

High Pressures at Low Temperatures

Manuel Núñez Regueiro



Pressure Techniques :

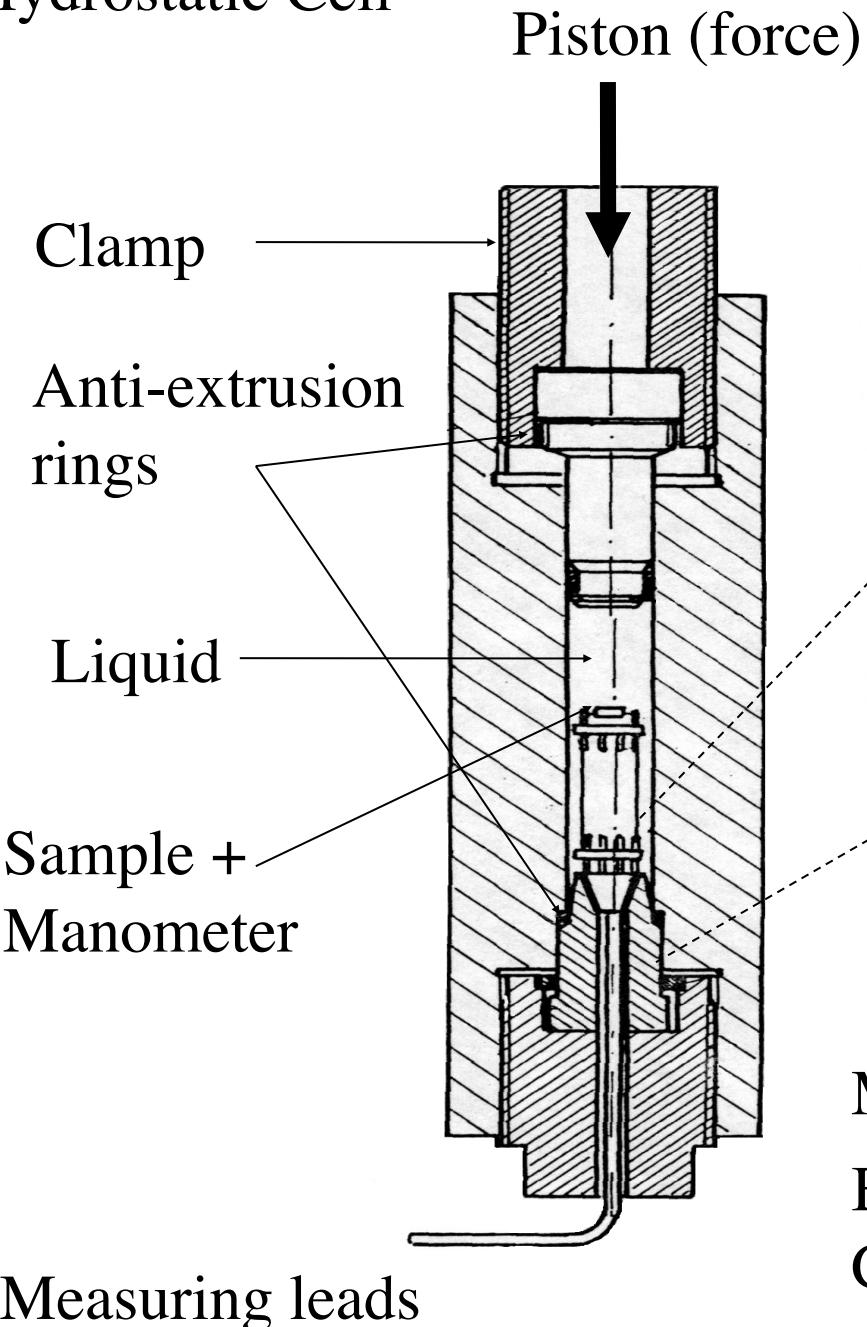
$$P = F / S$$

Hydrostatic $P < 3\text{GPa}$ (30000 atm)
Liquid or He gas

Quasi-Hydrostatic (Diamond Anvil Cells; $< 250\text{GPa}$)

High pressure Experimental Methods
M. Eremets Oxford Science Publications (1996)

Hydrostatic Cell



Electrical resistance
Magnetic susceptibility
 $P < 3\text{GPa}$

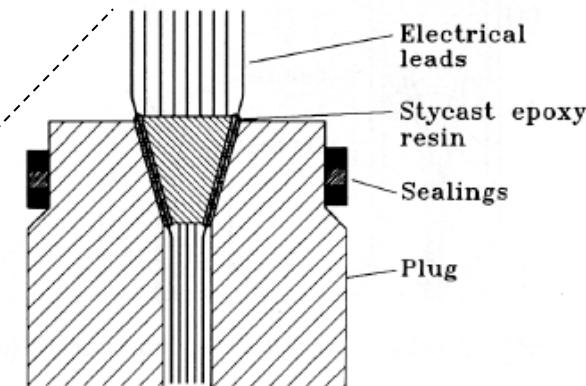


FIG. 6.23. A conical leadthrough. Wires are placed regularly around the conical surface and sealed with the aid of the steel conical stopper, using the unsupported-area principle. Stycast epoxy resin serves as a gasket and for insulation.

Liquid must remain amorphous on cooling
but, pressure loss on cooling

Manometer : Resistive InSb probe

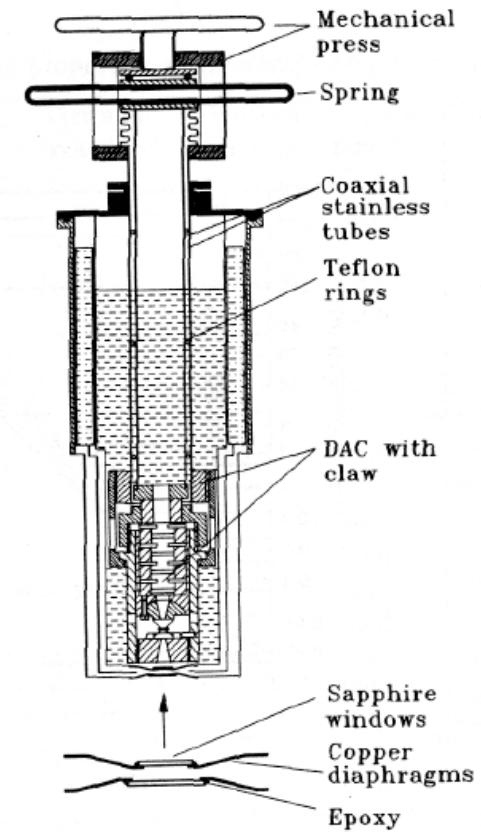
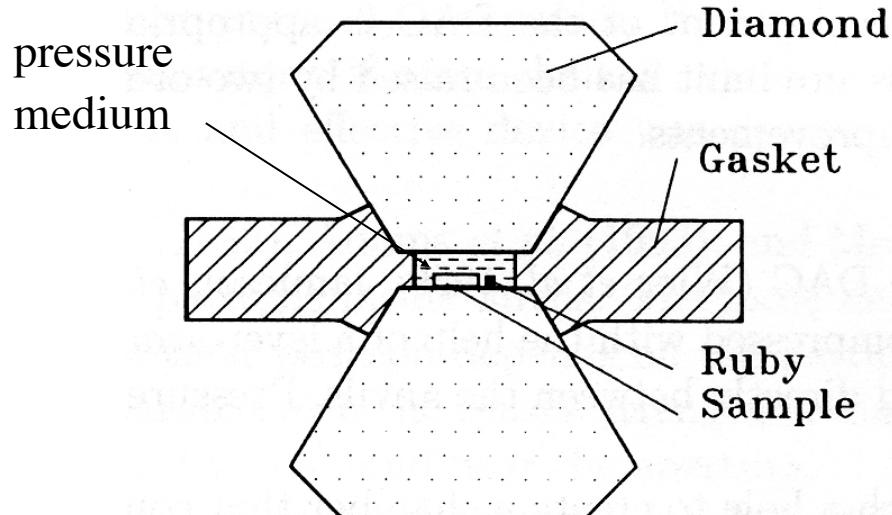
Building Material:

CuBe alloy

elastic down to very low temperatures

Quasi hydrostatic

Diamond Anvil Cell (DAC) 250GPa...



hydrostatic range of pressure mediums:

Silicon oil <7GPa

Ne < 30GPa

He ~ 100GPa

Manometer:
Ruby fluorescence spectra

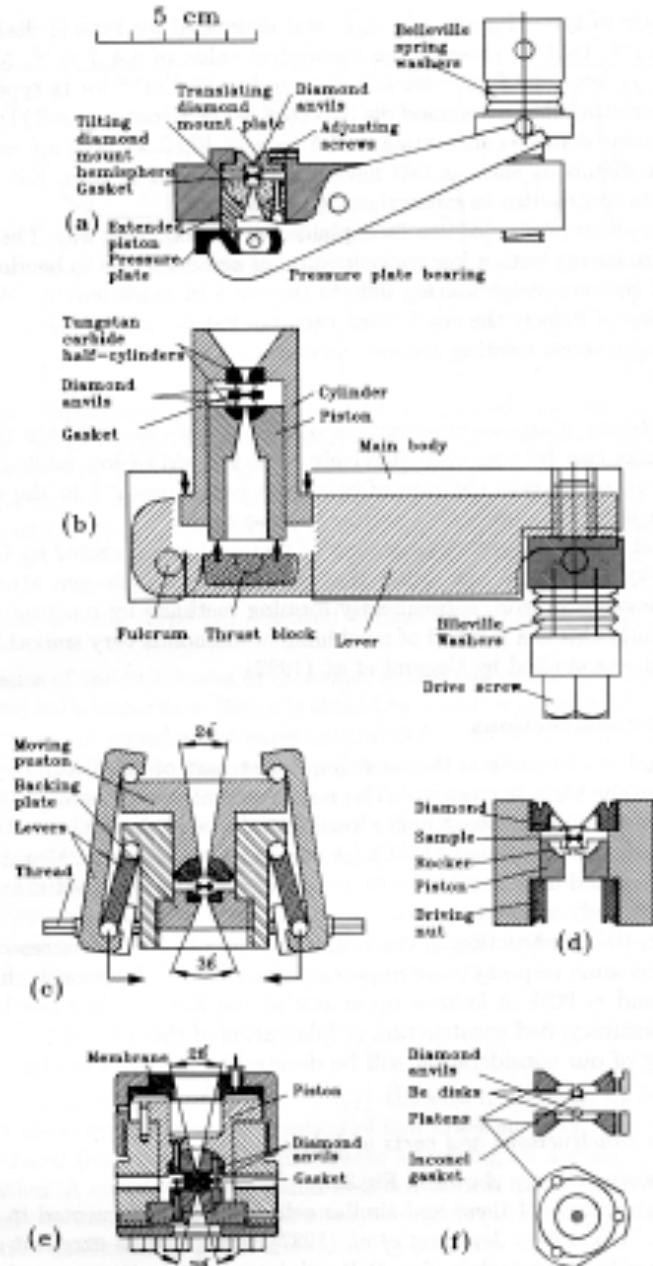


FIG. 3.5. Constructions of the best-known cells (in scale). (After (a) Piermarini and Block 1975; (b) Mao and Bell 1977; (c) Huber *et al.* 1977; (d) Bassett *et al.* 1967; (e) LeToullec *et al.* 1988; (f) Merrill and Bassett 1974.)

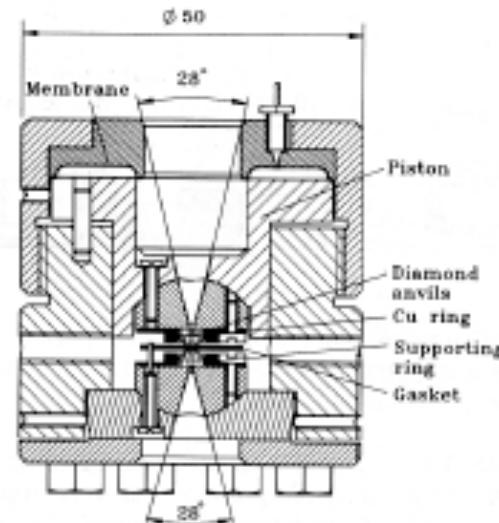


FIG. 3.11. Diamond anvil cell with membrane unit. After LeToullec *et al.* (1988).

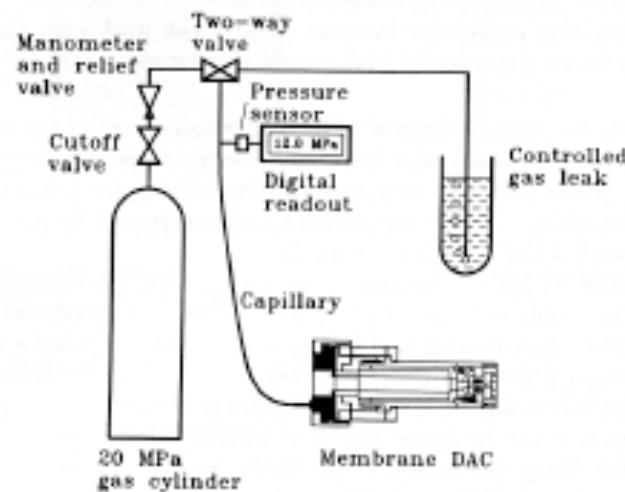
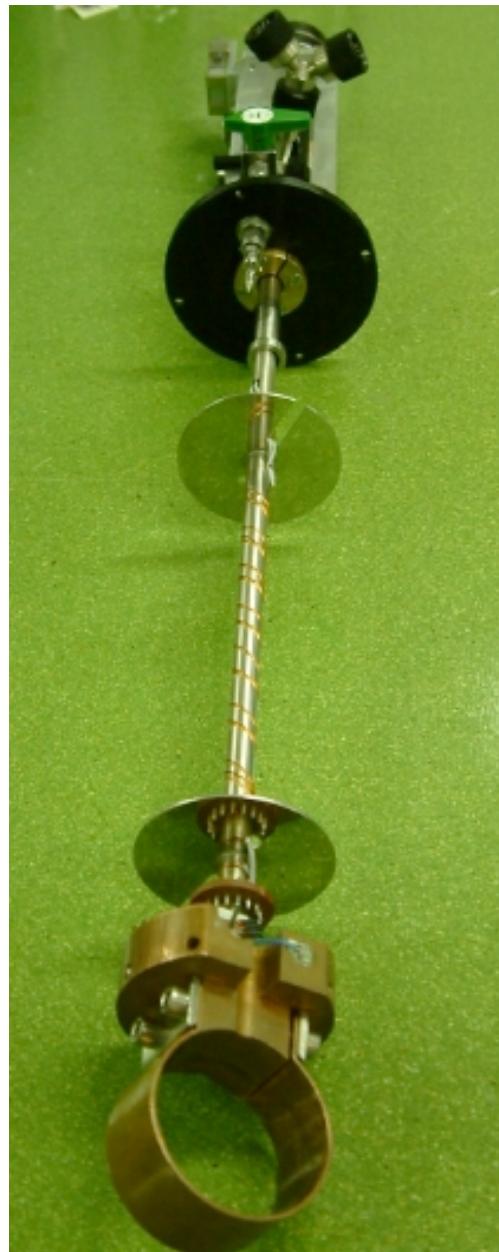


FIG. 3.12. Schematic diagram of membrane pressurization. (After LeToullec *et al.* 1988.)

A membrane press driven by helium works effectively down to 4.2 K because helium does not freeze. The membrane DAC is connected with a gas cylinder through a very thin and long capillary of outer diameter ~ 1 mm, and can easily operate at low temperature in X-ray, Raman and other complex experiments (LeToullec *et al.* 1992; Chervin *et al.* 1993). The membrane cell with bevelled



ID27- ESRF



What can we measure?

