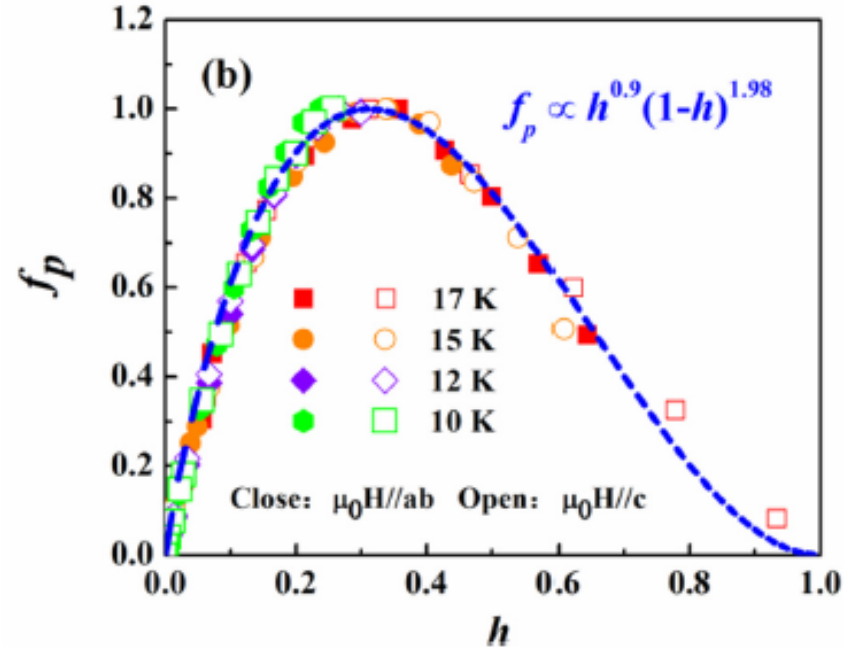


- $BaFe_2As_2$:P (this work @ 12K, 3T)
- $BaFe_2As_2$:P + BZO (15K, 1T, ref.26)
- O-rich $BaFe_2As_2$/$BaFe_2As_2$:Co SL (14K, 4T,
- STO / $BaFe_2As_2$:Co SL (11K, 4T, ref.28)
- $BaFe_2As_2$:P (10K, 3T, ref.7)
- $BaFe_2As_2$:Co/Fe buffer (10K, 3T, ref.29)

H.Sato, et al., APL 104, 182603 (2014)

11 thin films grown on CaF_2 substrates



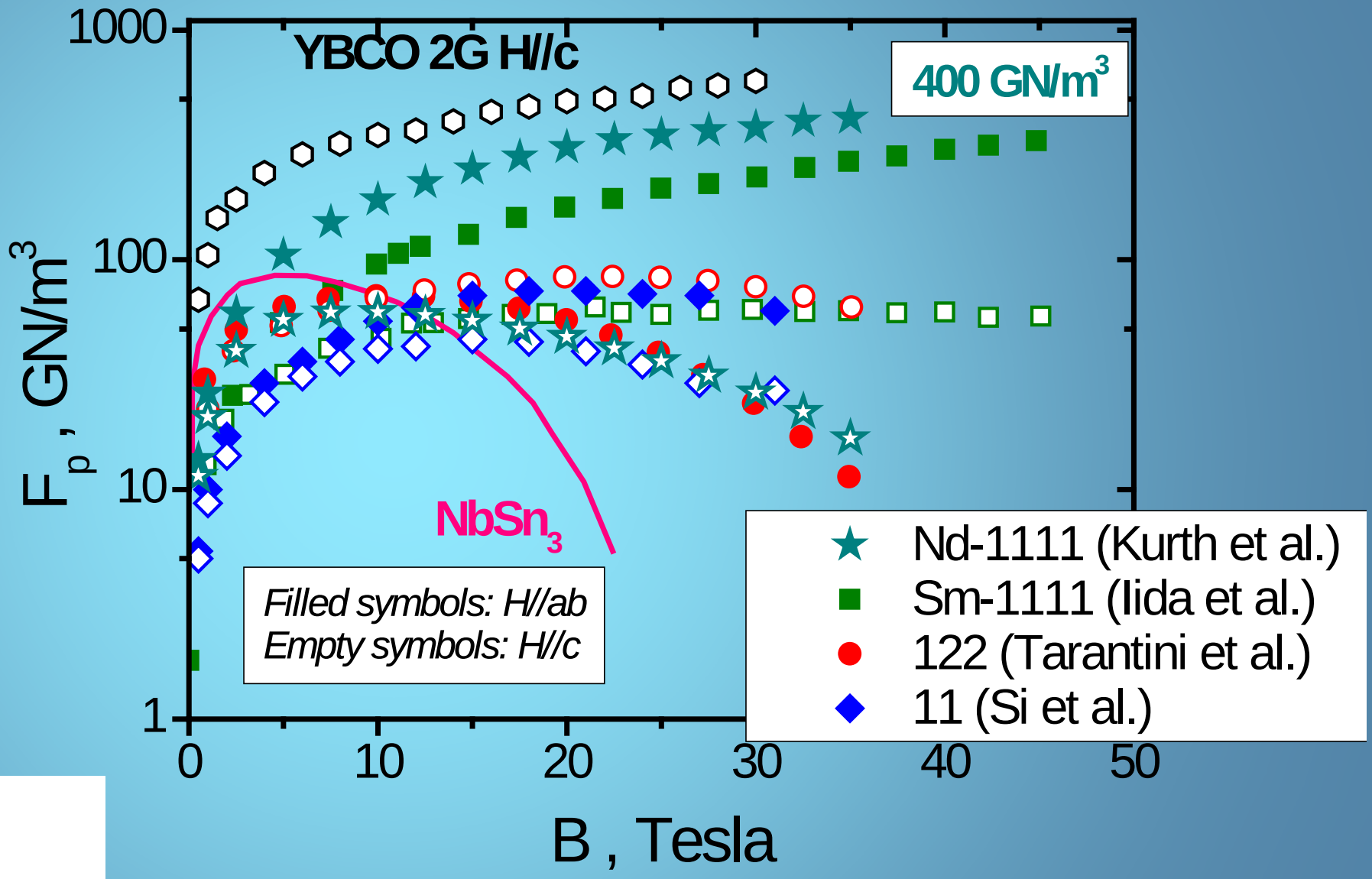


Critical current density:

- J_c is almost isotropic with increasing both the temperature and the magnetic field.
- J_c remains above 10^5 A/cm^2 @0.8 Tc
- Pinning by point defects

