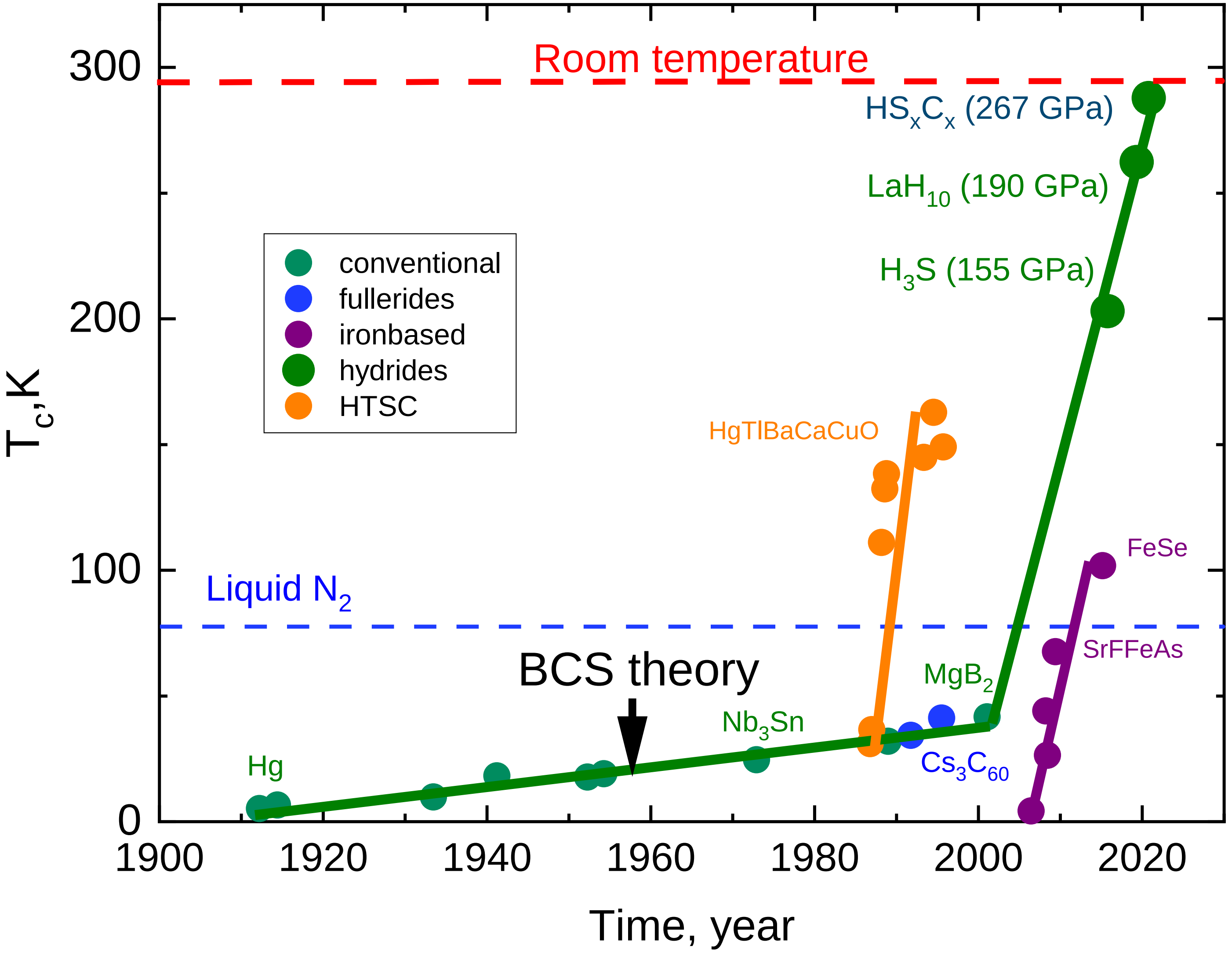
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk1P1 given at the virtual ASC 2020, October 26, 2020.

High-temperature conventional superconductivity at high pressures

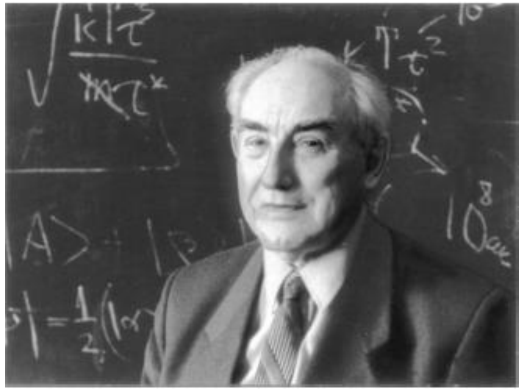
M. I. Eremets

Max-Planck-Institut fur Chemie, Hahn-Meitner Weg 1, 55128 Mainz, Germany

Critical temperature of superconductivity with time



The list of 'especially important and interesting problems' of 1999



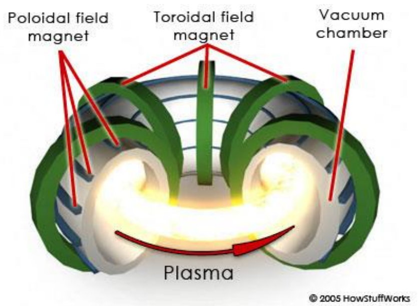
V. L. Ginzburg
Nobel Prize in Physics in 2003

1. Controlled nuclear fusion.
2. High - temperature and room – temperature superconductivity.
3. Metallic hydrogen. Other exotic substances
4. Two-dimensional electron liquid (the anomalous Hall effect and other effects).
5. …

the 21st century.

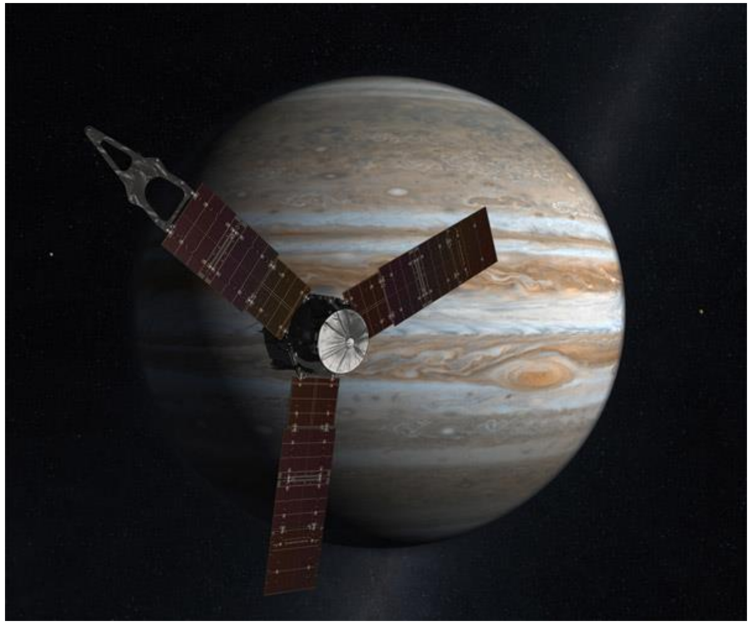
1. Controlled nuclear fusion.
2. High-temperature and room-temperature superconductivity.
3. Metallic hydrogen. Other exotic substances.
4. Two-dimensional electron liquid (the anomalous Hall effect and other effects).
5. Some questions of solid-state physics (heterostructures in semiconductors, quantum wells and dots, metal-dielectric transitions, charge- and spin-density waves, mesoscopics).
6. Second-order and related phase transitions. Some examples of such transitions. Cooling (in particular, laser cooling) to superlow temperatures. Bose-Einstein condensation in gases.
7. Surface physics. Clusters.
8. Liquid crystals. Ferroelectrics. Ferrotoroics.
9. Fullerenes. Nanotubes.
10. The behavior of matter in superstrong magnetic fields.
11. Nonlinear physics. Turbulence. Solitons. Chaos. Strange attractors.
12. X-ray lasers, gamma-ray lasers, superhigh-power lasers.
13. Superheavy elements. Exotic nuclei.
14. Mass spectrum. Quarks and gluons. Quantum chromodynamics. Quark-gluon plasma.
15. Unified theory of weak and electromagnetic interactions. $W^{\pm}$ and Z^0 bosons. Leptons.
16. Standard Model. Grand unification. Superunification. Proton decay. Neutrino mass. Magnetic monopoles.
17. Fundamental length. Particle interaction at high and superhigh energies. Colliders.
18. Nonconservation of CP invariance.
19. Nonlinear phenomena in vacuum and in superstrong magnetic fields. Phase transitions in a vacuum.
20. Strings. M theory.
21. Experimental verification of the general theory of relativity.
22. Gravitational waves and their detection.
23. The cosmological problem. Inflation. The Λ term

Nuclear Fusion



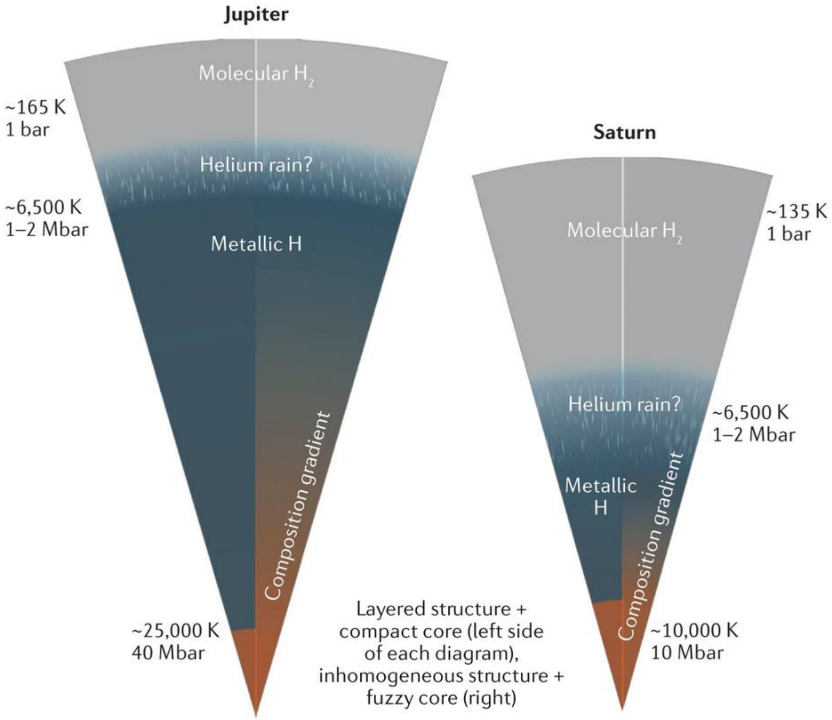
Metallic hydrogen

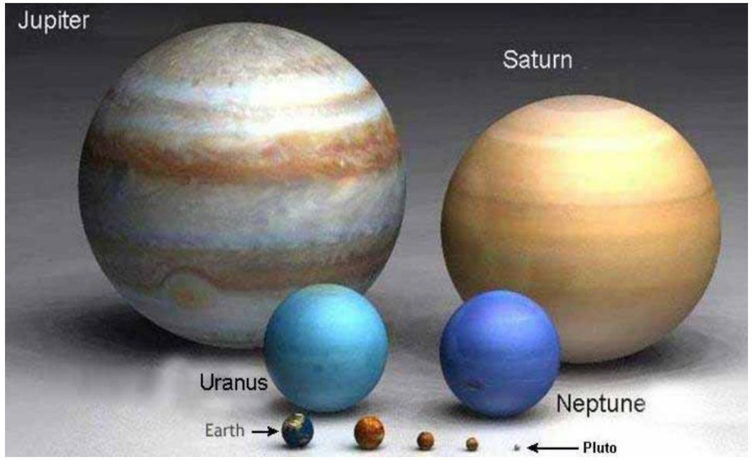
Hydrogen in the Solar system



Juno mission

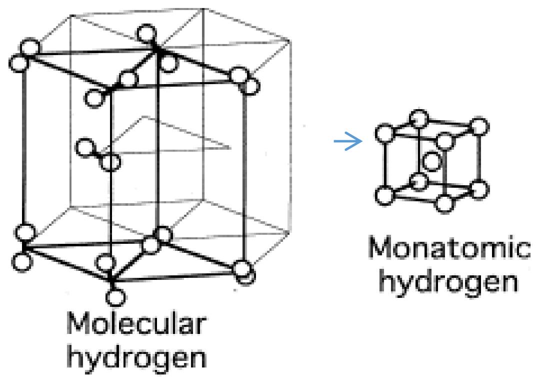
July 4, 2016
1.1 billion USD





Helled *et al* 2020

Metallic hydrogen



Wigner and Huntington (1935)

Superconductivity and superfluidity in metallic hydrogen

Ashcroft 1968 PRL Babaev *et al* (2004)

$T_c \sim 0.2 \sqrt{\lambda}\, \omega_D$ $T_c = 0.2 \sqrt{2}\ 2000K$ $\rightarrow$ $T_c \sim 500\ K$

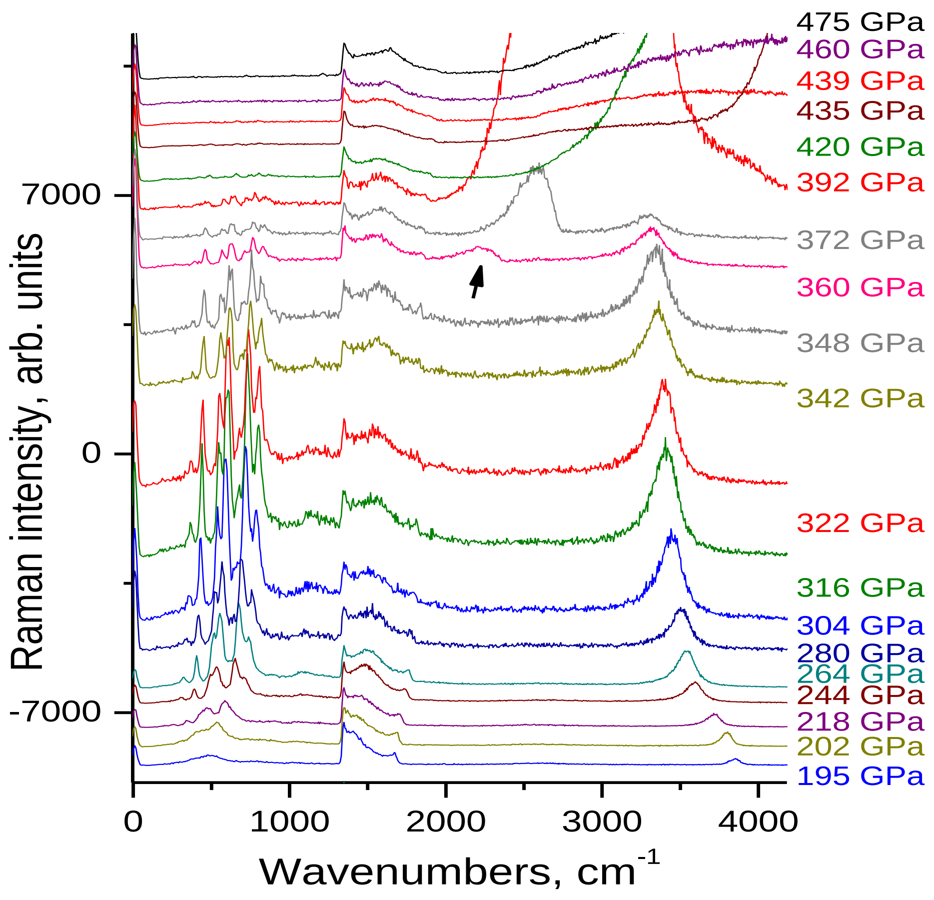
T_c ~ 350-700 K

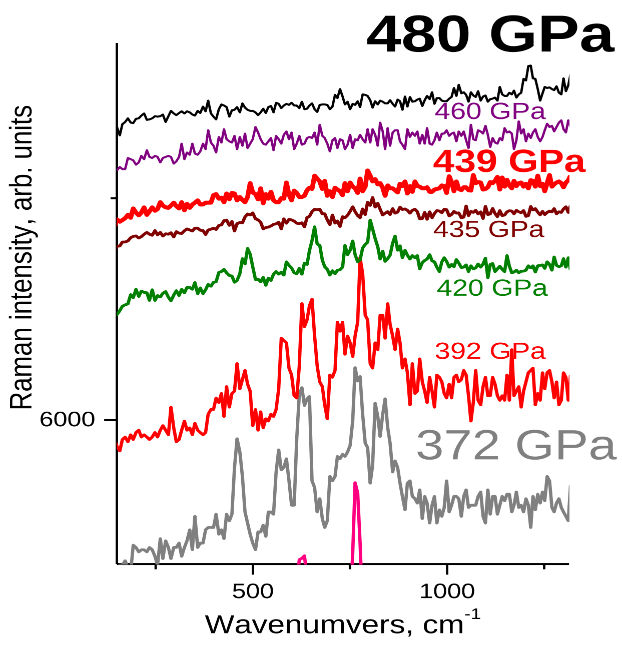
P ~500 Gpa

McMahon and Ceperley (2012)