Optical properties : Brillouin / Raman scattering, infrared absorption

Structural Properties : X-rays, synchrotron radiation, neutrons

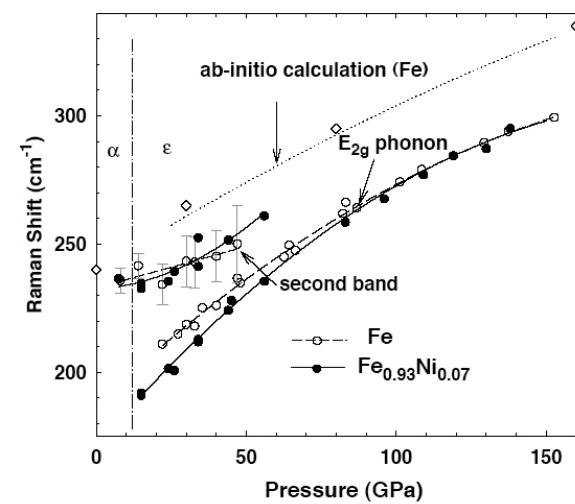
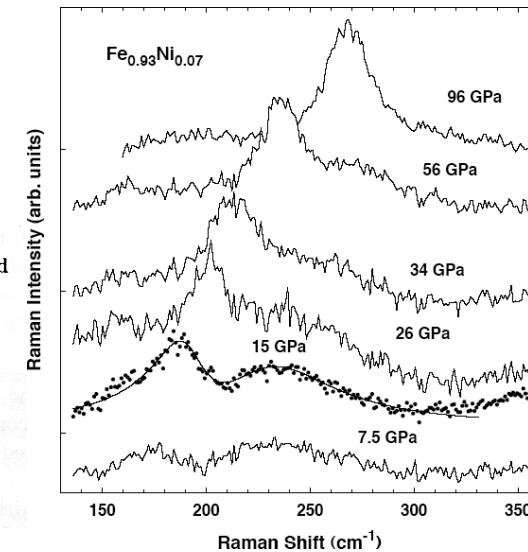
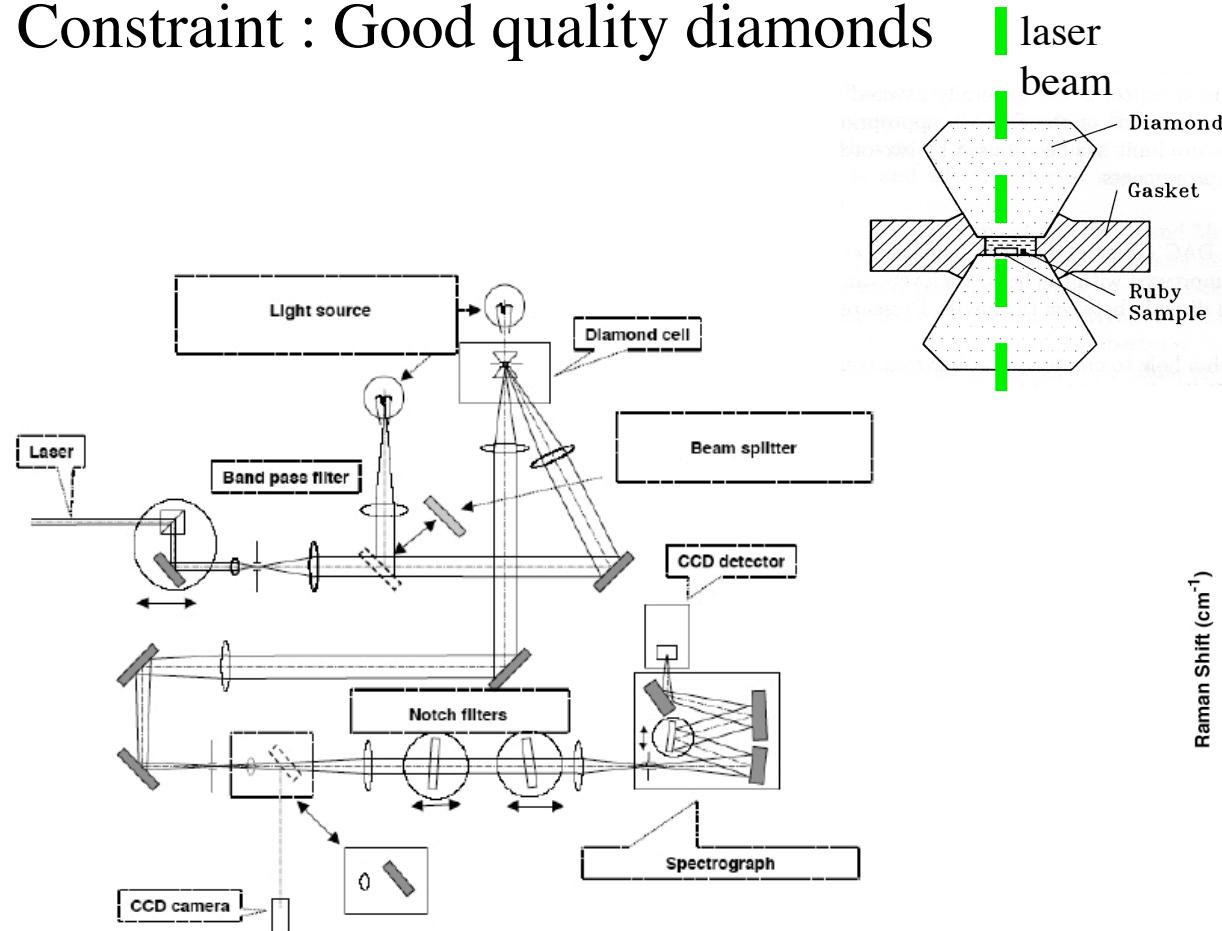
Transport properties : electrical resistivity, thermoelectric power

Thermal properties : specific heat

Magnetic Properties : susceptibility

Optical properties : Example Raman

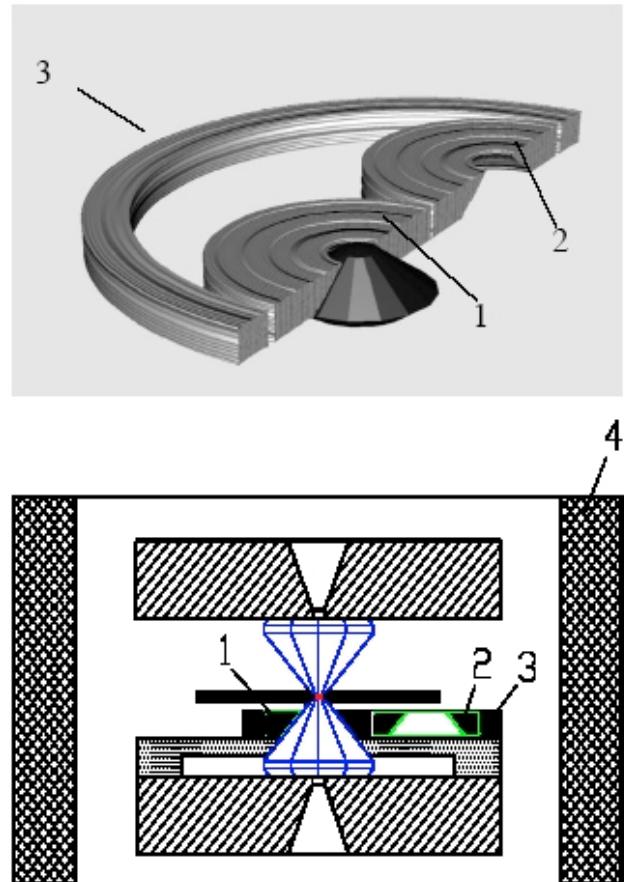
Constraint : Good quality diamonds



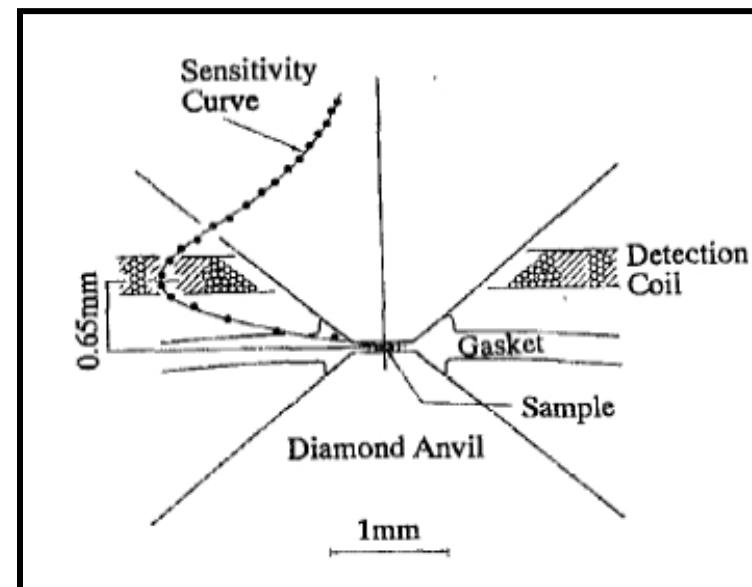
The development of optical spectroscopy instrumentation make it now possible to obtain the Raman spectra of metals to megabar ($>100 \text{ GPa}$) if not multimegabar pressures. The information obtained includes the behavior of first-order phonon modes and their coupling to the electronic and (possibly) magnetic excitations. It can be used to estimate the elastic moduli, and to obtain diagnostics of phase transformations and electronic topological transitions. (Gontcharov *et al.* *J. Raman Spect.* 34(2003)532)

Magnetic Susceptibility Measurements

Compensated Coil



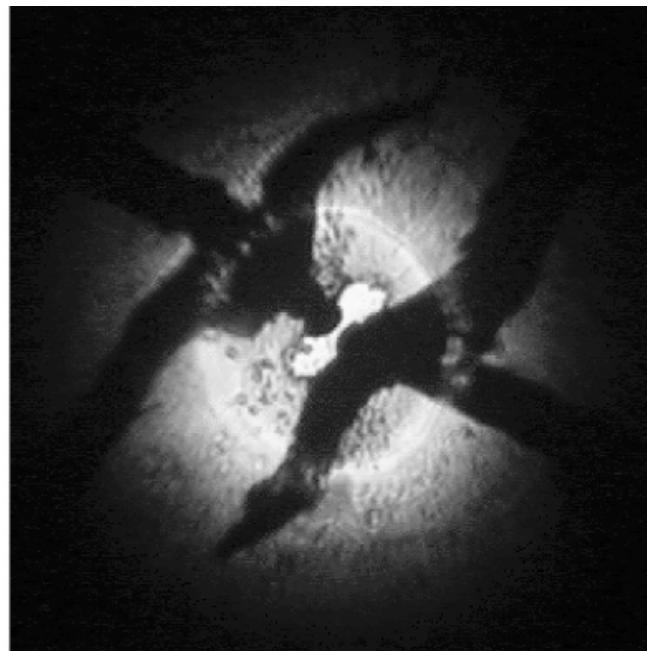
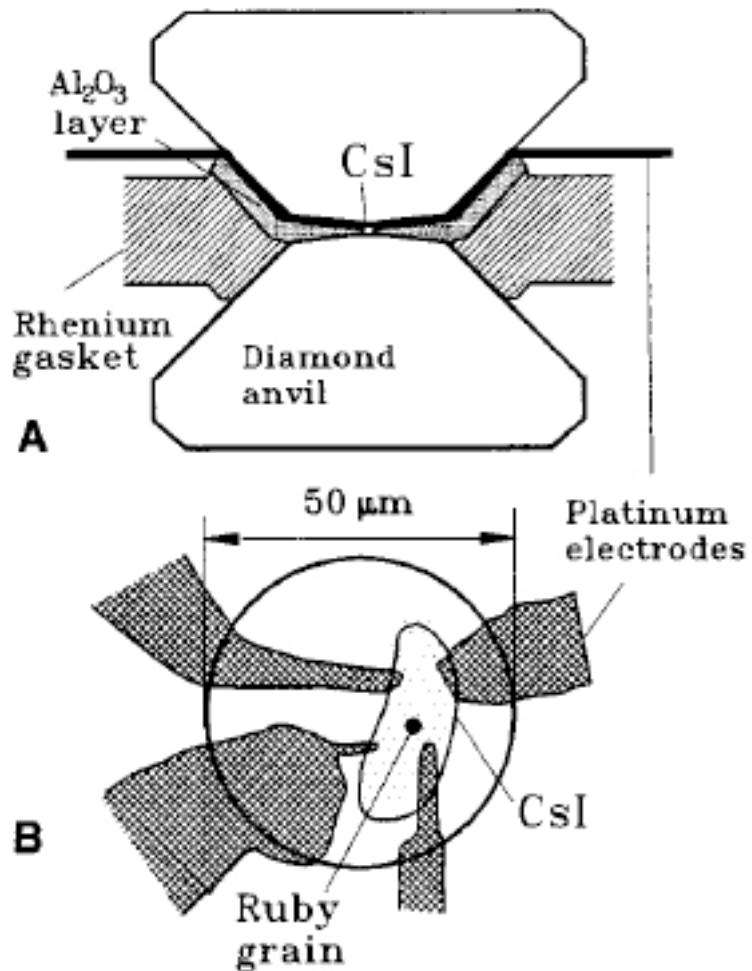
Vibrating Coil



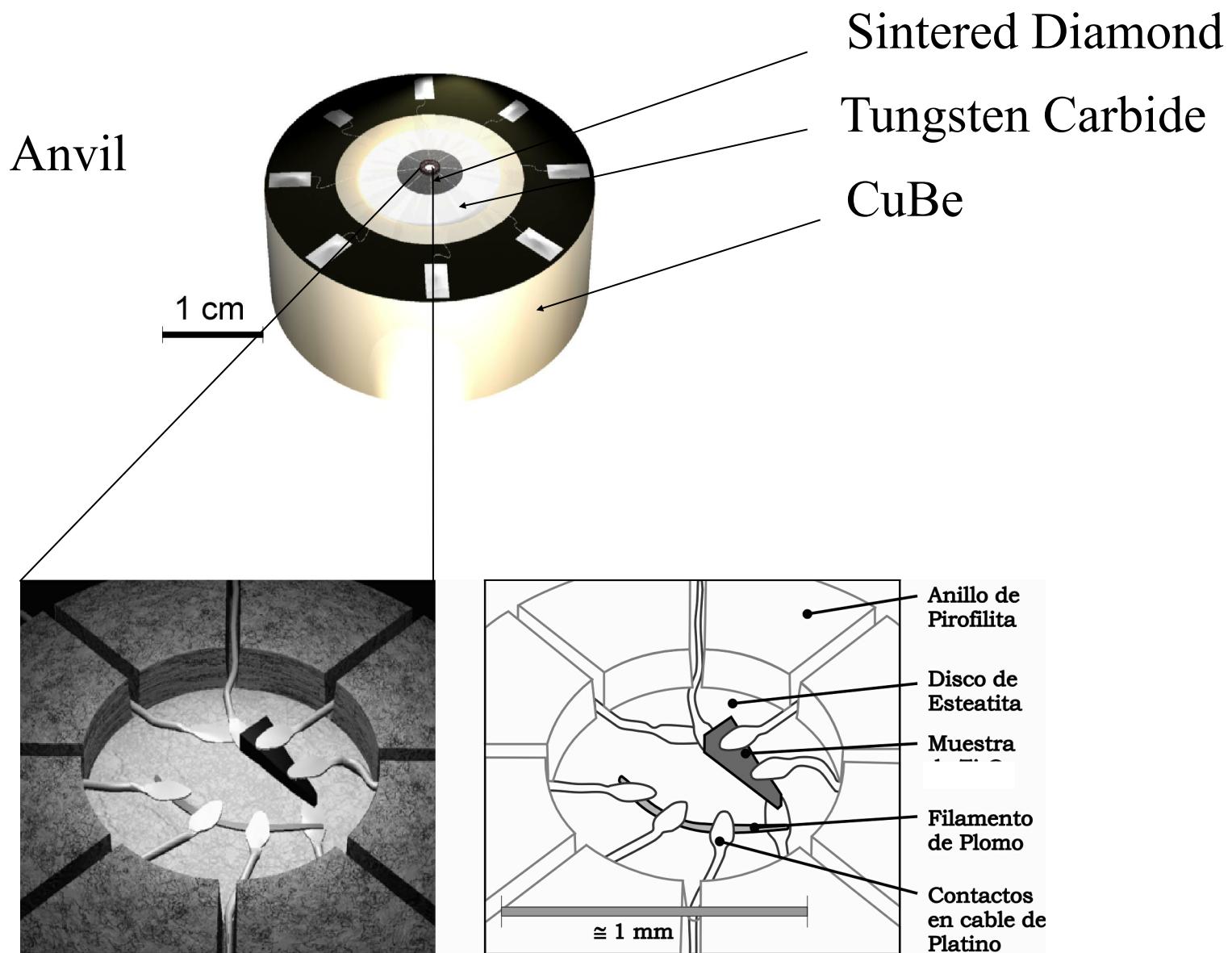
(Ishikuza et al. Rev. Sci. Instrum., 66(1995)3309)

(Timofeev et al. Rev. Sci. Instrum. 73(2002) 371)