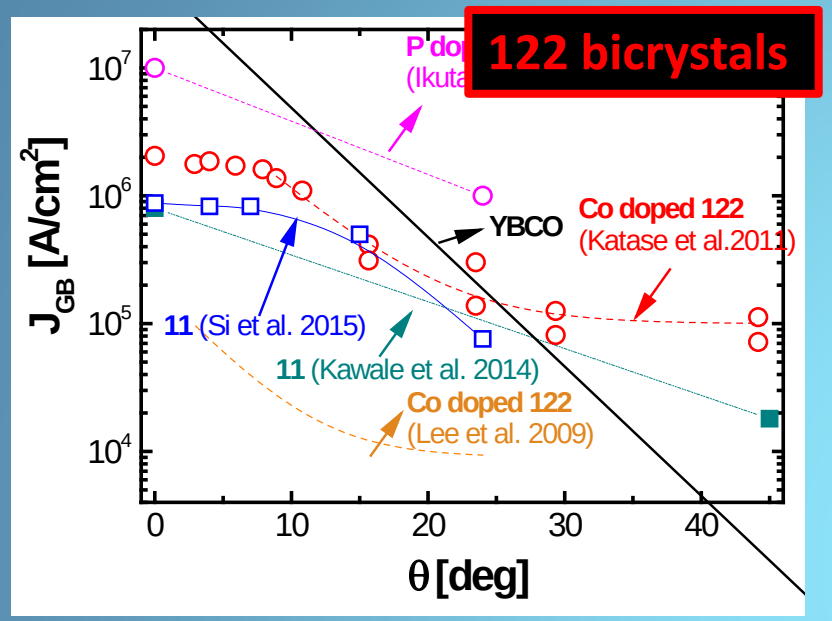
P. Yuan et al., SUST 29 (2016) 035013

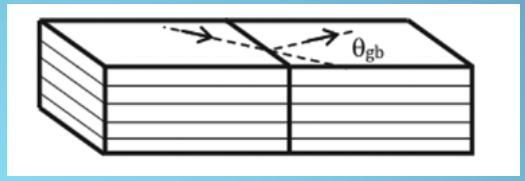
Pinning Force



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 misorientation angle



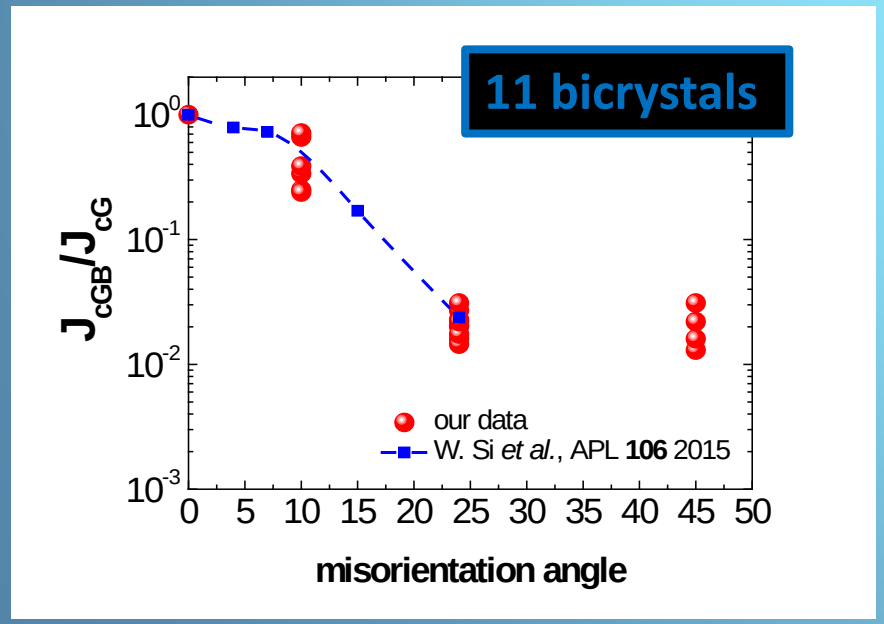


122 bicrystals

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)*



- ✓ Also in IBS Jc is suppressed by misaglined grains
- ✓ In HTS $\boldsymbol{\theta_C \sim 4°}$
- ✓ In IBS $\boldsymbol{\theta_C \sim 10°}$
- ✓ IBS has Advantageous GBs over HTS

OUTLINE

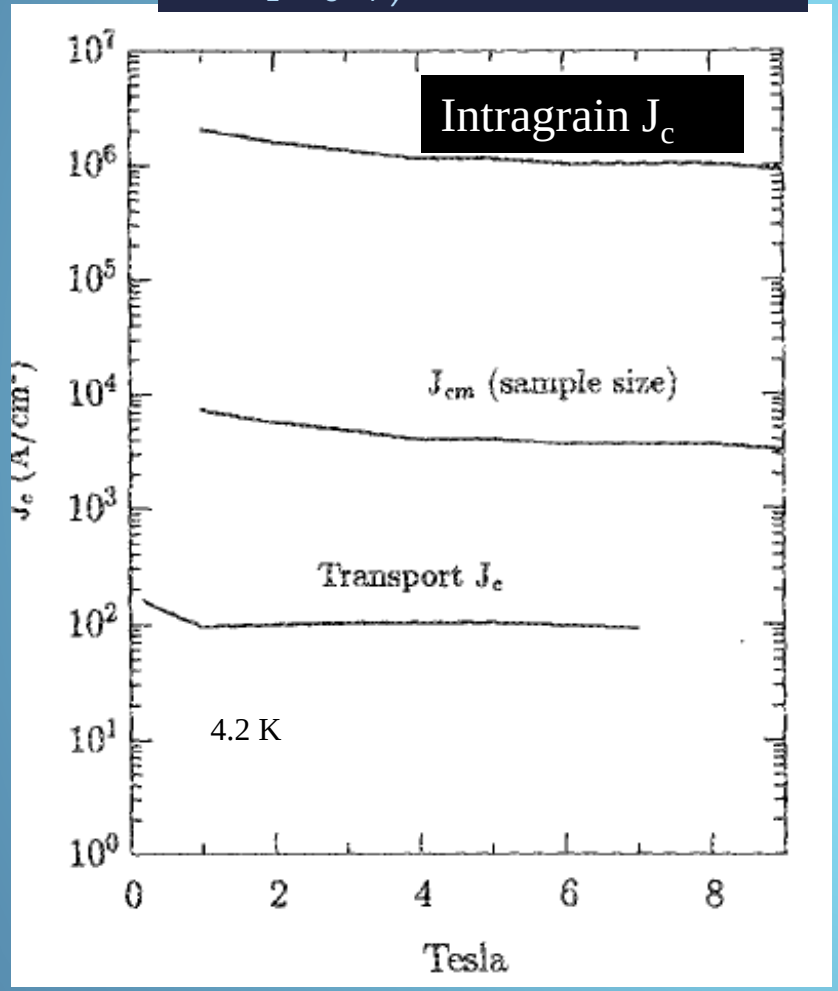
The lecture will **review**:

1) the **basic properties** of IBS , including the interplay between superconductivity and AFM, unconventional pairing;
2) the **superconducting properties,** including the upper critical field Hc2 , the critical current density Jc and the critical parameters;
3) **the development and fabrication of wires and tapes.**

