# Road to Higher $T_c$

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- **$T_c$ stopped rising in 1993 (more than 20 years 'silence'), but signatures of higher $T_c$'s have come out quite recently:**

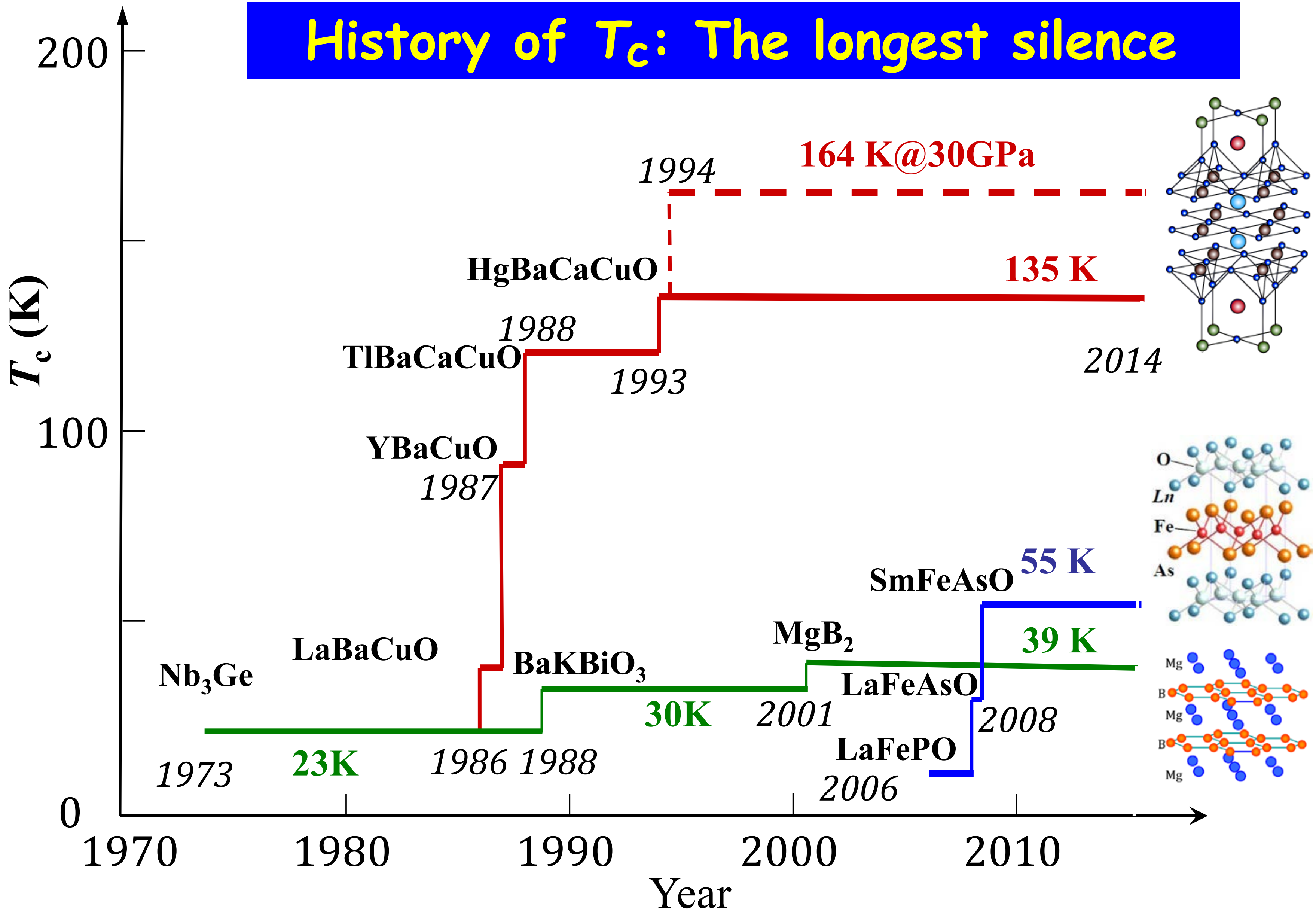
**(1) Monolayer FeSe on $SrTiO_3$**

**(2) Sulfur Hydride under 200 GPa pressure**

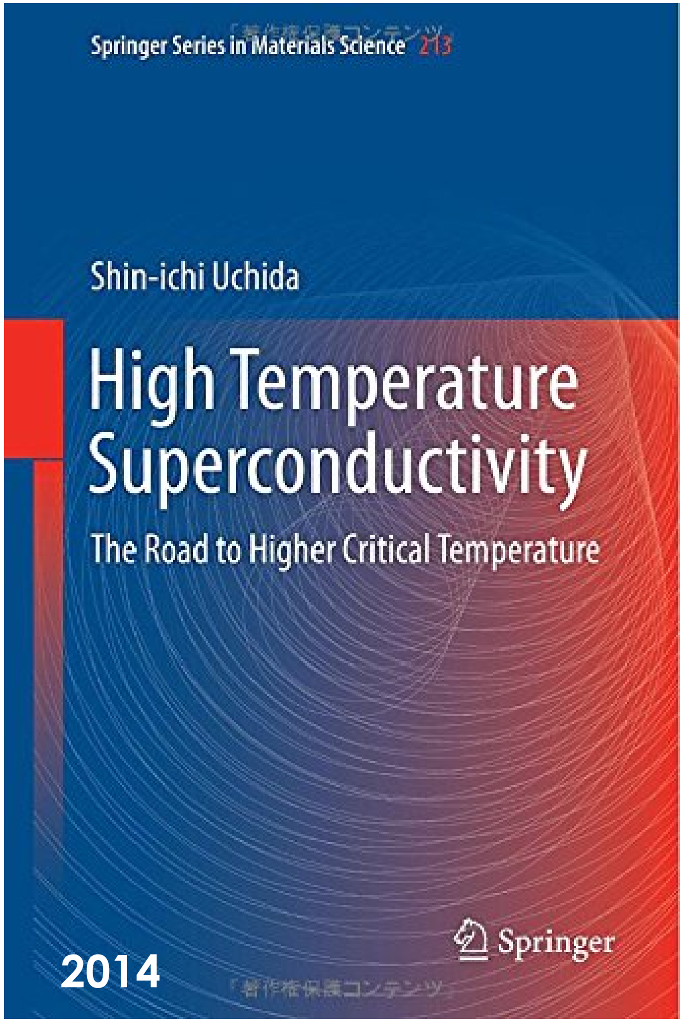
**(3) YBCO under THz laser pulse excitation**

\- *Overview of recent discoveries of higher-$T_c$ signatures* ***under extreme conditions***