Electrical Resistance Measurements in DAC



(Eremets et al. *Science* 281(1998)1333)



quasi-hydrostatic measurements

Thermoelectric Power

$$S = \Delta V / \Delta T$$

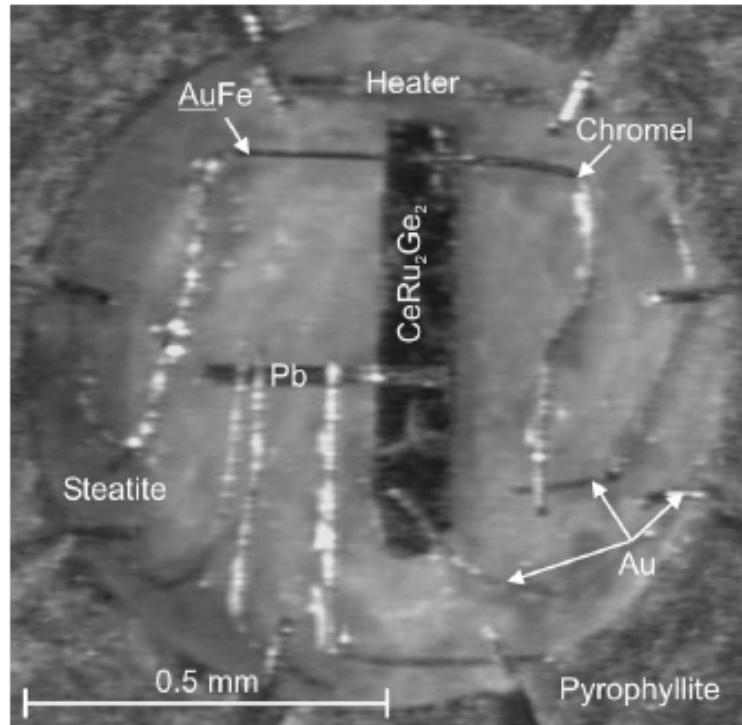
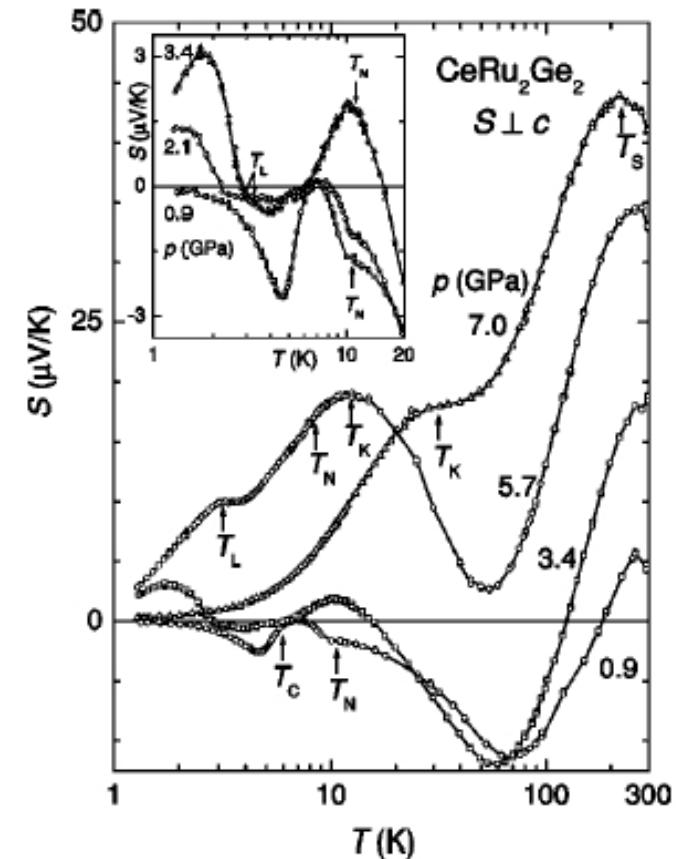


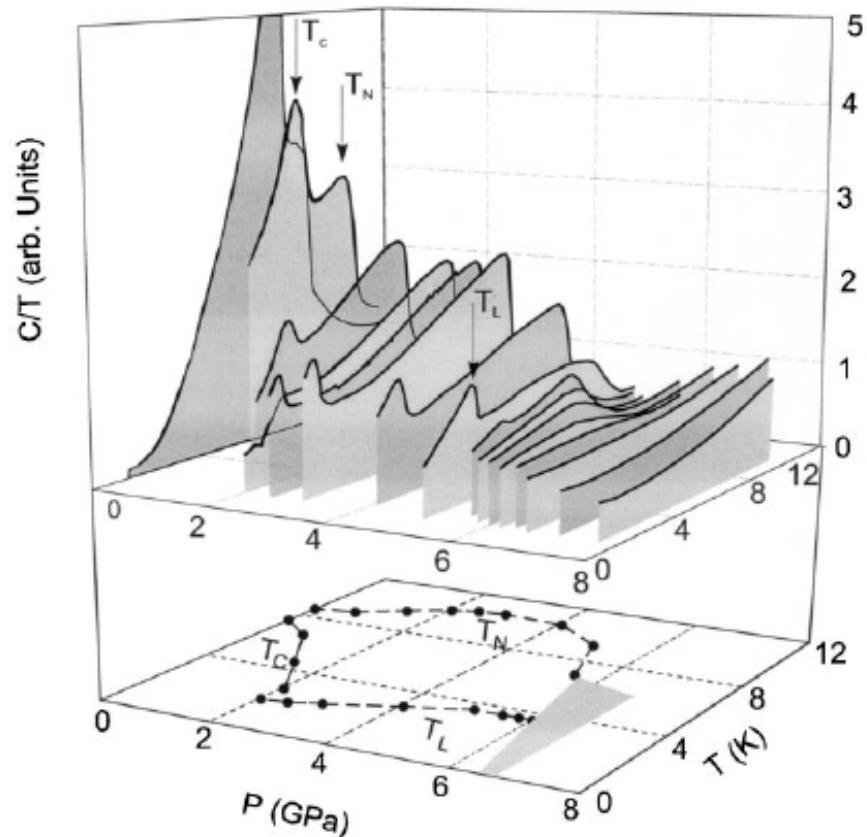
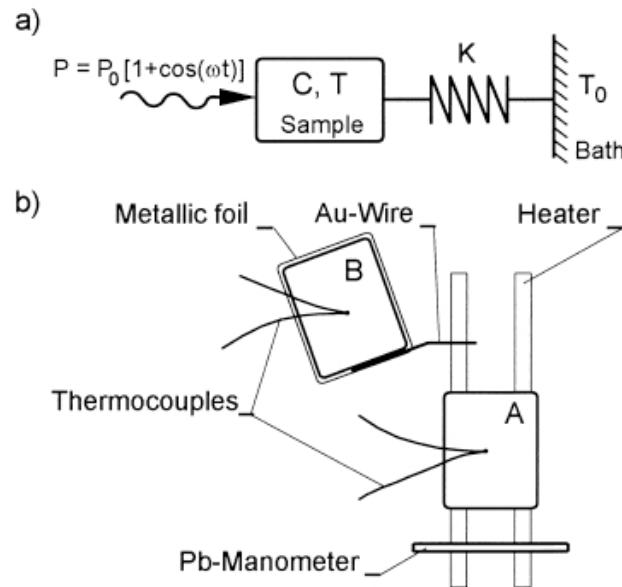
FIG. 1. Top view of the inner part of the pressure chamber before closing. Close to the heater two thermocouples (AuFe and Chromel) are located on top of the sample. The Au wire connected at the opposite edge of the sample is chosen as a reference point for the two thermovoltages V_{AuFe} and V_{Chromel} . Lead is used as pressure gauge. Au wires establish the connection through the pyrophyllite gasket. Steatite serves as pressure transmitting medium.



(*Wilhelm & Jaccard Phys.Rev.B69(2004)214408*)

AC Specific Heat Sintered Diamonds

$$T_{ac} = \left| \frac{P_0}{K + iC\omega} \right|$$

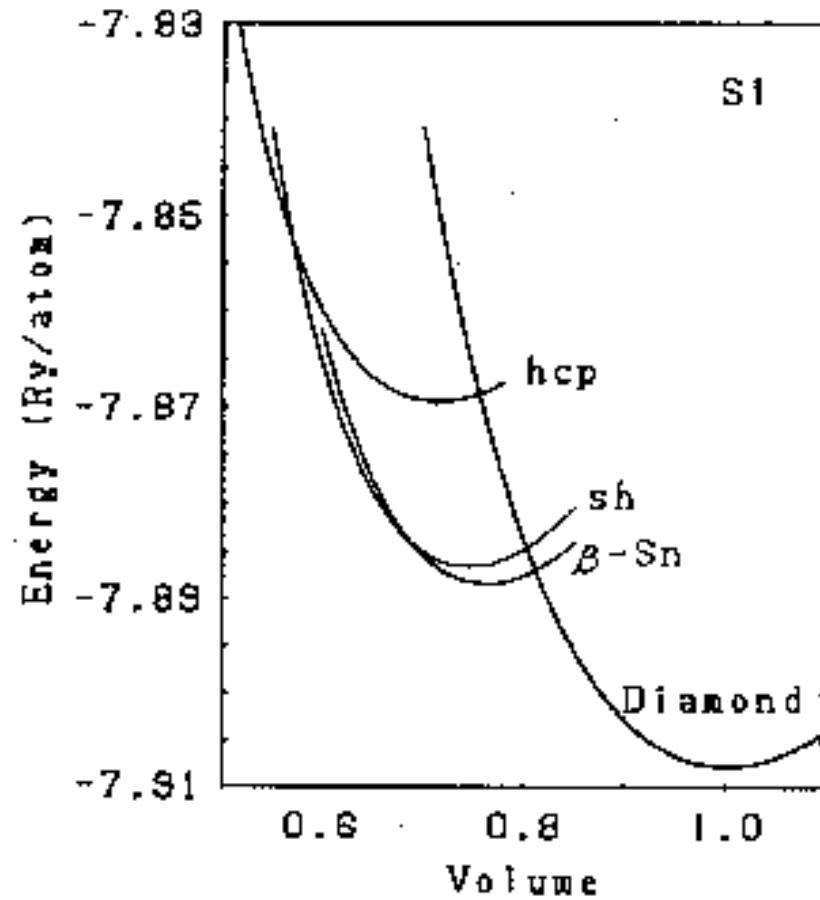


Problem: pressure medium
should have low heat conductivity
& low heat capacity
Stearite good choice in this example

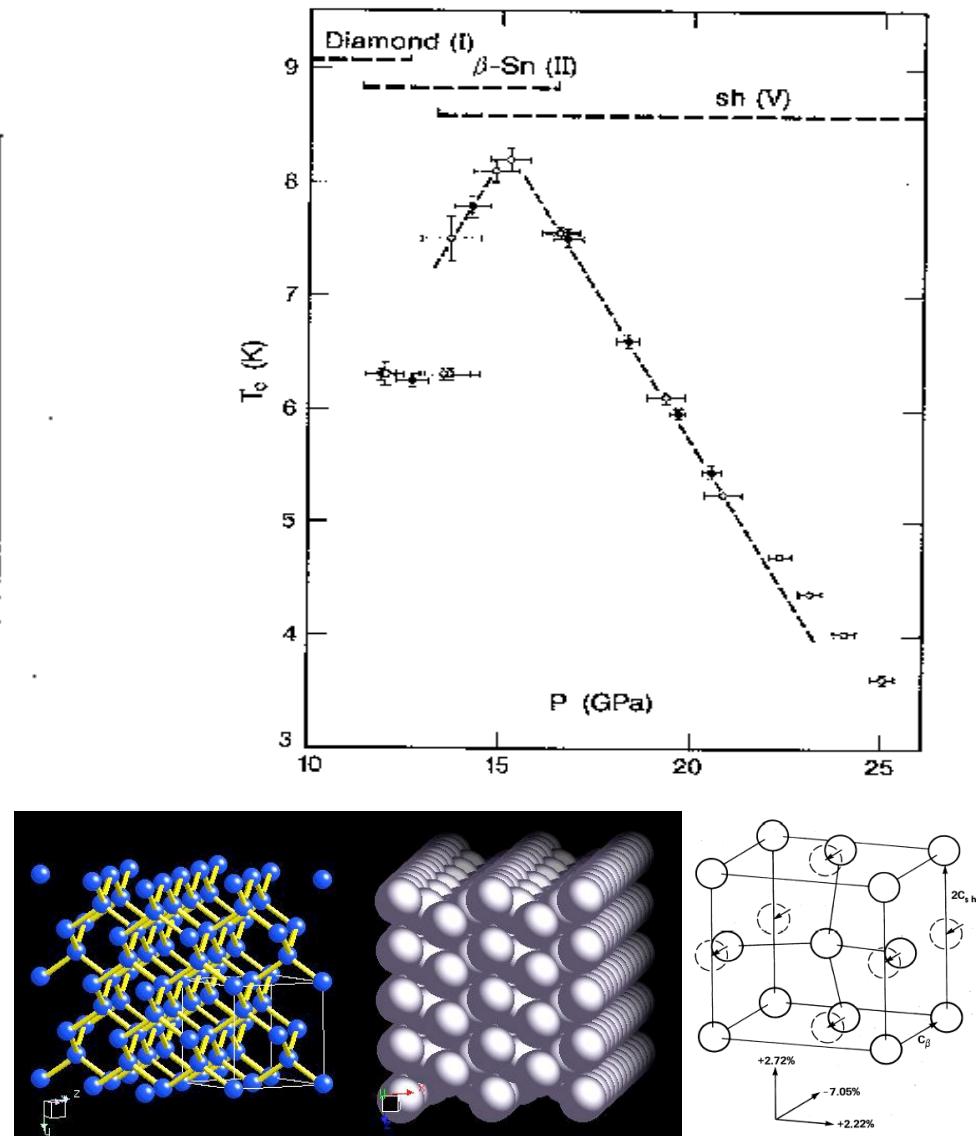
CeRu_2Ge_2
(Bouquet et al. Sol.State Comm. 113(2000)367)

*Large
Structure
deformation*

Silicon under pressure : from semiconductor to superconductor

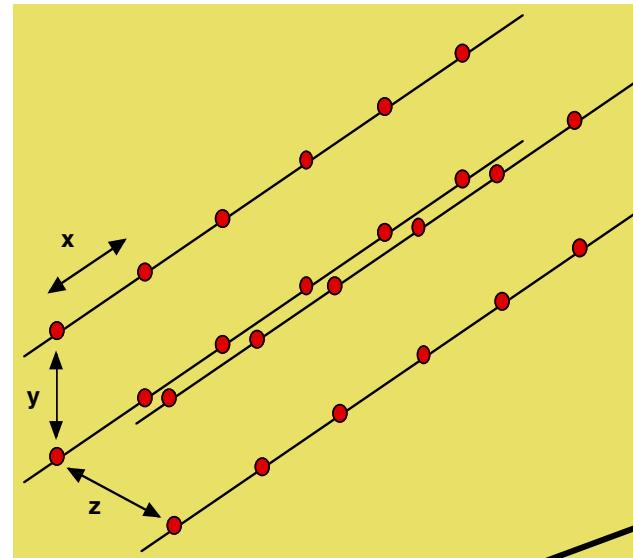


(Chang, Mignot et al.
Phys. Rev. Lett. 54(1985)2375)



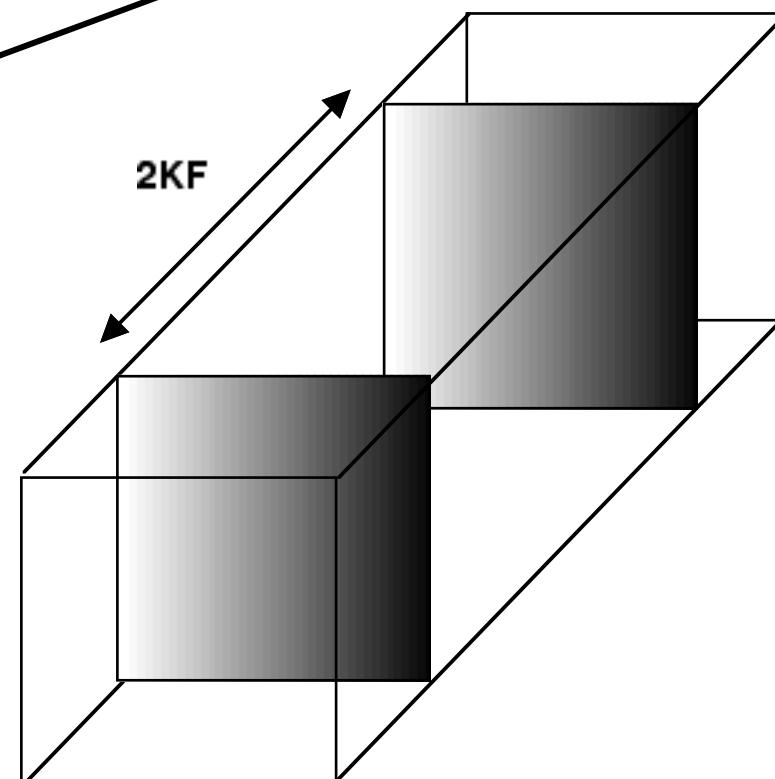
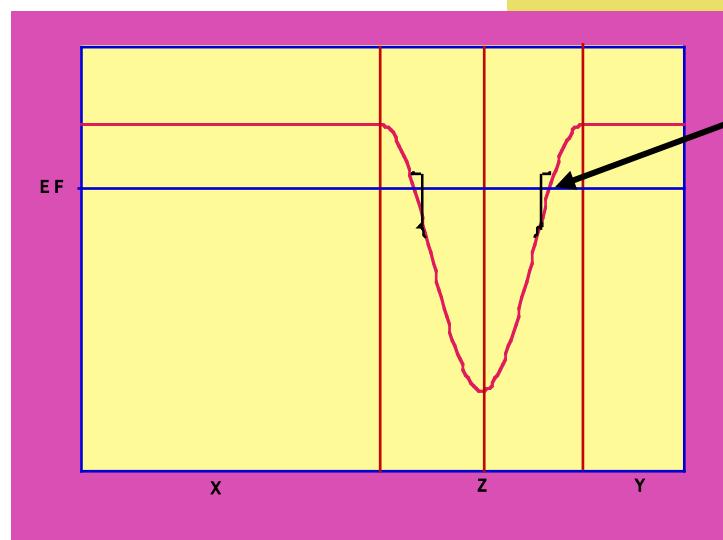
Band deformation