Comparison of polycrystalline IBS & HTS

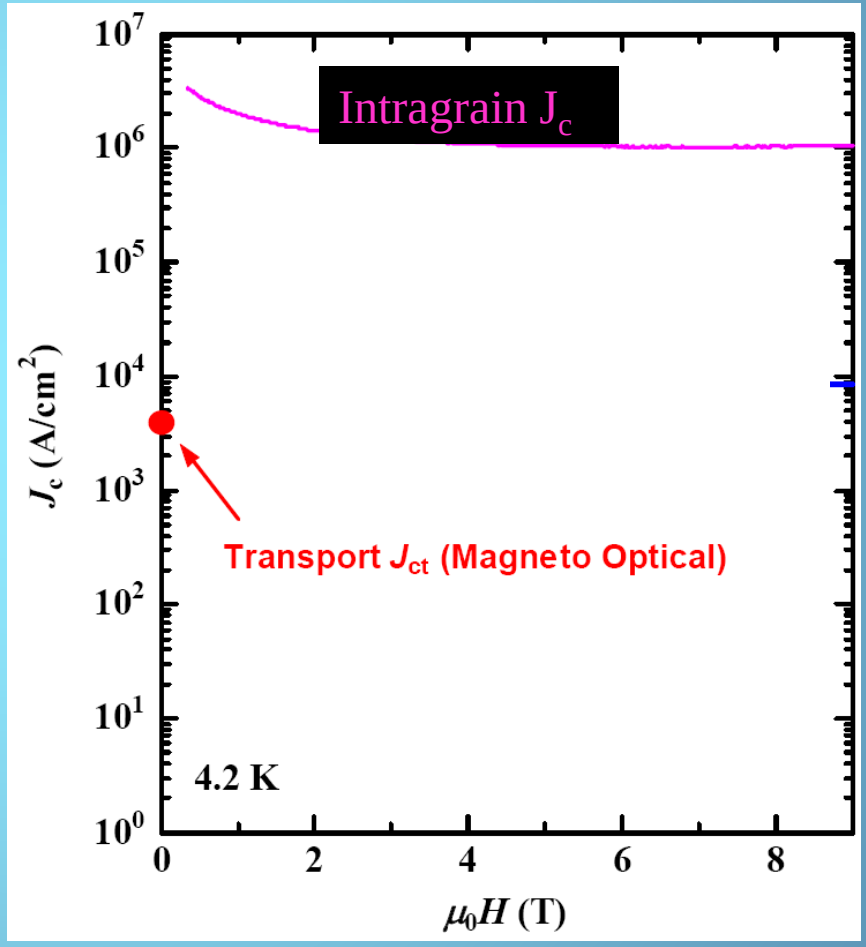
From Eucas 2009

$DyBa_2Cu_3O_{7-y}$ polycrystal



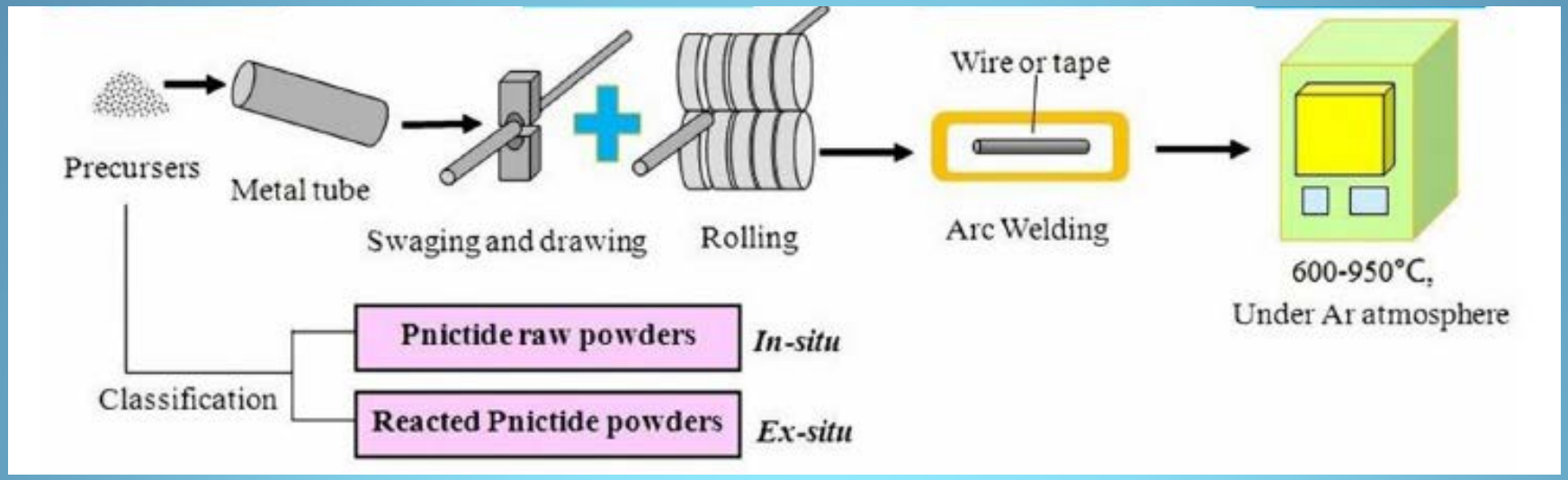
Seuntjens *et al.*, *JAP.* 67, 2007 (1990)

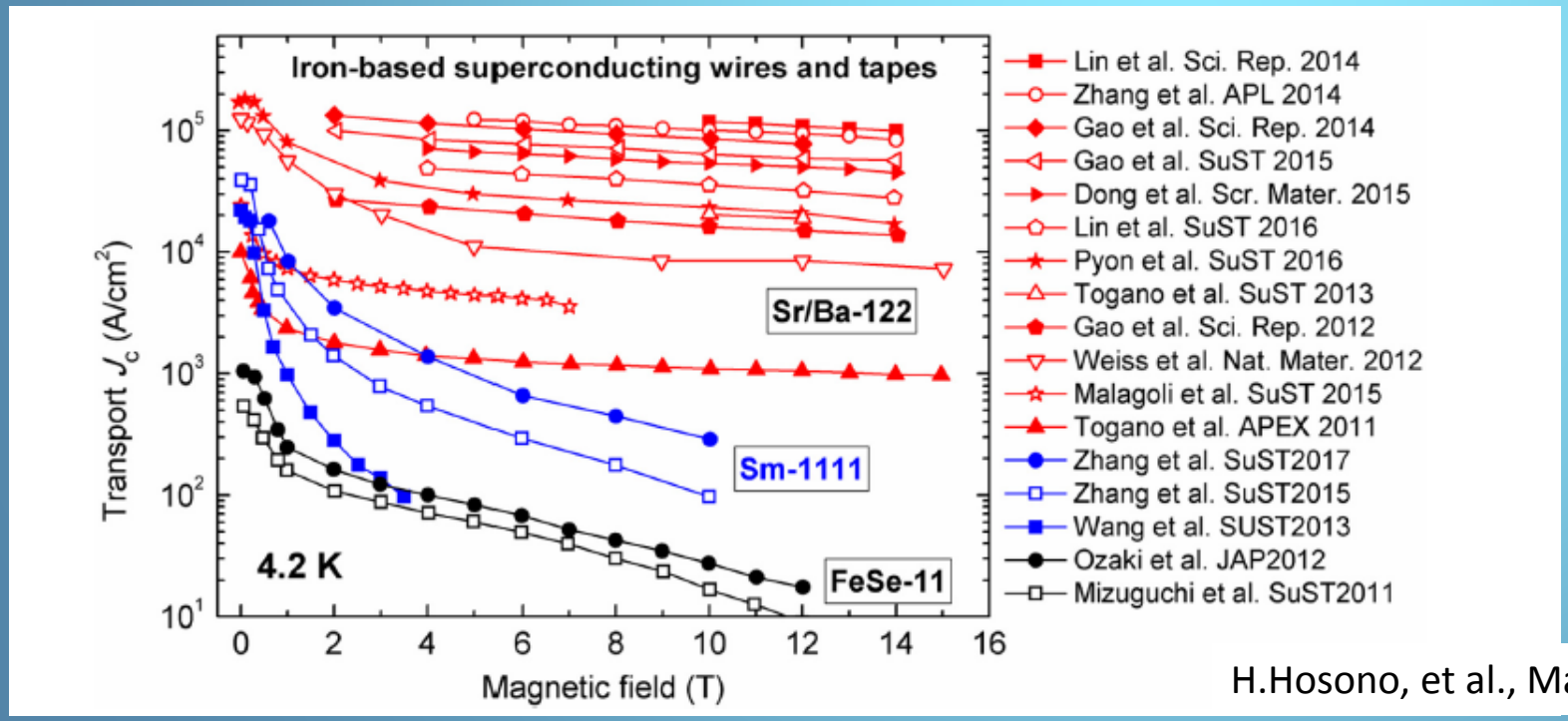
$SmFeAsO_{0.85}$ polycrystal



Yamamoto *et al.*, *SUST* 21, 095008 (2008)