# History of $T_c$: The longest silence



# Road to Higher $T_c$

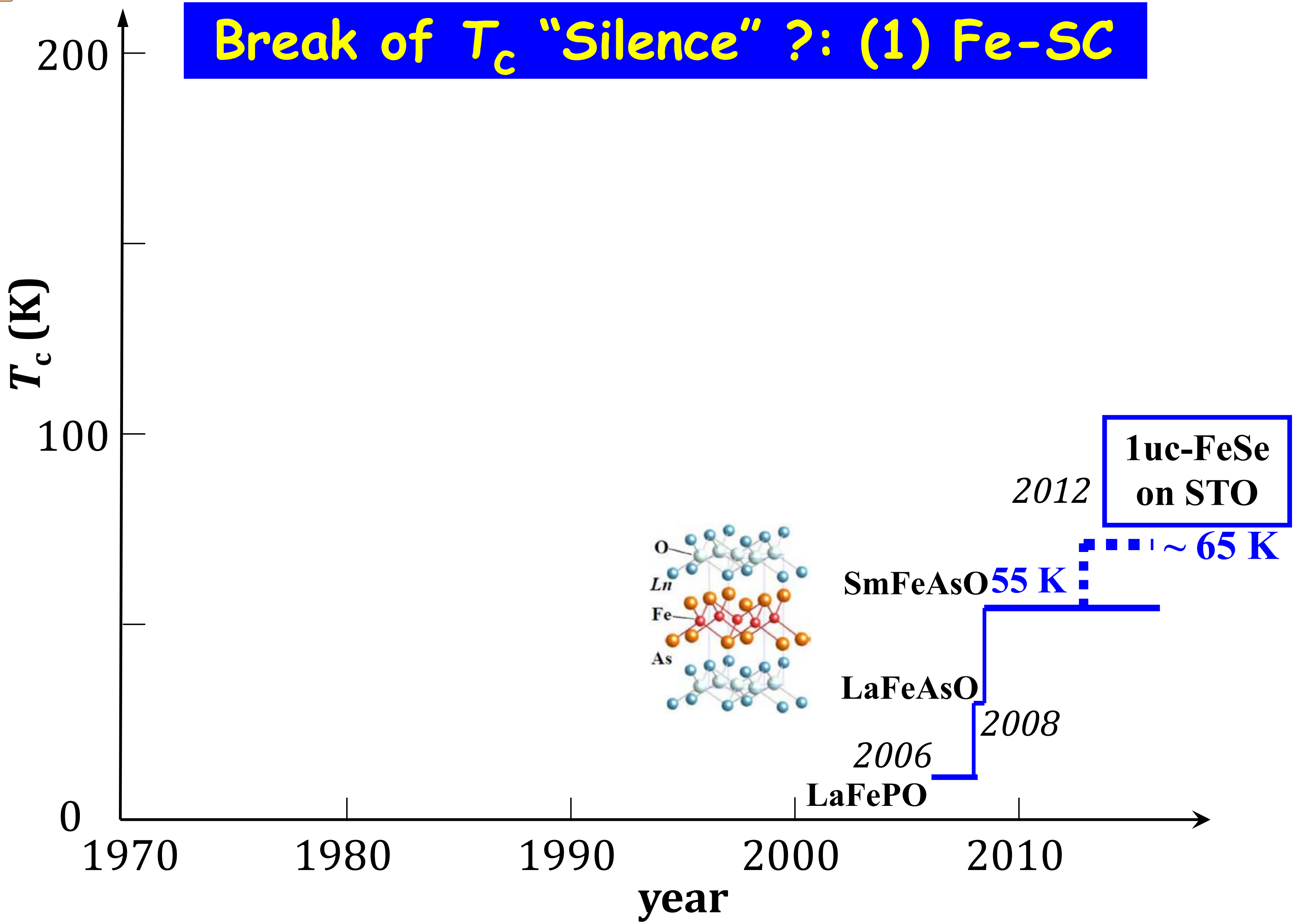



Chapter 2: Phonon-SC

Chapter 3: High-$T_c$ cuprates

Chapter 4: Fe-based SC

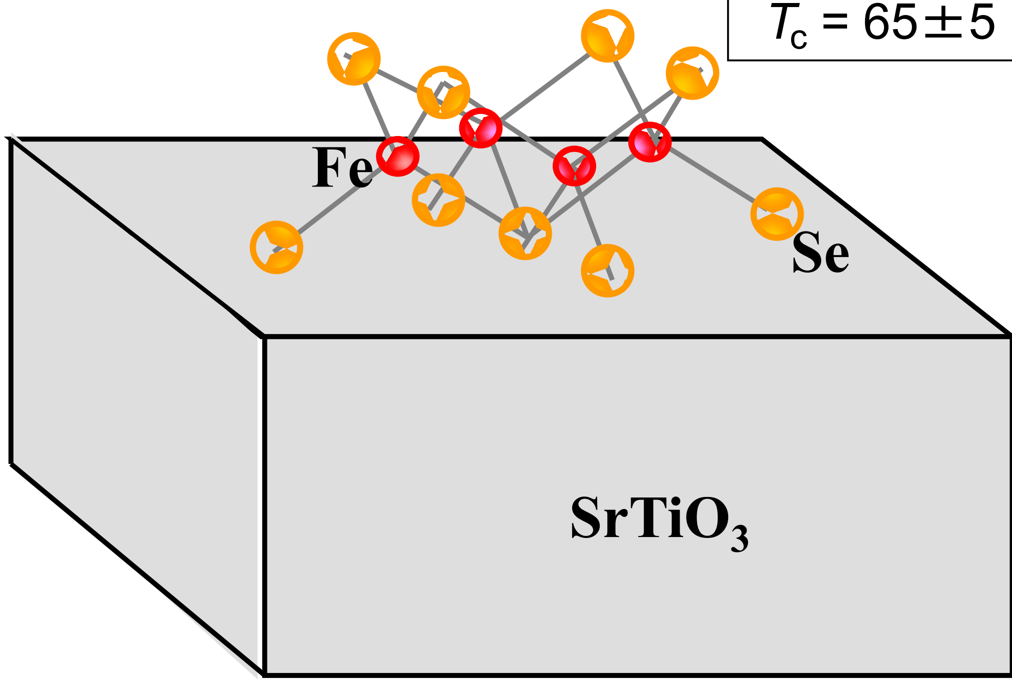
# Break of $T_c$ "Silence" ?: (1) Fe-SC



# FeSe Monolayer on a $SrTiO_3$ Substrate

$T_c = 65 \pm 5$ K

*cf.* $T_c = 8$ K for bulk FeSe




**Q.Y. Wang *et al.*, Chin. Phys. Lett. 29, 037402 (2012).**

**S. He *et al.*, Nature Mater. 12, 605 (2013).**

**J.J. Lee, Z.-X. Shen *et al.*, Nature 515, 245 (2014).**

**J.F. Ge, Q.K. Xue, J.F. Jin *et al.*, Nature Mater. 14, 285 (2015).**

**Y. Miyata *et al.*, Nature Mater. 14, 775 (2015),**

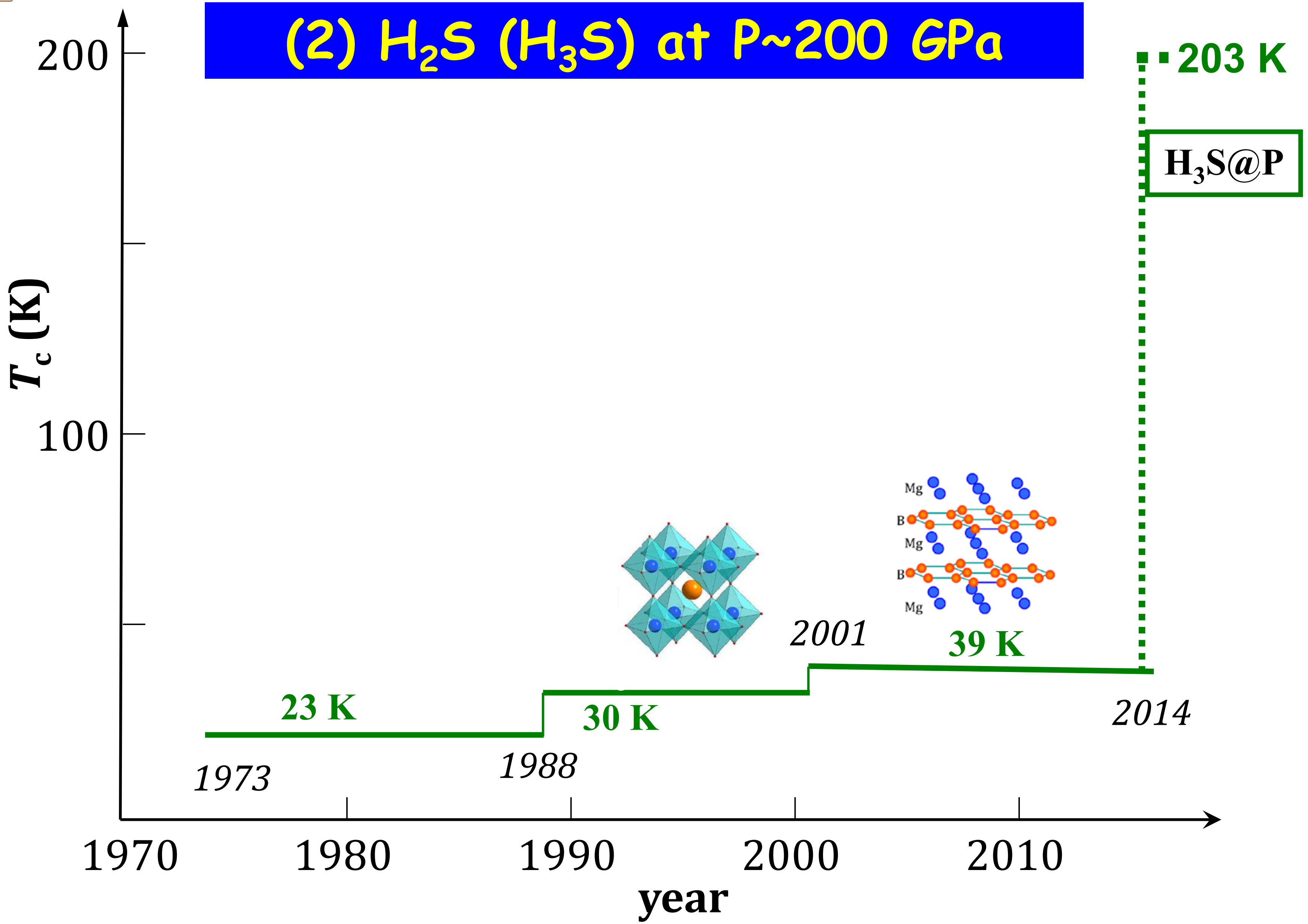
**and many others**

**Review**

**I. Bozovic & C. Ahn, Nature Phys. 10, 892 (2014).**

**Dung-Hai Lee, arXiv: 1508.02461 (2015).**

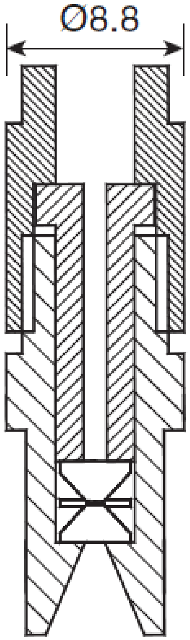
# (2) $H_2S$ ($H_3S$) at P~200 GPa



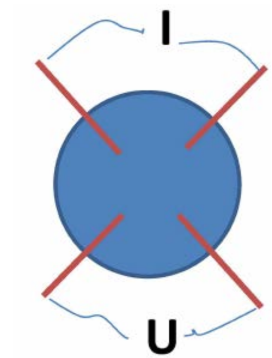
# Sulfur Hydride @200 GPa : Phonon-SC (?)

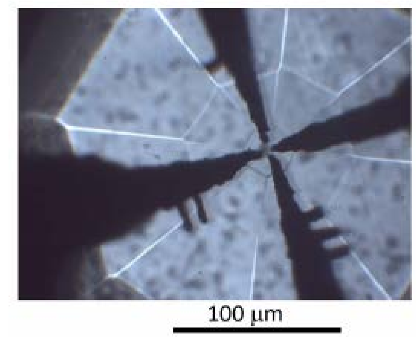
A.P. Drozdov, M.I. Eremets, I.A. Troyan, arXiv:1412.0460.

A.P. Drozdov, M.I. Eremets, I.A. Troyan, V. Ksenofontv & S.I. Shylin, Nature **525**, 73 (2015). (Max Planck, Mainz)




$T_c$ = 203 K



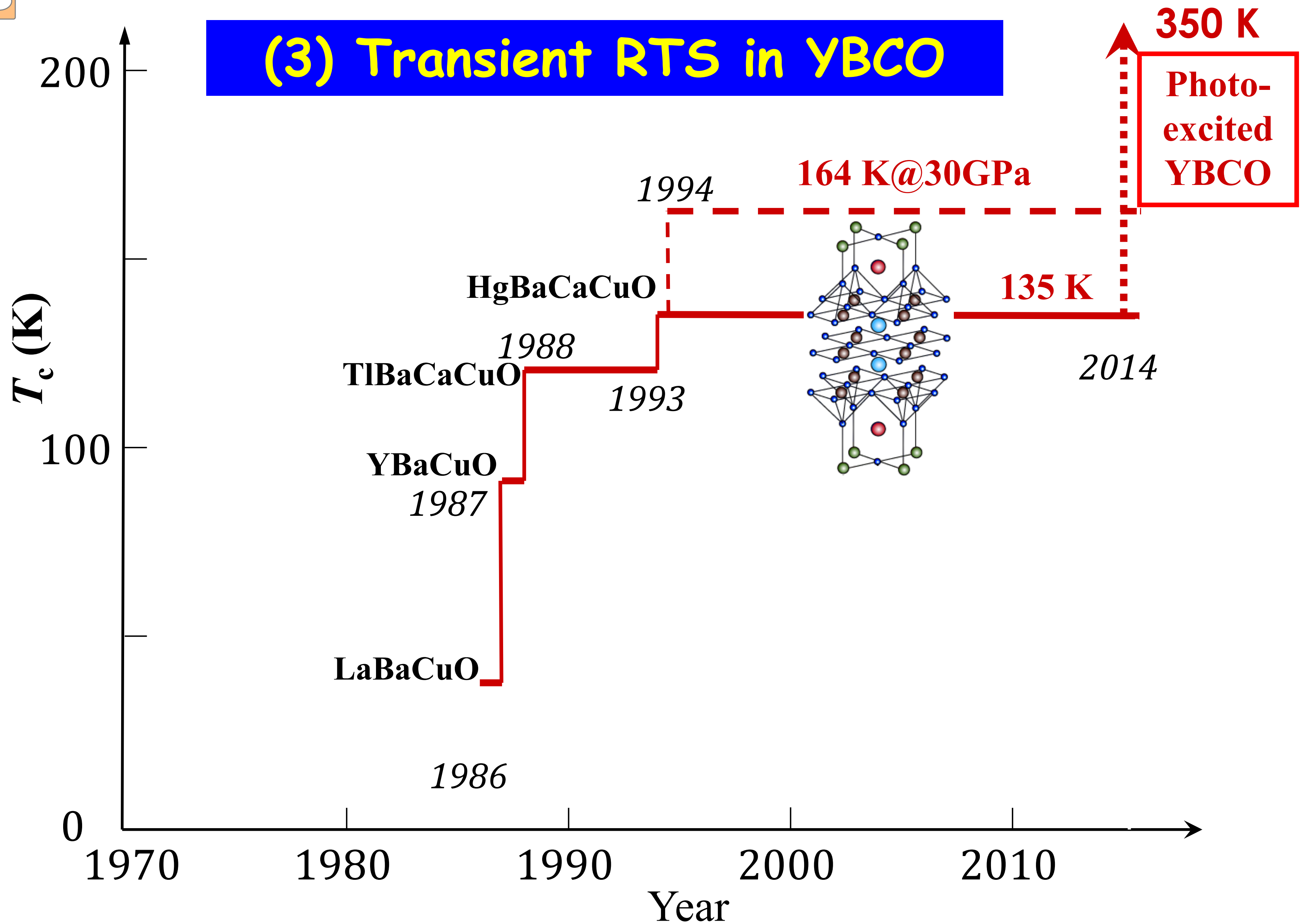

*cf.* Ca @ 210 GPa ($T_c$ = 29 K),

Crystal volume **$V/V_0$ ~ 1/5**

**Theoretical prediction:**

"P-induced metallization of dense $(H_2S)_2H_2$ with high-$T_c$ superconductivity"
D. Duan *et al.*, Sci. Reports **4**, 06968 (2014). (Jilin Univ., Changchun)