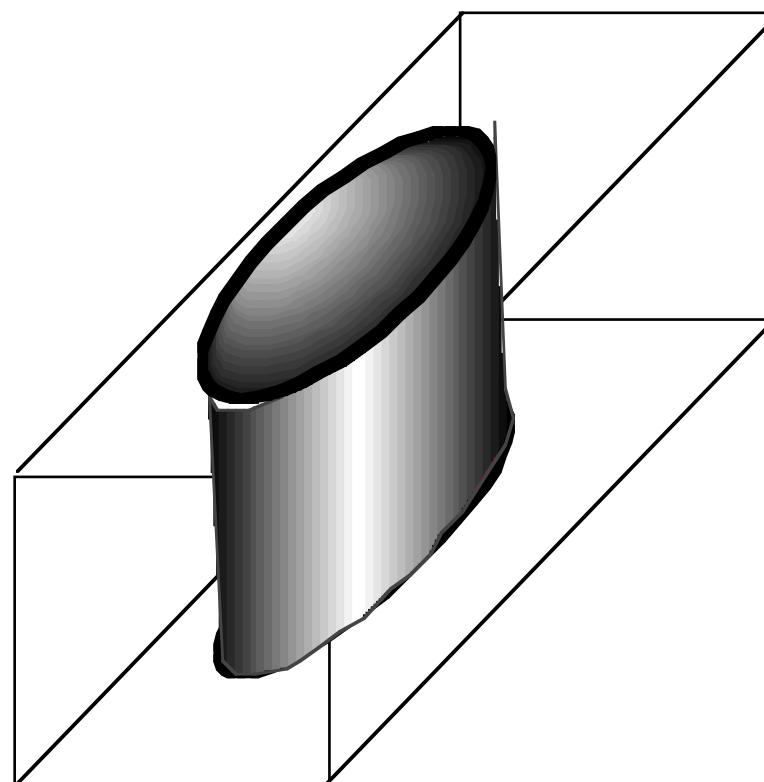
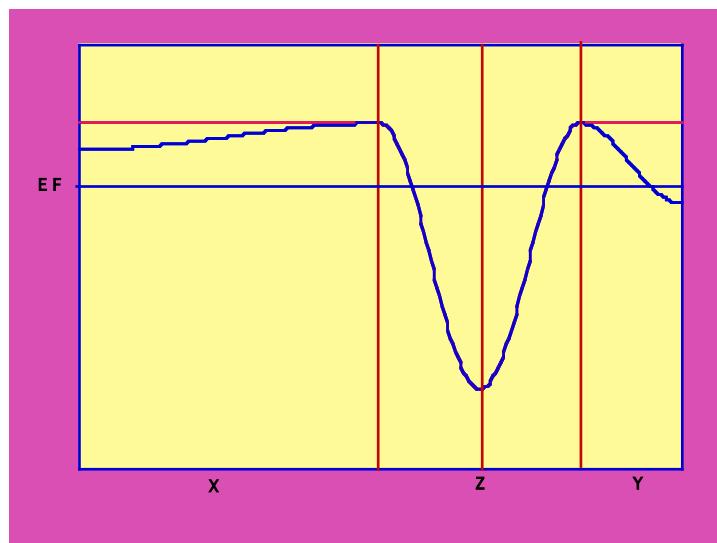
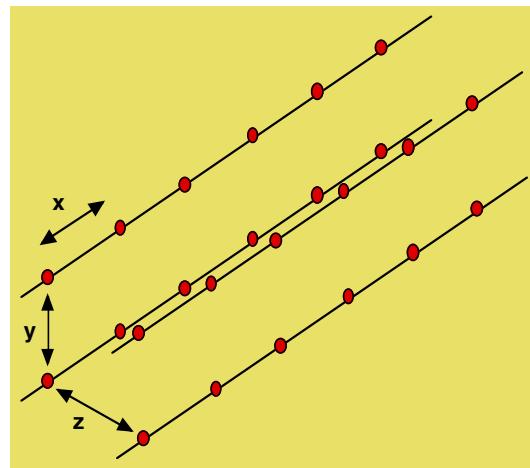
Charge density waves materials



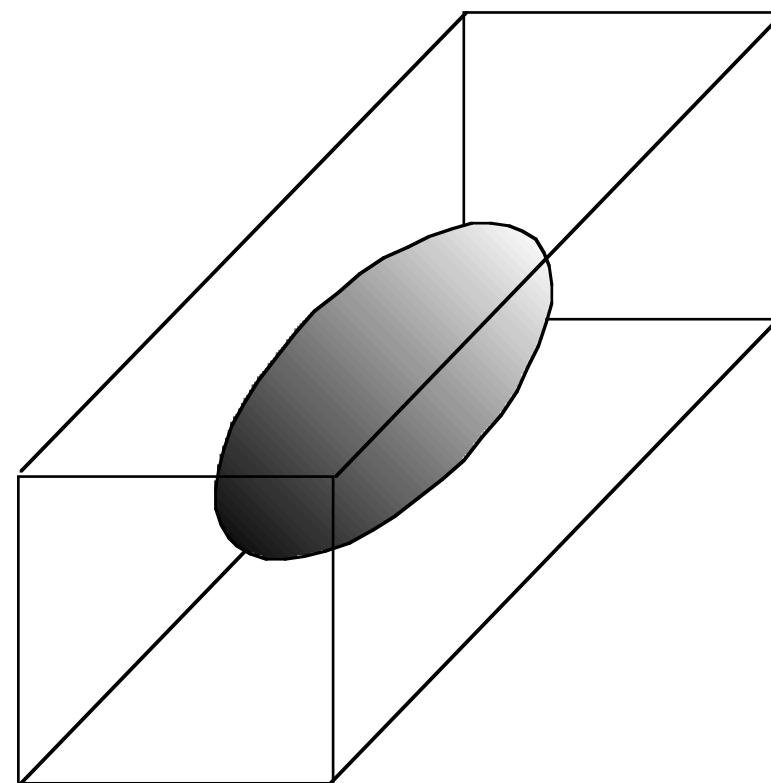
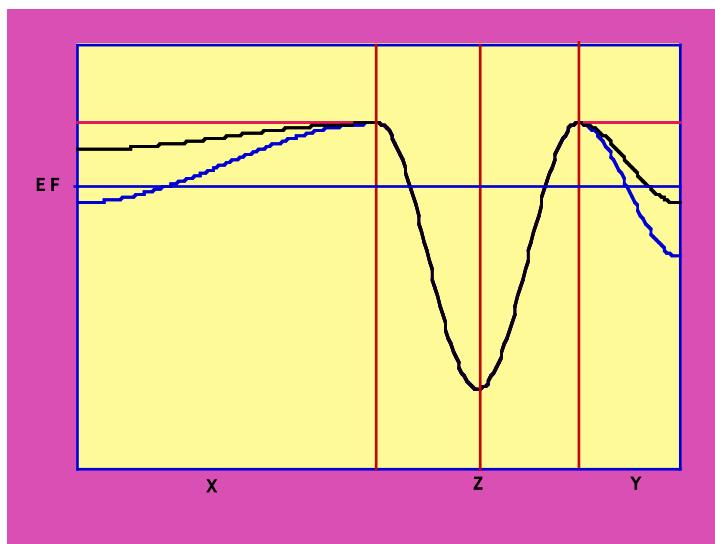
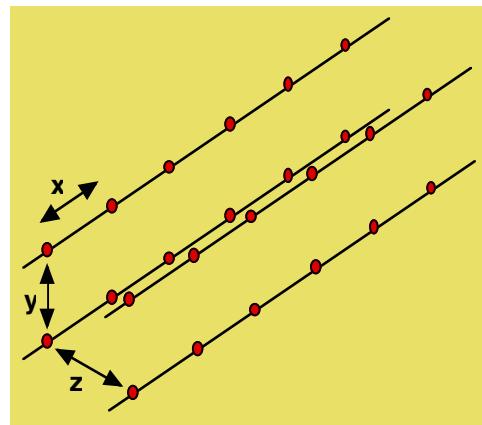
$$X_q \approx \sum_k \frac{f_k - f_{k-q}}{\epsilon_k - \epsilon_{k-q}}$$

Diverges for
 $k=2KF$
instability for 2KF phonon
lattice distortion
gap formation

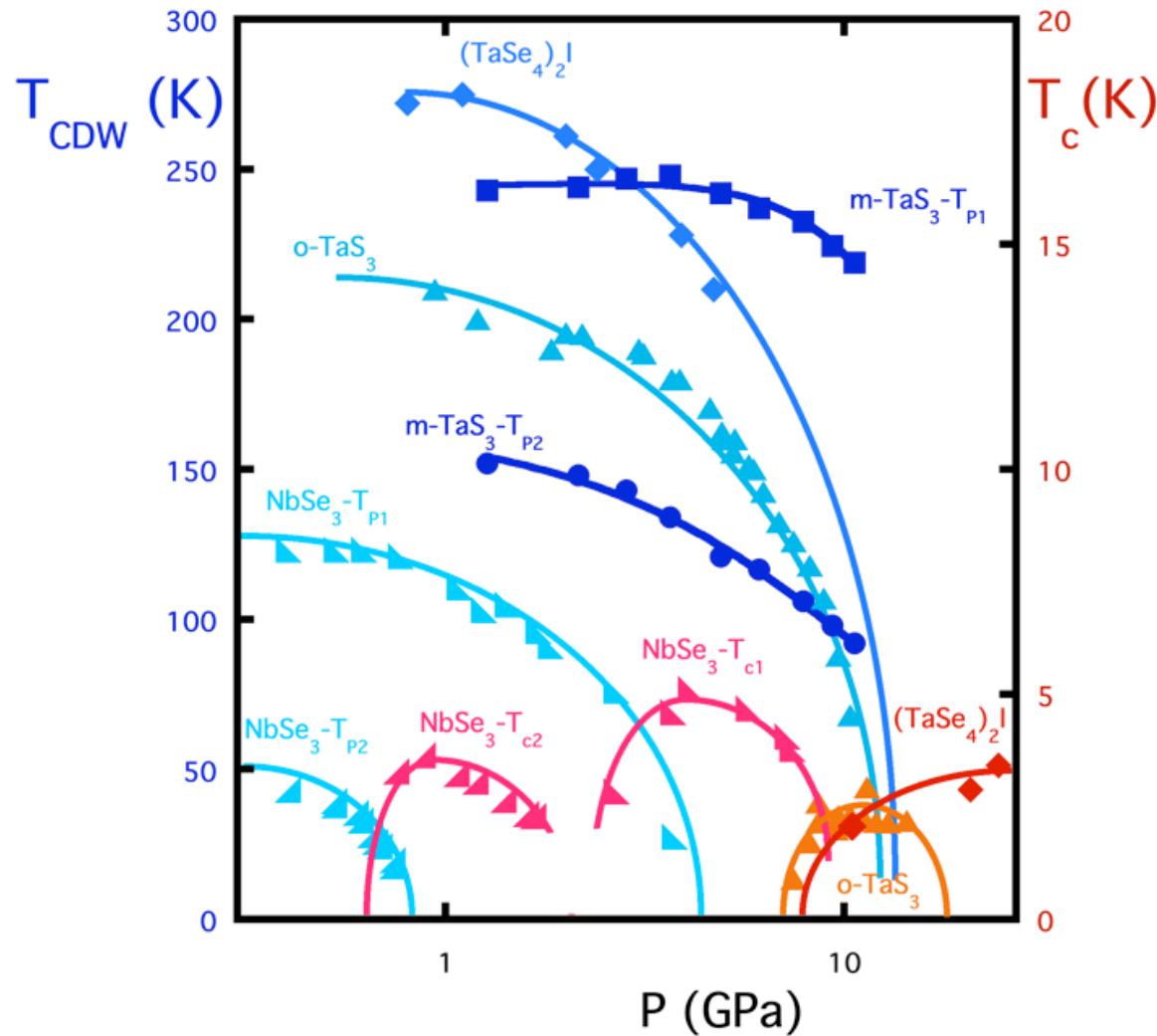




filling up of the gap



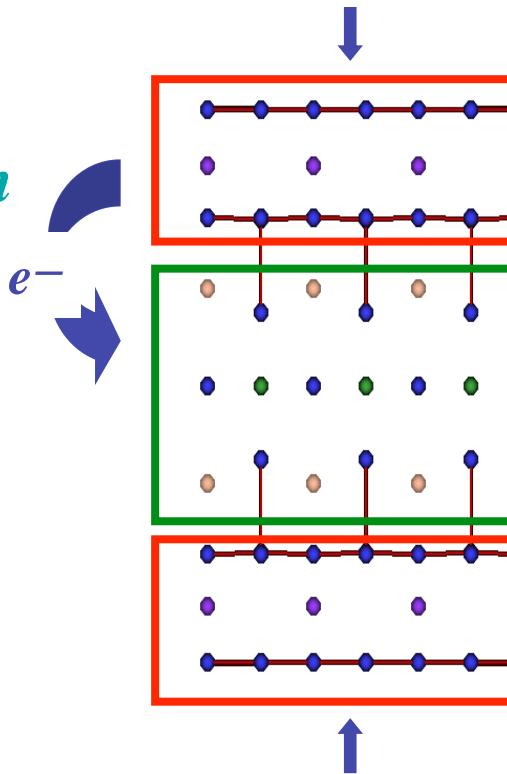
Typical Examples : Linear Chalcogenides



M. Núñez Regueiro, P. Monceau, A. Levy 1991

Small Deformation

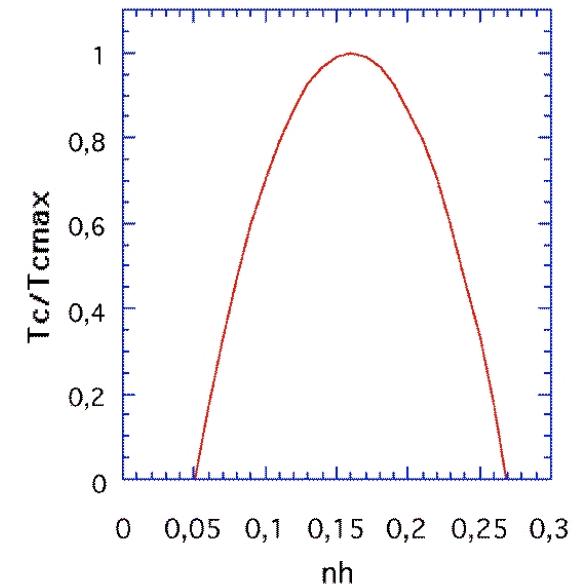
Charge Transfer in Cuprates



CuO₂ layers

Charge reservoir

CuO₂ layers



$$T_c(P) = T_{c\max}(P) \{ 1 - \beta [n_{h\max} - n_h(P)]^2 \}$$

$$n_h(P) = n_h + \Delta n_h(P) \quad \Delta n_h(P) = P \frac{dn(P)}{dP}$$

$$T_{c\max}(P) = T_{c\max} + \Delta T_{c\max}(P) \quad \Delta T_{c\max}(P)$$

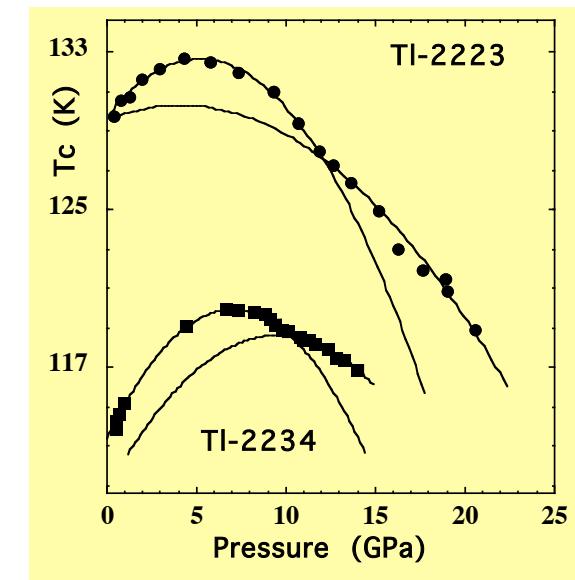
$$= P \frac{dT_c(P)}{dP}$$

then :

$$T_c(n_h, P) = T_c(n_h, 0) + \{ \frac{dT_c(P)}{dP} + 2 \beta T_{c\max} \frac{dn(P)}{dP} \}$$