Diamond ω_D =1860 K

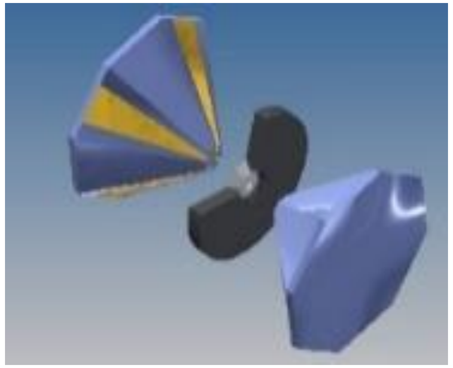
Raman spectra of hydrogen at 480 GPa



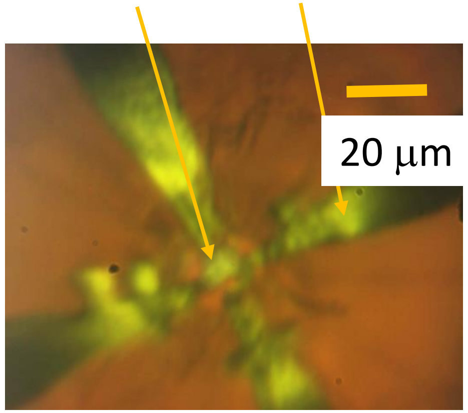


Eremets et al (2019) *Nature Physics* **15** 1246

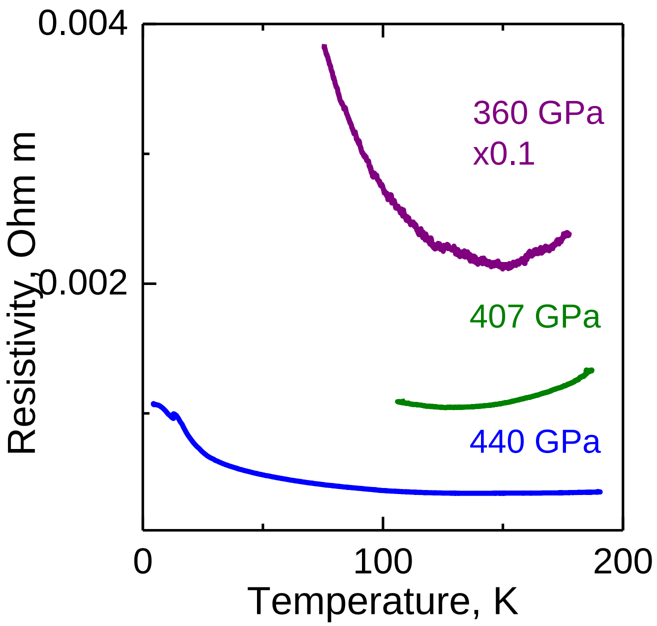
Semimetallic hydrogen

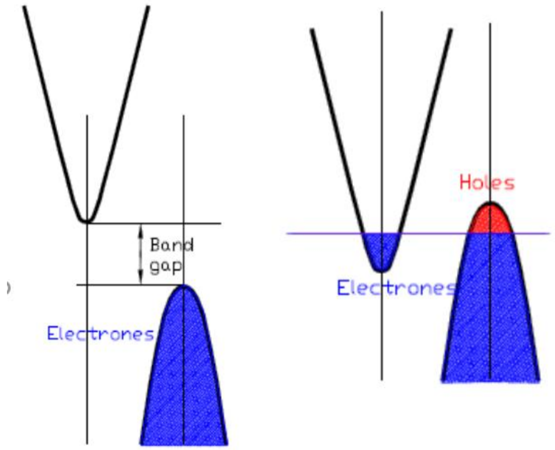


Hydrogen Electrodes



380 GPa and 180 K





Semimetals
Graphite
Bismuth

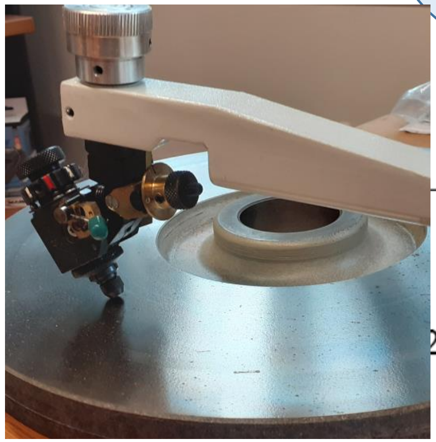
Hydrogen transforms to metal
at ~360 GPa in molecular state.
No superconductivity

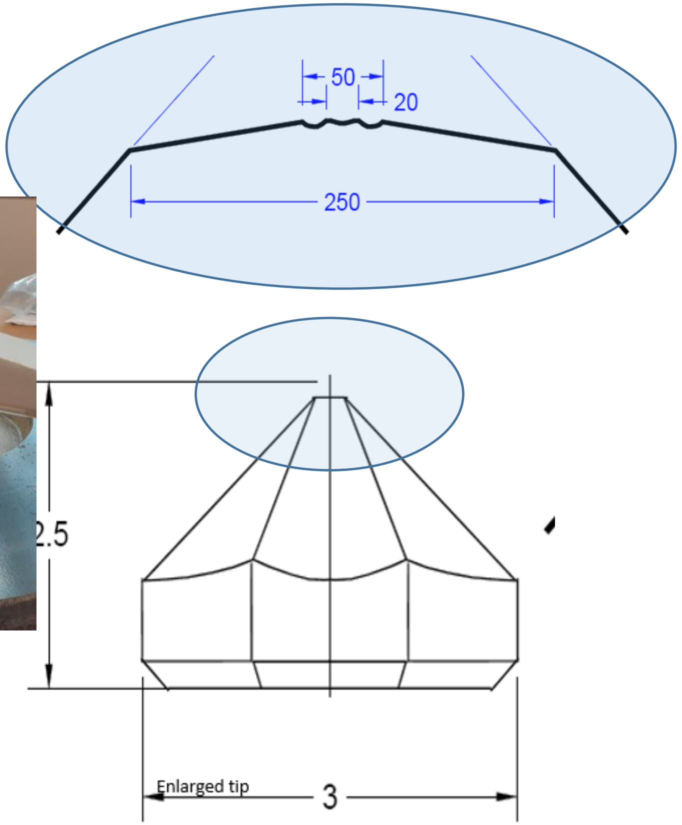
Theory
Monacelli et al (2020) *Nature Phys.*
Gorelov et al (2020) PRL (2020) 124, 116401

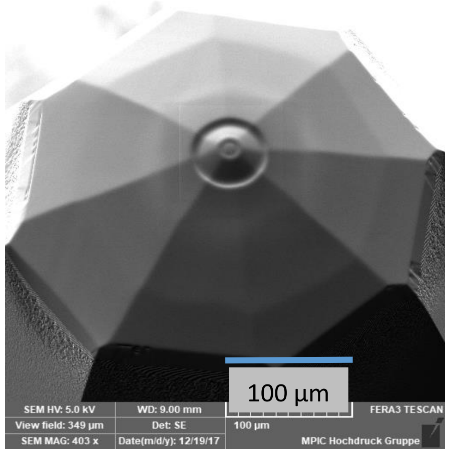
Experimental techniques
Diamond anvil cell

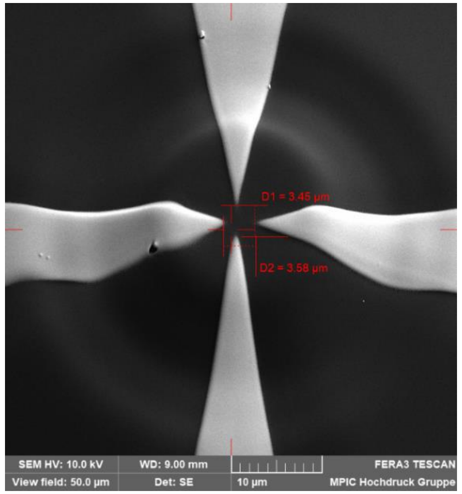
Focused ion beam

500 GPa









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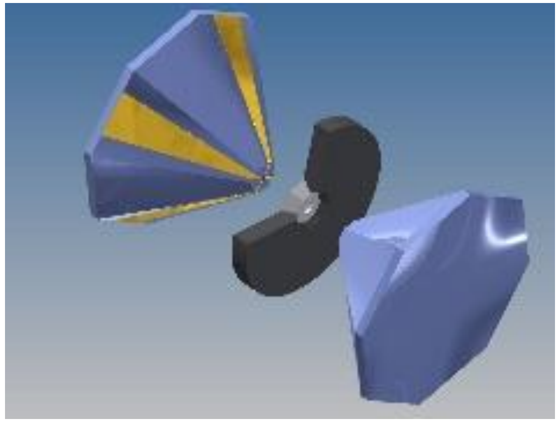
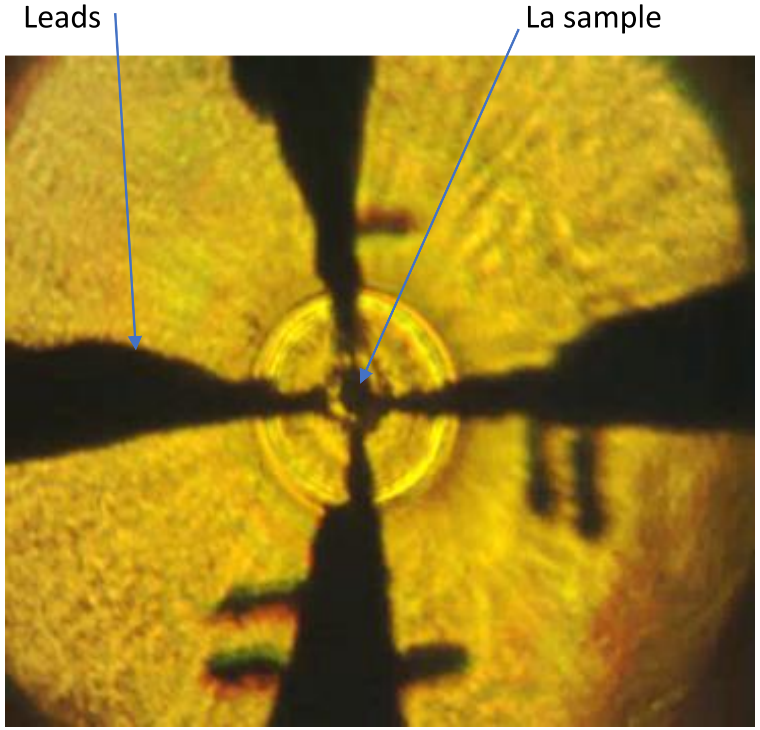
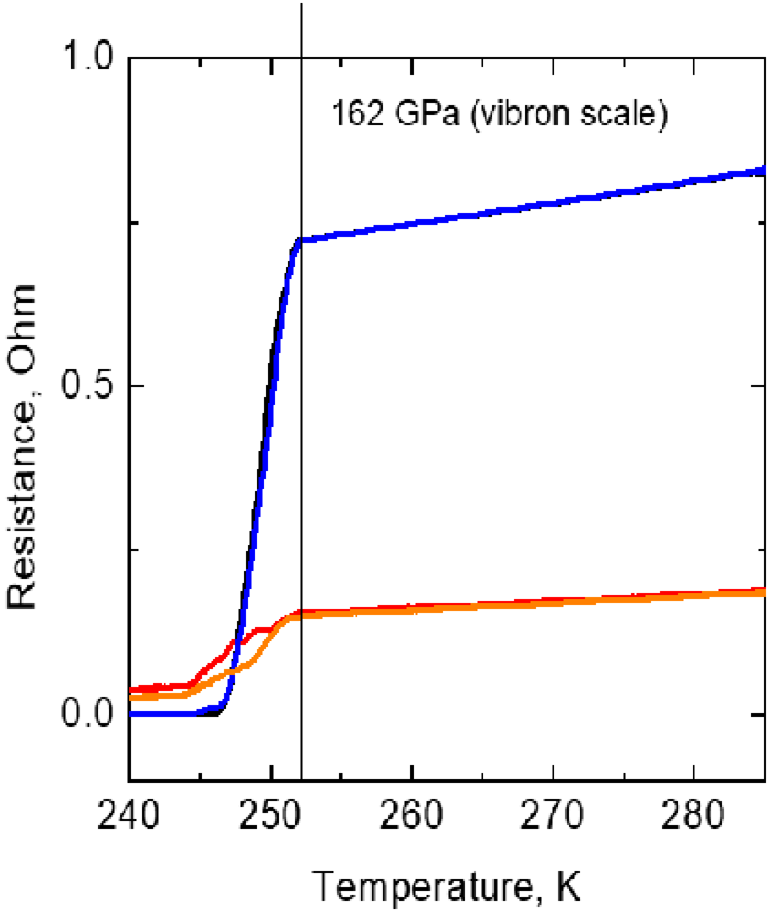
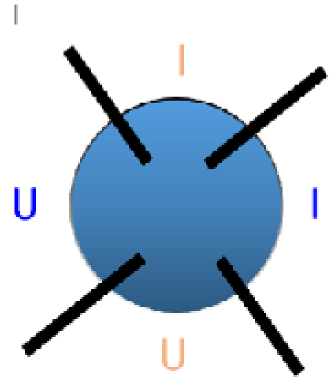


Electrical measurements







N. Ashcroft 2004:

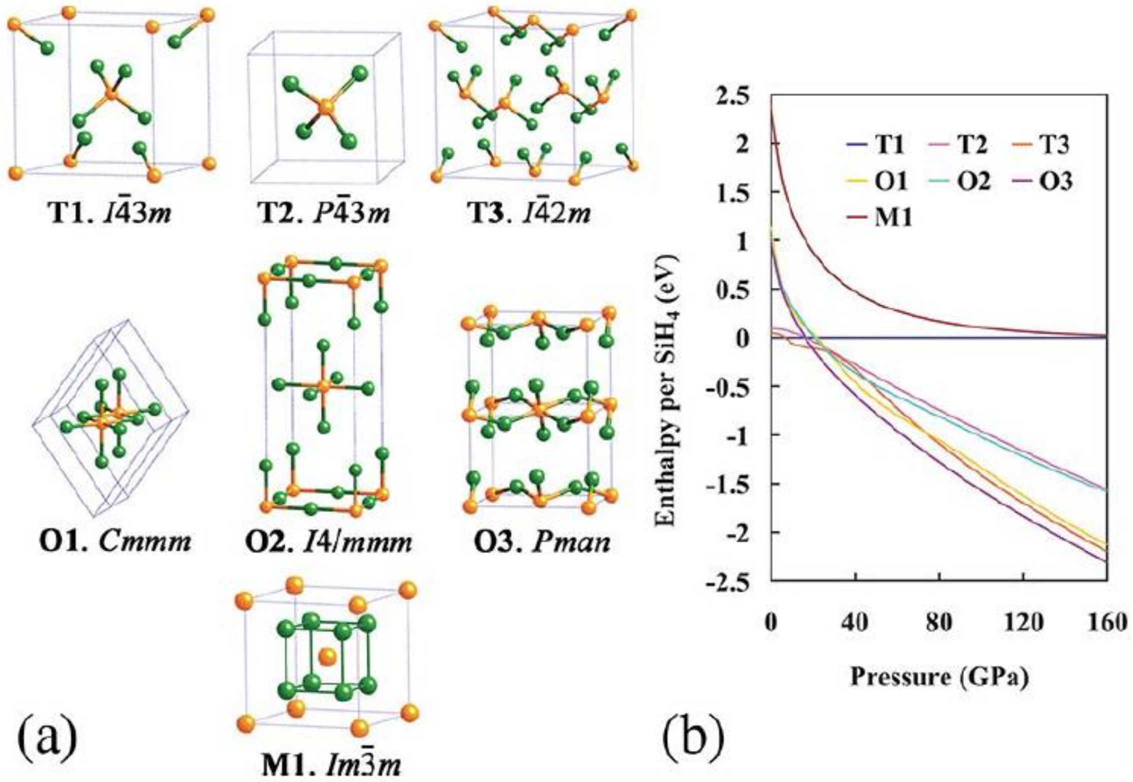
Superconductivity in Hydrogen dominant materials:
CH_4, SiH_4, GeH_4 …

metallic at high pressures ~100- 200 GPa

N. Ashcroft 2004:
Superconductivity in Hydrogen dominant materials: CH_4, SiH_4, GeH_4 …

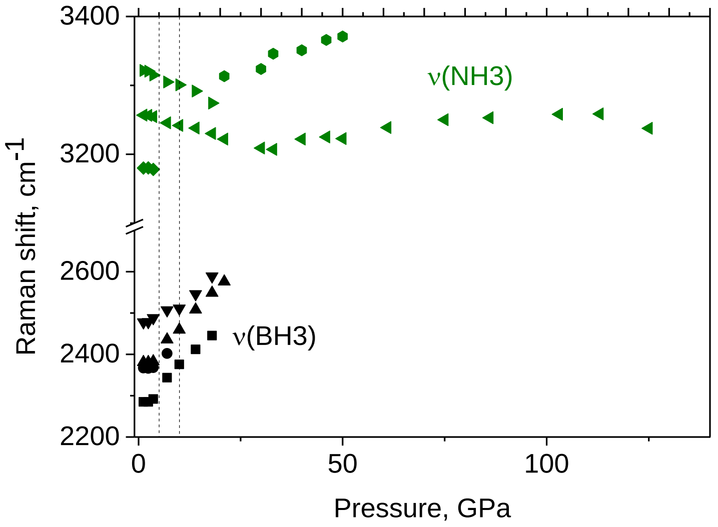
chemical intuition

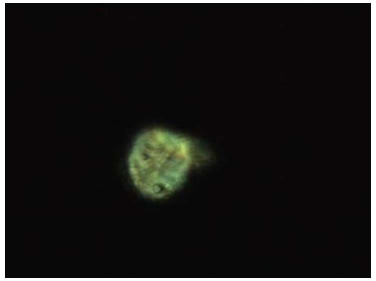
SiH4 at High Pressure. PRL **96,** 017006 (2006)
structure **O3,** metallization onset 91 GPa
Tc=**166 K** at 202 GPa