Manifacturing of IBS-PIT



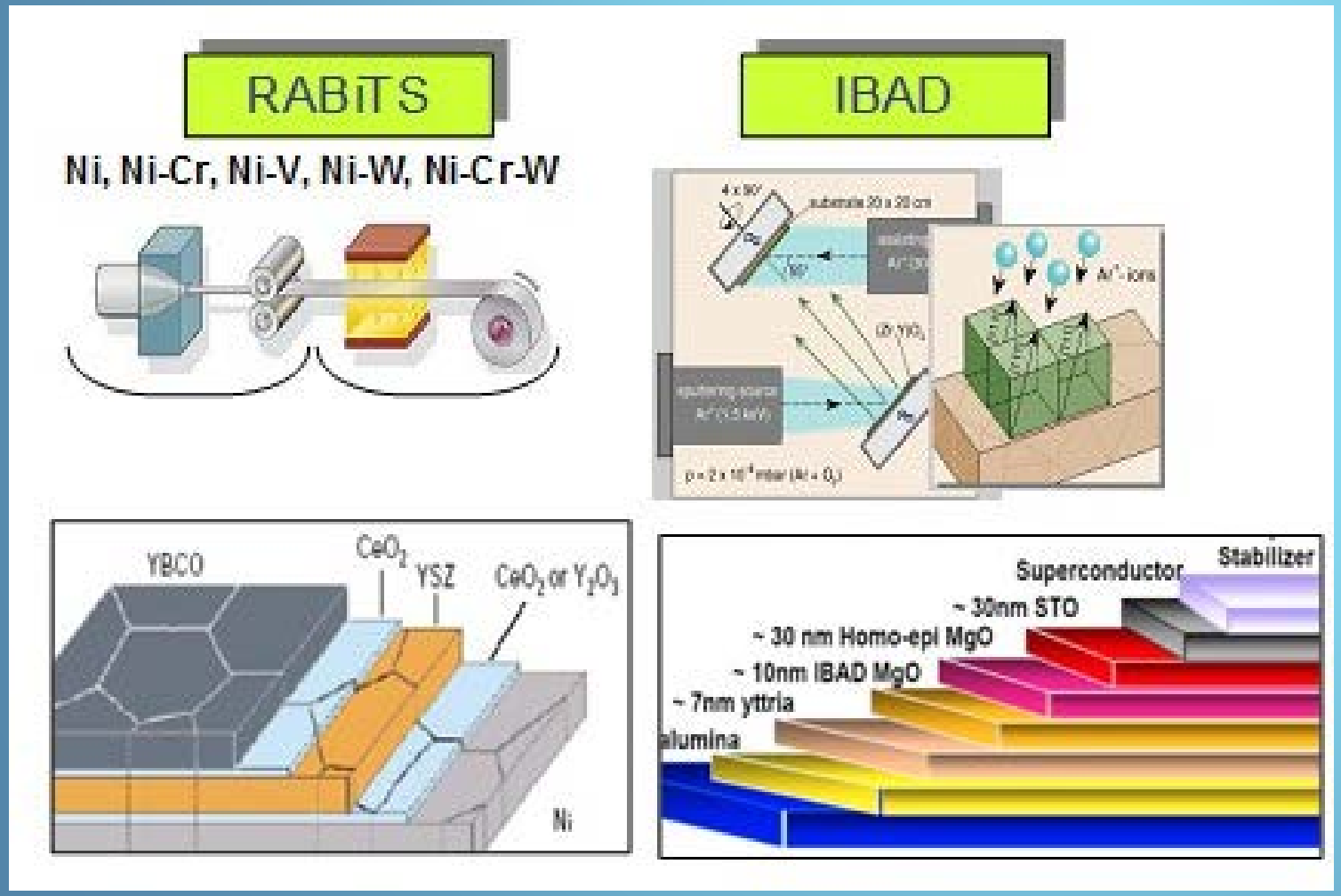


- Best performaces for the 122 family
- J_c rather flat and in the best samples close to 10^5 A/cm^2 above 10 T

H.Hosono, et al., Mater. Today 21 (2018) 278.

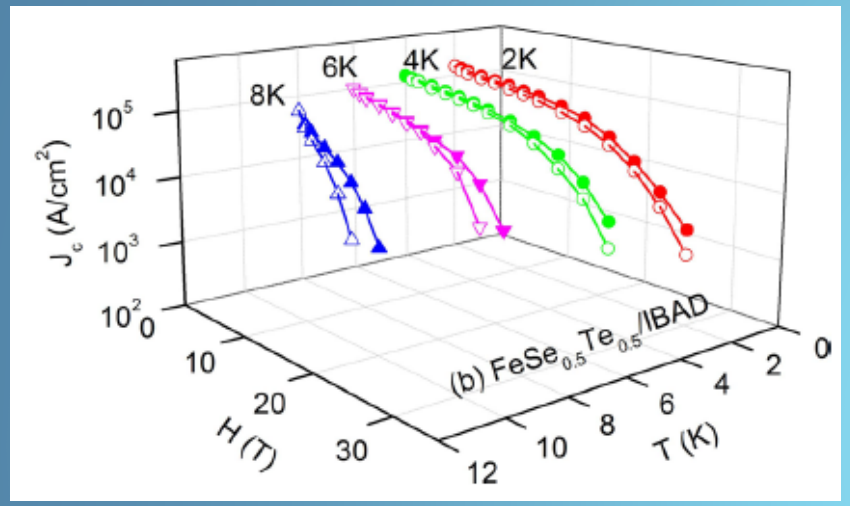
Manifacturing of CC-IBS

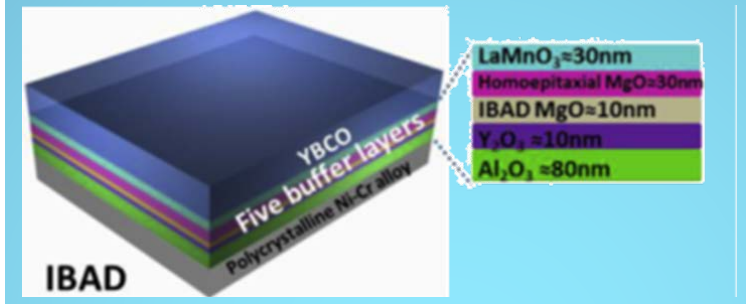
Main technologies for ReBCO-CC manufacturing



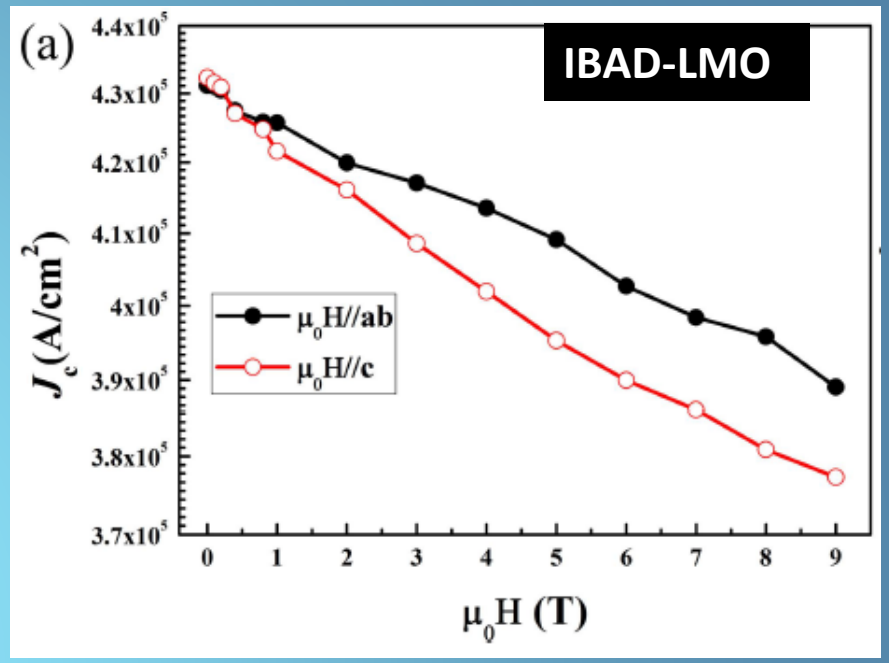
The goal:
to achieve highly in-plane oriented practical metal-tape substrates.