# (3) Transient RTS in YBCO



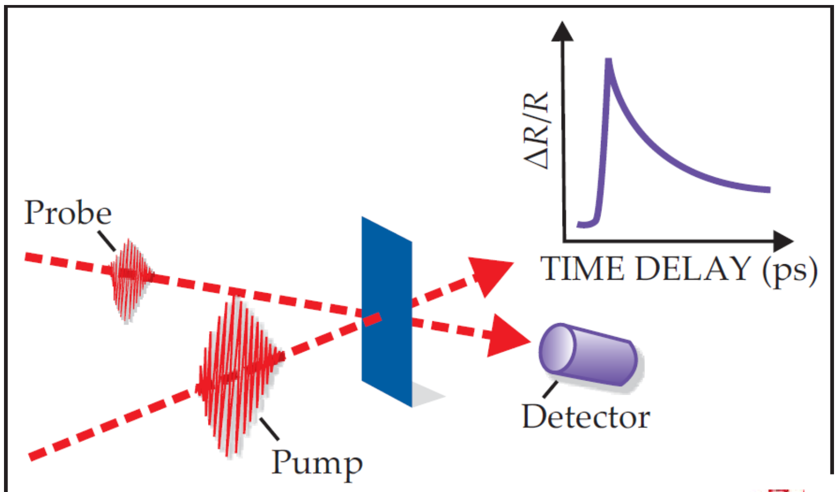
# Optically Induced SC (?) at T≥ 300K in YBCO

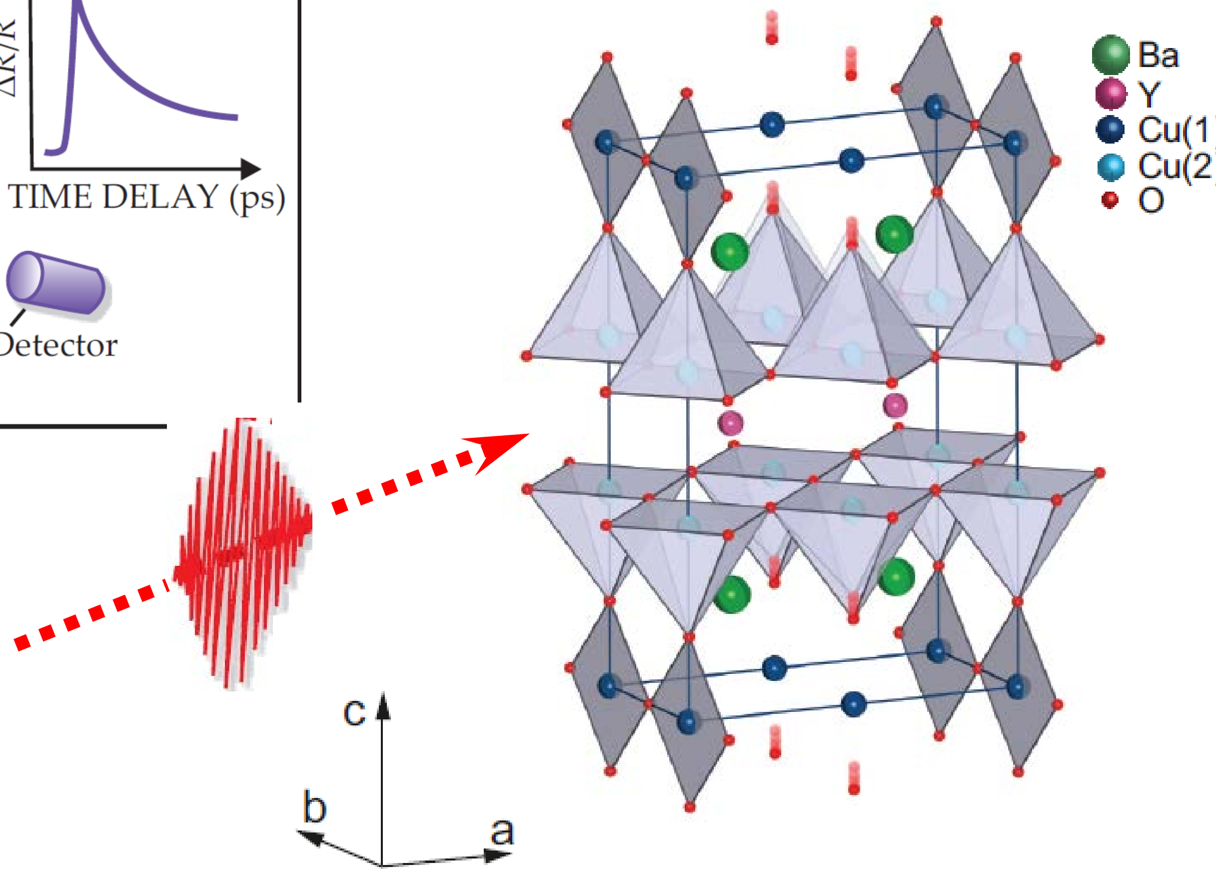
S. Kaiser, A.Cavalleri *et al.*; PRB **89**, 184516 (2014).

W. Hu, A. Cavalleri *et al.*; Nat. Phys. **13**, 705 (2014).

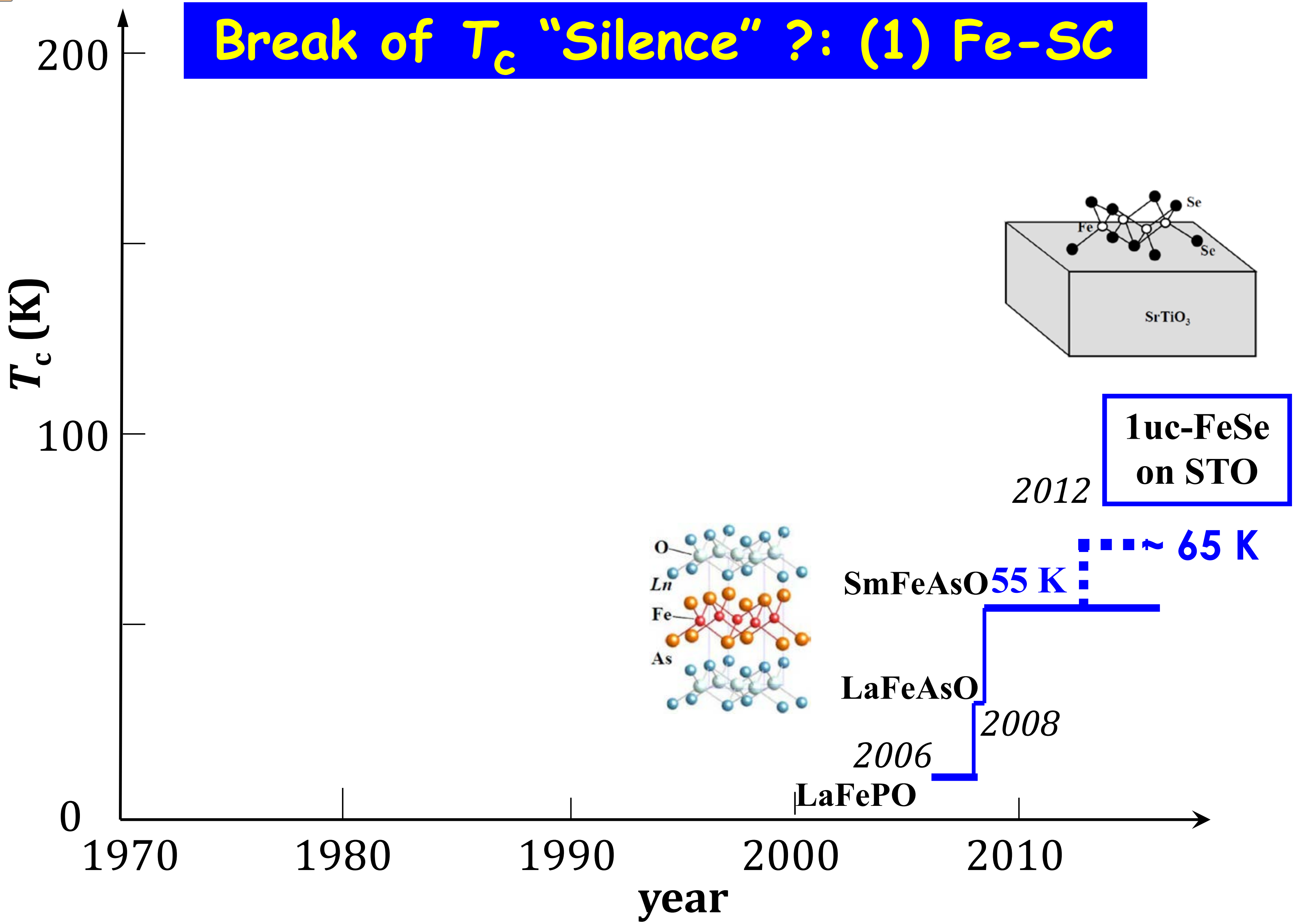
$T_c$ ~ 350 K

(Max Planck, Hamburg)