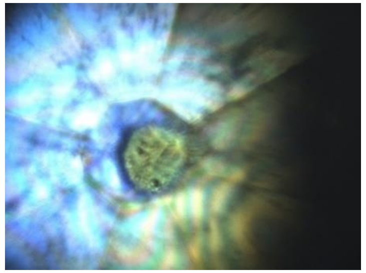


Superconductivity in hydrogen-rich materials

NH_3BH_3







Experiment: no superconductivity

LiH+H2 150 GPa

$LiBH_4$ P>200 GPa

$NaBH_4$ at P<130 GPa

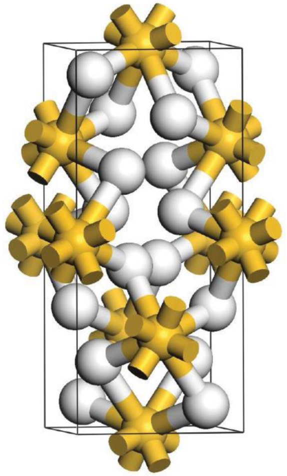
$Si(CH_3)_4$ at P<140 GPa

$B_{10}H_{14}$ at P<200 GPa

NH_3BH_3 at P<200 GPa

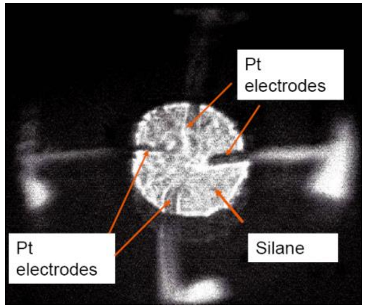
Li_2S at P<200 GPa

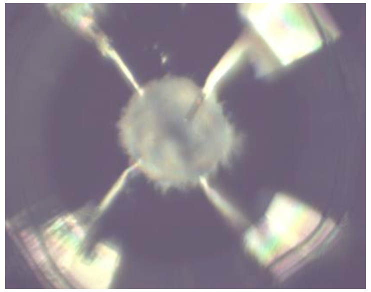
Metallization and superconductivity in silane



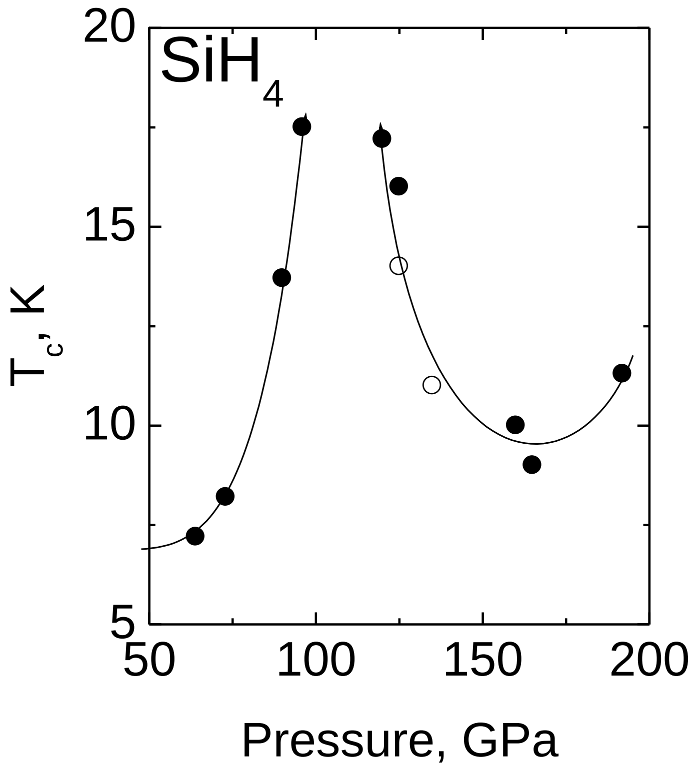
I4$_1$/a

Predictions: Pickard and Needs
Phys. Rev. Lett. **97** 045504 (2006)





P=50-100 GPa



M. Eremets *et al Science* 2008

DFT theory – accurate calculation of electronic and phonon spectra

Crystal predictions

Random sampling
Evolutionary algorithms
Particle swarm optimization

CaH_6 T_c ~ 220–235 K at 150 Gpa (2012)
YH_6 251–264 K at 120 GPa
LaH_{10} 280 K at 210 GPa

$SiH_4(H_2)_2$ – 98–107 K at 250 GPa
$GeH_4(H_2)_2$ – 76–90 K at 250 GPa
Si_2H_6: 139 K at 275 GPa
GaH_3 73–86 K at 160 GPa
GeH_3 100 K at 180 GPa
GeH_4. 64 K at 220 GPa
SnH_4 62 K at 200 GPa
H_2S 80 K at 160 GPa
KH_6 60 K at 166 – 300 GPa
$LiH+H_2$: LiH_6 82 K at 300 GPa. LiH_8 T_c = 31 K at 100 GPa
SiH_4. Metallic phase C2/c at 262 GPa, with T_c ~16 K.
AlH_3 24 K at 110 GPa
NbH_4 38 K at 300 GPa
BeH_2 30-40 K P>200 GPa 2014
LiH P>300 GPa (Zurek et al PNAS 2009)
$Xe(H_2)_8$ metallization at 250 GPa
$LiBeH_3$ Hu et al PRB 79, 134116 (2009) – insulating to 530 GPa

Some reviews:

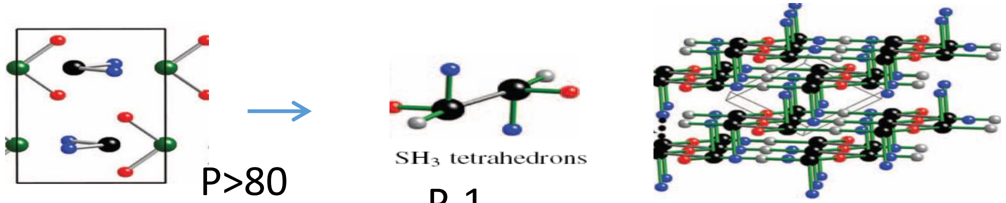
1. Flores-Livas, J. A. *et al.* A perspective on conventional high-temperature superconductors at high pressure: Methods and materials. *Physics Reports* **856**, 1-78 (2020).
2. Pickard, C. J., Errea, I. & Eremets, M. I. Superconducting hydrides under pressure. *Annual Review of Condensed Matter Physics* **11**, 57-76 (2020).
3. Pickett, W. & Eremets, M. I. The quest for room-temperature superconductivity in hydrides. *Physics today* **72(5)** 52-58 doi:10.1063/PT.3.4204. (2020).
4. Gor'kov, L. P. & Kresin, V. Z. High Pressure and Road to Room Temperature Superconductivity. *Rev. Modern Phys.* **90**, 011001 (2018).

Hydrogen sulfide

THE JOURNAL OF CHEMICAL PHYSICS **140**, 174712 (2014)

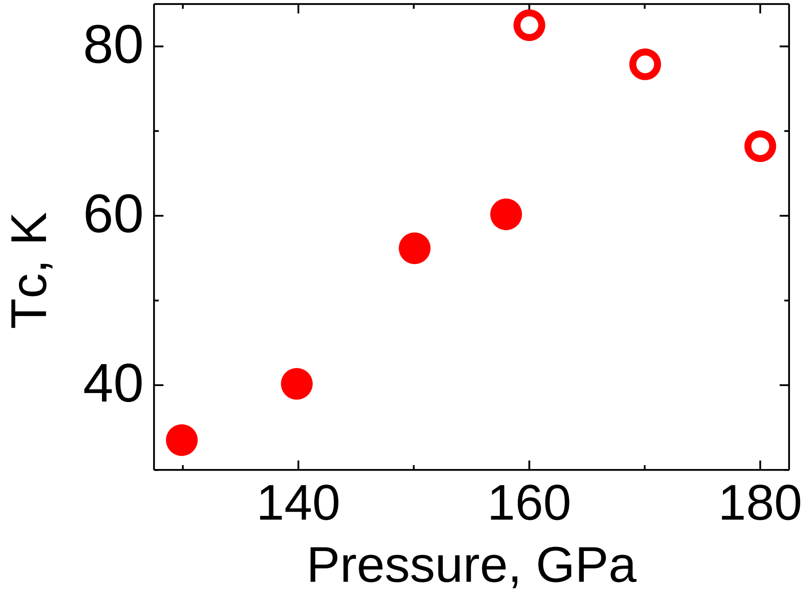
The metallization and superconductivity of dense hydrogen sulfide

Yinwei Li,[1,a)] Jian Hao,[1] Hanyu Liu,[2] Yanling Li,[1] and Yanming Ma[3,b)]



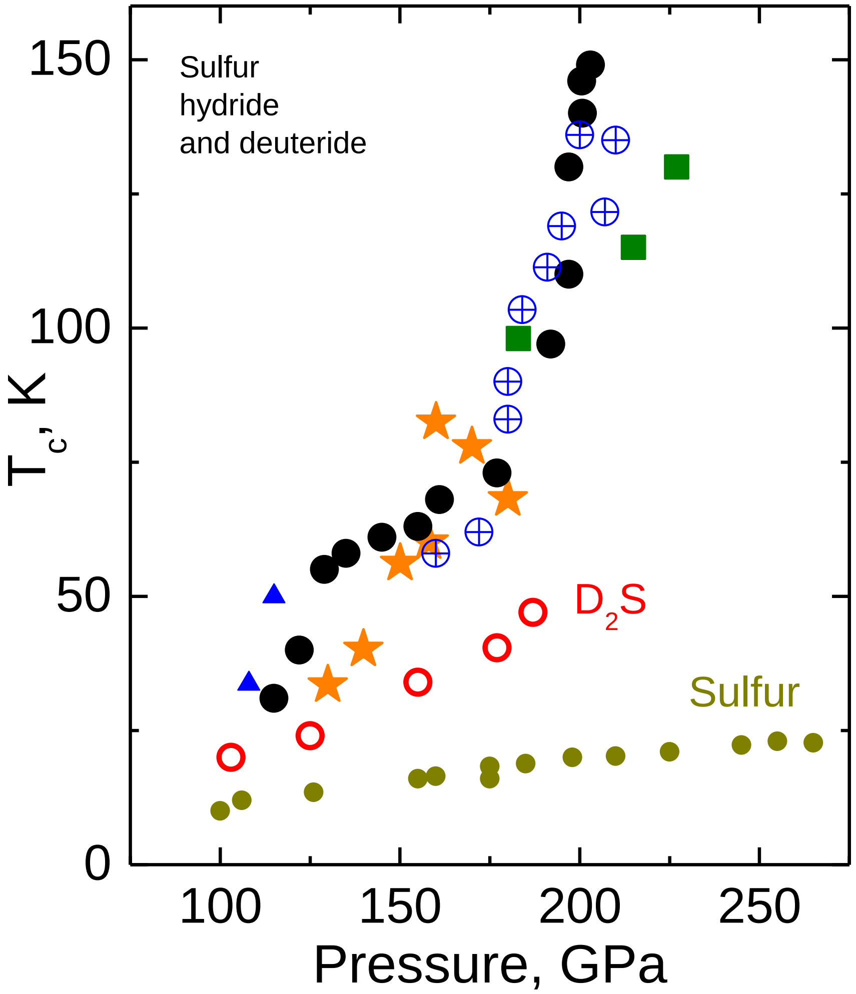
P>80 GPa

P-1



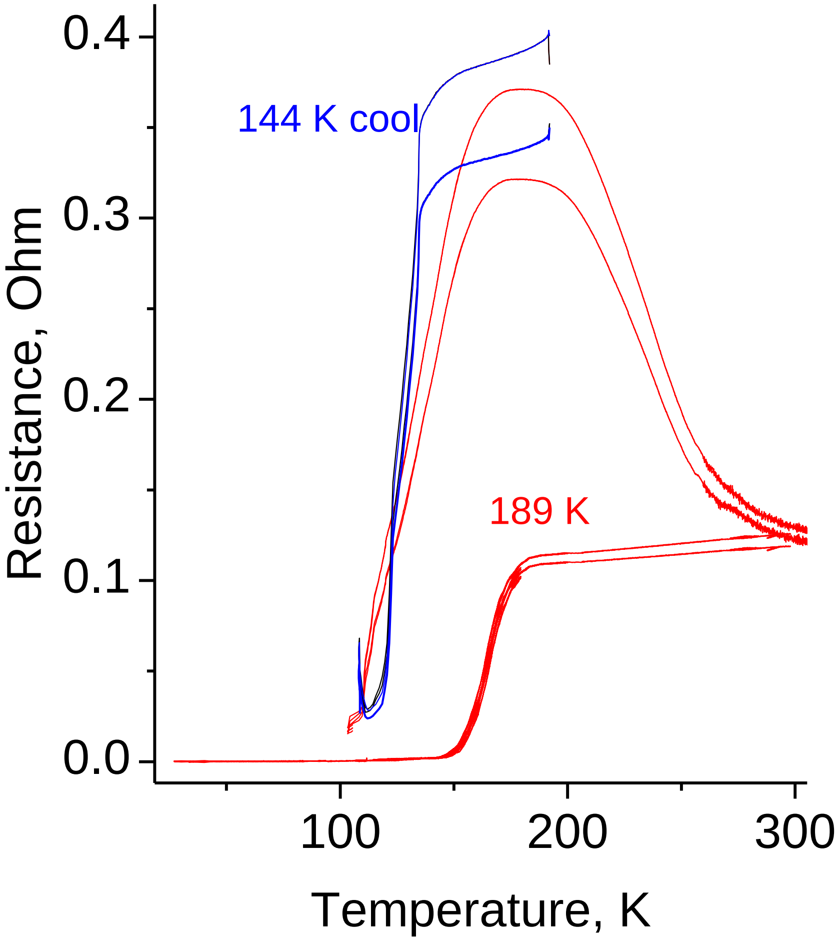
Hydrogen sulfide

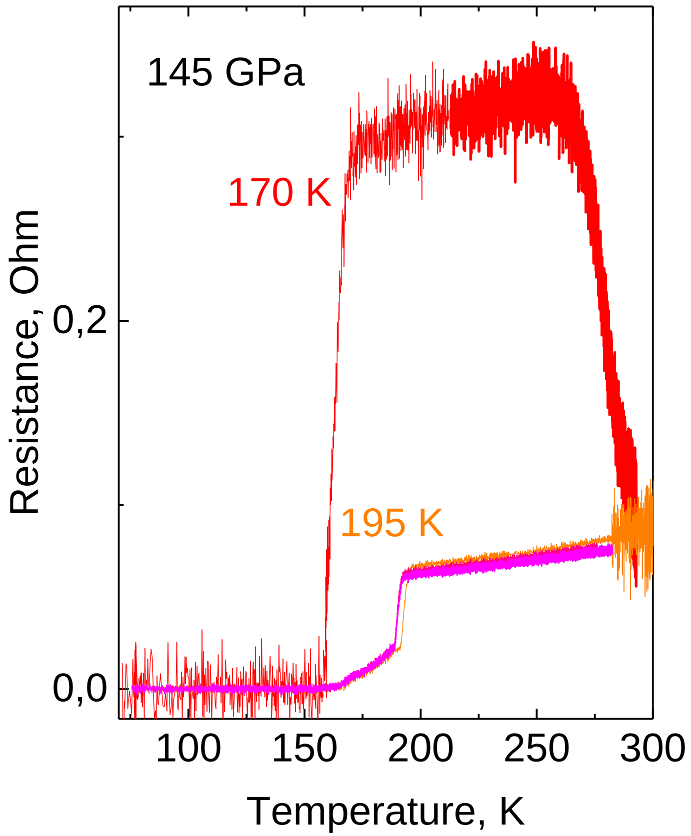
Alexander Drozdov



A. Drozdov, M, Eremets et al, *Nature* **525**, 73 (2015)

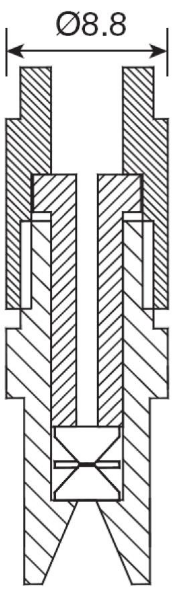
Temperature effect on the sample

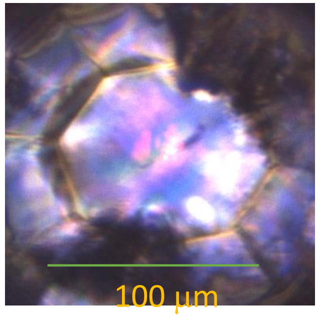




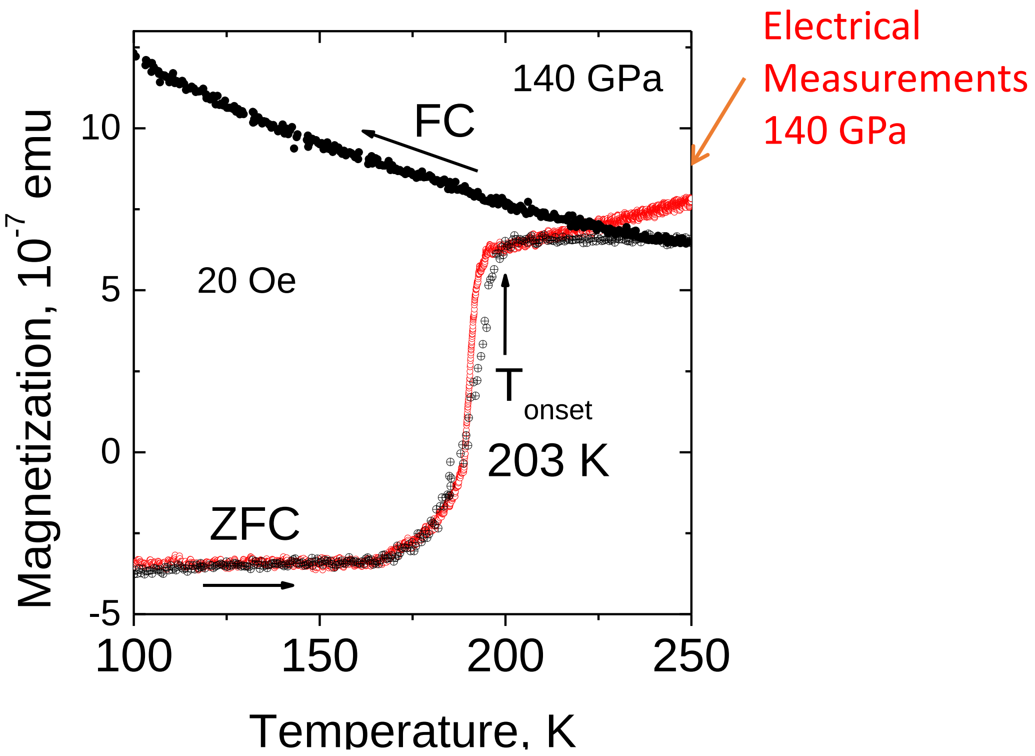
Evidence of the superconductivity in sulfur hydride