State of the art 11 IBS-CC

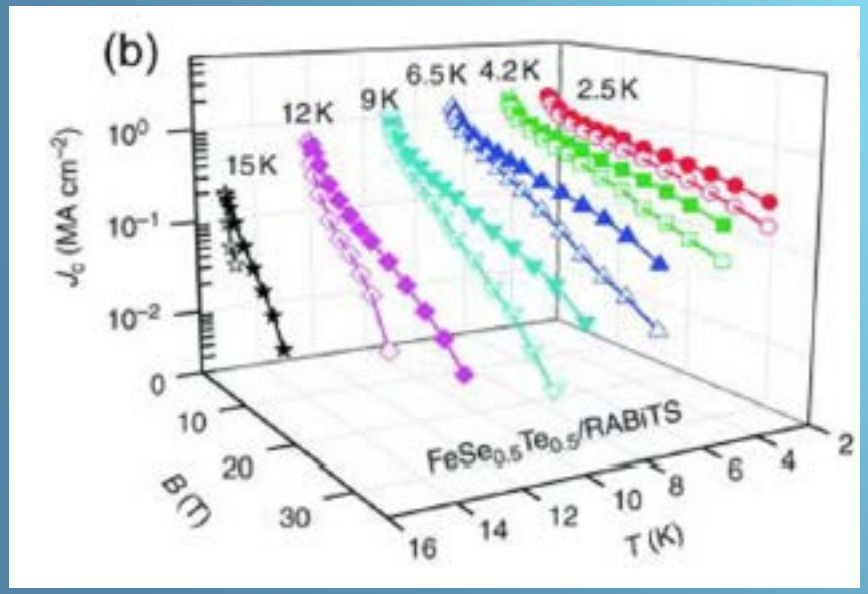




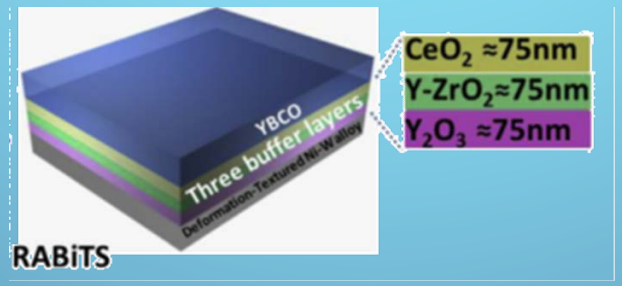
Si W. et al, APL98 (2011) 262509



Xu Z. et al., SUST 30 (2017) 035003

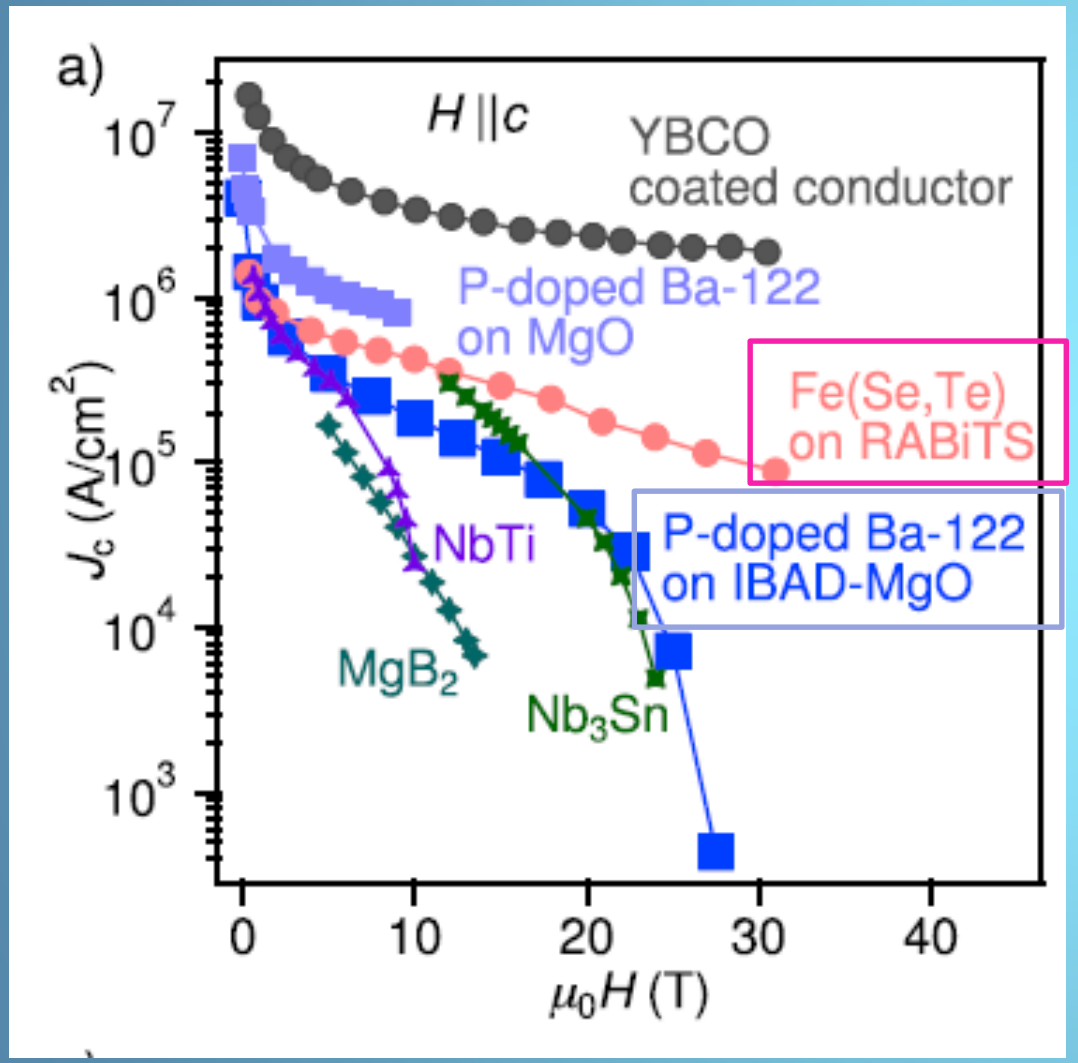


Si W. et al, Nat. Comm 4 (2013) 1347

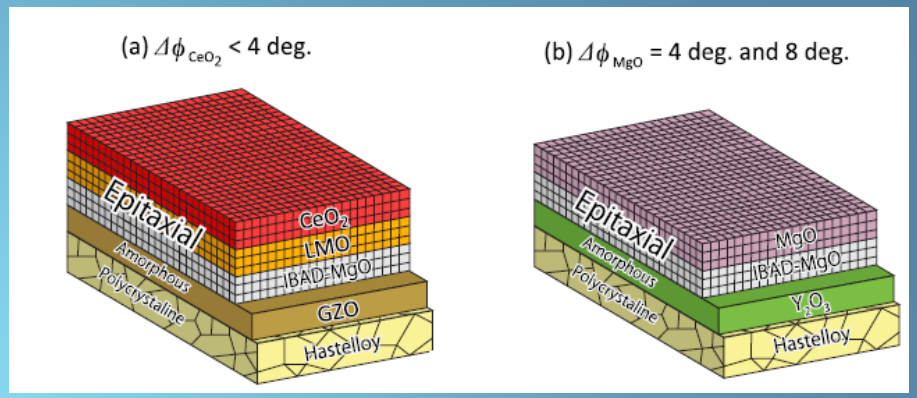


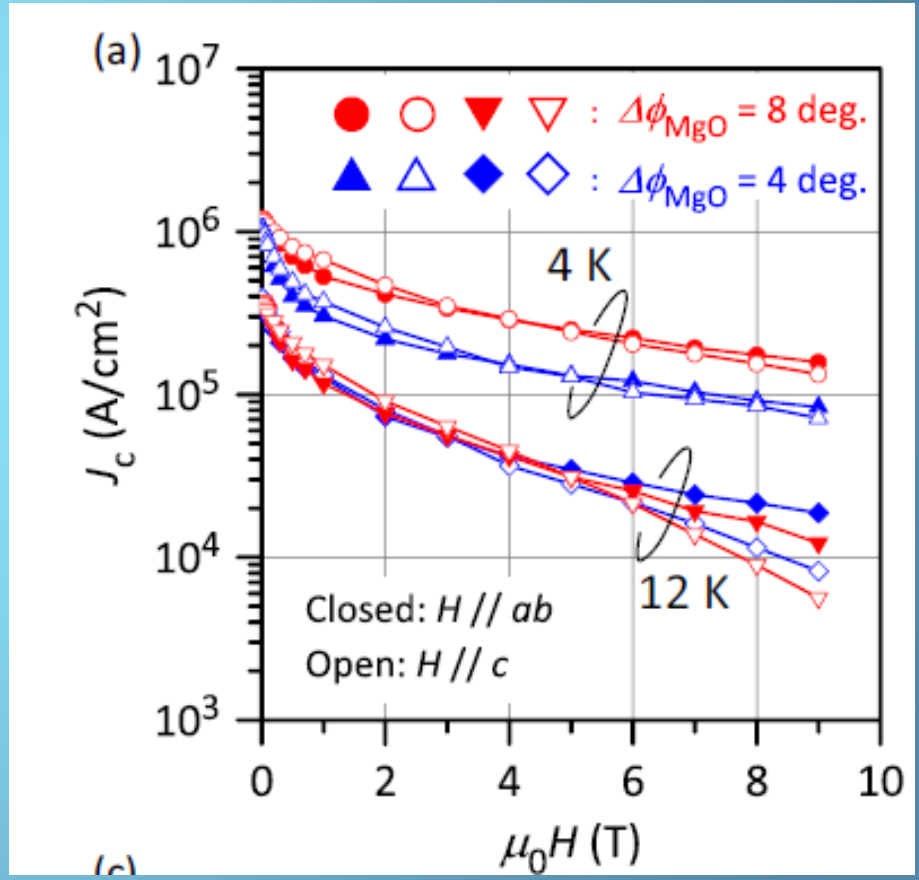
- ✓ Excellent results obtained on 11 thin films growth on IBAD and RABiTS
- ✓ **Jc>$10^5 A/cm^2$ @ 35 T** on RABiTS
- ✓ **Jc>$10^5 A/cm^2$ @ 9 T** on IBAD-LMO with in-plane misaglinment **$\Delta\phi$ ~7.7°**