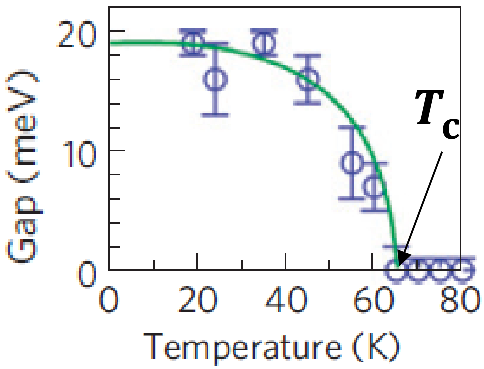


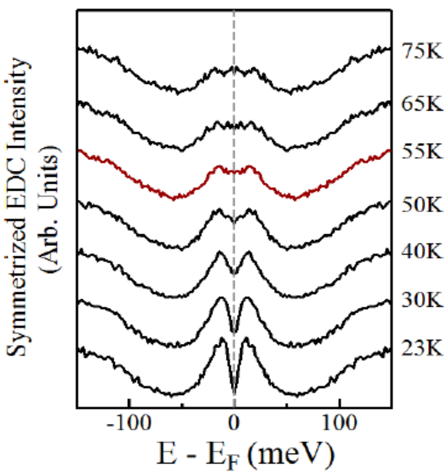



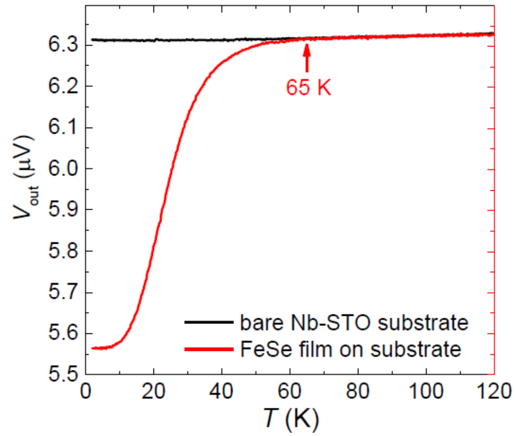
# Break of $T_c$ "Silence" ?: (1) Fe-SC

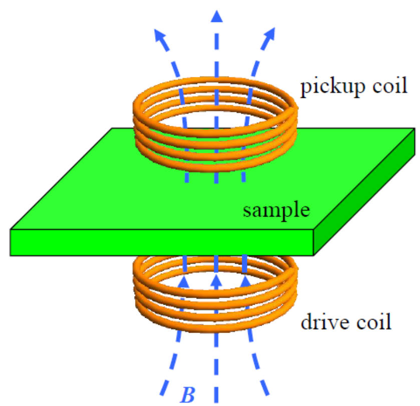


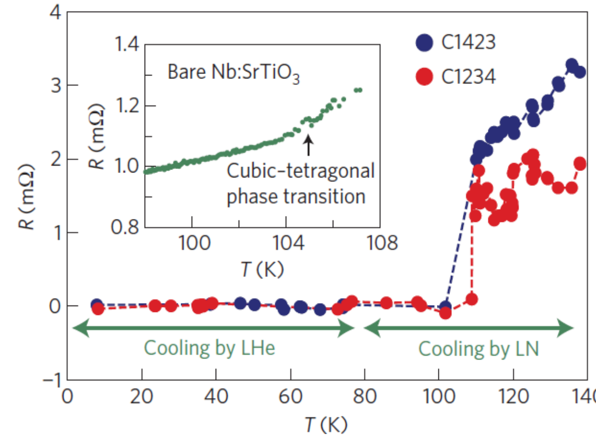
# FeSe Monolayer on a $SrTiO_3$ Substrate



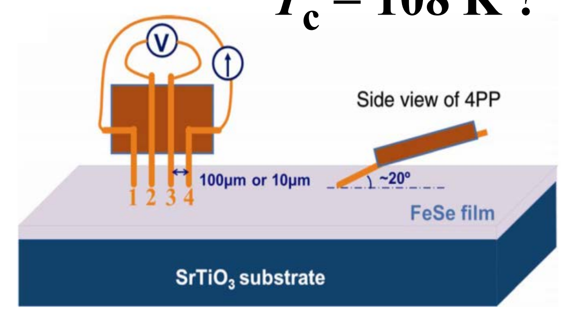




**$T_c$ = 108 K ?**



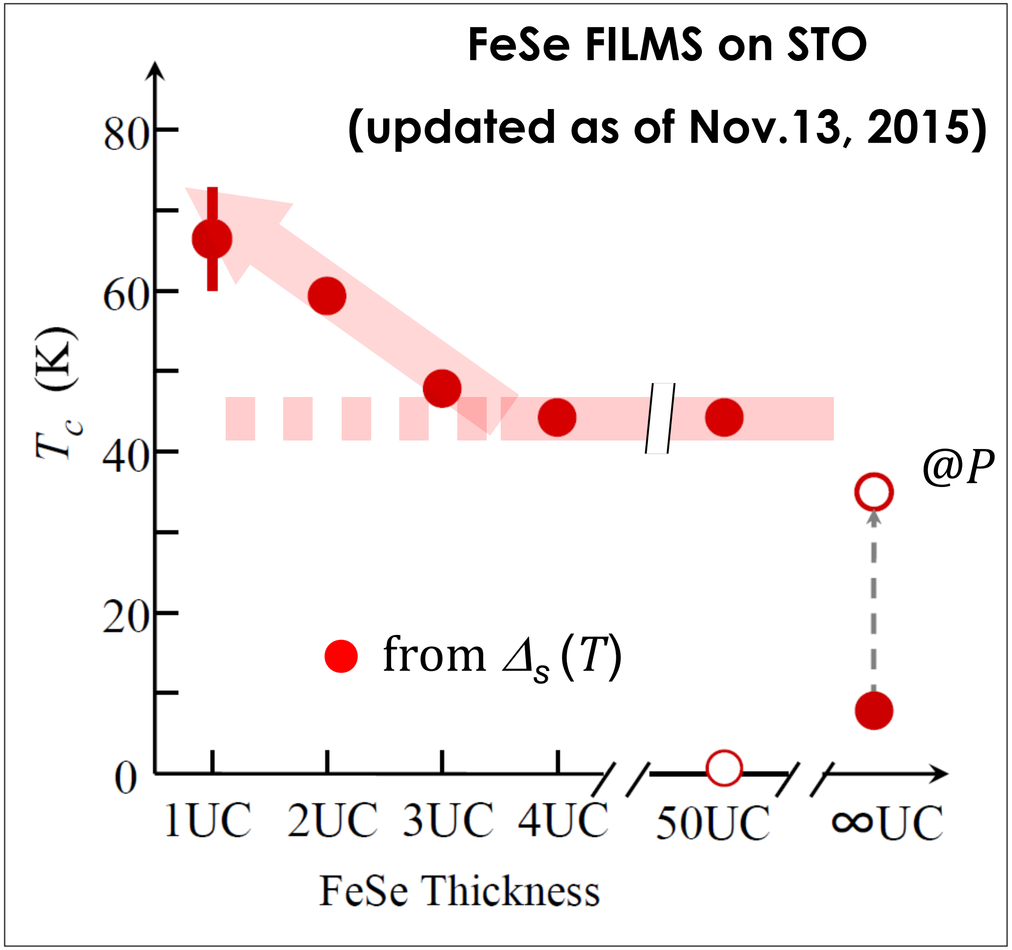

**S. He, Q-K. Xue, X.J. Zhou *et al*., Nature Mater. 12, 605 (2013).**

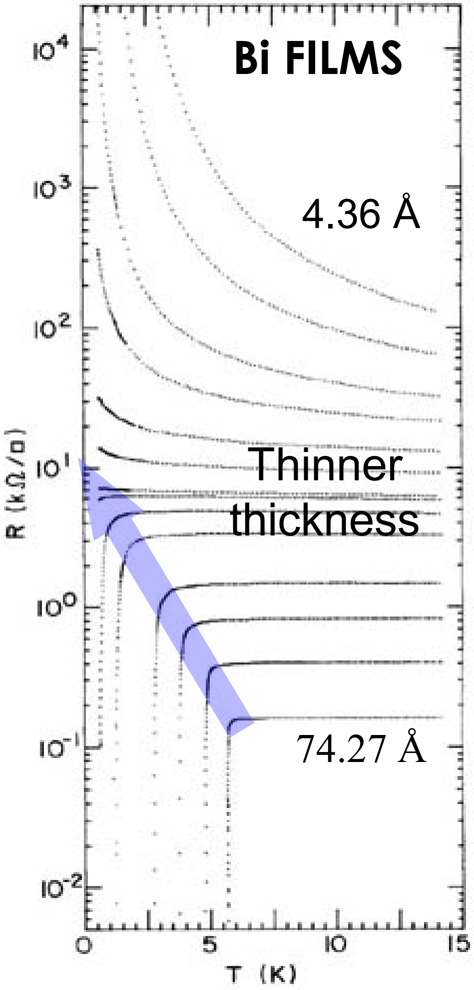
**Z. Zhang, D.-L. Feng, Yayu Wang *et al*., arXiv: 1507.00129**

**J.F. Ge, Q.K. Xue *et al*., Nature Mater. 14, 285 (2015).**

Science Bulletin 60 (14), 1301-1304 (2015)