Susceptibility measurements in SQUID





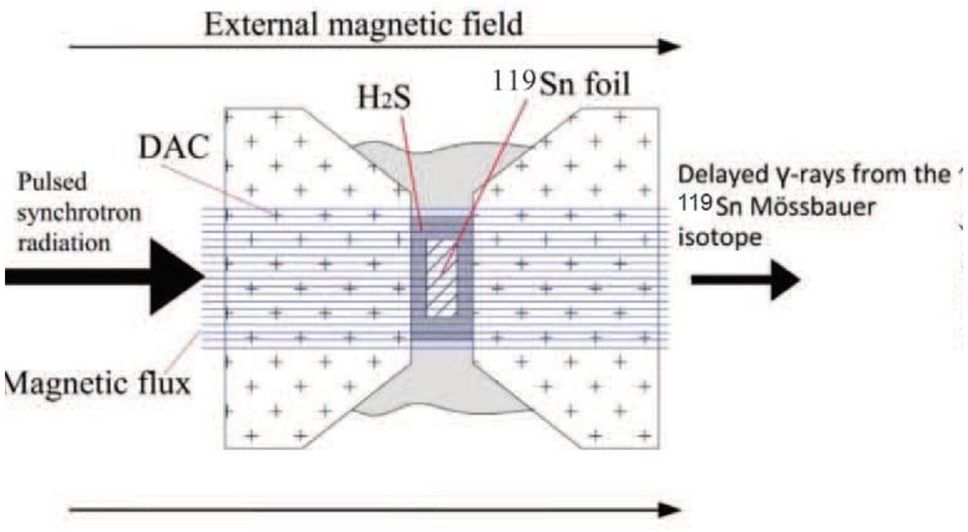
140x120x25 μm^3
Rev Sci Instr 2009



$$M(disk) \approx 0.2\, r^3 H$$

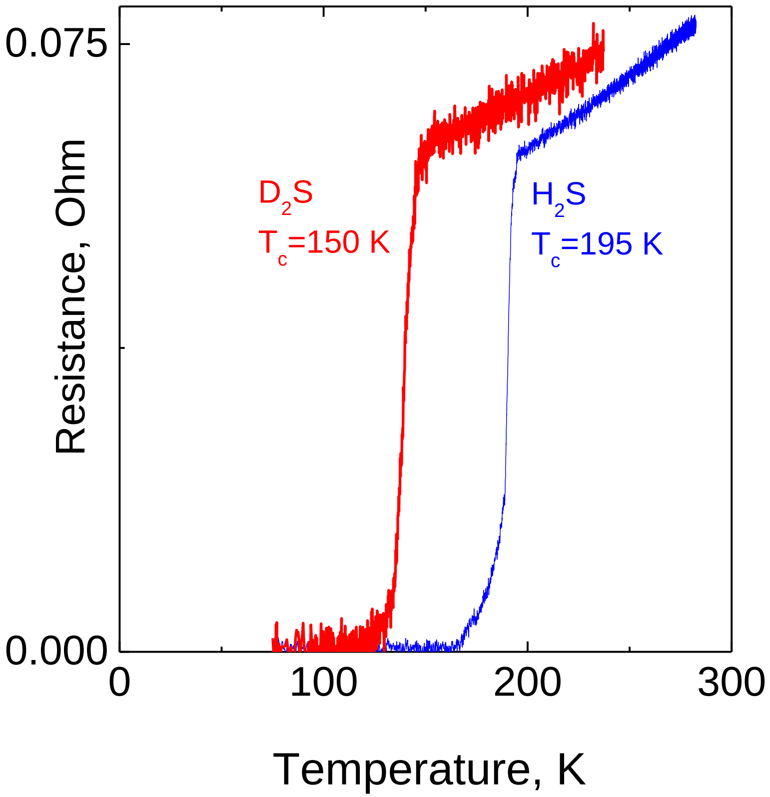
R=50 μm, H=20 Oe **M=6 10^{-7} emu**

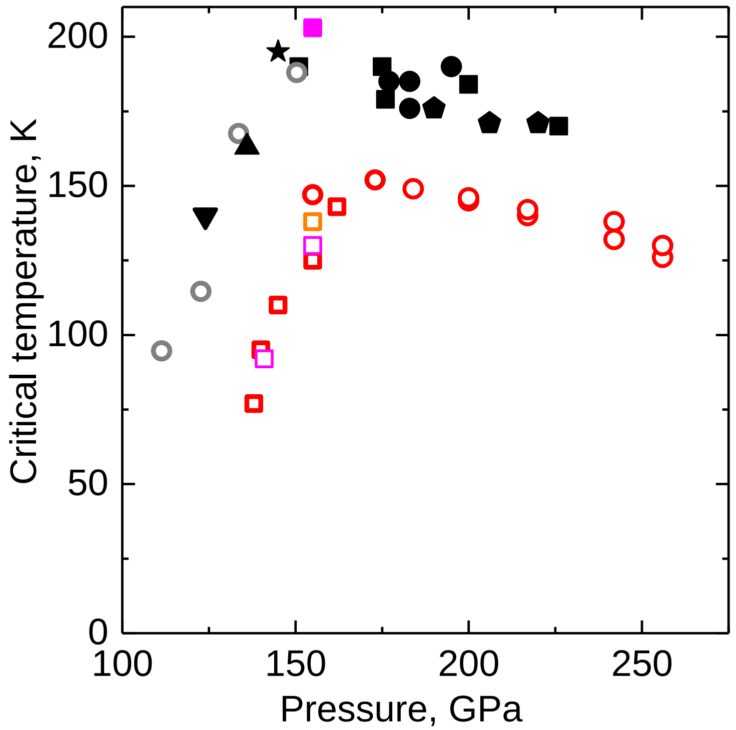
Observation of superconductivity in hydrogen sulfide from nuclear resonant scattering



I. A. Troyan *et al* (2016) Science, 351, 1303

Isotope effect

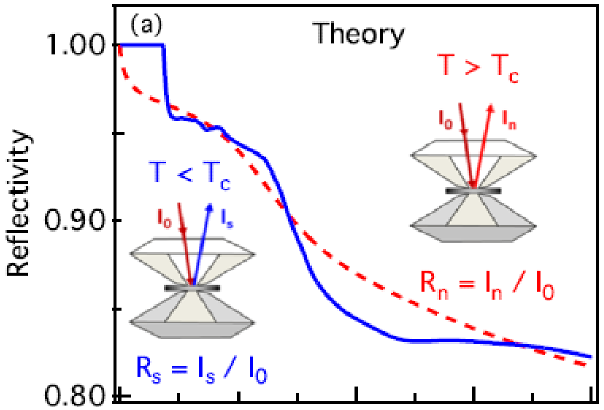


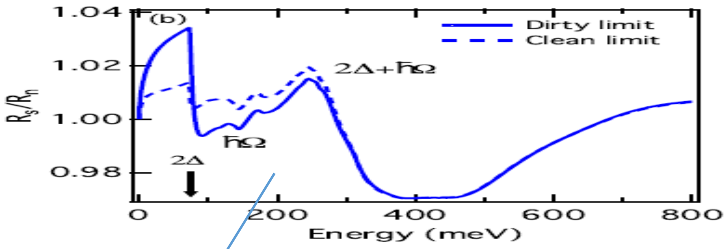


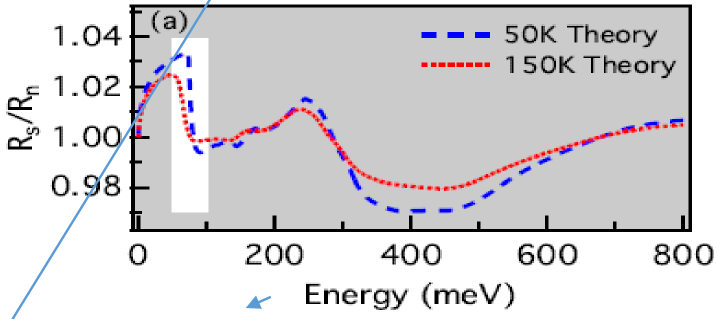
β = 0.3

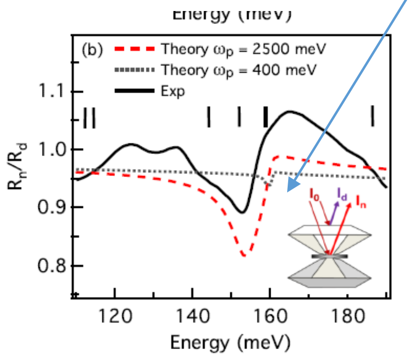
$$\beta \equiv -d \ln T_c / d \ln M$$

Infrared studies









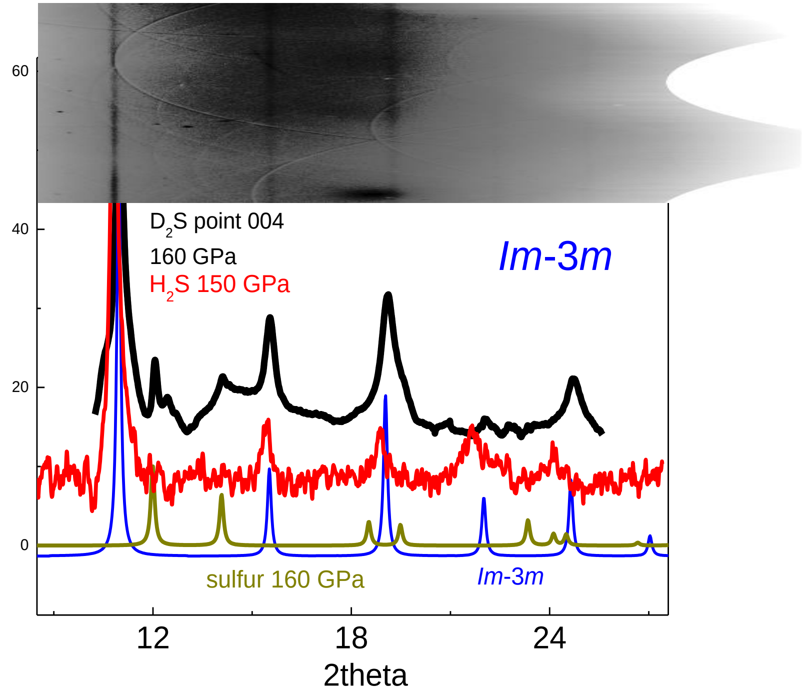
SC gap 70 meV, i.e. ~550 cm^{-1}

$2\Delta/T_c=4$

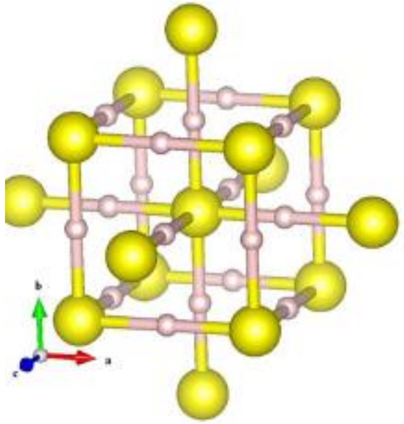
Electronic Raman

Capitani, F. *et al. Nature Phys,* **13**, 859 (2017)

X-ray diffraction



SPring-8 BL10XU in collaboration with K. Shimizu



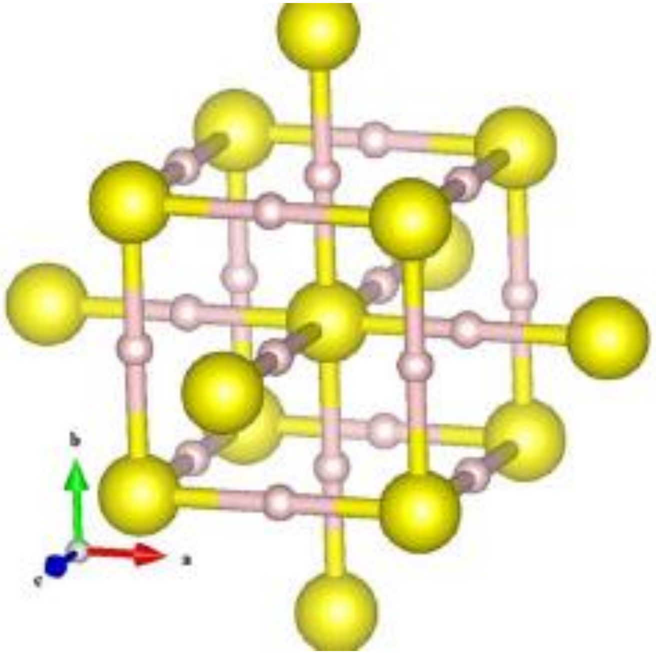
Duan, D. *et al. Sci. Reports* **4**, 6968 (2014).

Transformation of H_2S to H_3S

Sulfur – hyper valence **SF_6**

$H_2S \rightarrow H_2 + S$
no H_2 vibron

$2SH_2 \rightarrow S\mathbf{H_4} + S$, or
$3SH_2 \rightarrow \mathbf{SH_6} + 2S$



Duan DF *et al.* Pressure-induced metallization of dense (H2S)2H2 with high-*Tc* superconductivity. *Sci Rep* 2014; **4**: 6968.

Duan, D. *et al.* Pressure-induced decomposition *of* solid hydrogen sulfide. *Phys. Rev. B* **91**, 180502(R) (2015).

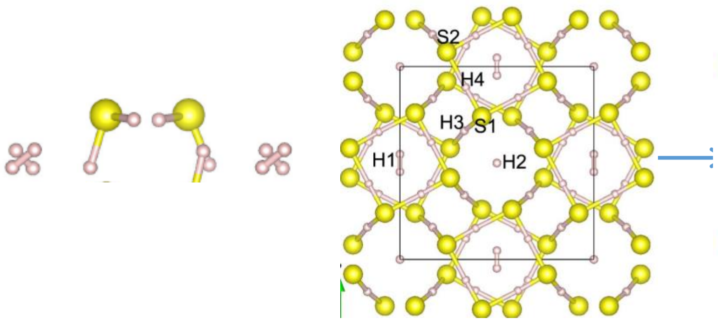
Pressure-induced metallization of dense $(H_2S)_2H_2$ with high-T_c superconductivity

Defang Duan[1,2], Yunxian Liu[1], Fubo Tian[1], Da Li[1], Xiaoli Huang[1], Zhonglong Zhao[1], Hongyu Yu[1], Bingbing Liu[1], Wenjing Tian[2] & Tian Cui[1]