State of the art 122 IBS -CC



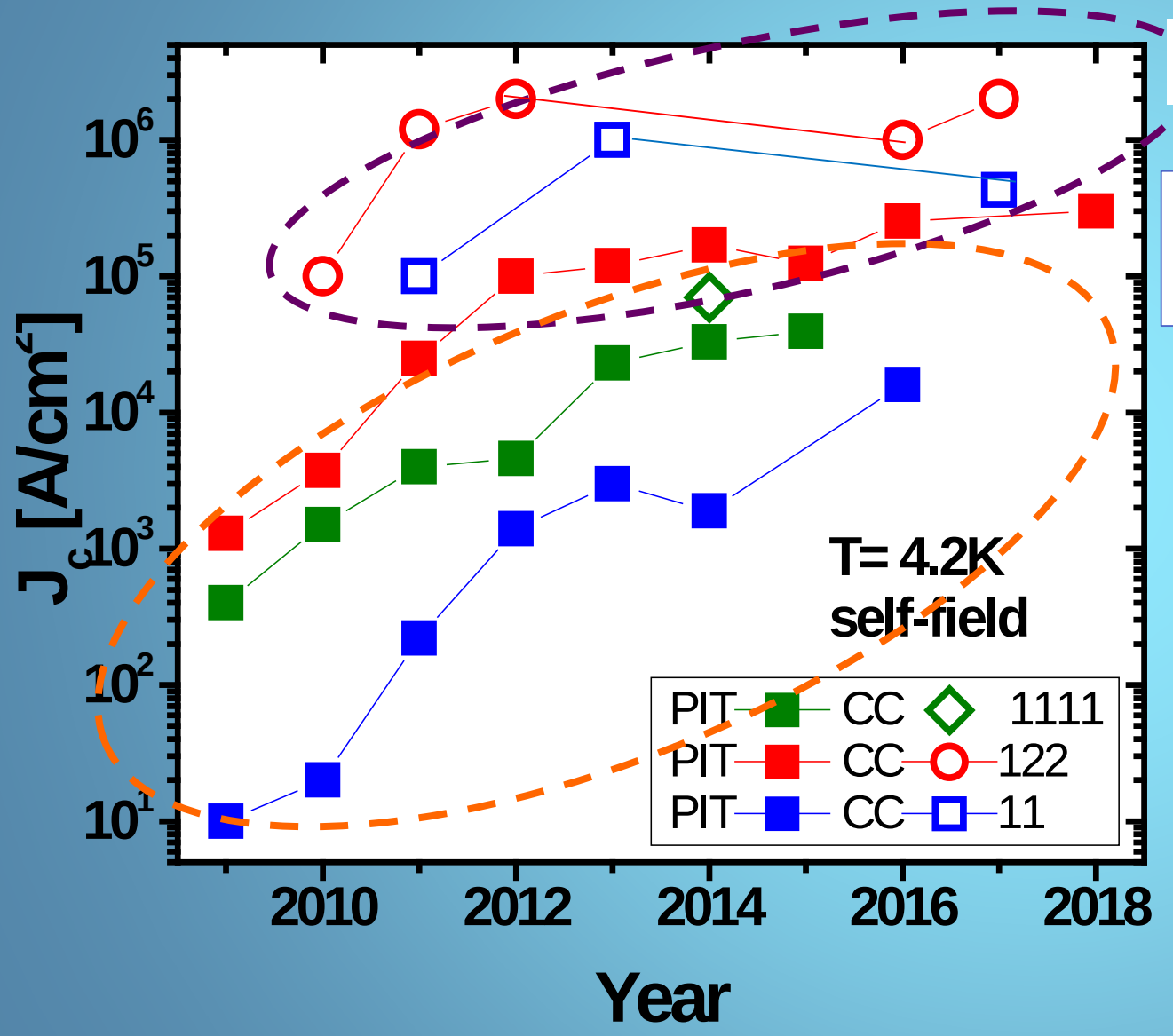
K. Iida et al., Sci. Rep. 7 (2017) 39951.