# Thickness dependence of $T_c$ for FeSe films on STO



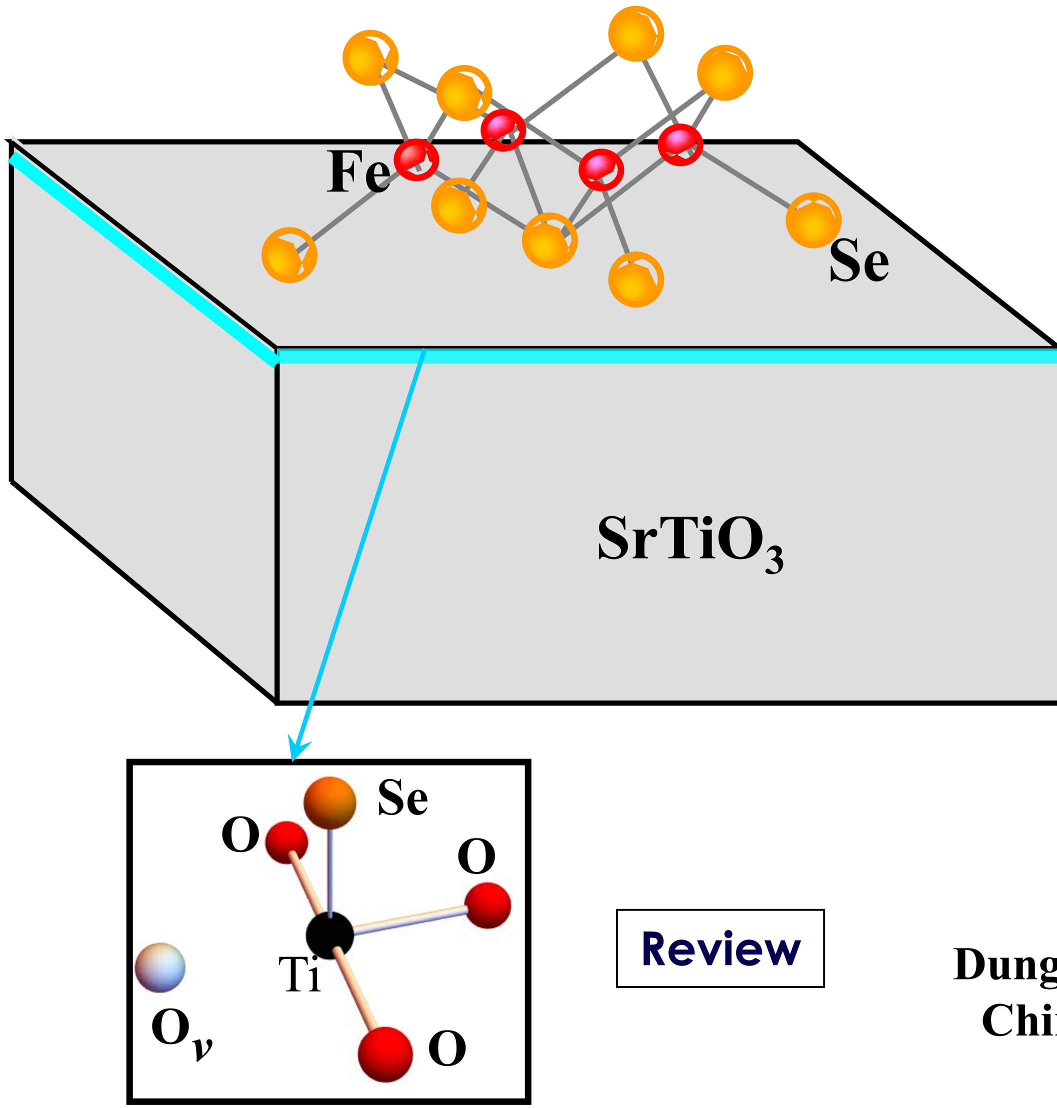

C. Tang, Q.-K. Xue *et al.*, Phys. Rev. B 92, 180507 (2015).

Y. Miyata, T. Takahashi *et al.*, Nature Mater. 14, 775 (2015).

C.H.P. Wen, D.-L. Feng *et al.*, arXiv: 1508.05848.

D.B. Haviland, Y. Liu & A.M. Goldman, Phys. Rev. Lett. 62, 2180 (1989).

# Interface Effects in FeSe Monolayer on STO




$T_c = 65 \pm 5$ K

Interface effects :

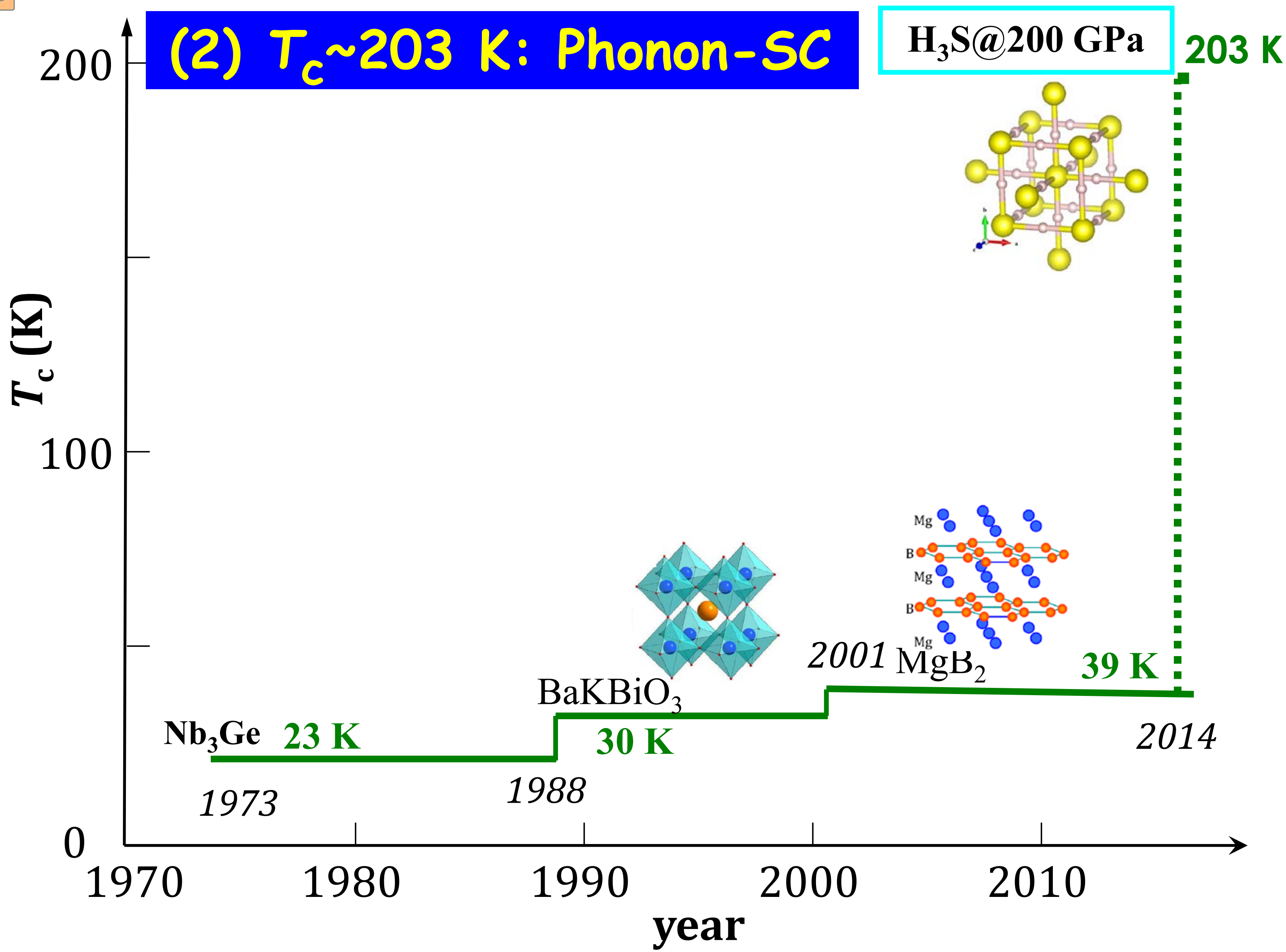
1) An additional pairing channel from a coupling with the bond-stretching O vibrations ($\Omega_0$ ~ 100 meV) in $SrTiO_3$.

2) Electron transfer (doping) from O vacancies in STO

Review

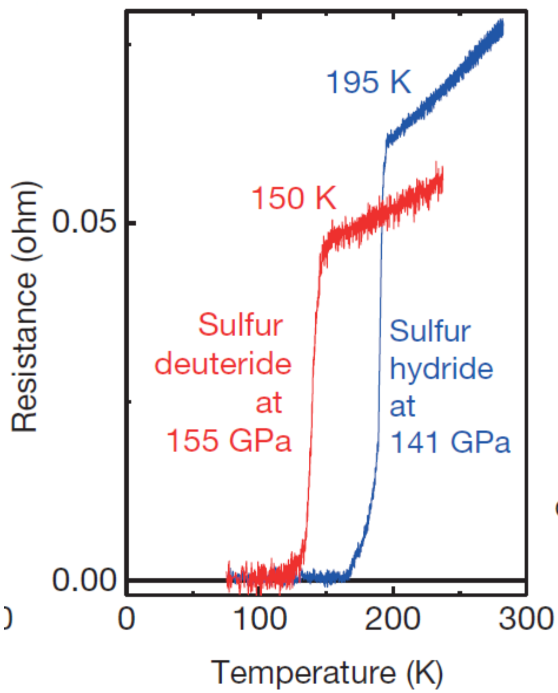
Dung-Hai Lee, arXiv: 1508.02461;
Chin. Phys. B24, 117405 (2015).

# (2) $T_c$~203 K: Phonon-SC

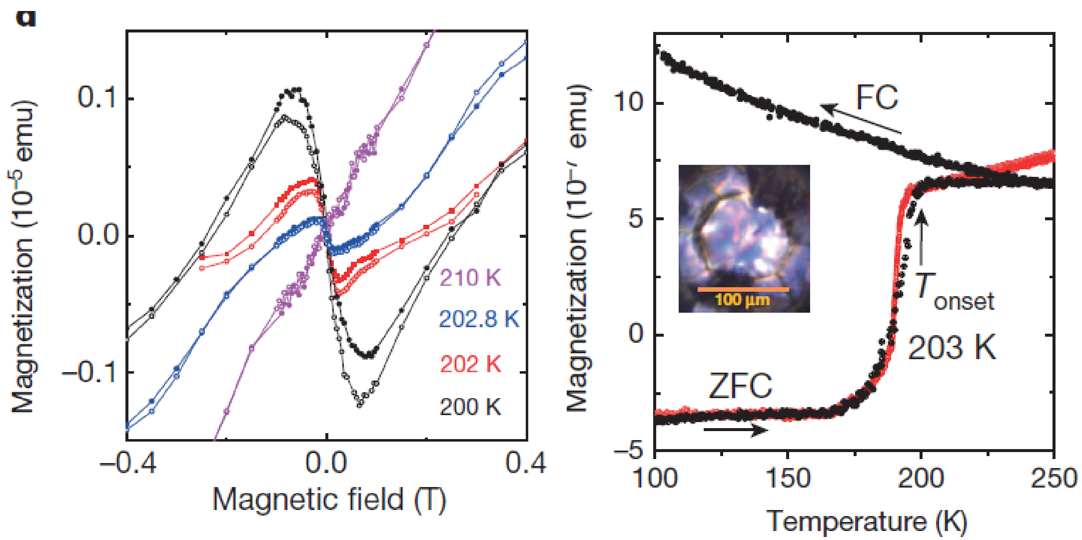


# $T_c$ = 203 K Superconductivity in Sulfur Hydride ($H_3S$) @ P=200 GPa

## Resistance




## Magnetization/ Meissner




A.P. Drozdov, M.I. Eremets, I.A. Troyan, V. Ksenofontv & S.I. Shylin, Nature **525**, 73 (2015).

# $T_c$ bound (ceiling) of "phonon" SC

(McMillan-Allen-Dynes)

$$k_B T_c = \frac{\hbar \langle\omega\rangle}{1.2} \exp\left[-\frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)}\right].$$

Weak to moderate el-ph coupling: $k_B T_c \sim \hbar \Omega_0 \, e^{-1/\lambda}$

For very large $\Omega_0$ and moderate $\lambda$,
no $T_c$ ceiling as long as $\hbar\Omega_0 \ll E_F$

"Hydrogen Dominant Metallic Alloys: HTS?"
N.W. Ashcroft, Phys. Rev. Lett. **92**, 187002 (2004).

Strong el-ph coupling:

*For large* $\lambda$; $T_c \sim \lambda^{1/2}$

⟷ No $T_c$ ceiling as long as a lattice instability can be avoided.

# No $T_c$ bound for "phonon" SC (?)

**4. *H @ 2000 GPa,*** **$T_c$ ~ 750 K**

$\Omega_0 = (K/M)^{1/2}$ ~ 400 meV, $<\omega>$ ~ 2300 K, $\lambda$ ~ 3

J.M. McMahon & D.M. Ceperley, Phys. Rev. B **84**, 144515 (2011).