$$(n_{h\max} - n_h) \} . P +$$

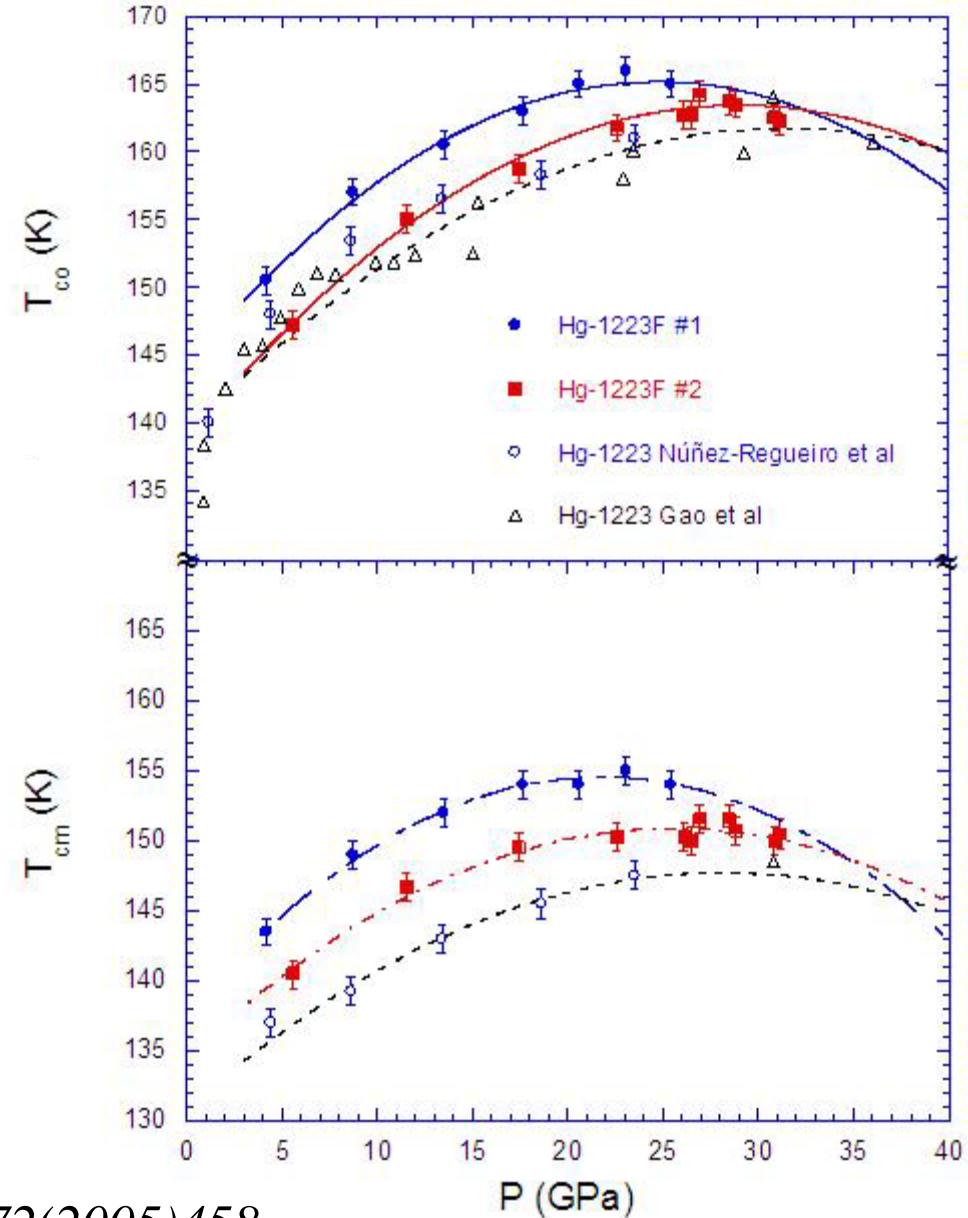
$$\pm \frac{dT_c}{dP} \cdot P \quad \frac{dn(P)}{dP} \quad 12 \text{~GPa} \quad \text{D2}$$



Pressure increases both T_c 's
following a parabolic law

$$T_c(P) = T_c(0) + \alpha P - \beta \cdot P^2$$

The obtained values for the
transition temperatures are
the highest ever obtained for
a superconductor



Monteverde et al. *Europhys. Lett.* 72(2005)458

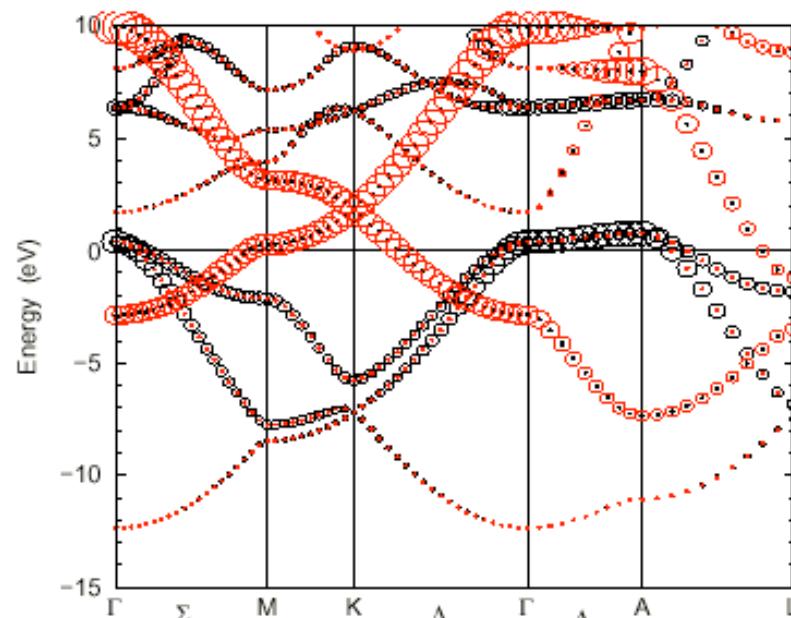
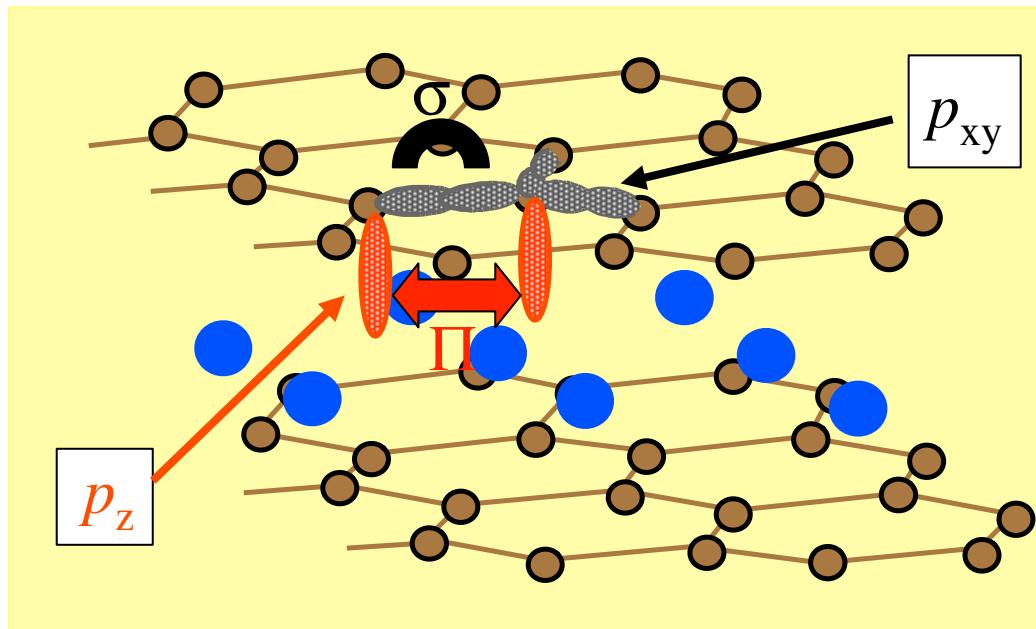
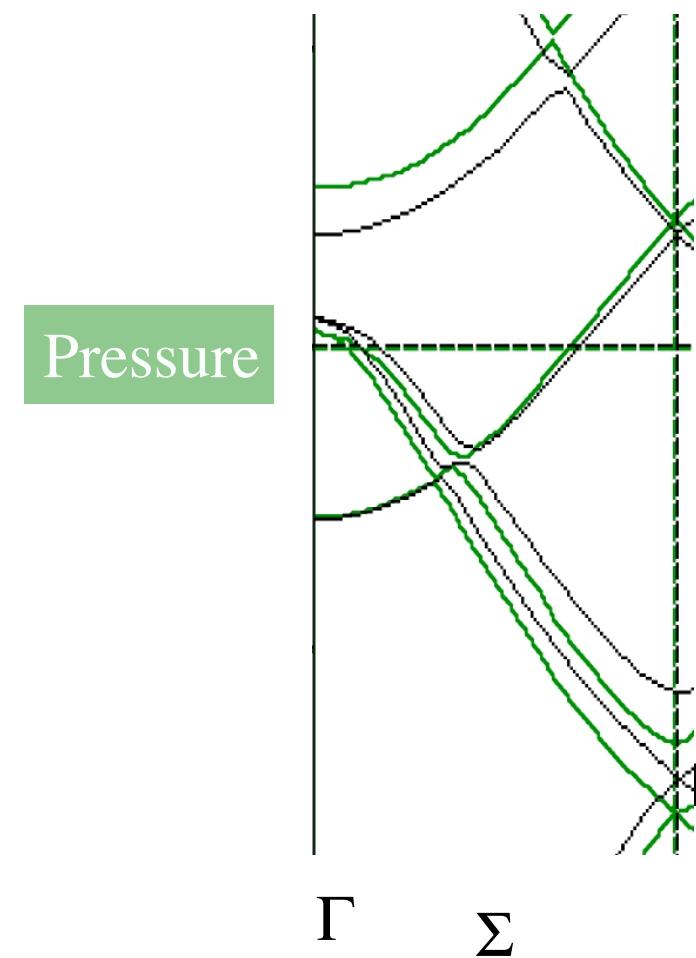
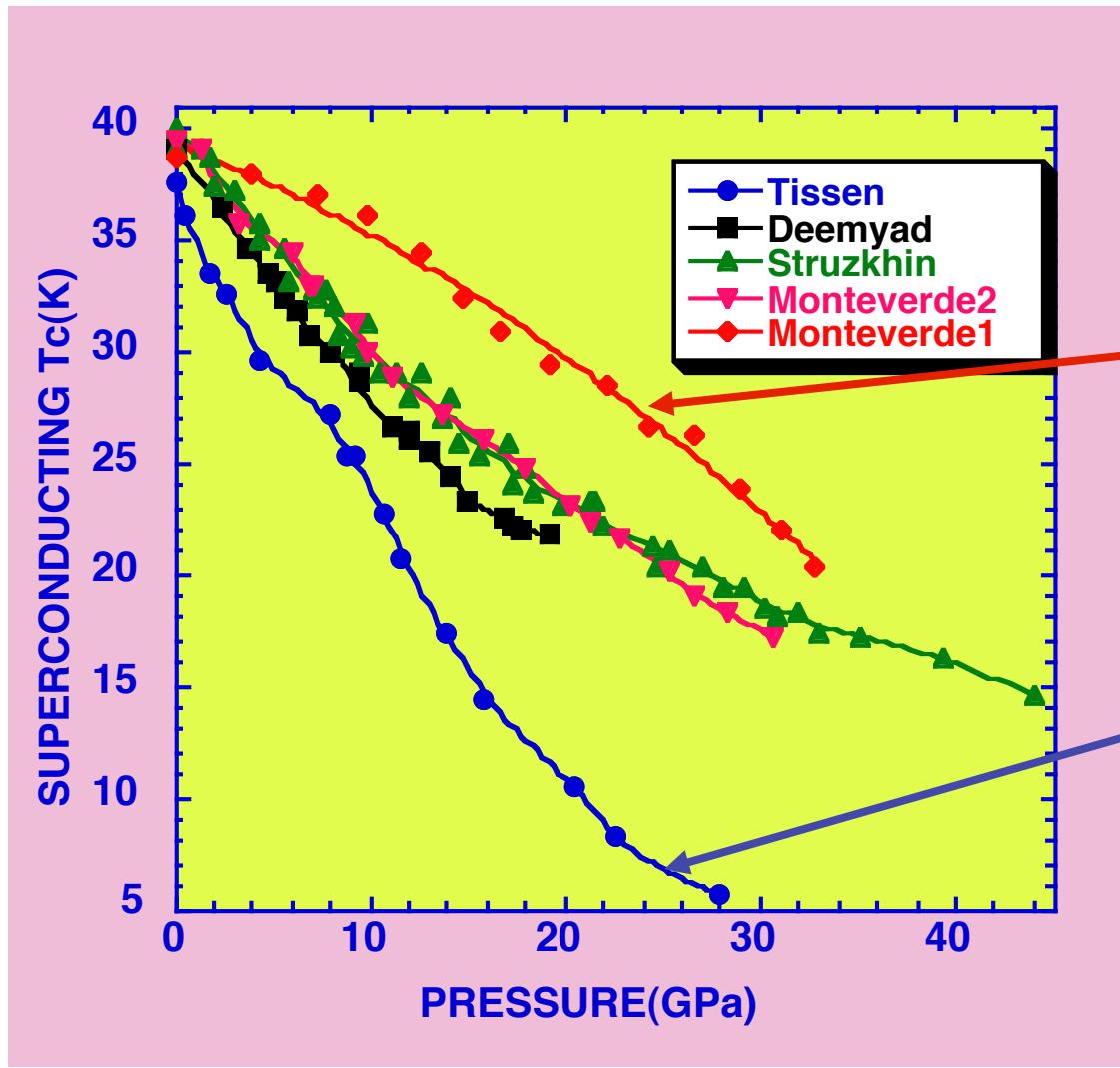


FIG. 1. Bandstructure of MgB_2 with the B p-character. The radii of the red (black) circles are proportional to the B p_z ($B\ p_{x,y}$) character.