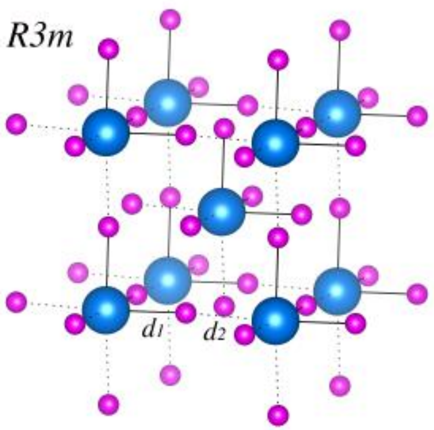
SCIENTIFIC REPORTS | 4

Strobel *et al* 2011 P> 3.5 GPa **$(H_2S)2H_2 = H_3S$**

Cccm

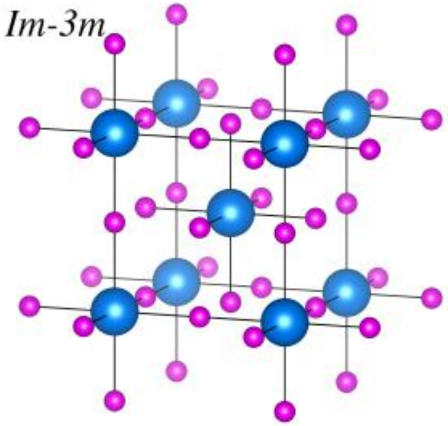


37 – 111 GPa



P>110 GPa

T_c ~ 160 K



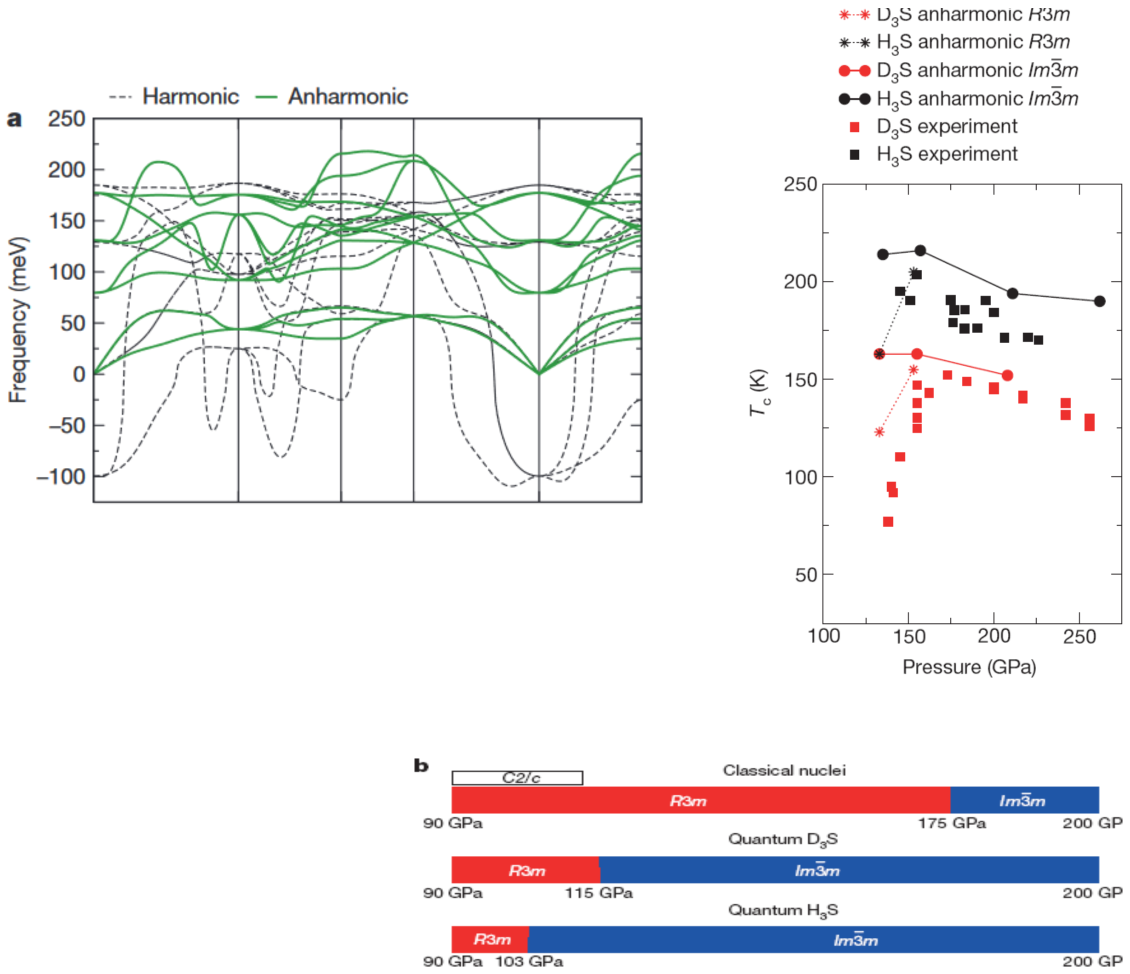
H_6S

*Im*3*m*

P>180 Gpa

T_c~200 K

Corrections to calculated T_c

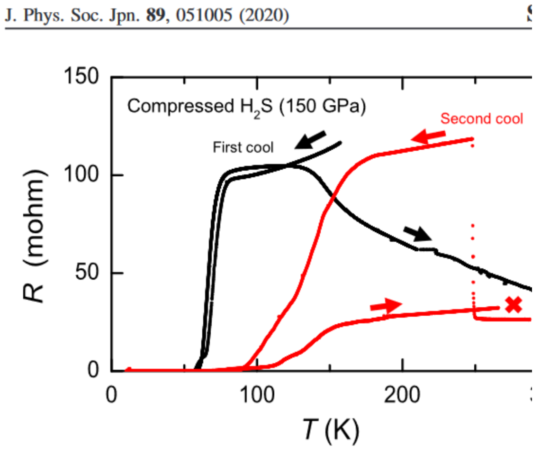


Errea, I. *et al. Nature*, **5 3 2,** 8 1 (2016)

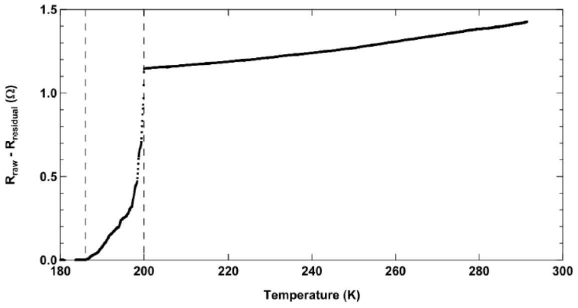
	T_c (K)	Remark
Duan *et al.* [19]	184	McMillan ($\mu^* = 0.13$)
Errea *et al.* [27]	190	const. DOS ME ($\mu^* = 0.16$) + anharmonicity
Flores-Livas *et al.* [25]	180	SCDFT ($P = 200$ GPa)
Akashi *et al.* [26]	211	SCDFT + plasmon different approximation with Ref. [25]
This work	181	
	∼147	static vertex correction ∼−34 K
	∼167	plasmon effect ∼+20 K
Experiment [15]	∼160	extrapolation of Fig. 2 of Ref. [15]

W. Sano et al. *Phys. Rev. B* **93**, 094525 (2016)

Verification in other laboratories

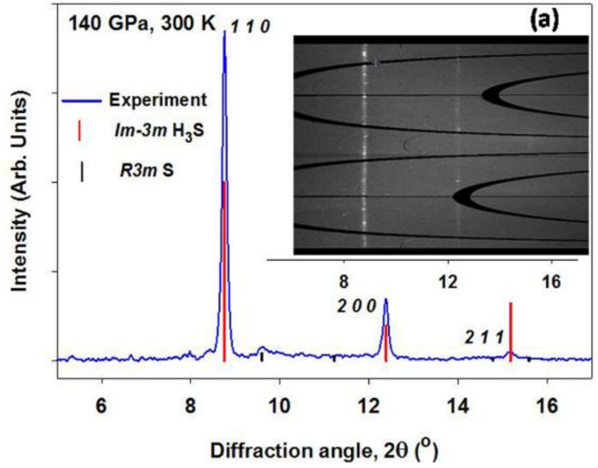


K. Shimizu, Osaka University

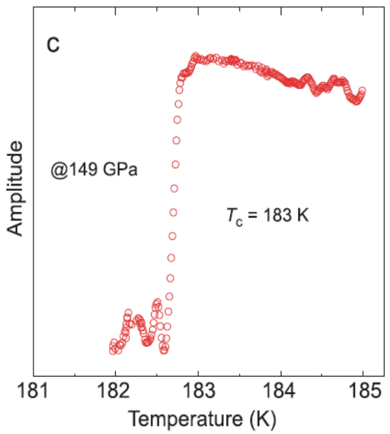


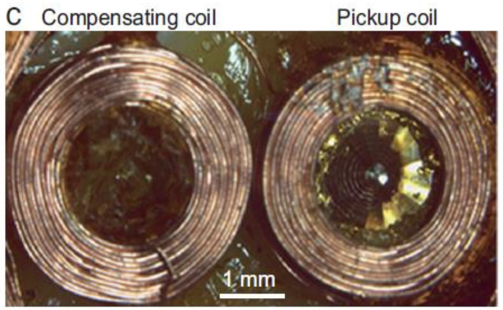
Nakao et al J. Phys. Soc. Jpn 88, 123701 (2019)

X-ray

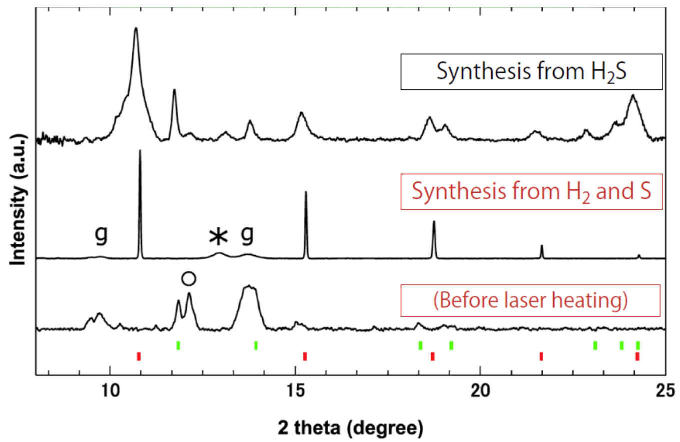


Goncharov et al Pys. Rev, B95, 140101(R) (2017)





X. Huang et al, *Nat. Sci. Rev.* 6: 713, 2019

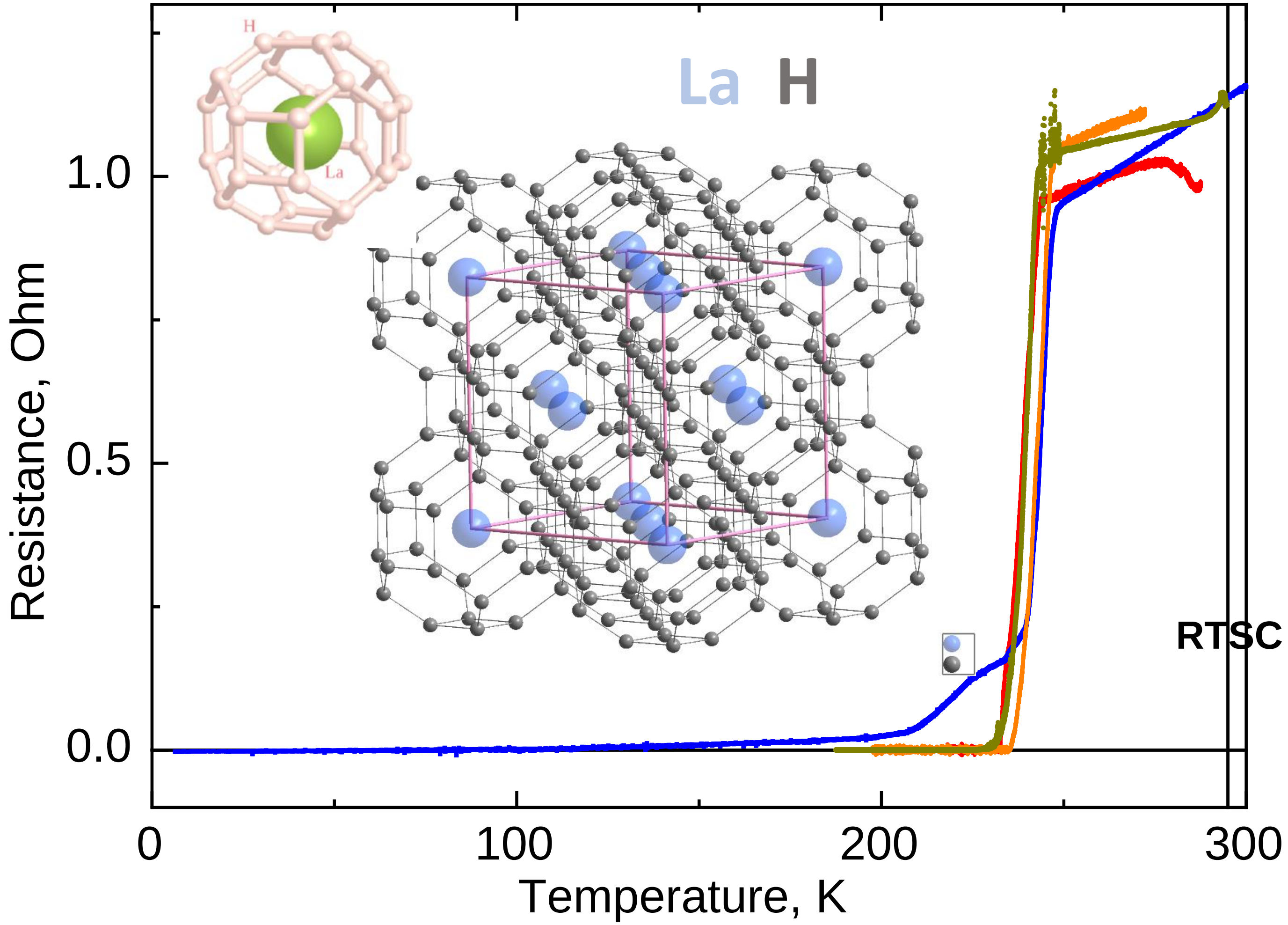


A firm basis for the study on the pressure-induced hydride superconductors is thus established

R. Akashi JPSJ News and Comments 16, 18 (2019)

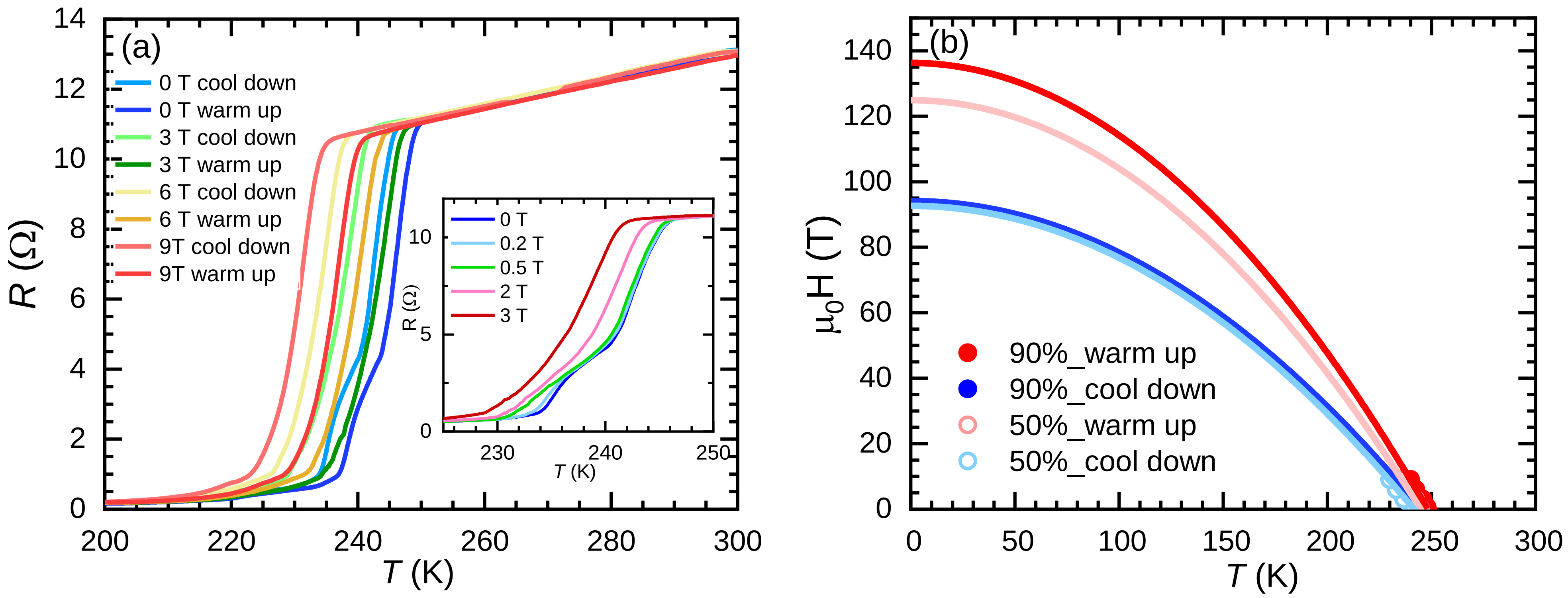
Lanthanum hydride

Superconductivity in lanthanum hydride

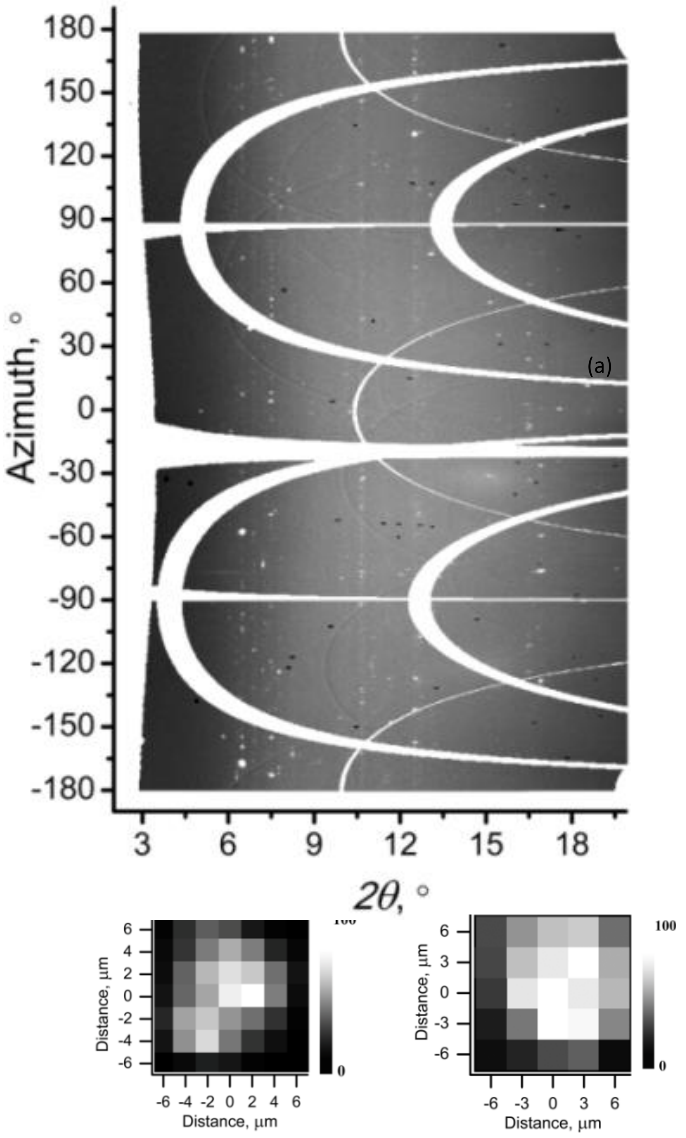


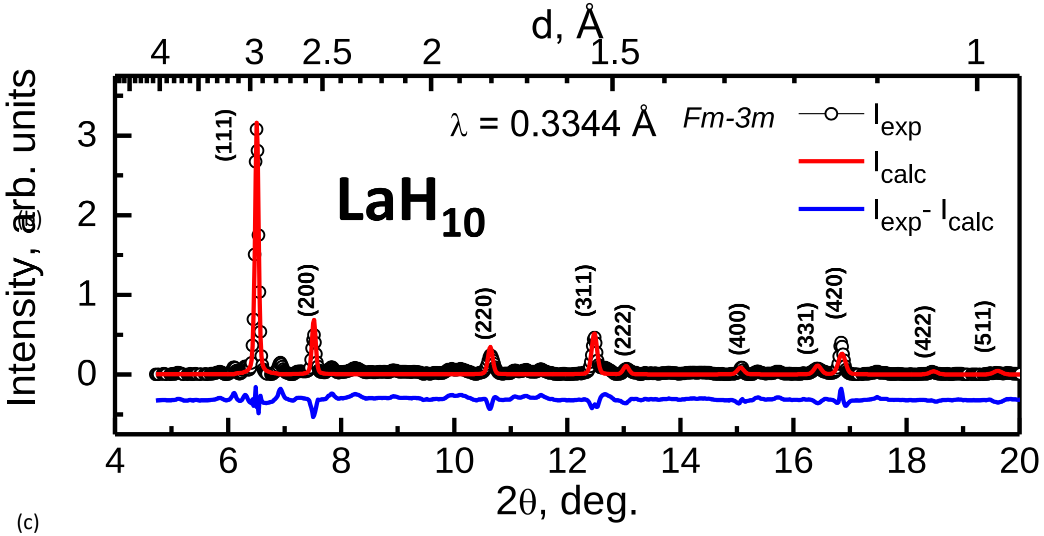
Drozdov, A. P. *et al. Nature* **569** 528 (2019)