**3. *$H_3S$ @ 200 GPa,*** **$T_c$ ~ 200 K**

$\Omega_0 = (K/M)^{1/2}$ ~ 200 meV, $<\omega>$ ~ 1300 K, $\lambda$ ~ 2.2

**2. *$MgB_2$ @ 0 Pa,*** **$T_c$ ~ 40 K**

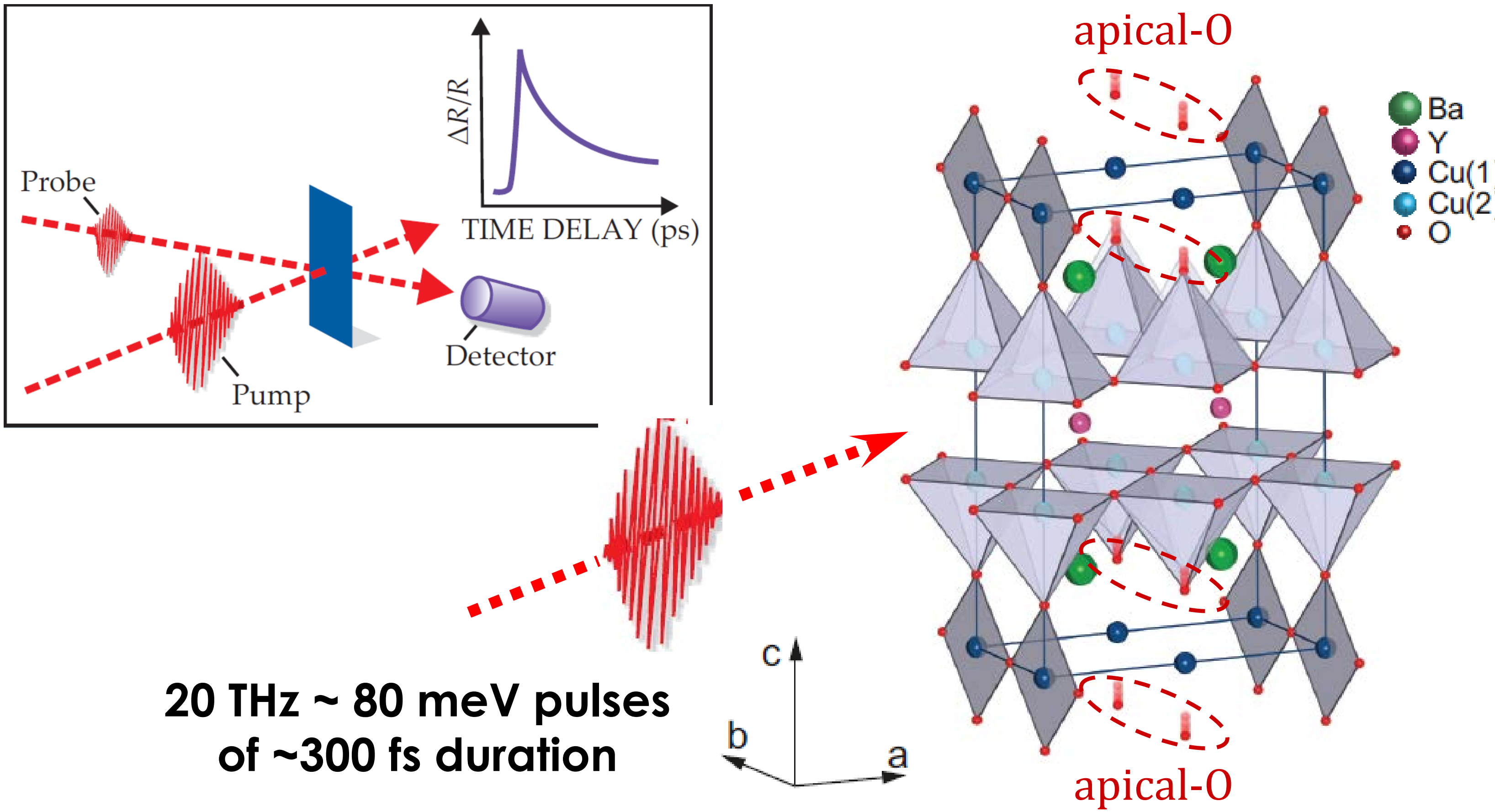
$\Omega_0 = (K/M)^{1/2}$ ~ 80 meV, $<\omega>$ ~ 600 K, $\lambda$ ~ 1

**1. *doped $BaBiO_3$ ,*** **$T_c$ ~ 30 K**

*Unstable against CDW*

# (3) Resonant excitation of 20THz apical-O phonon in underdoped YBCO

S. Kaiser, A.Cavalleri *et al.*; PRB **89**, 184516 (2014).



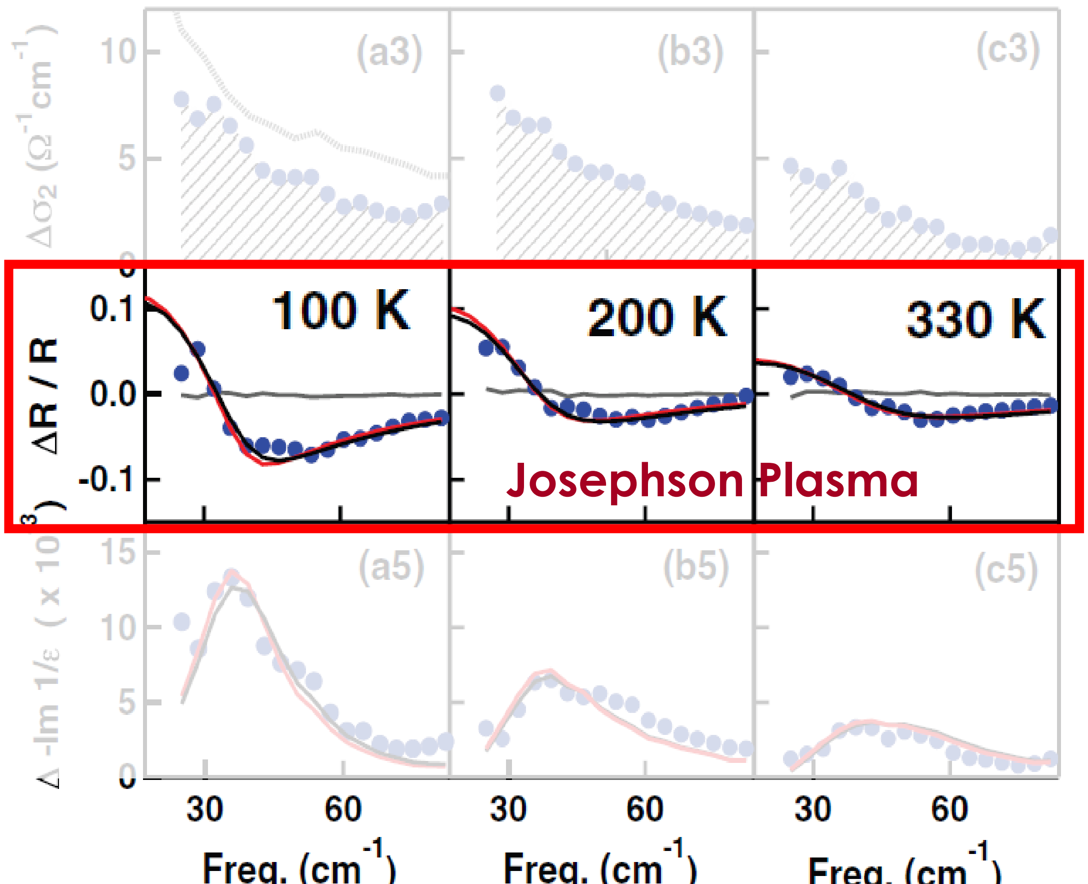

**20 THz ~ 80 meV pulses of ~300 fs duration**

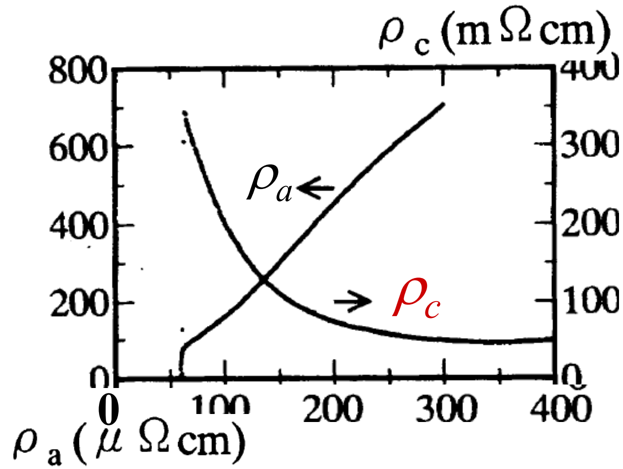
# Transient "RTS" ('$T_c$' > 300 K) in YBCO

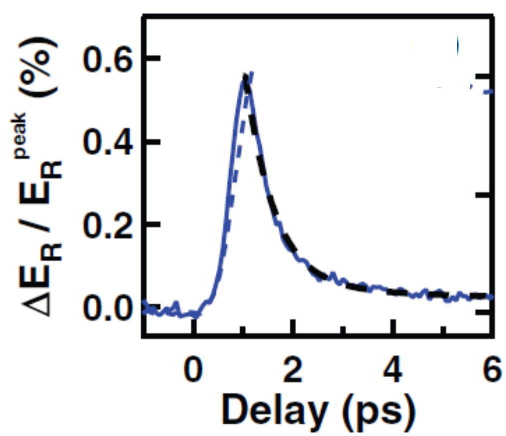
Emergence of Josephson plasma in several picosec. duration