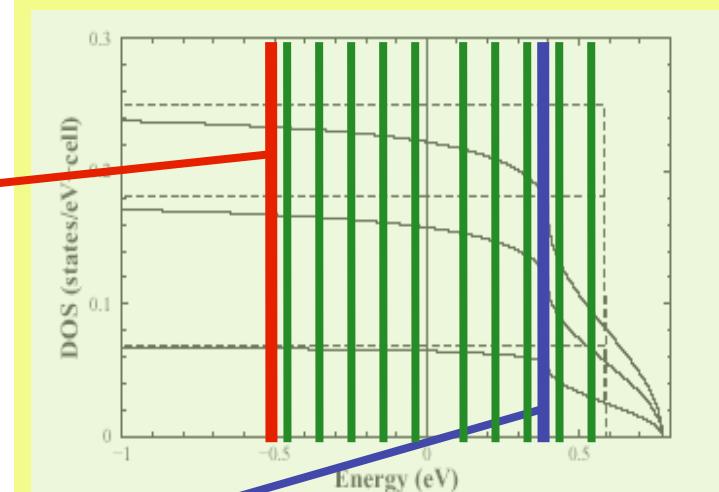


The T_c change with pressure
is sample dependent

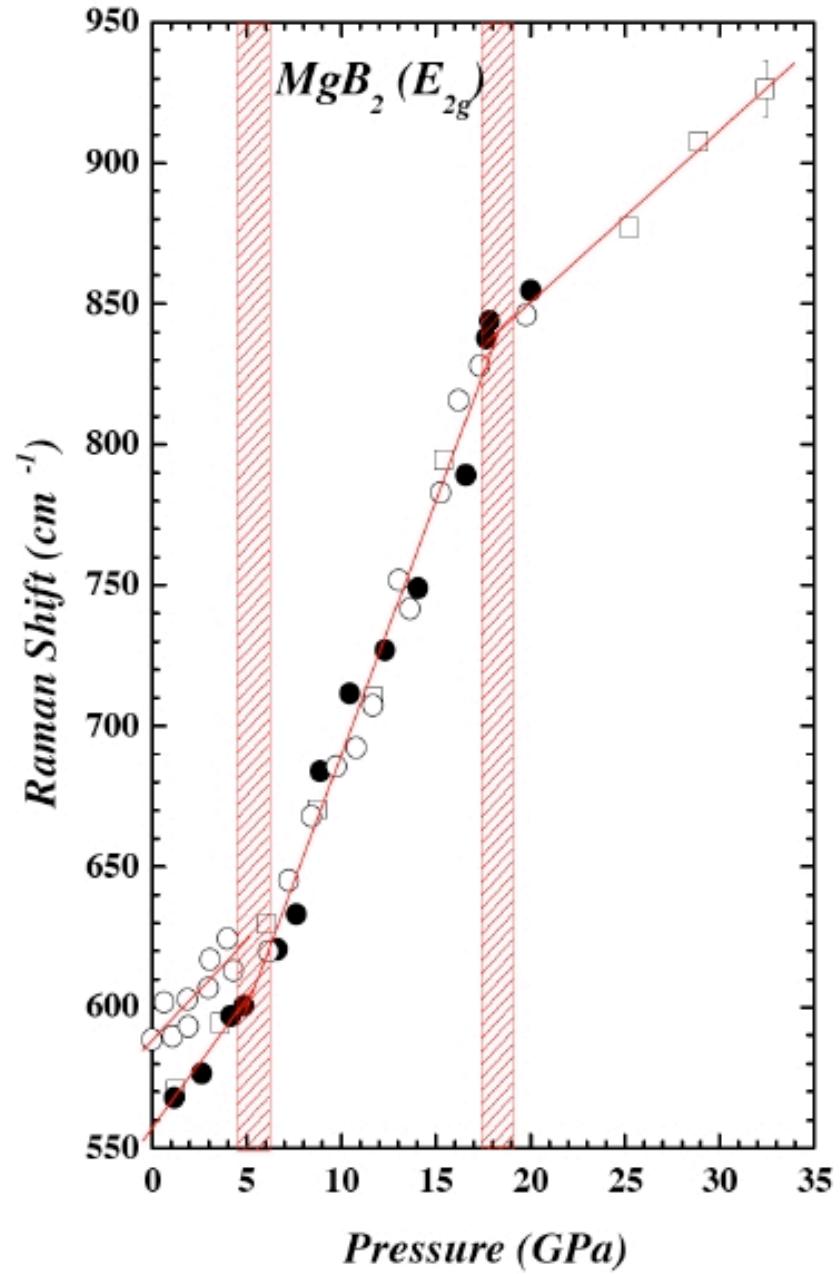
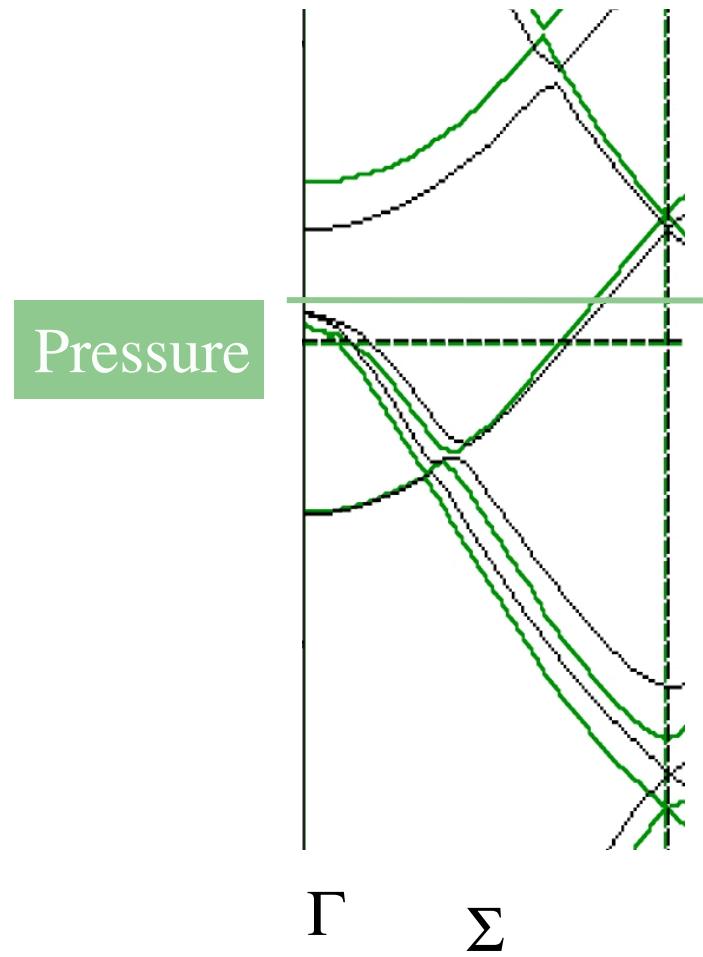
Mg non-stoichiometry



A different P=0 position
of the Fermi level can
explain the differences



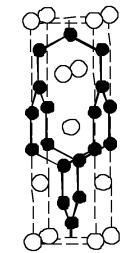
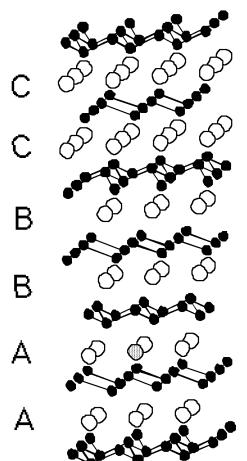
Lifshitz Topological Transition



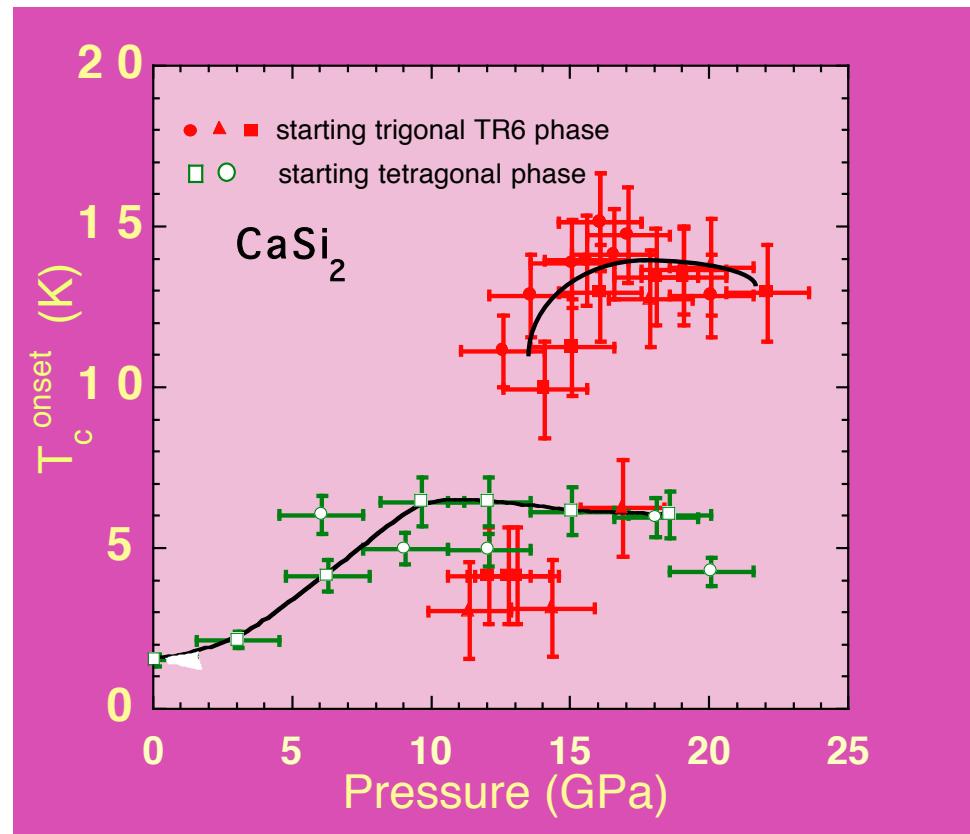
Meletov et al. JETP75(2002)456

CaSi_2

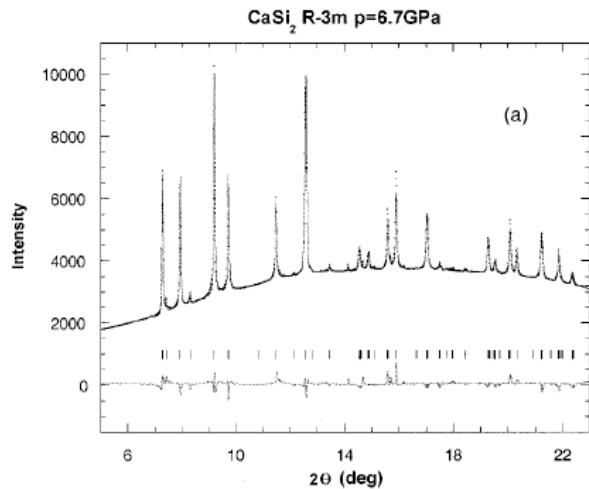
TR6



tetragonal

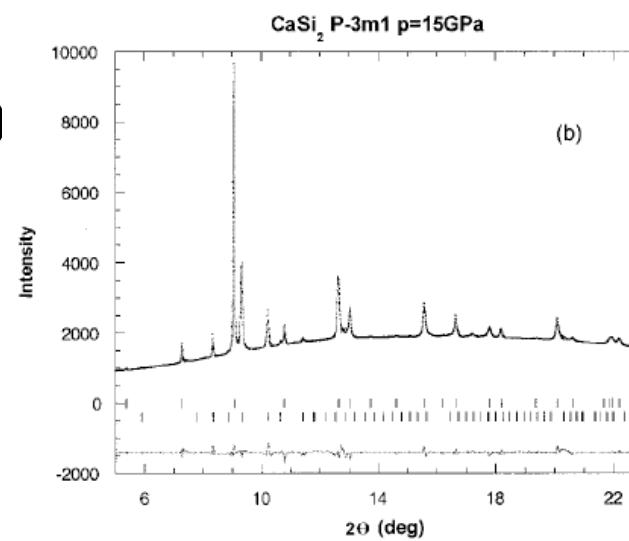


in collaboration with M. Affronte, S. Sanfilippo, G. Olcese

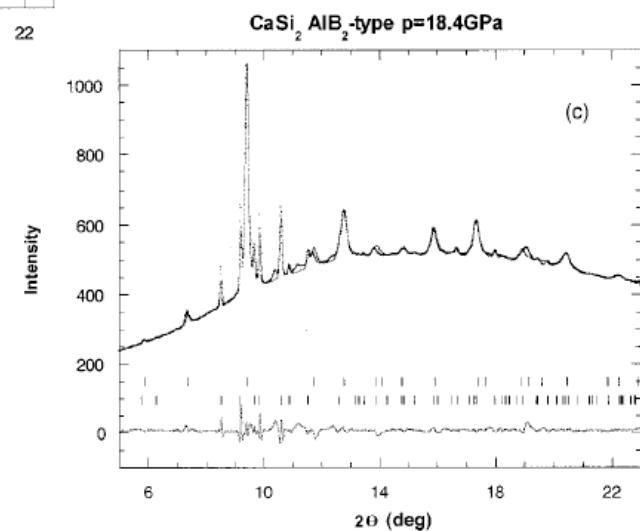


TR6 (Rhombohedral)

in collaboration with
P. Bordet
M. Hanfland

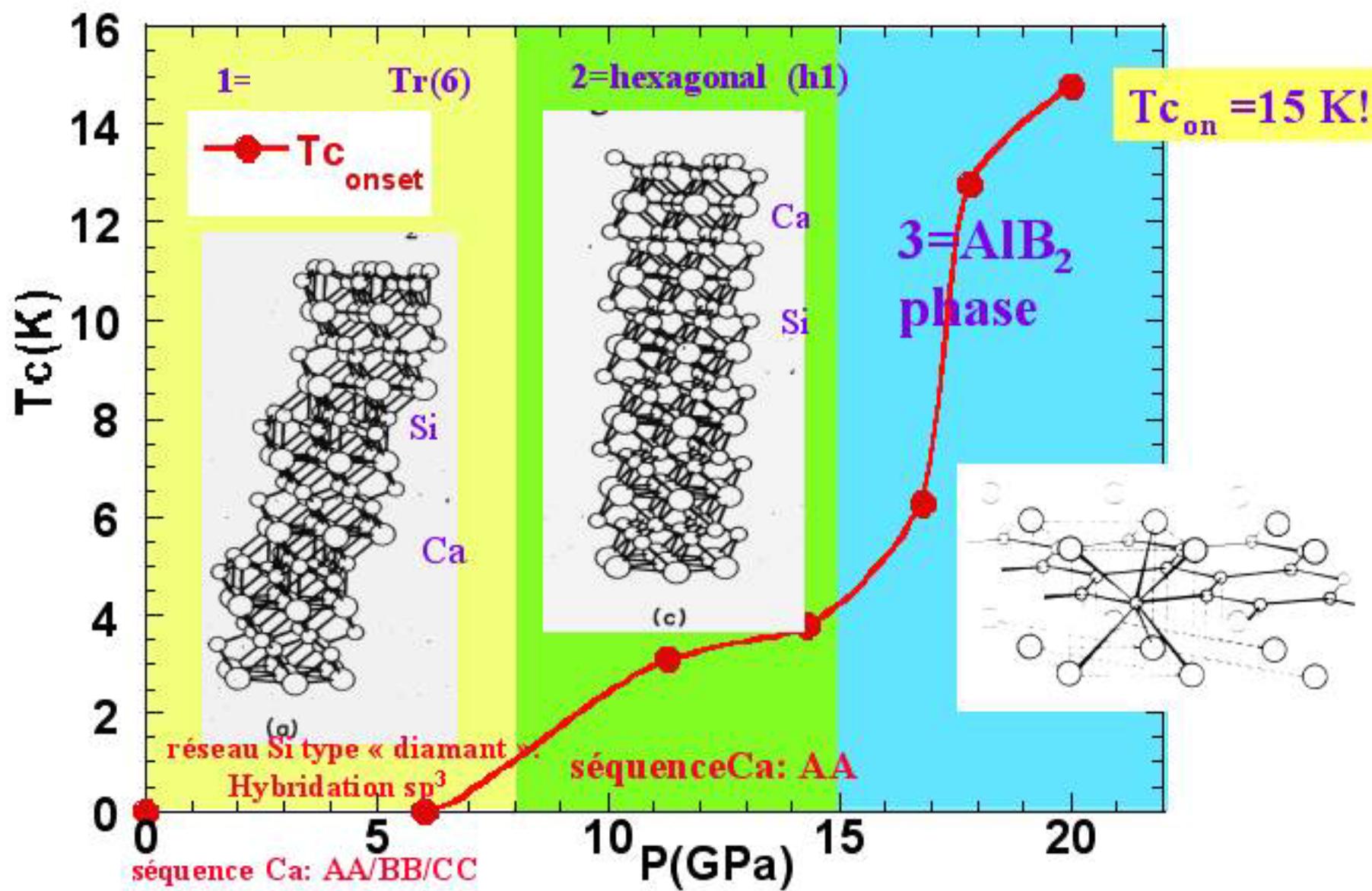


h1



AlB_2 :
 isostructural
 to MgB_2

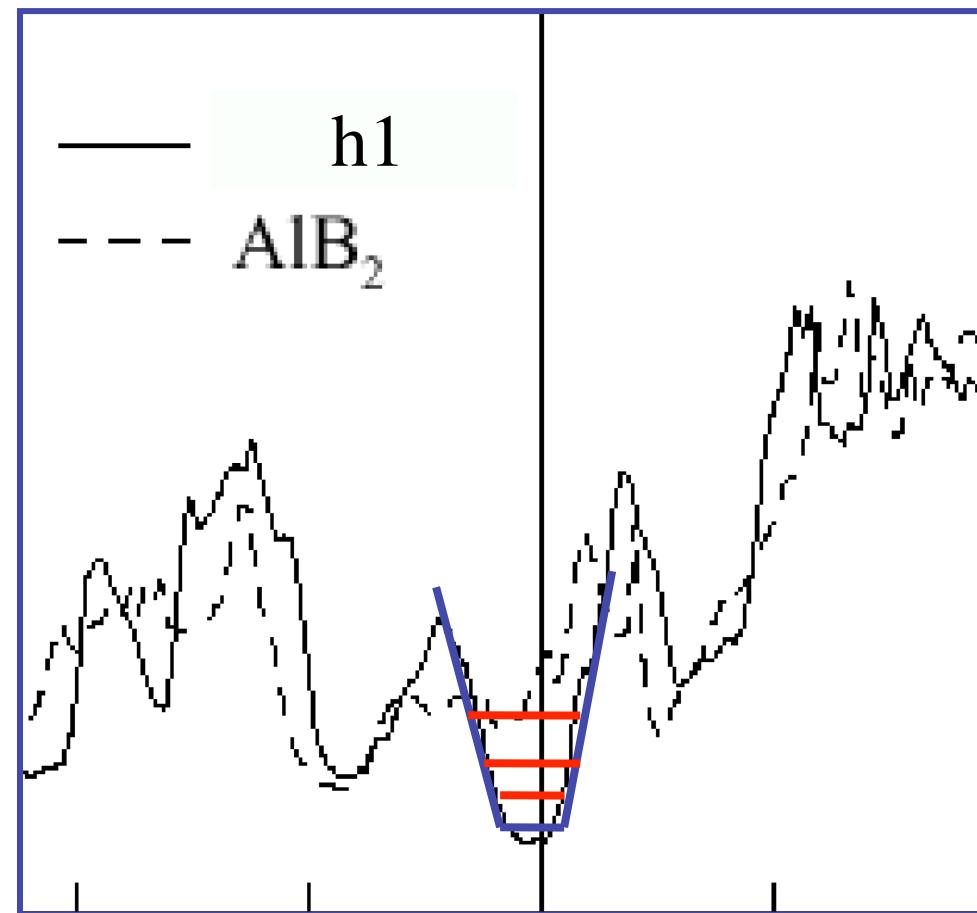
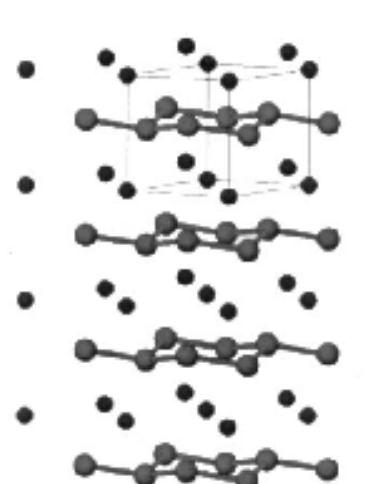
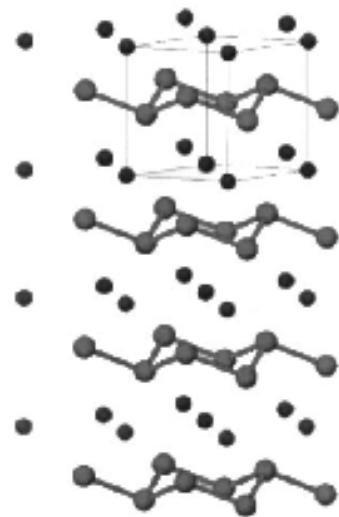
p(T,P) + diffraction X sous pression sur CaSi₂ (trigonal)