Superconducting transition in dependence on external magnetic fields

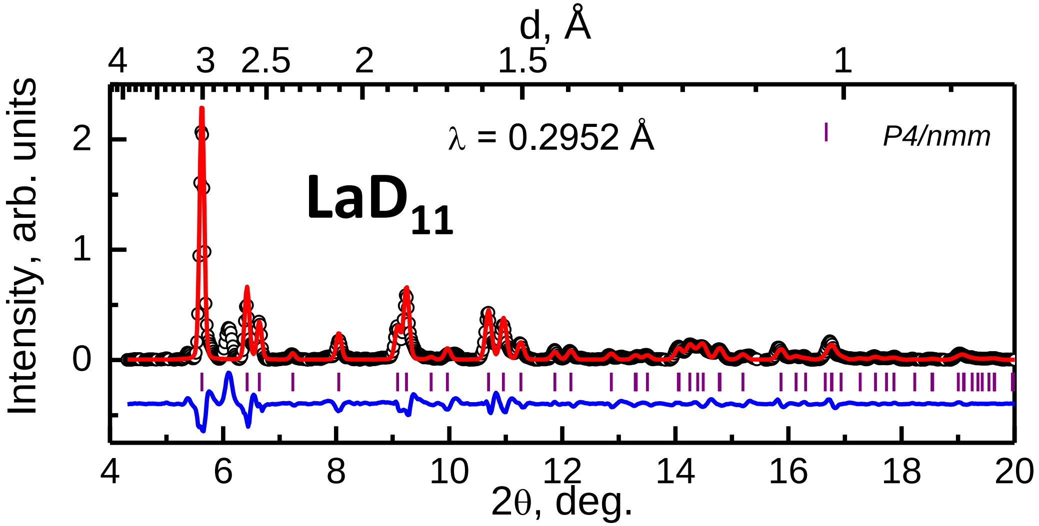


X-ray diffraction

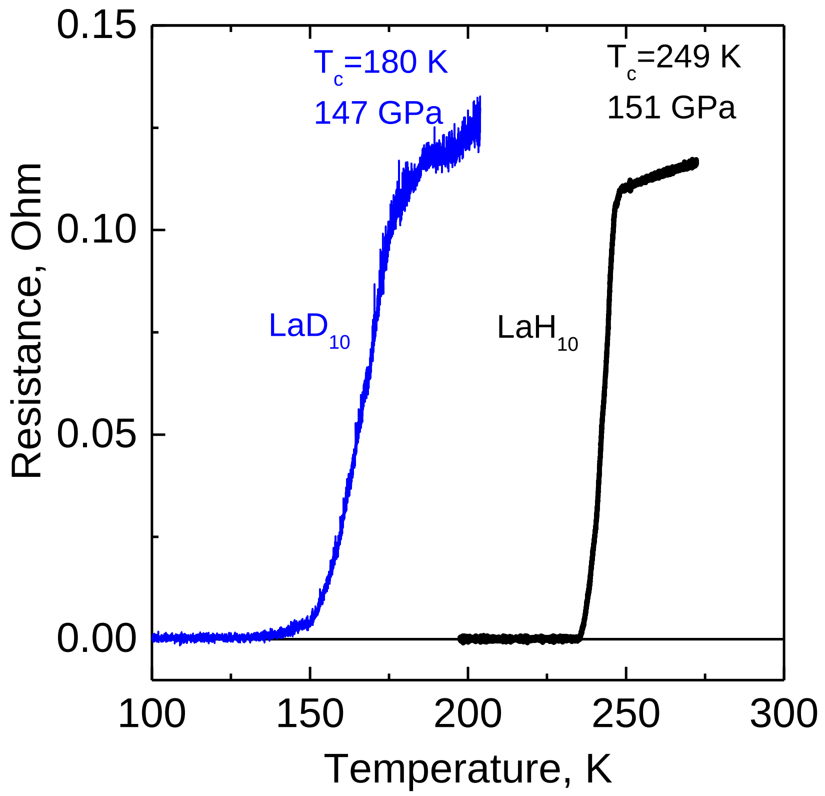


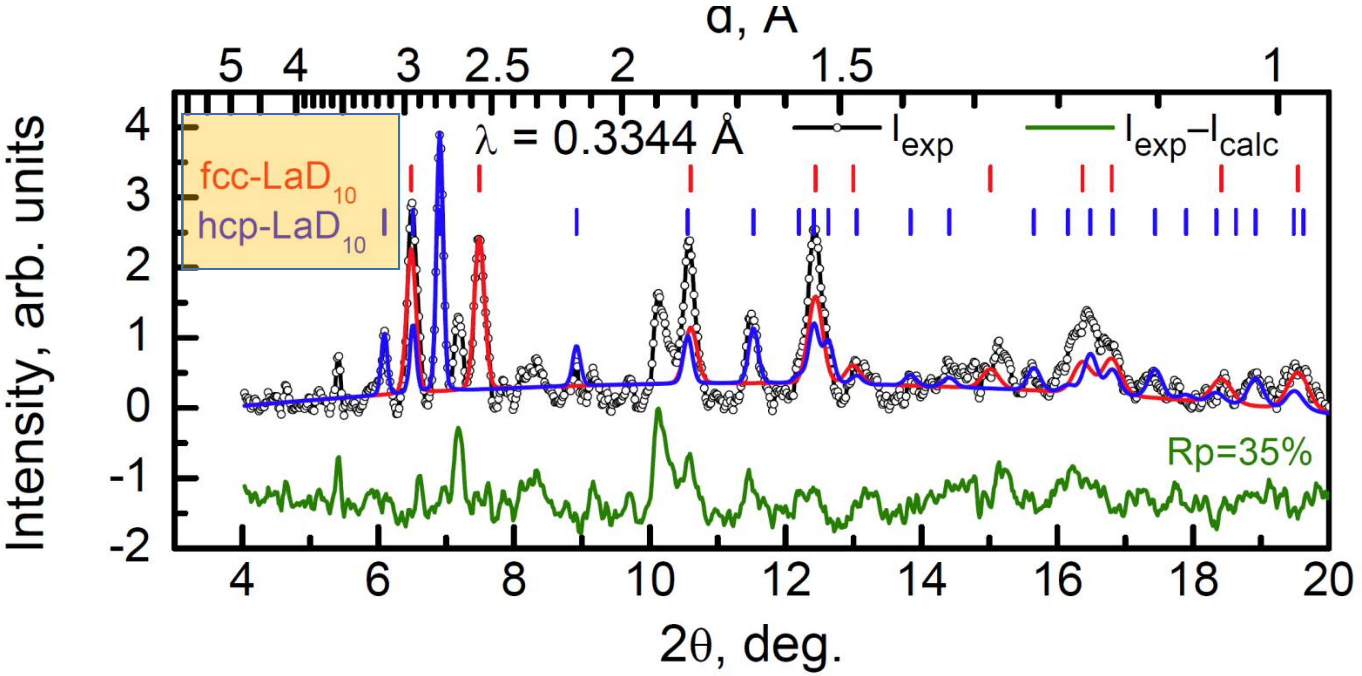


(c)



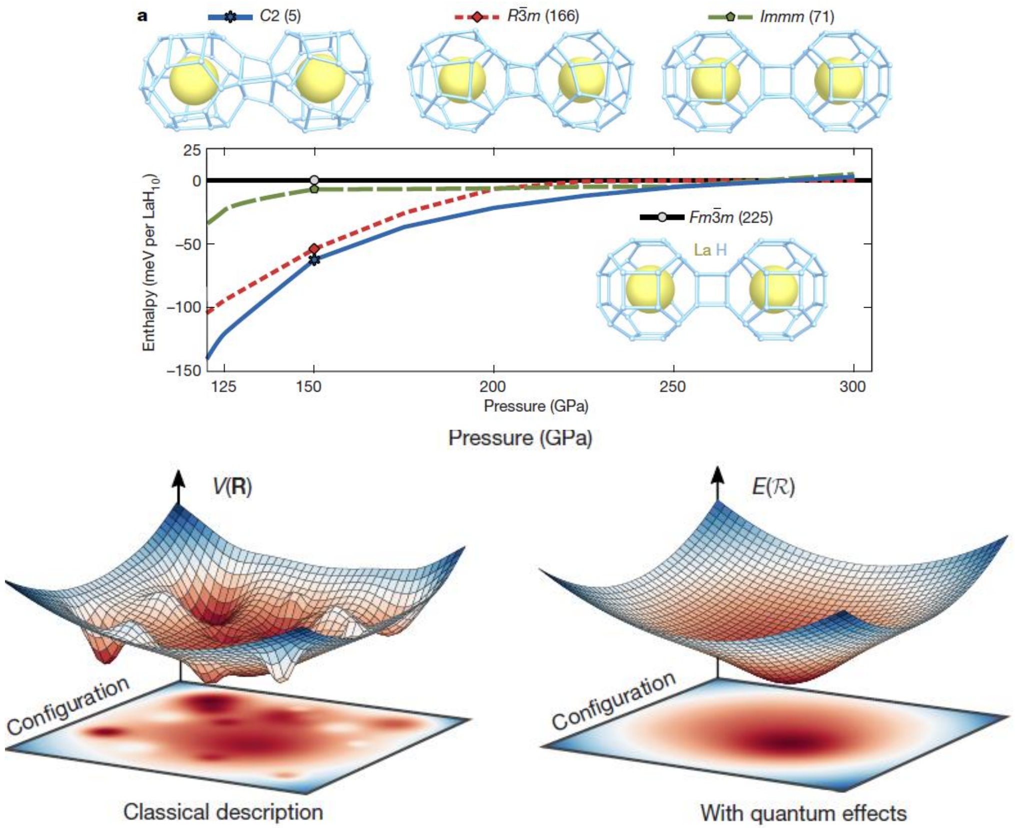
Isotope effect for LaH_{10}





α=0.46

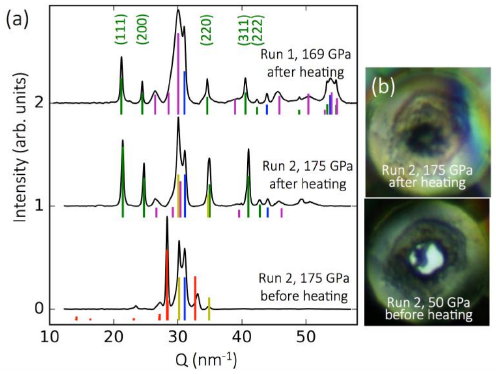
Quantum crystal structure in the 250-kelvin superconducting lanthanum hydride

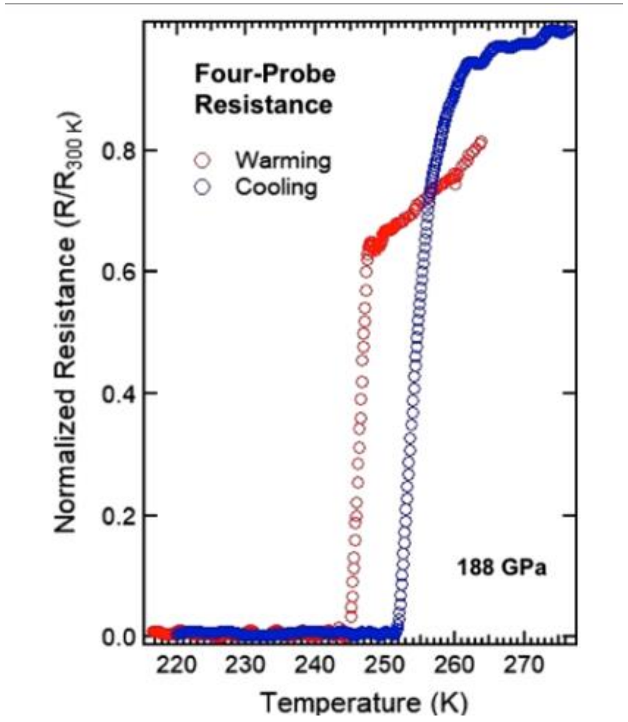


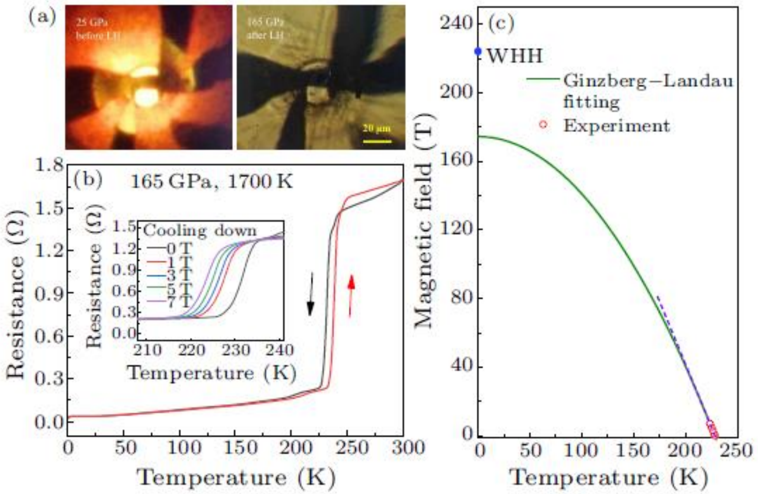
… if we consider correctly quantum fluctuations probably we will find high-Tc superconductors at much lower pressures.

Errea et al *Nature* **578** (2020).

Other laboratories







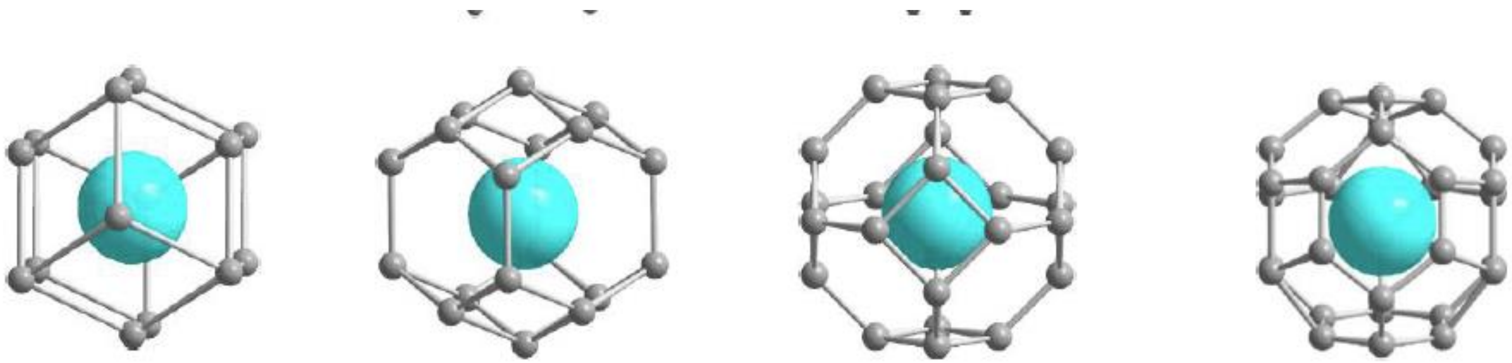
F. Hong et al Chin. Phys. Lett.37 (2020) 107401

Evidence for Superconductivity above 260 K in Lanthanum Superhydride at Megabar Pressures

Maddury Somayazulu,[1,*] Muhtar Ahart,[1] Ajay K. Mishra,[2,‡] Zachary M. Geballe,[2] Maria Baldini,[2,§] Yue Meng,[3] Viktor V. Struzhkin,[2] and Russell J. Hemley[1,†]