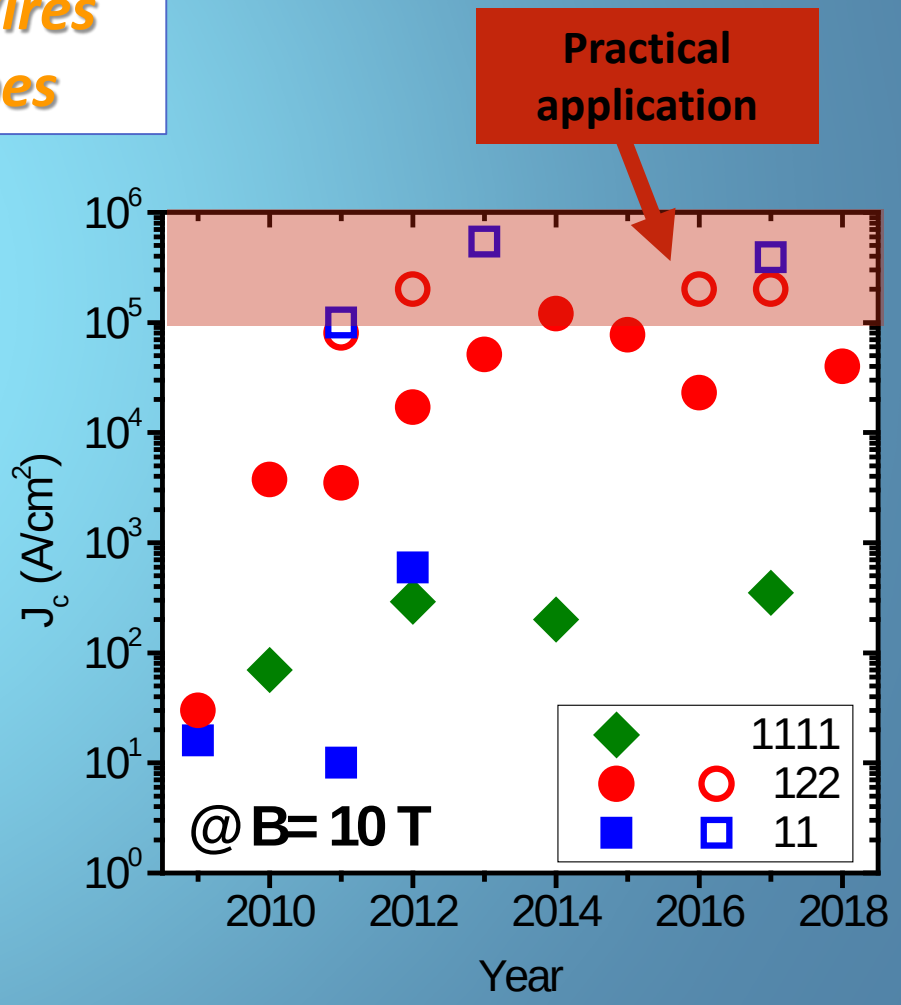




H. Sato et al., Sci. Rep. 6 (2016) 36828

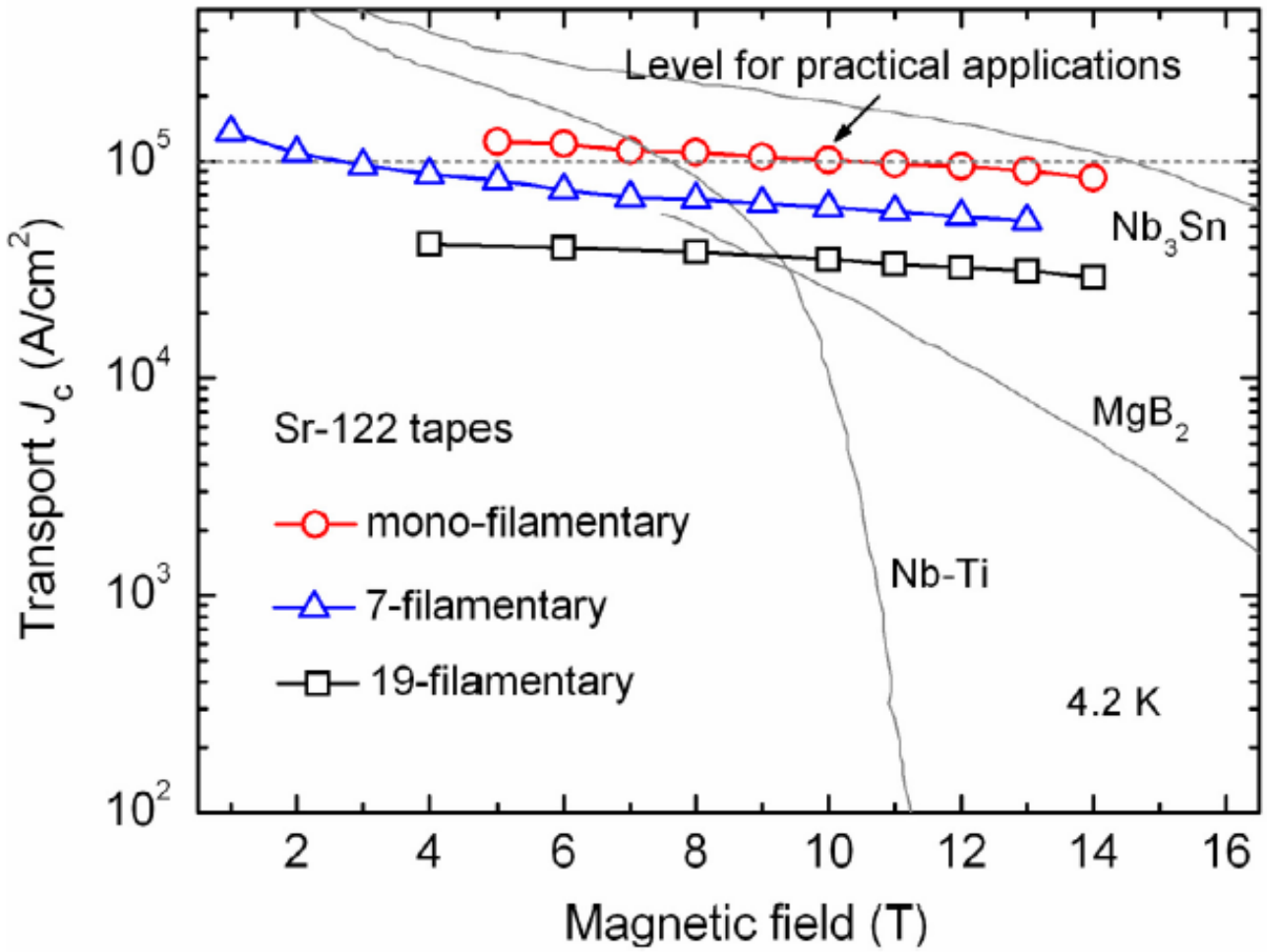
Development of IBS technical conductors over the years





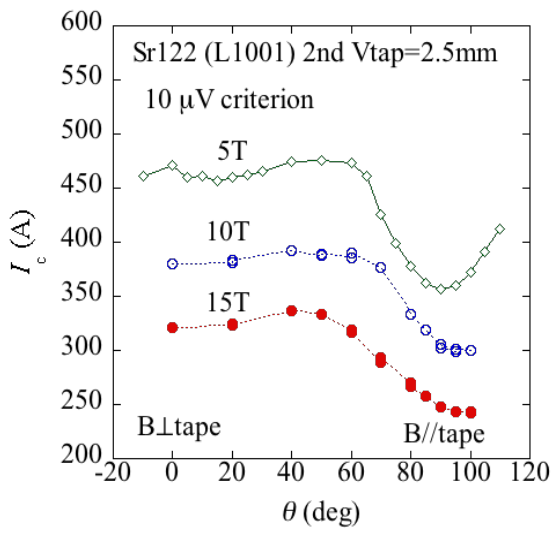
I. Pallecchi, M. Eisterer, A. Malagoli, M. Putti, SUST (2015) 28

122 tapes



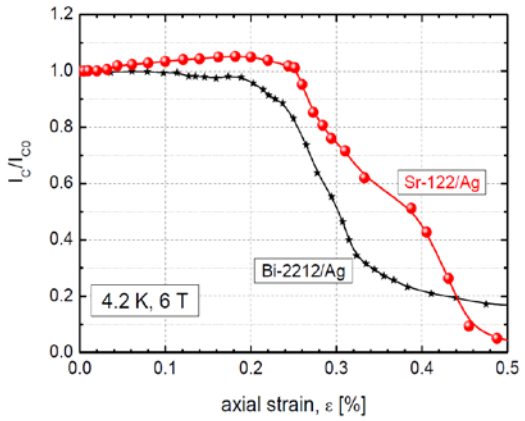
Jc anisotropy

Awaji EUCAS2015



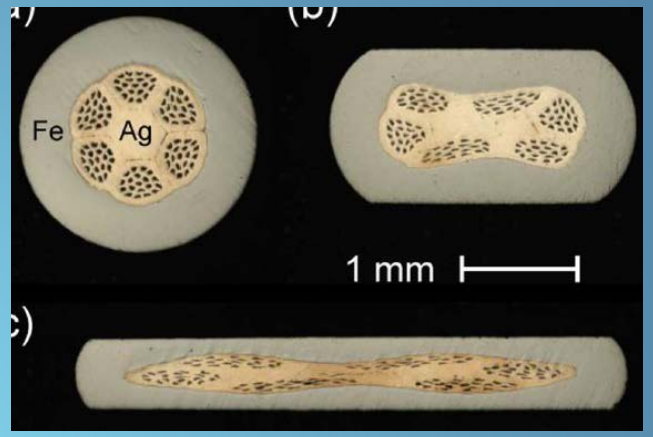
Courtesy: Y.Ma CAS

Effect of strain



H.Hosono, et al., Mater. Today 21 (2018) 278.

Development of 122-PIT wires&tapes using scalable industrial processes at the Institute of Electrical Engineering, Chinese Academy of Sciences (IEECAS).



Cross-section of 114 multi filamentary 122 wires&tapes

The first 100-m-class 122 wire

H.Hosono, et al., Mater. Today 21 (2018) 278.