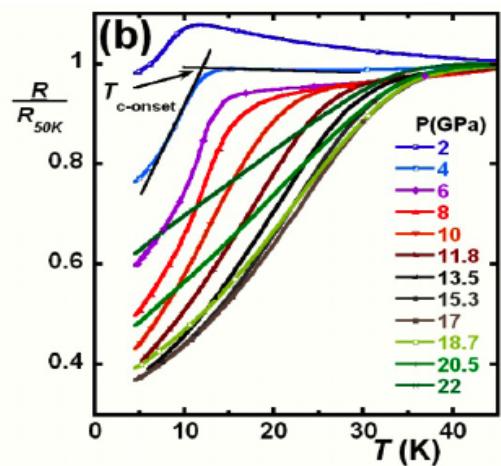
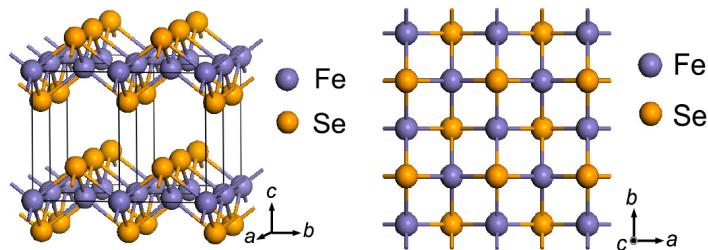
[Sanfilippo et al., PRB rapid com. **61**, N°6 (2000)]

h1

AlB_2

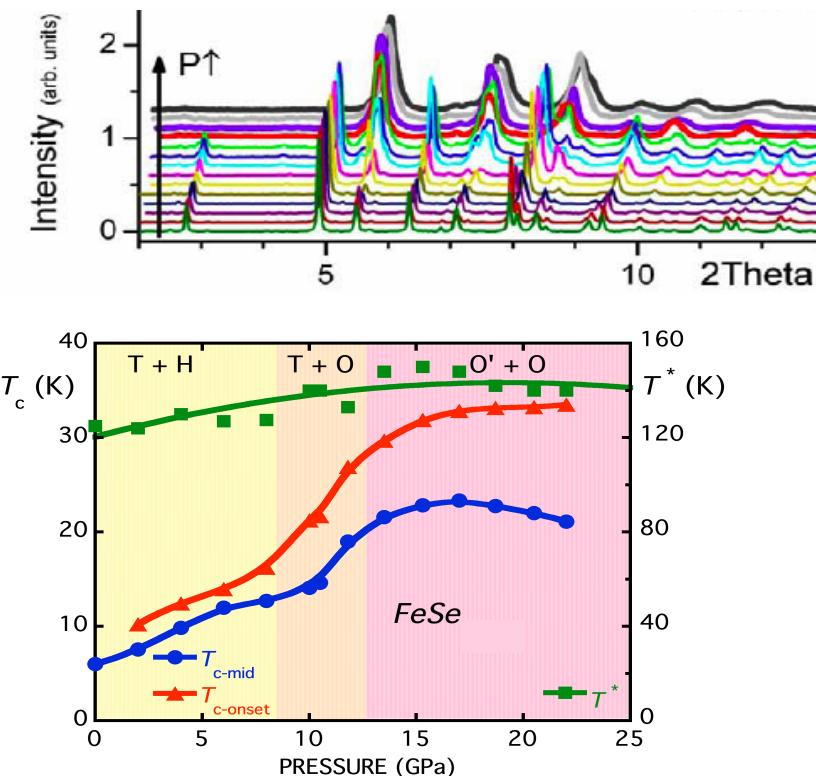


New Iron HTSC Superconductors: FeSe

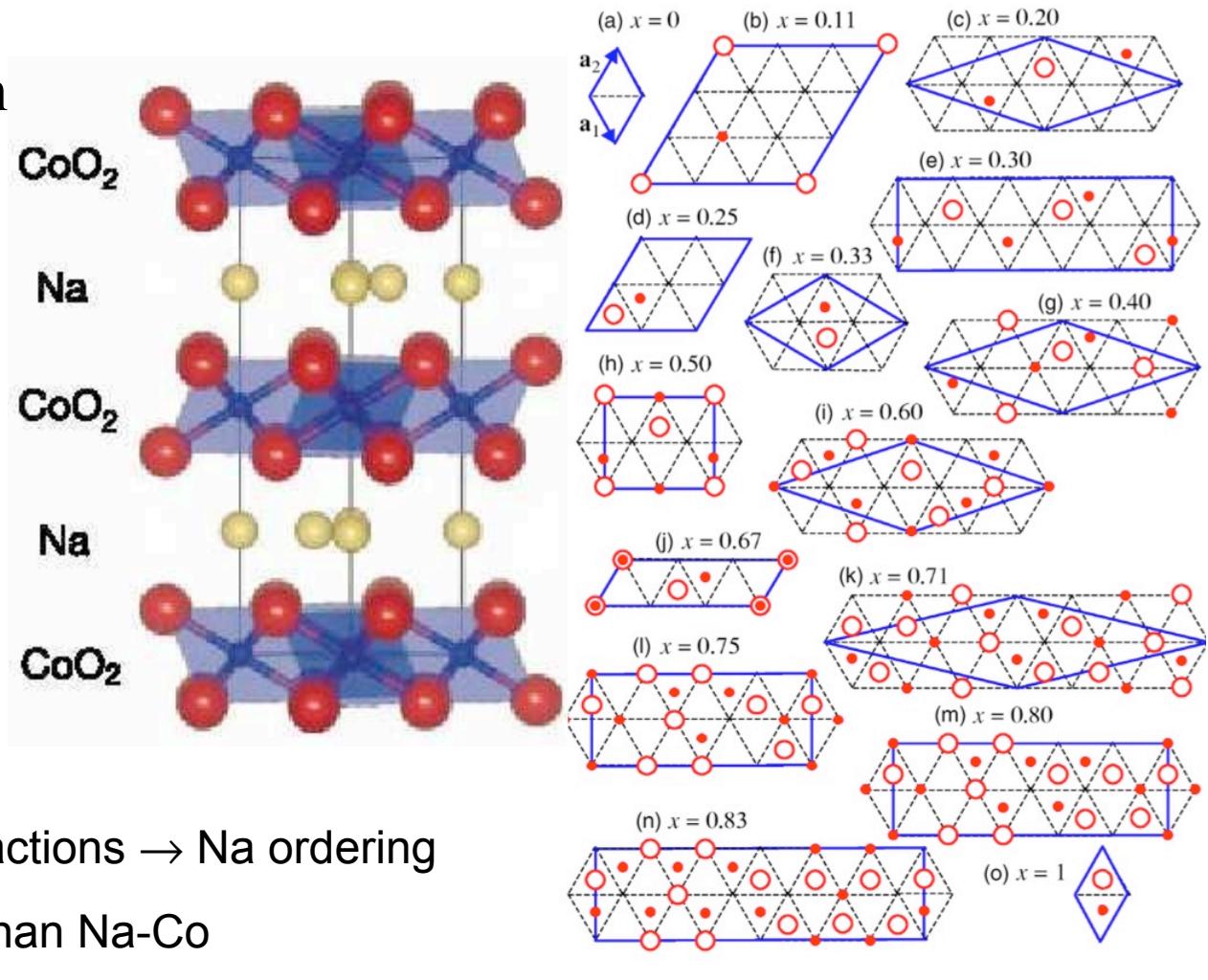


New High T_c High Pressure Phase

G. Garbarino, MNR, A. Sow, P. Lejay
A. Sulpice, P. toulemonde, EPL86(2009)27001

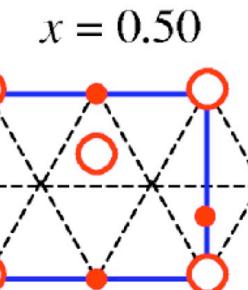


Increasing the interaction
between sublattices



- Screened electrostatic interactions → Na ordering
- Na-Na interaction stronger than Na-Co
- Charge and magnetic orderings on CoO_2 at low energy scale → Affected by Na ordering
- $\text{Na}(2)$ is ~0.1eV/Na lower in energy than $\text{Na}(1)$
For $x=0.50$ occupied in equal ratios

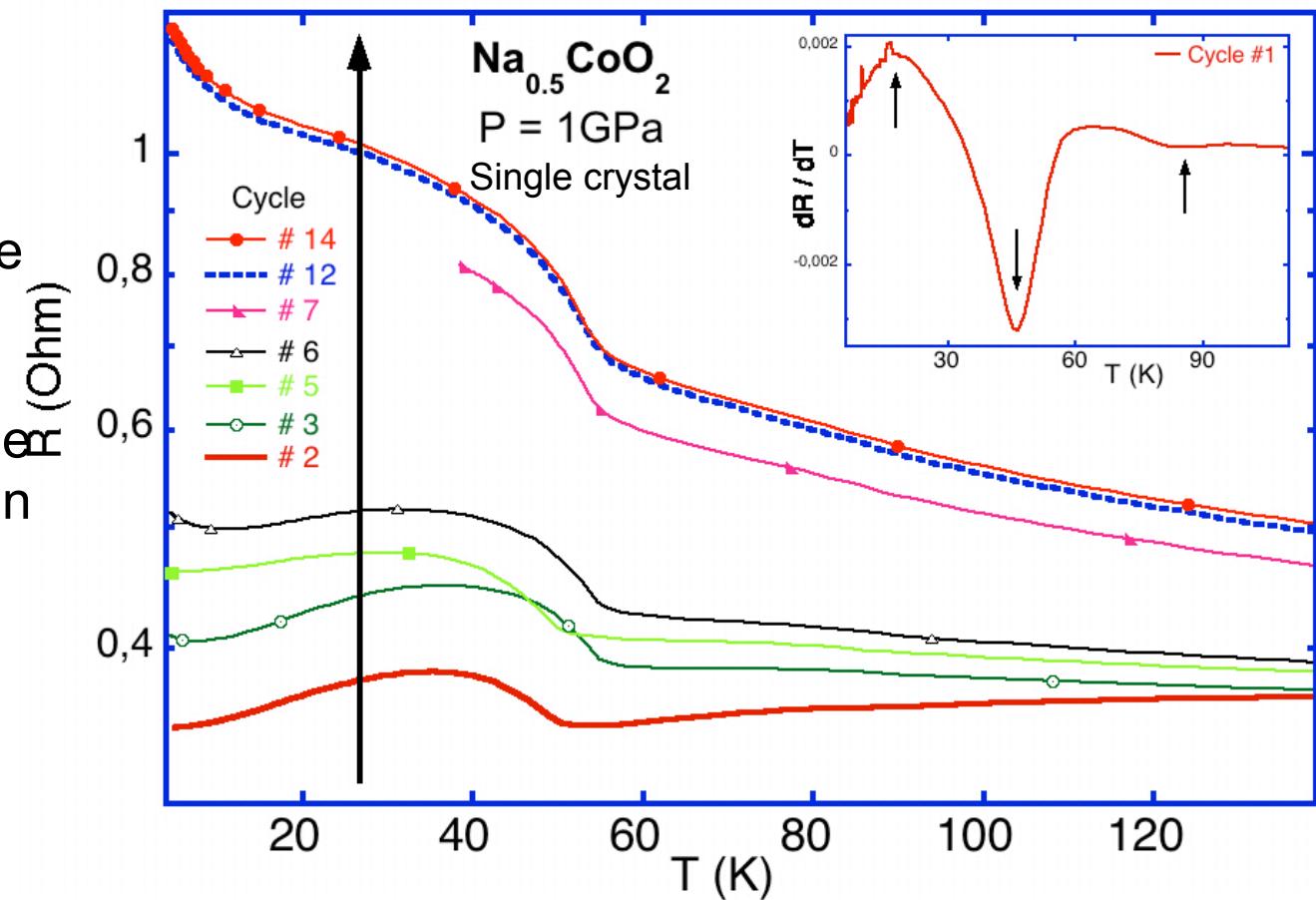
Zhang et al
PRB 71 p153102 (2003)



$\text{Na}_{0.50}\text{CoO}_2$

P=1GPa Fixed

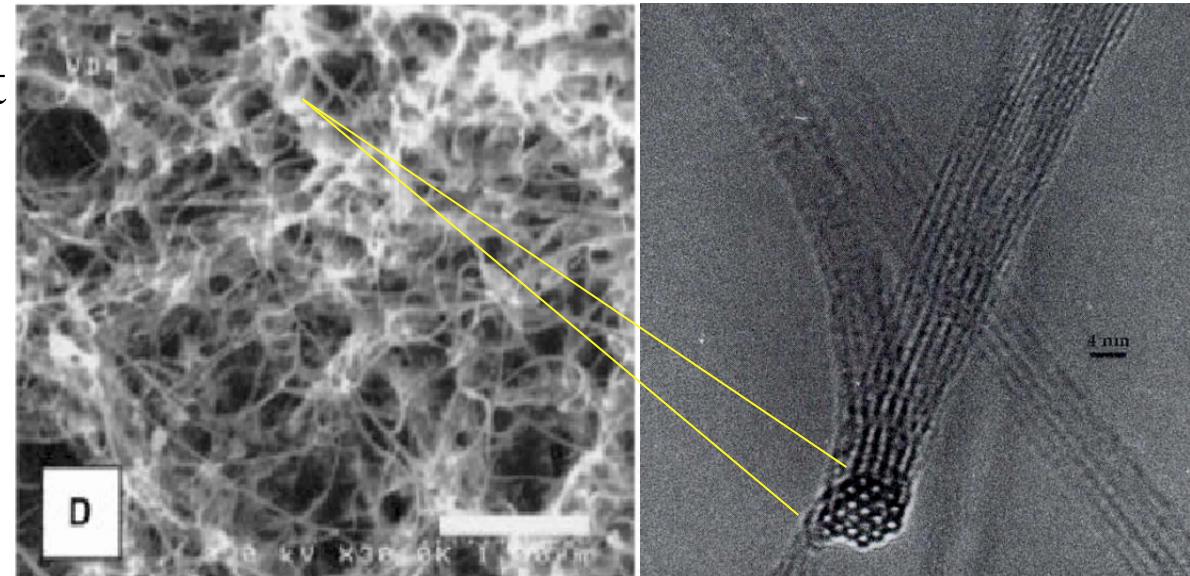
- Cycling temperature
→ resistance increase
- In each cycle charge carrier are localized in "pinning" positions.