Yttrium hydride

YH_3	YH_4	YH_6	YH_9

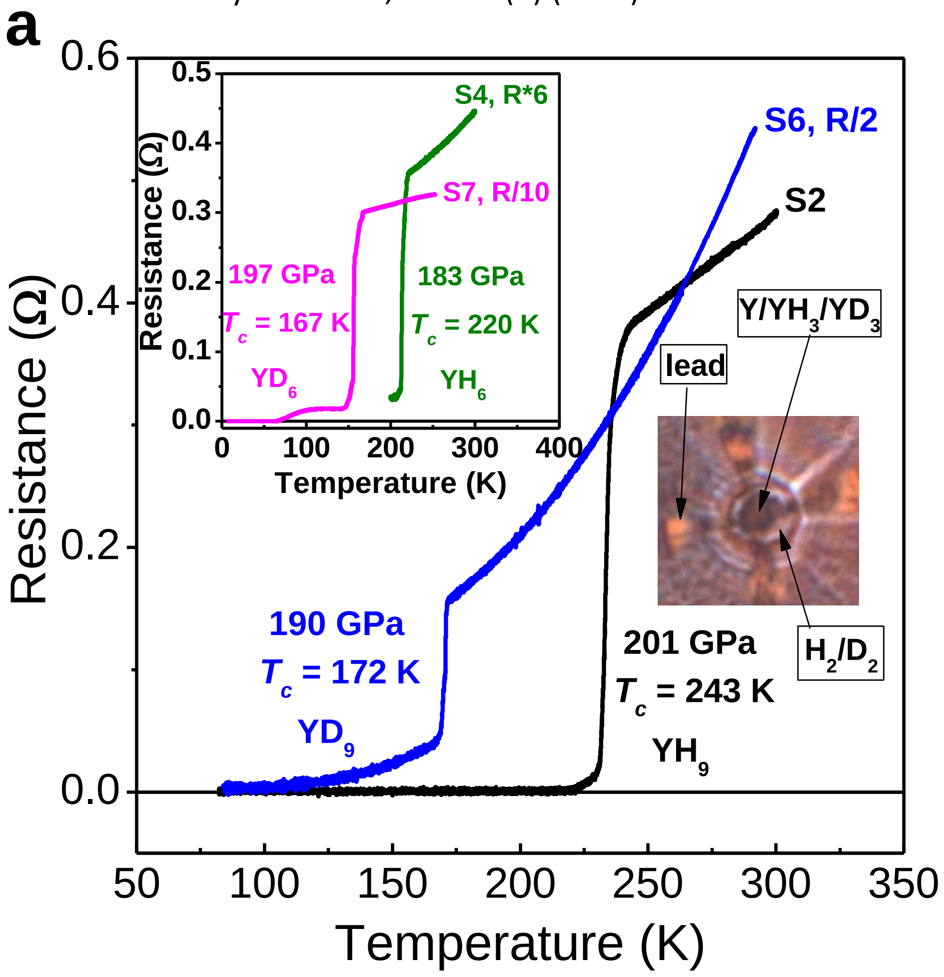


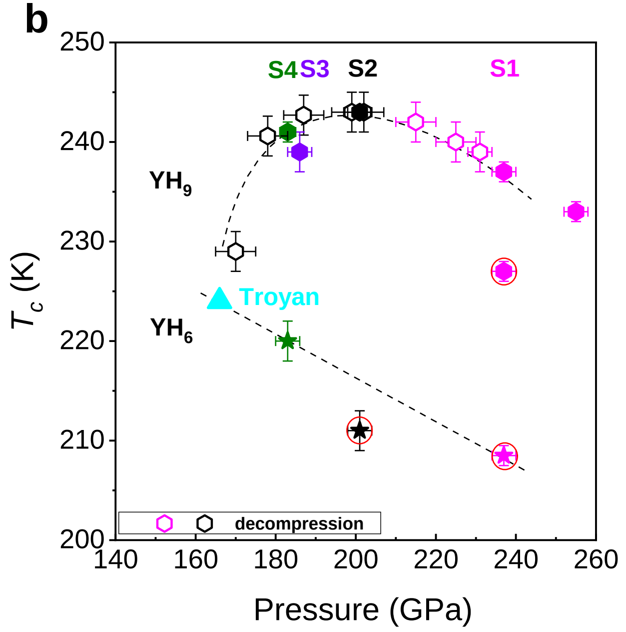
YH_{14}	YH_{18}	YH_{24}	YH_{29}
Fm-3m	I4/mmm	Im-3m	P63/mmc

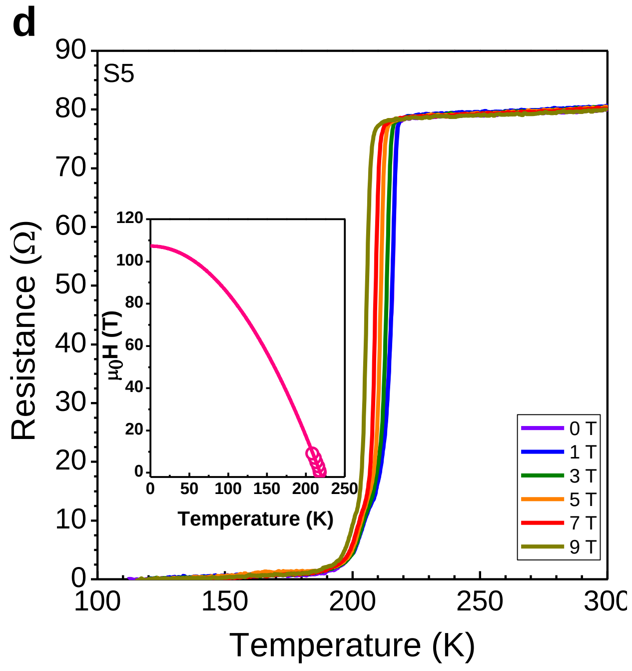
Yttrium hydride

YH_6 T_c ~ **260 K** at 110 GPa T_c ~ **227 K** at 237 GPa
YH_9 T_c ~ **265 K** at 200 GPa, T_c ~ **243 K** at 200 GPa
YH_{10} T_c ~ **315 K** at 250 Gpa T_c ??????

H. Liu et al *Proc. Nat. Acad. Sci*. 114, 6990 (2017)
F. Peng et al *Phys. Rev. Lett*. 119, 107001 (2017)
Heil et al Phys. Rev B99, 220502(R) (2019)

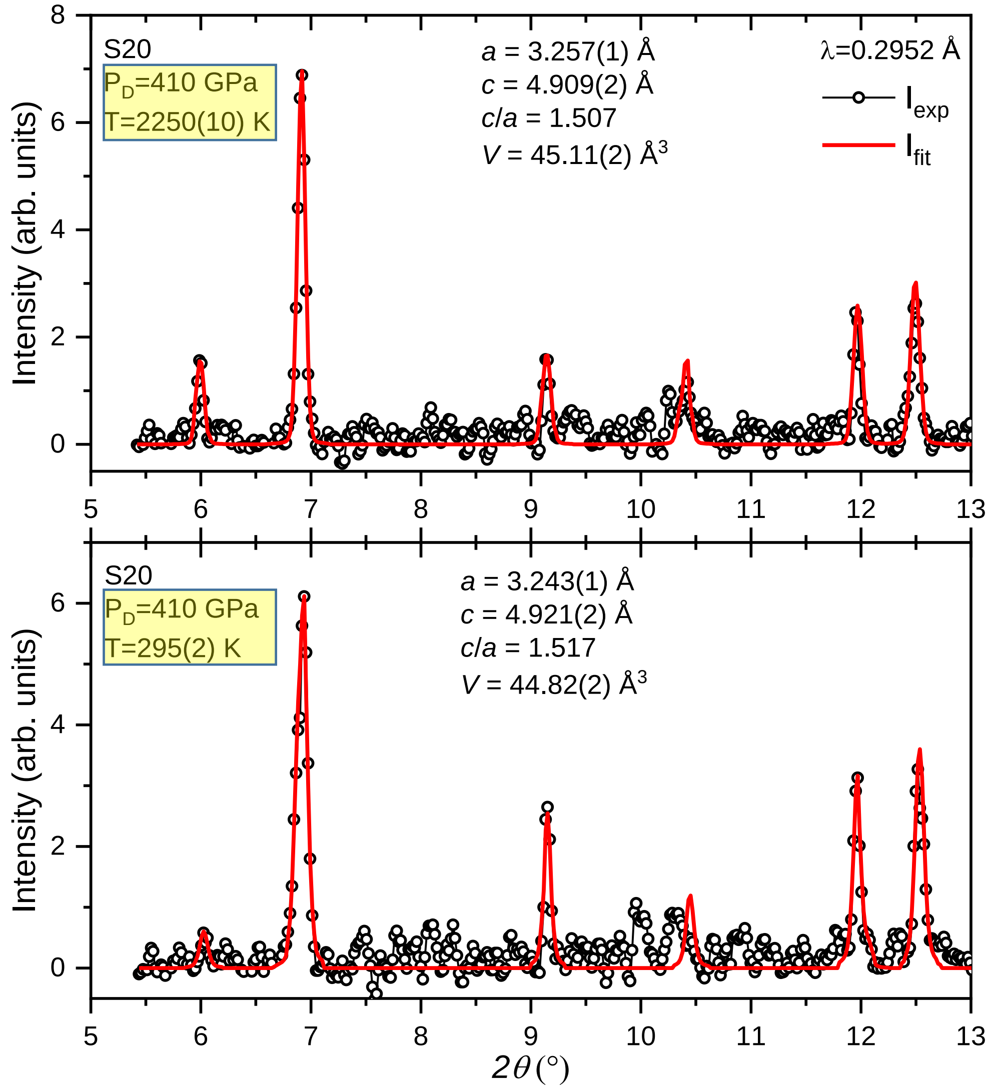


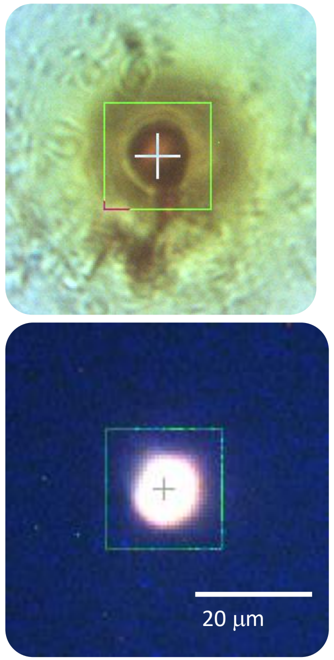


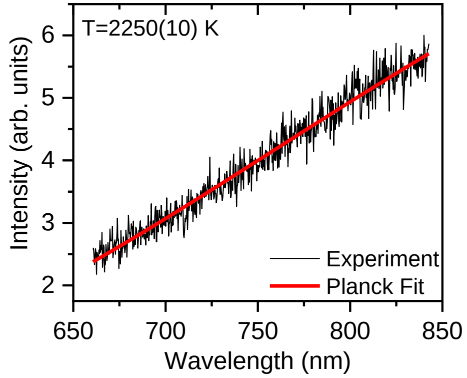


Kong, P. P. *et al.* Superconductivity up to 243 K in yttrium hydrides under high pressure *arXiv:1909.10482* (2019)

X-ray diffraction from YH9 at 410 GPa and 2230 K





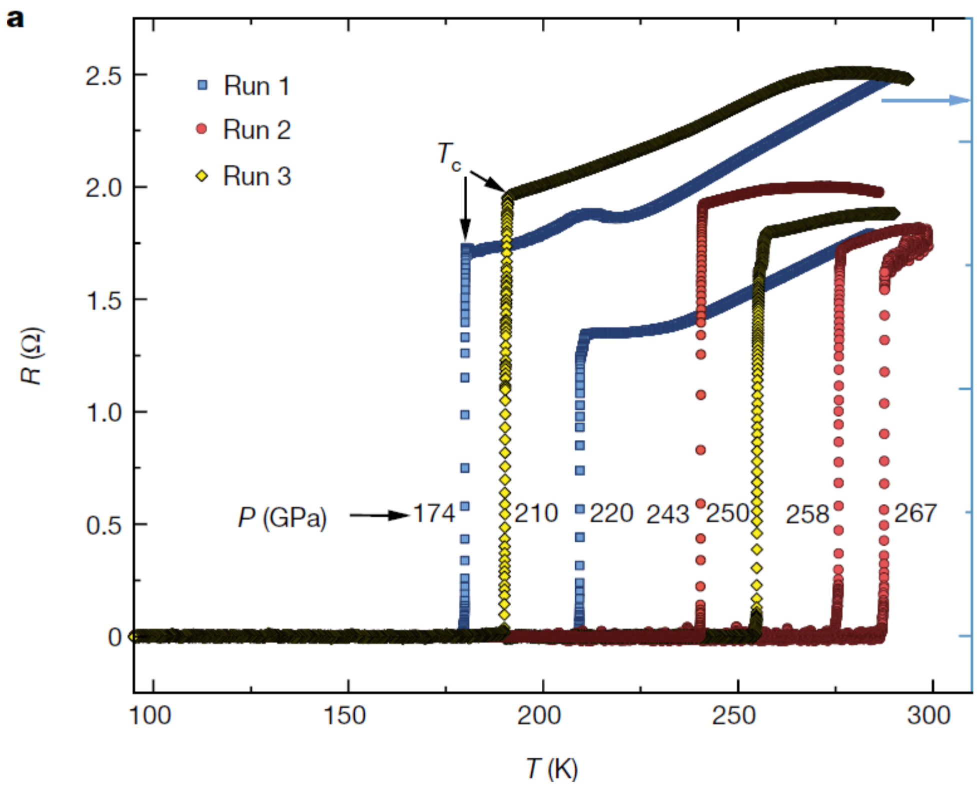


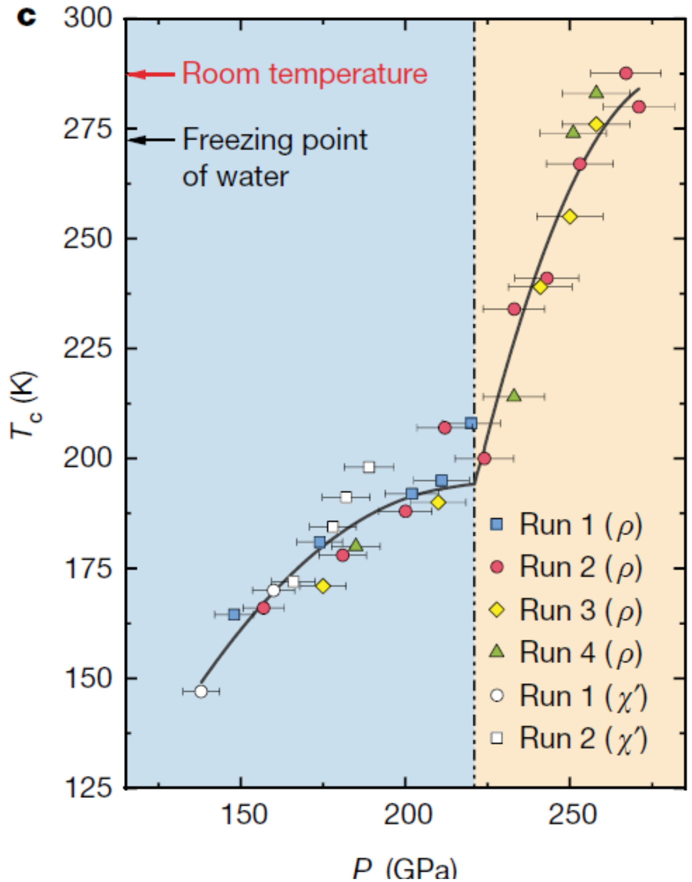
Room-temperature superconductivity in a carbonaceous sulfur hydride

https://doi.org/10.1038/s41586-020-2801-z

Received: 31 August 2020

Elliot Snider[1,6], Nathan Dasenbrock-Gammon[2,6], Raymond McBride[1,6], Mathew Debessai[3], Hiranya Vindana[2], Kevin Vencatasamy[2], Keith V. Lawler[4], Ashkan Salamat[5] & Ranga P. Dias[1,2]✉



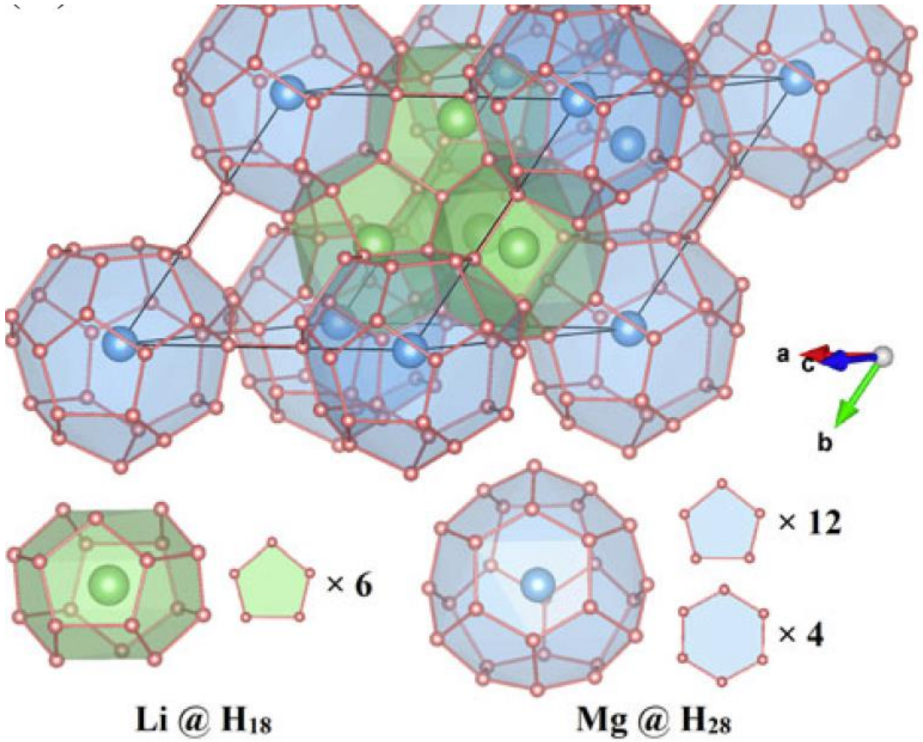


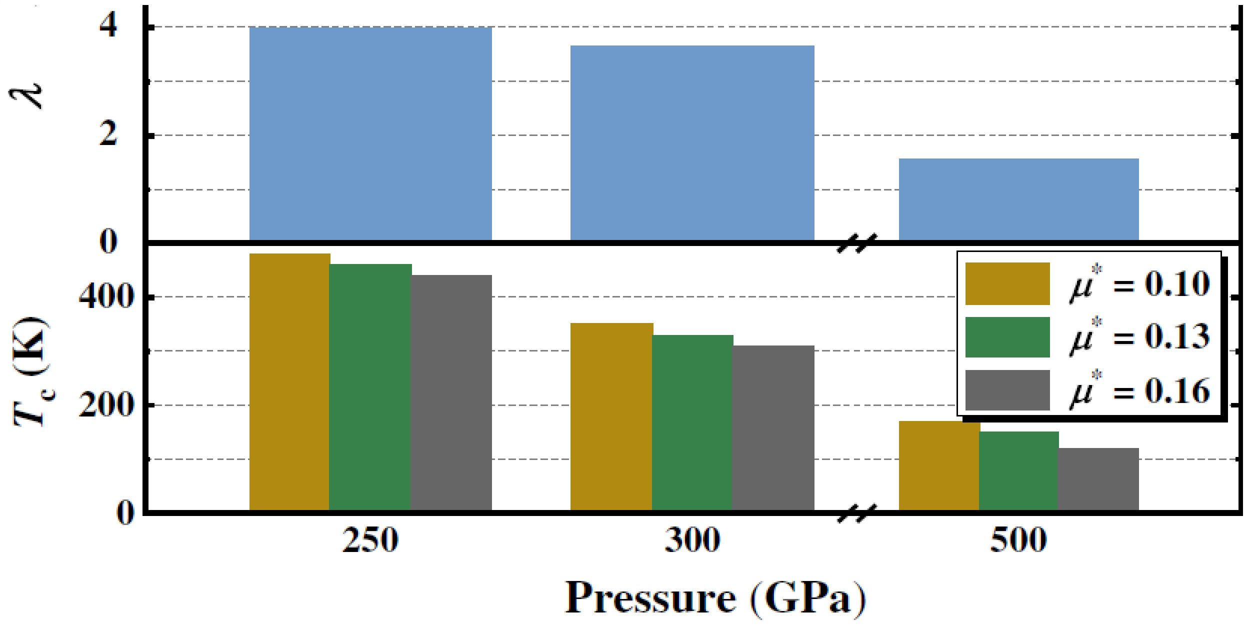
PHYSICAL REVIEW LETTERS **123,** 097001 (2019)