S. Kaiser, A.Cavalleri *et al.*; PRB **89**, 184516 (2014).

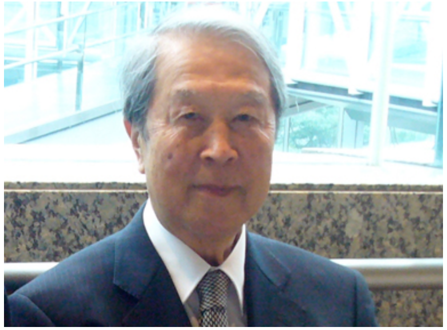
$YBa_2Cu_3O_{6.45}$ $T_c$ = 35 K



# Consequences of Broken Gauge Symmetry: SC



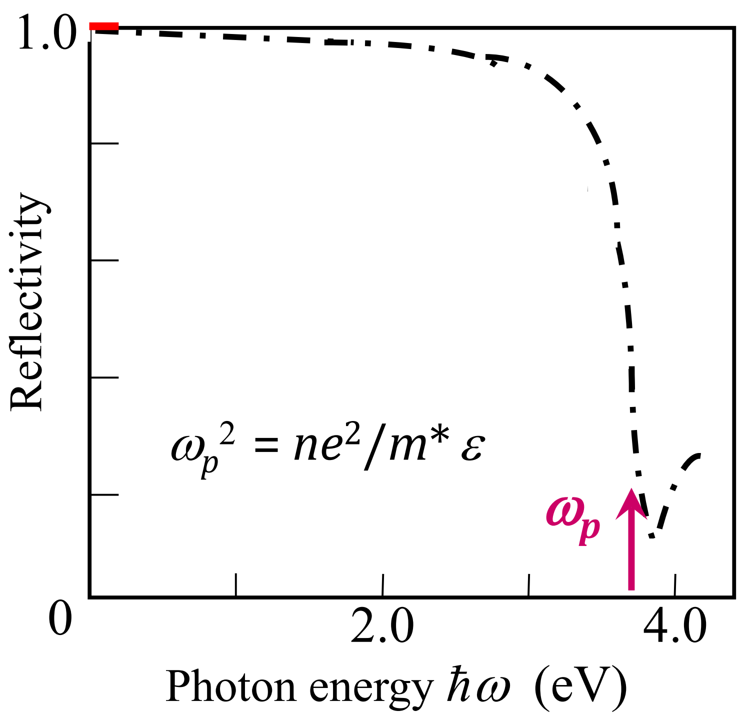
Yoichiro Nambu

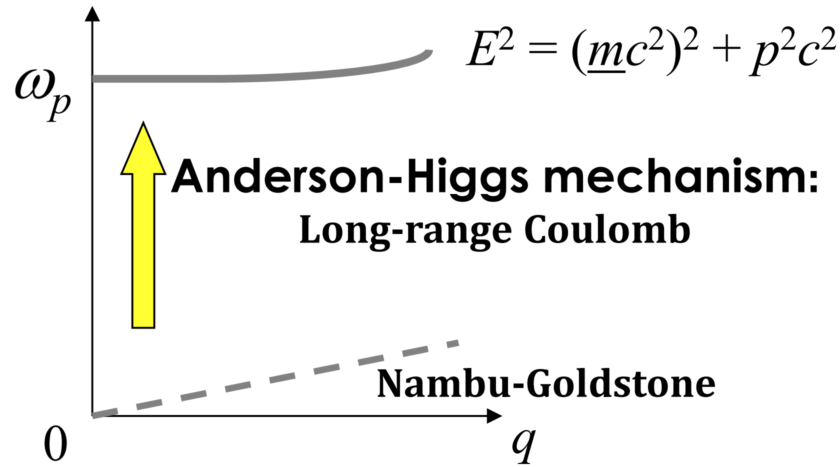
**Emergence:**

1. "Stiffness": *Zero resistance & Meissner effect*
2. Topological defects: *Vortex*
3. Collective mode: *Anderson-Higgs*

# Broken Gauge Symmetry: "Collective mode"

Reflectivity spectrum of a conventional superconductor



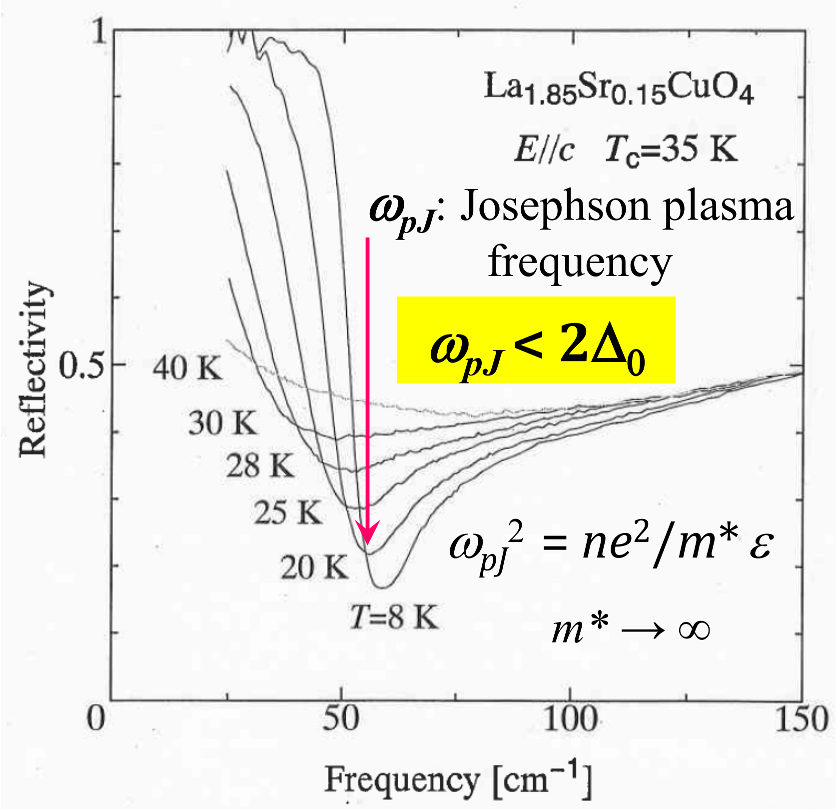

**Indistiguishable from the spectrum in the normal state ($T > T_c$)**

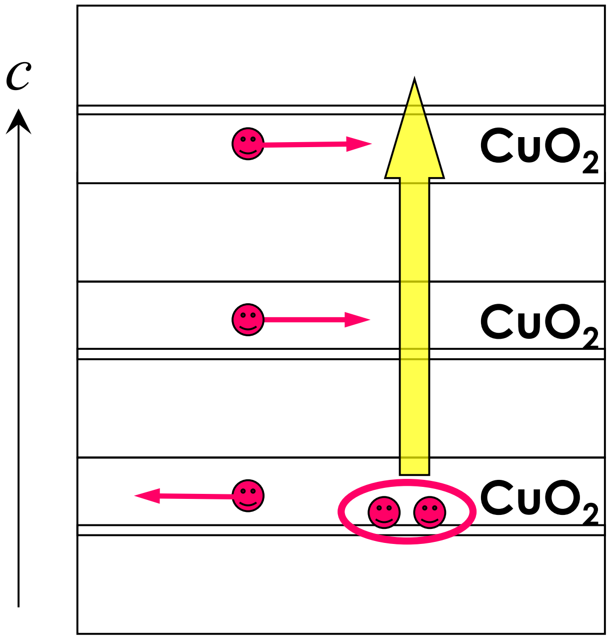
**P.W. Anderson: Phys. Rev. <u>130</u>, 439 (1963)**

**P.W. Higgs: Phys. Rev. Lett. <u>13</u>, 508 (1964)**

# Josephson Plasma Mode: c-axis high-$T_c$ cuprates

## Interlayer phase coherence is established at $T_c$: Forming a Josephson-junction array along the c-axis



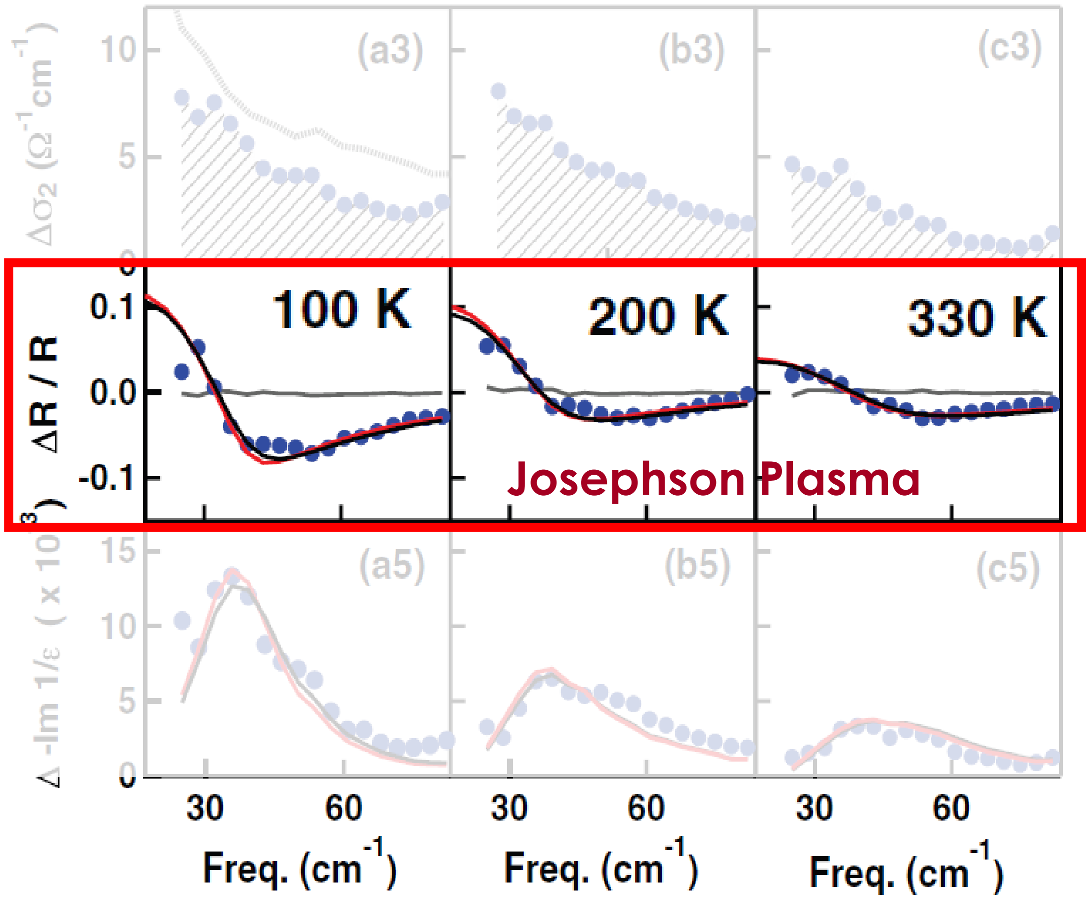

K. Tamasaku, Y. Nakamura & S. Uchida, Phys. Rev. Lett. **69**, 1455 (1992).
O.K.S. Tsui, N.P. Ong *et al*., Phys. Rev. Lett. **73**, 724 (1994).