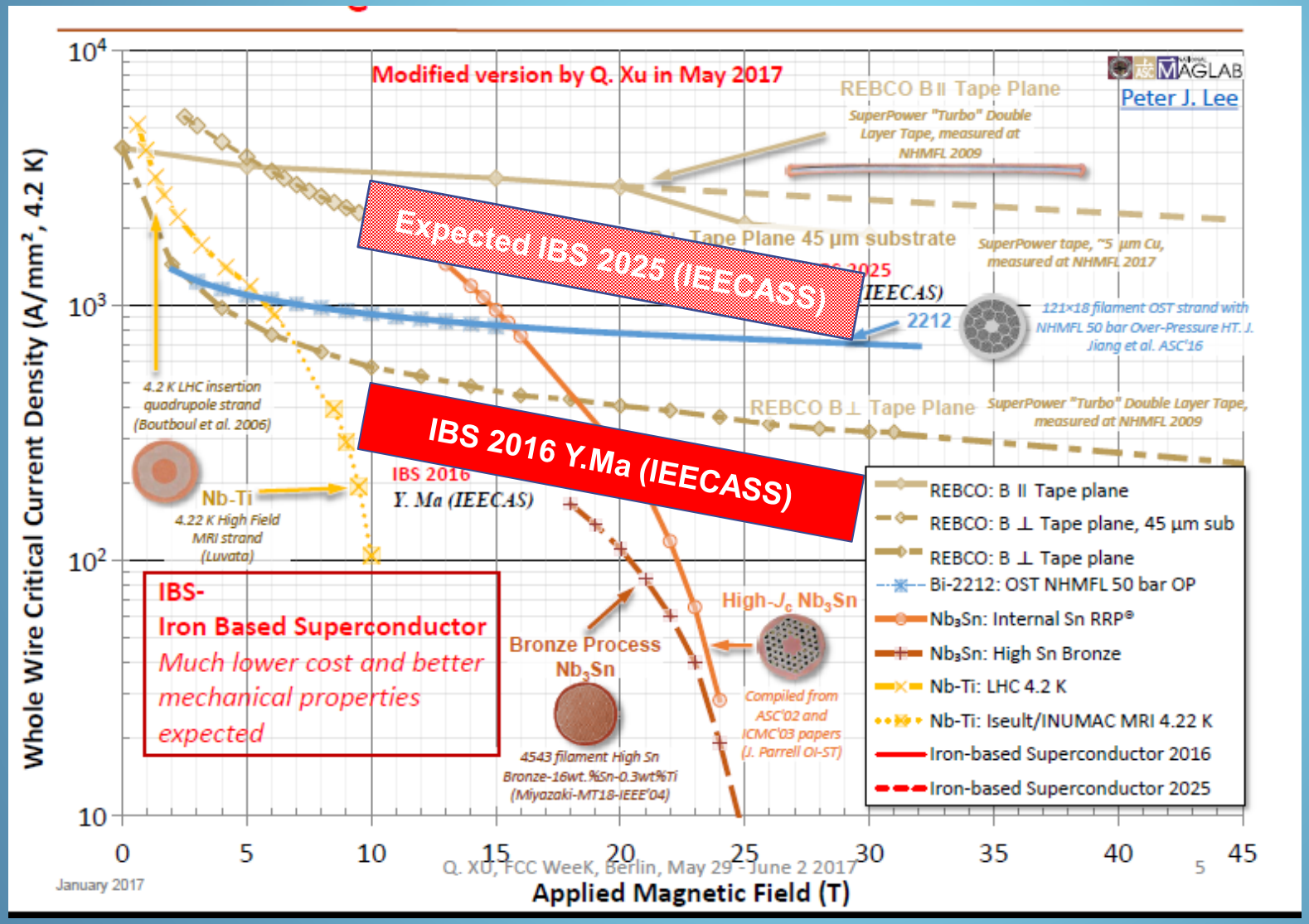
SppC Design Scope (201701 version)

Top priority: reducing cost!
Instead of increasing field

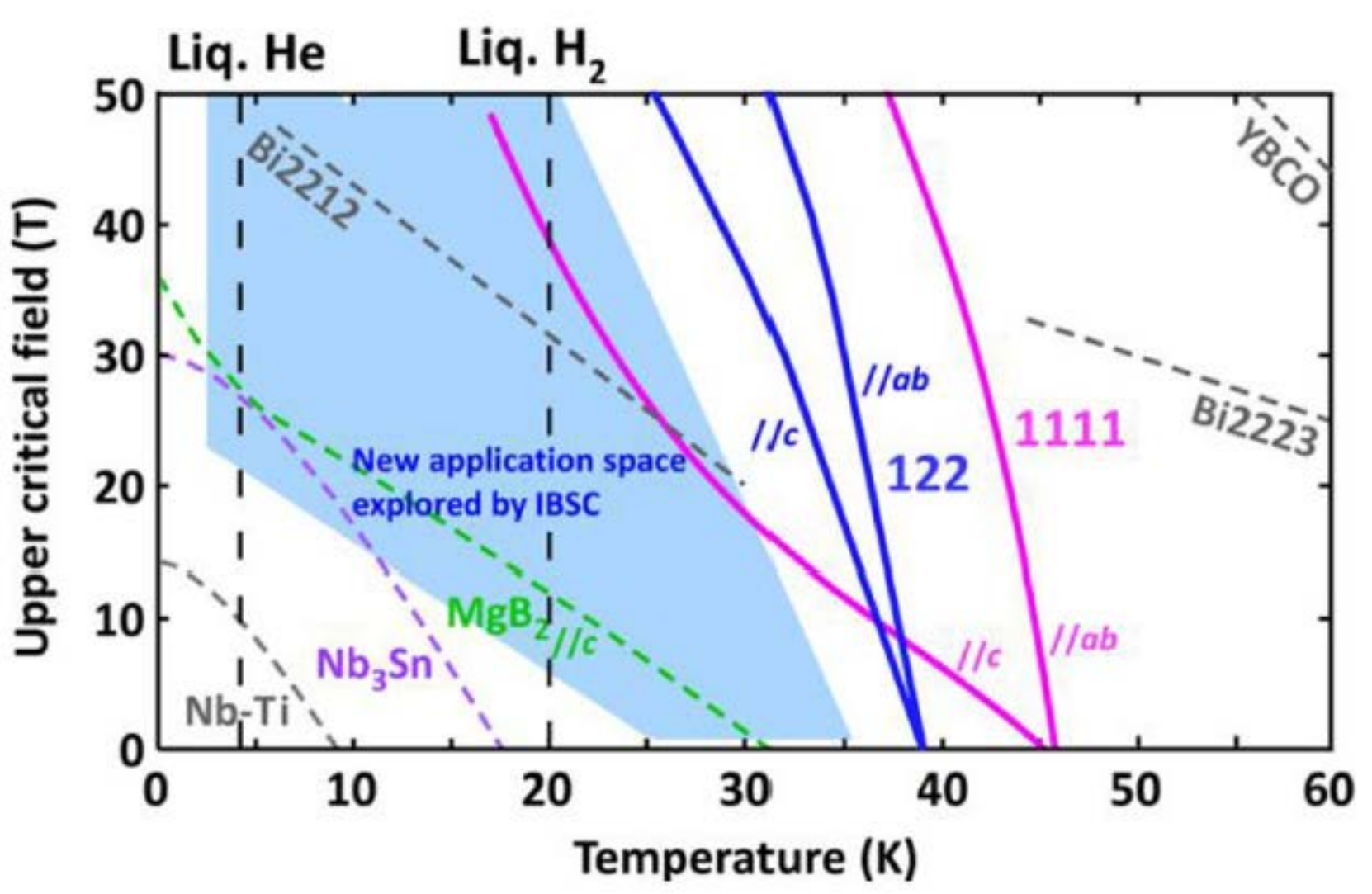
- **Baseline design**
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, iron-based HTS technology (IBS)
  - Center of Mass energy: >70 TeV
  - Injector chain: 2.1 TeV
- **Upgrading phase**
  - Dipole magnet field: 20 -24T, IBS technology
  - Center of Mass energy: >125 TeV
  - Injector chain: 4.2 TeV (adding a high-energy booster ring in the main tunnel in the place of the electron ring and booster)

Engineering critical current

Qingjin XU" Status of high field magnet technology for CEPC-SPPC" **2017 FCC Week** 29 May-2 June 2017 Berlin, Germany



Perspectives



H.Hosono, et al., Mater. Today 21 (2018) 278.

Advantages

- High field superconductors
- Isotropic Jc
- Effective pinning mechanisms
- Suitable for fabrication with cheap method

Disadvantages

- Moderate Tc
- Hazardous material
- Technology too young