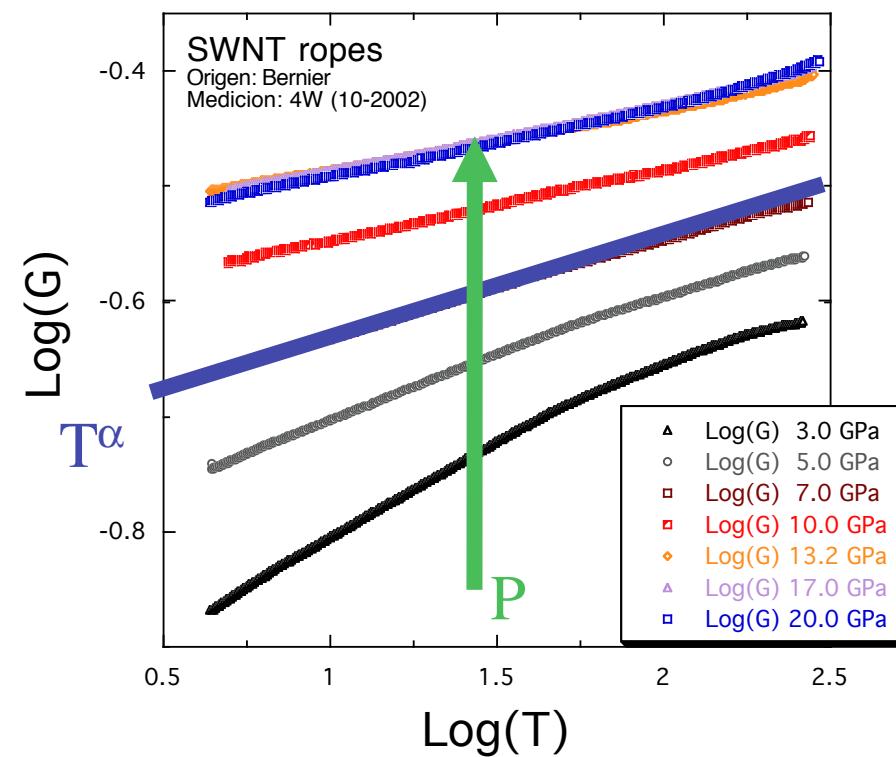
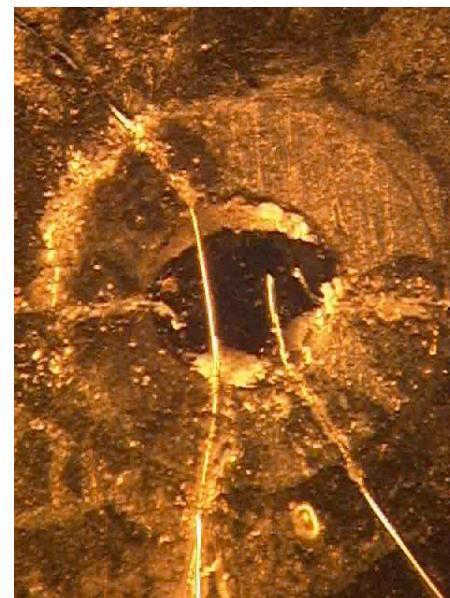
Cycling in temperature under pressure
causes disordering of the Na sublattice

due to the enhancement of the interaction with the CoO_2 sublattice

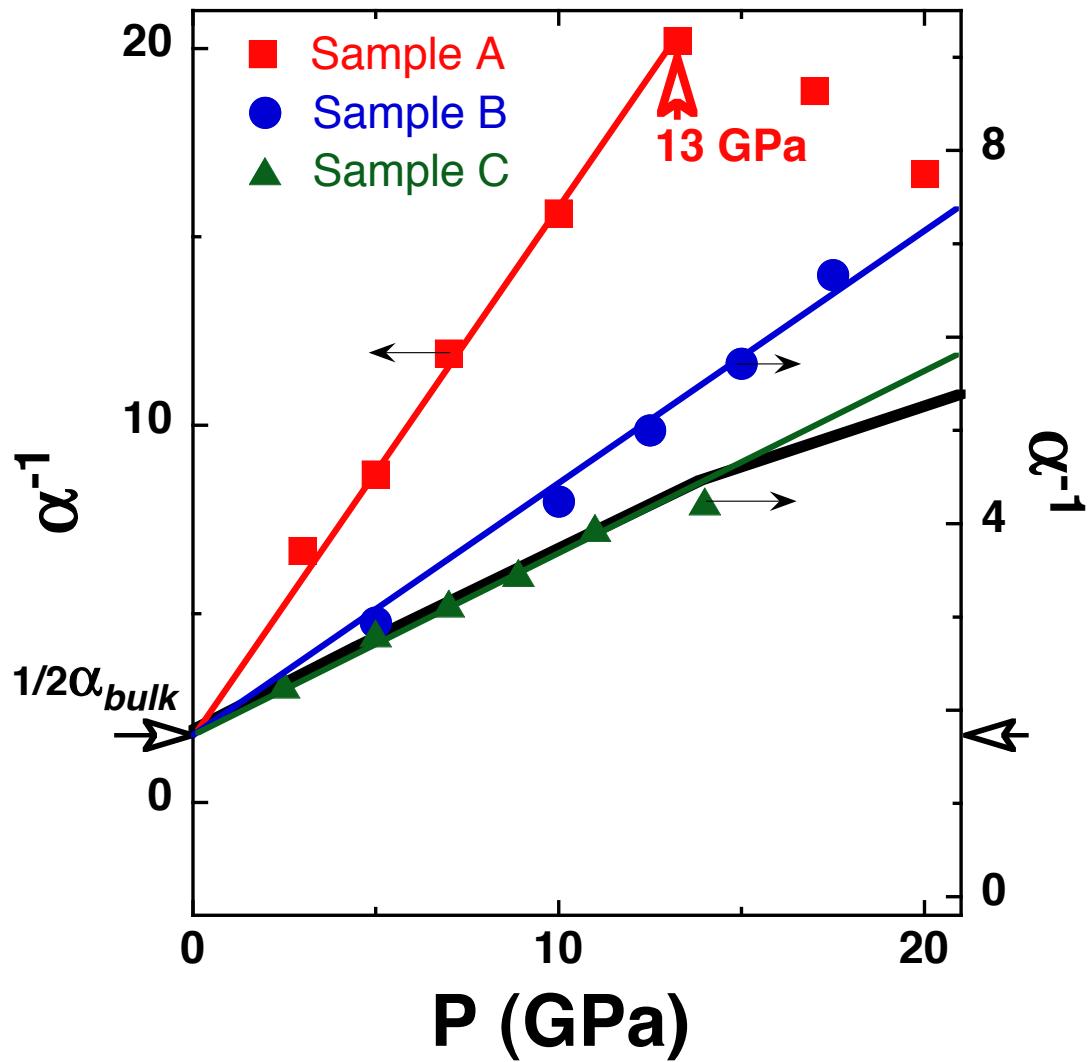
Pressure-induced contact
between nanotobject:
Carbon Nanotubes



Network of
Luttinger liquid
tunneling Junctions

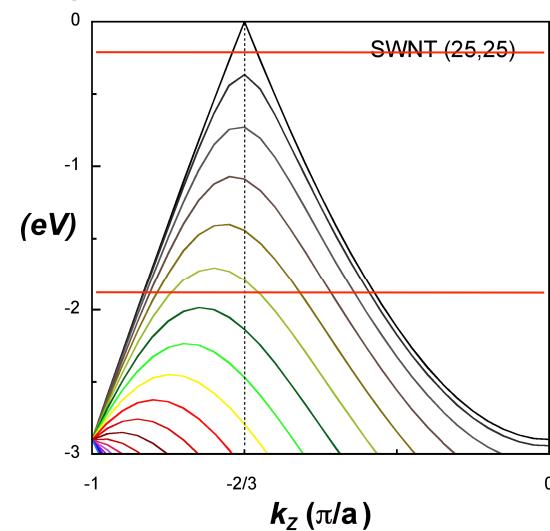
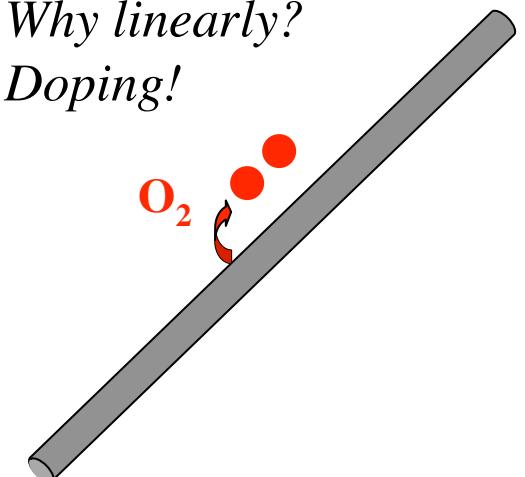


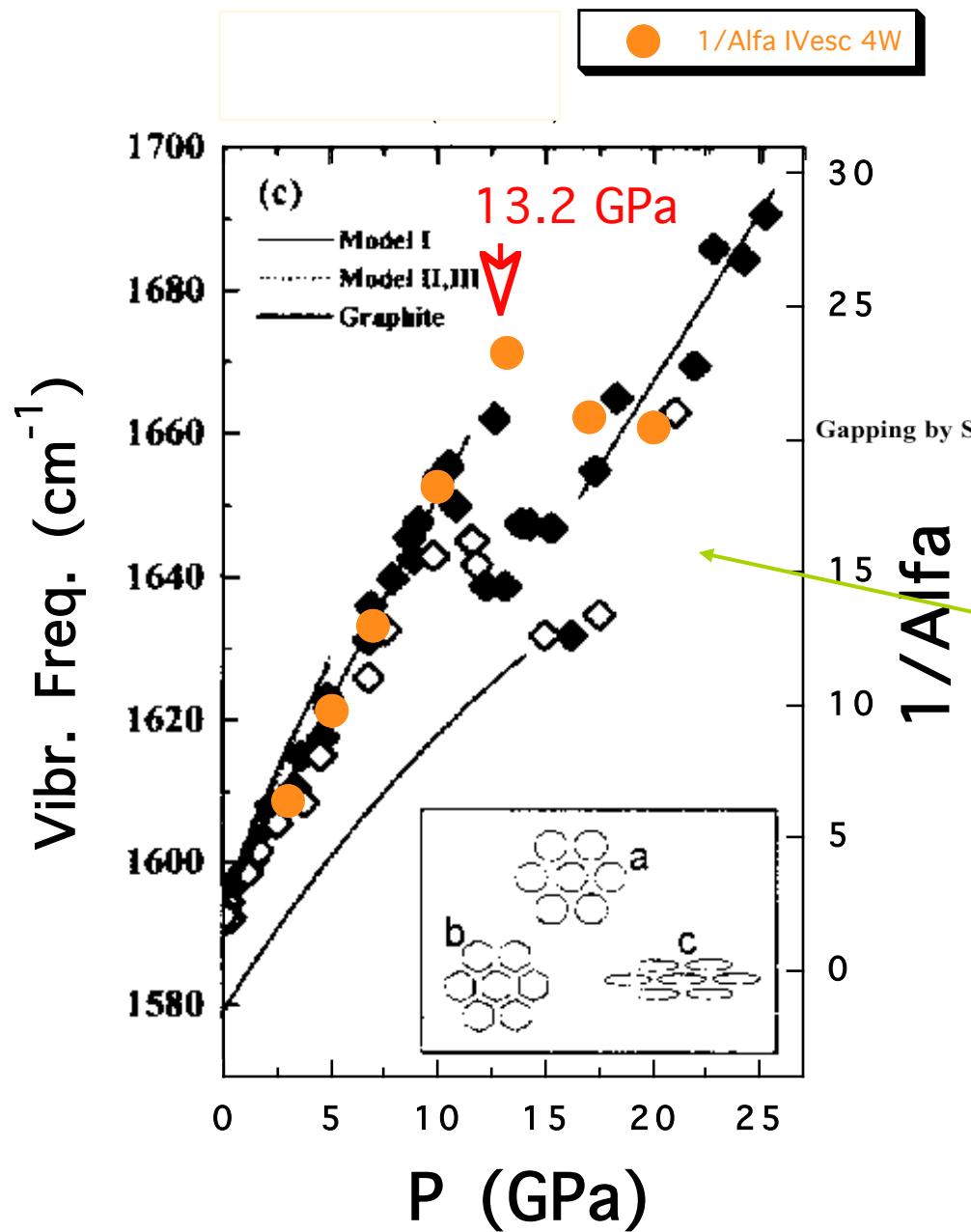
$$\alpha = (g^{-1} + g - 2)/(8N)$$



For a LL of $2N$ channels:

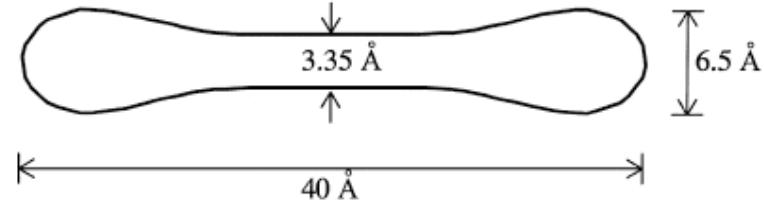
$\alpha_{N \text{ } b-b} = \alpha_{b-b} / N$
so the number of channels increases with pressure
Why linearly?
Doping!

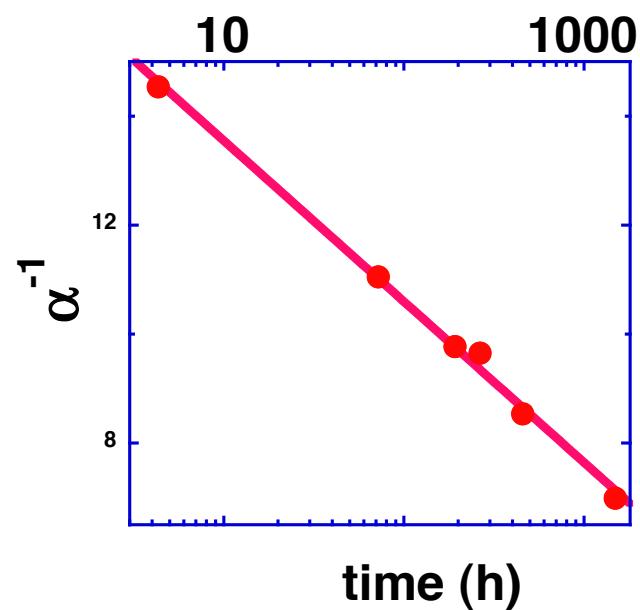
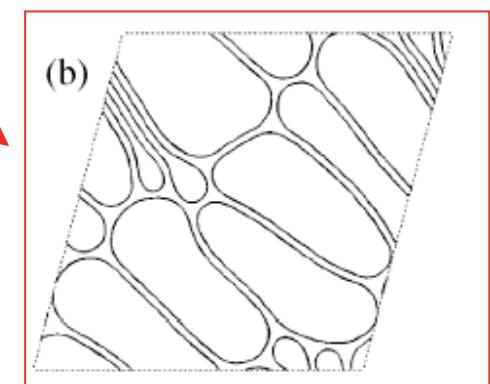
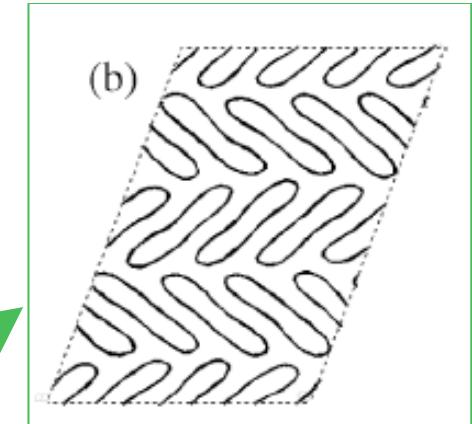
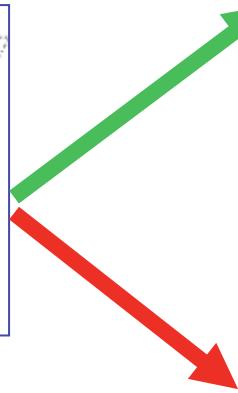
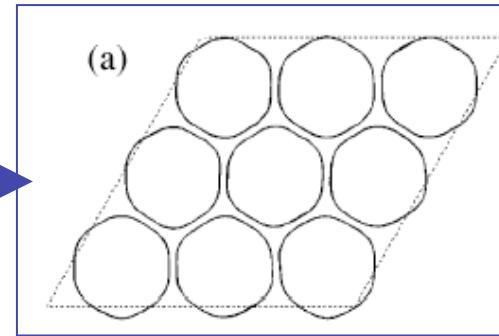
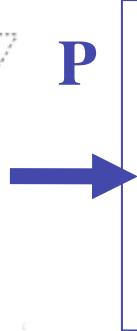
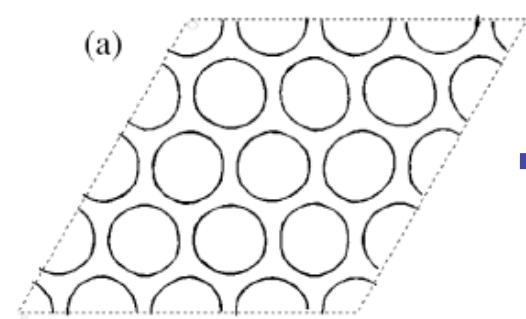




Gapping by Squashing: Metal-Insulator and Insulator-Metal Transitions in Collapsed Carbon Nanotubes

Paul E. Lammert, Peihong Zhang, and Vincent H. Crespi





log time dependence :
disordered system (e.g. spin glasses)

SUMMARY

Pressures up to 250GPa can be attained

Large spectra of physical properties can be studied

Ideal probe to seek for new interesting phases

Alternative probe for classical problems