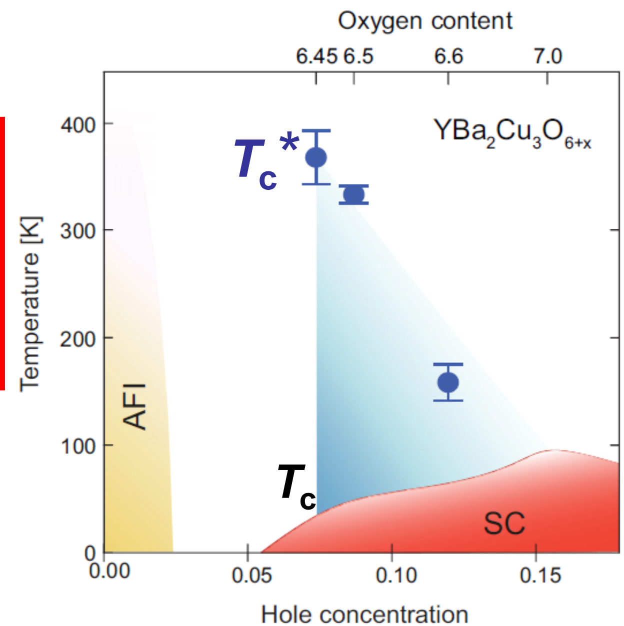
# Transient "RTS" ('$T_c$' > 300 K) in YBCO

## Excitation of large amplitude c-axis apical-O phonon

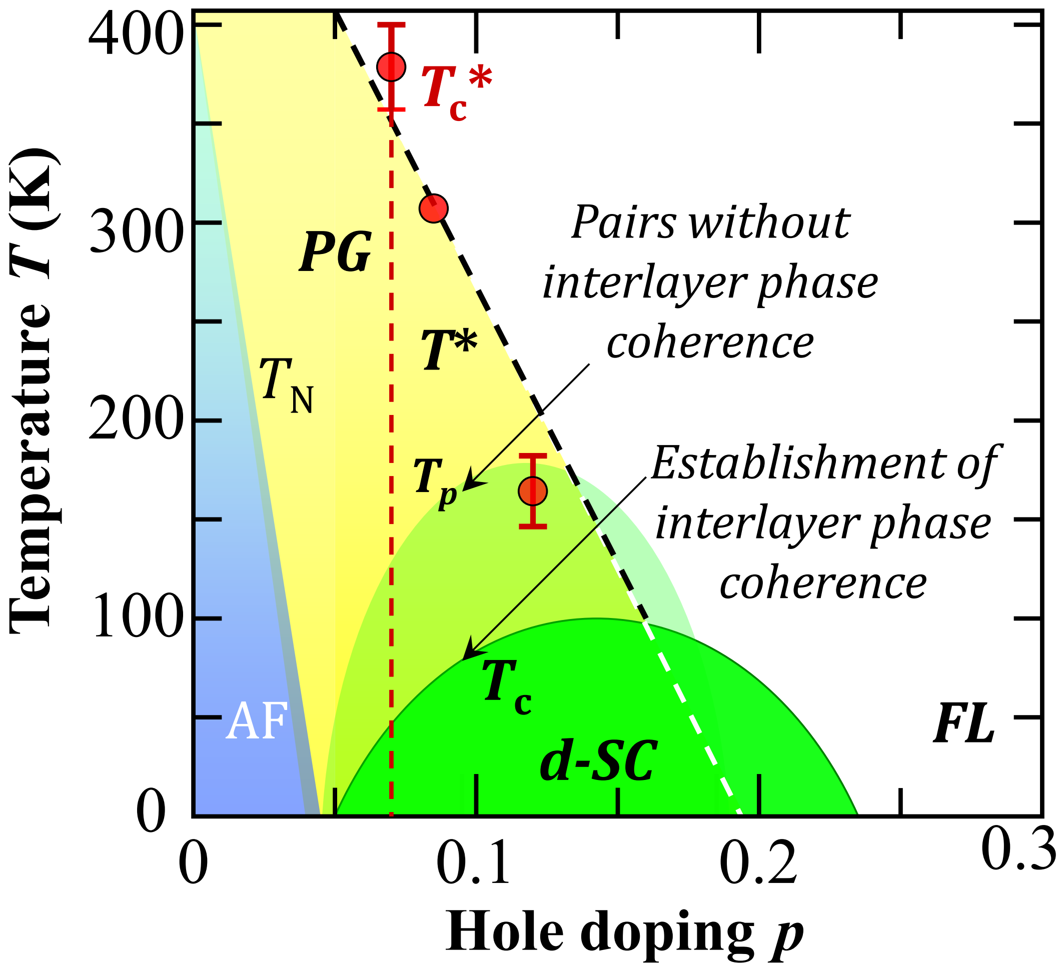
S. Kaiser, A.Cavalleri *et al.*; PRB **89**, 184516 (2014).

$YBa_2Cu_3O_{6.45}$ $T_c$ = 35 K



# More than establishment of interlayer coherence




**The emergence of a plasma edge at *T* where no signature of 'preformed pairs' is observed in equilibrium**

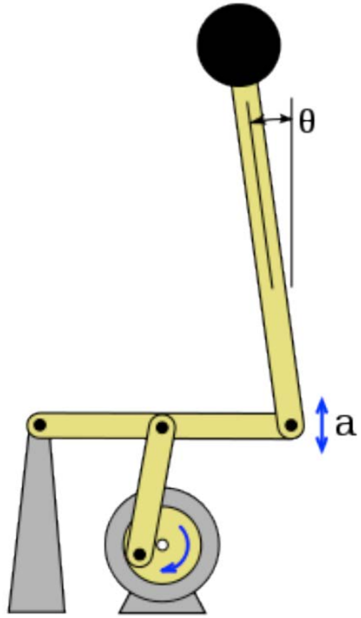
# What is the mechanism of driving pair formation and enhancing the interlayer coherence ?

- ***Excitation of large amplitude apical-O displacement: Transiently creates a displaced crystal structure with atomic positions more favorable for higher $T_c$***

- ***Reduction of the interbilayer fluctuations by a LASER (parametric) cooling***

Dynamically stabilized SC state ?

N. Peter Armitage, Nature Mater. **13**, 665 (2014).

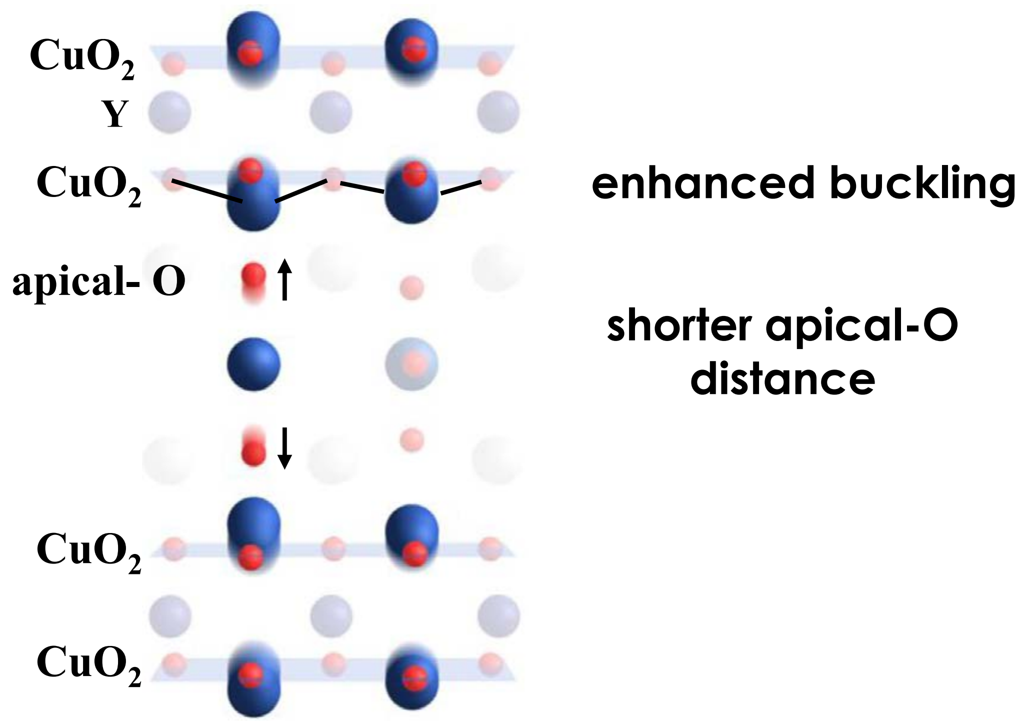



A Kapitza pendulum

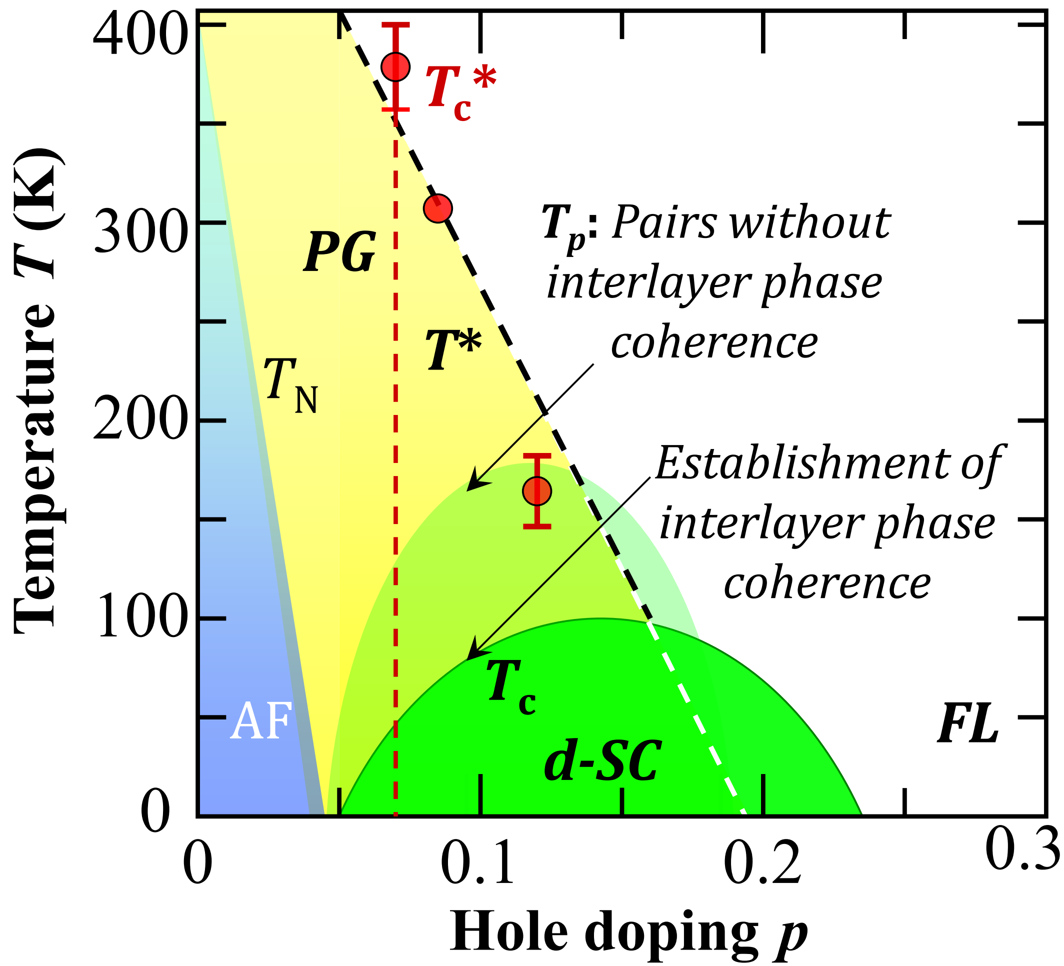
# Non-Equilibrium Lattice Distortions

**Resonant excitation of apical-O vibrations by *c*-axis polarized 20TH$_Z$ light pulse → transient lattice distortions**

R. Först *et al.*; PRB **90**, 184514 (2014). R. Mankowsky *et al.*; Nature **516**, 71(2014).



# More than establishment of interlayer coherence




**The emergence of a plasma edge at *T* where no signature of 'preformed pairs' is observed in equilibrium**

# Break of $T_c$ "Silence" in 2014 ?