Editors' Suggestion | Featured in Physics

Route to a Superconducting Phase above Room Temperature in Electron-Doped Hydride Compounds under High Pressure

Ying Sun,[1] Jian Lv,[1] Yu Xie,[1] Hanyu Liu,[1,*] and Yanming Ma[1,2,†]

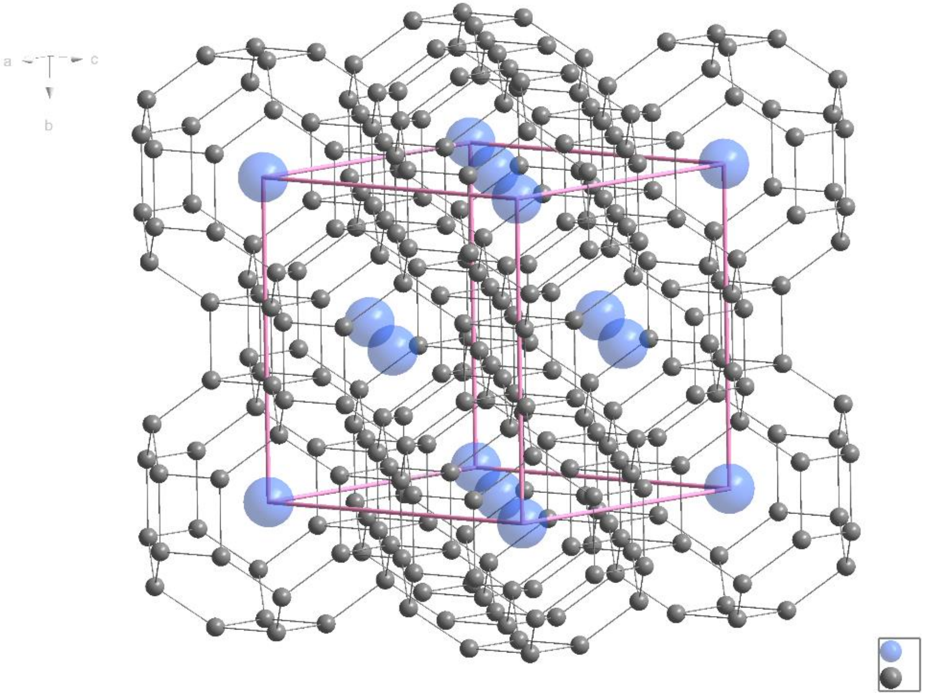




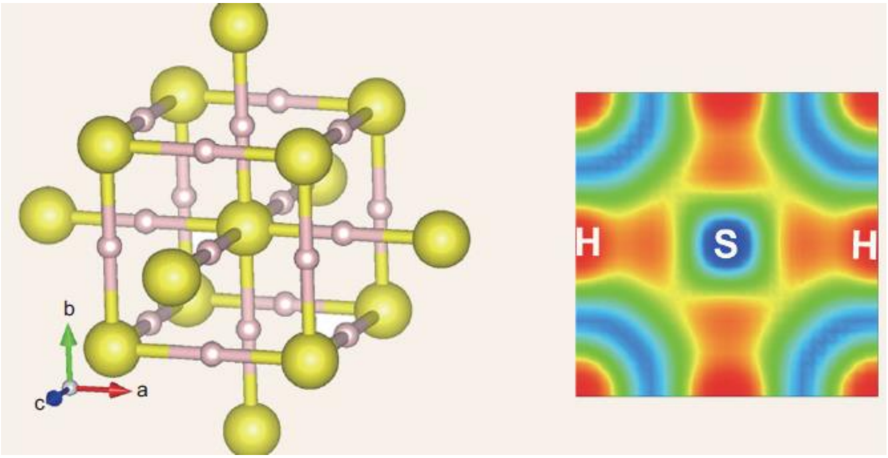
Li_2MgH_{16} $(Fd\bar{3}m)$

Experimentally studied hydrides

SiH_4 **17 K** Eremets et al , *Science* 319 68 1506 (2008)
$BaReH_9$ **7 K** Muramatsu et al, *J. Phys. Chem*. C 119 18007 (2015)
H_3S **203 K** Drozdov et al*, Nature* 525 (2015)
PH_3 **100 K** Drozdov et al, *arXiv:*1508.06224 (2015)
LaH_{10} **260 K** Somayazulu et al *Phys. Rev. Lett*. 122 027001 (2019)
LaH_{10} **250 K** Drozdov et al *Nature* (2019)
ThH_{10} **160 K** Semenok et al, *Materials Today* (2019)
YH_6 **224 K** Troyan et al *arXiv 1908.01534* (2019)
YH_6 **227 K** Kong et al *arXiv 1909.10482* (2019)
YH_9 **243 K** Kong et al *arXiv 1909.10482* (2019)
PrH_9 **9 K** Zhou et al, *Sci. Adv.* 2020; 6 (2020)



LaH_{10} – model of metallic hydrogen

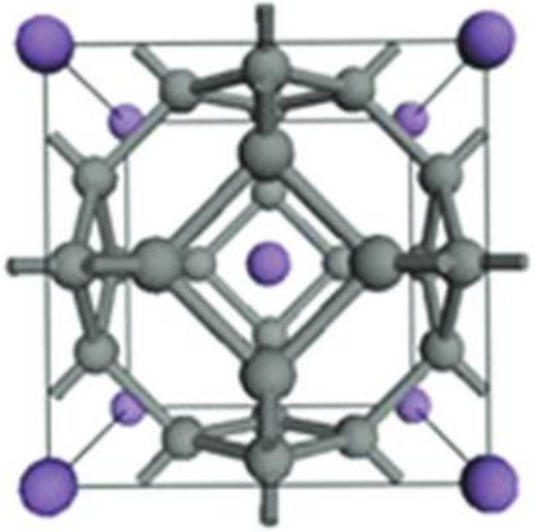


H_3S - covalent metal

Duan et al *Nation. Sci. Rev.* 4: 121–135, 2017

Ambient pressure conventional superconductivity

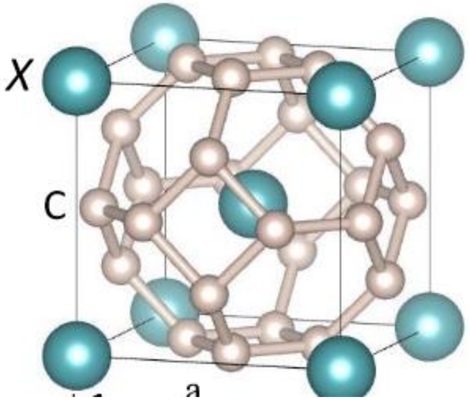
Ambient pressure superconductors

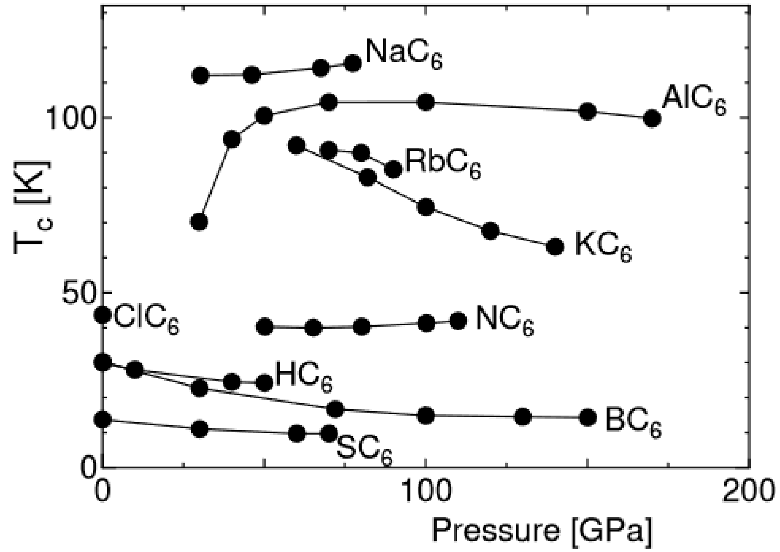


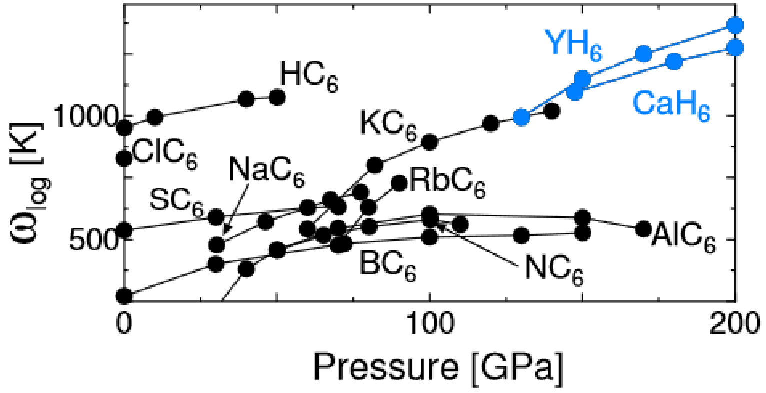
NaC_6 T_c=116 K

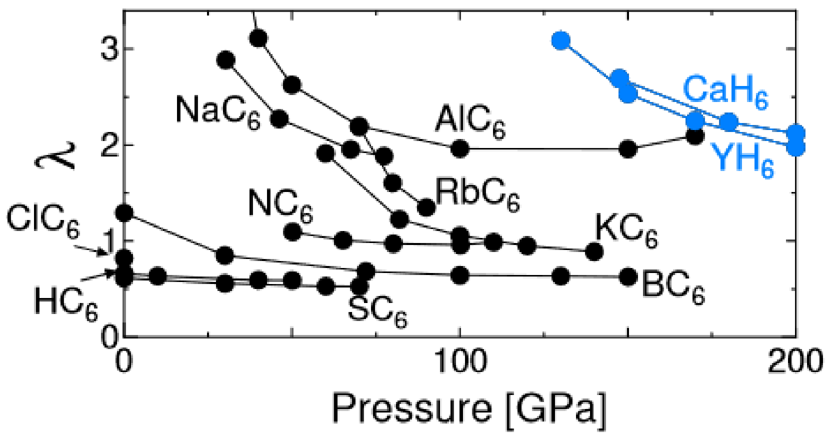
Lu *et al* Superconductivity in dense carbon-based materials, Phys. Rev. B **93**, 104509 (2016)

Superconductivity of carbon compounds with sodalite structure







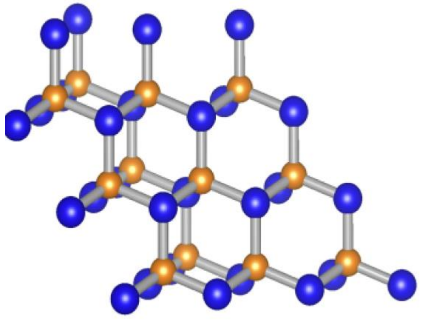


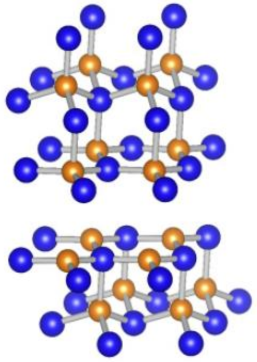
K, Sano *et al* arXiv:2002.02174 (2020)

PHYSICAL REVIEW B **102**, 024519 (2020)

High-temperature conventional superconductivity in the boron-carbon system: Material trends

Santanu Saha,[1,*] Simone Di Cataldo,[1,2] Maximilian Amsler,[3,4] Wolfgang von der Linden,[1] and Lilia Boeri[2]

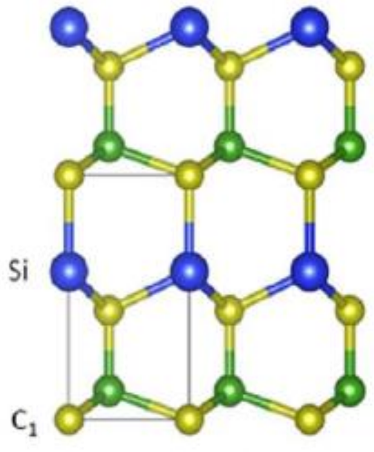




λ= 2.3 **T_c=75 K**

λ= 1.1 **T_c=53 K**

320 metastable structures with fixed composition **B:C** (50%/50%)



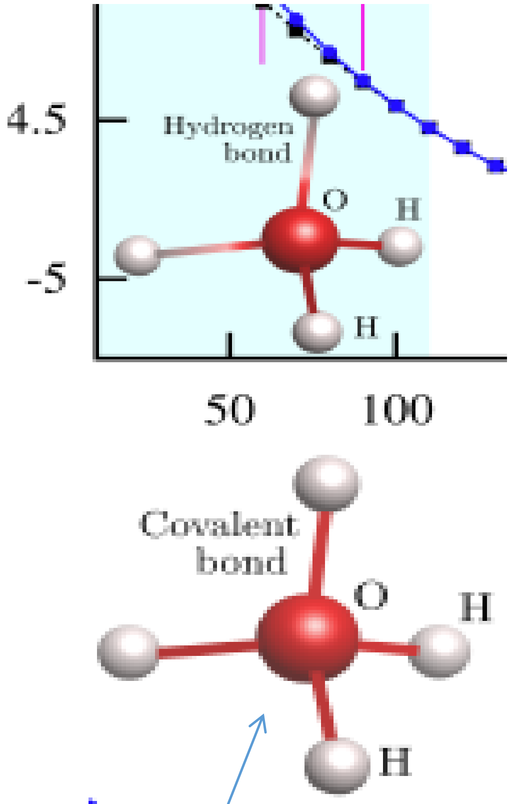
$BSiC_2$

***T_c*=74 K**

P. Chen and H.T.Jeng 2020
New J. Phys. 22 033046

Doping, alloying

H_2O



Dopants
B, C, **N**, P

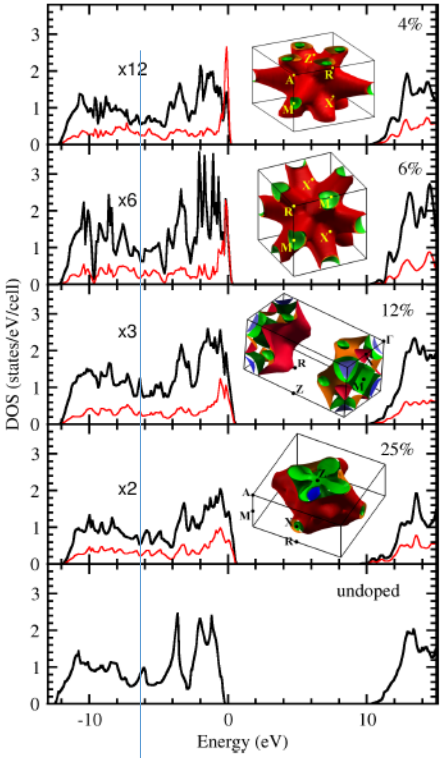
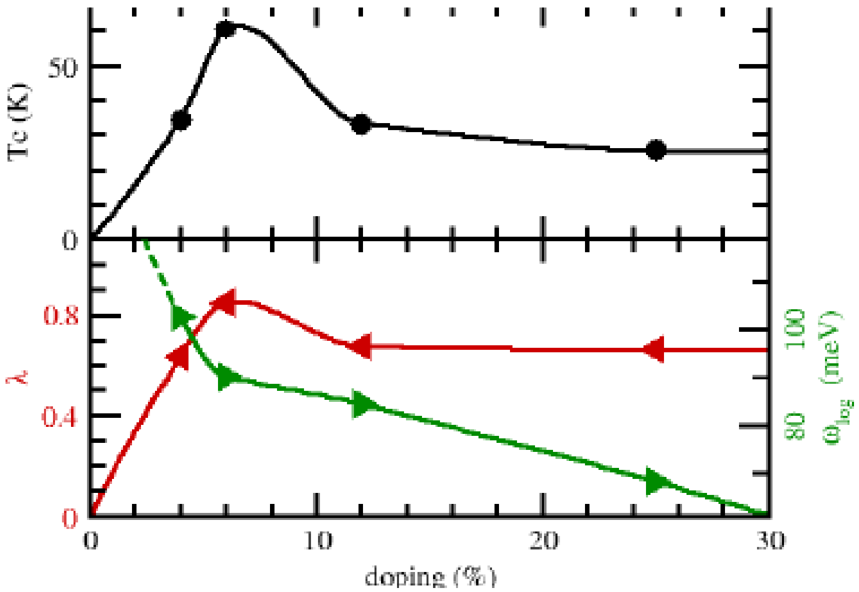


Figure 3. (Color online) Density of states (DOS) and Fermi



J.A. Flores-Livas *et al* Emergence of superconductivity in doped H_2O ice at high pressure ScI. Reports, 7. 6825 (2017)

Diamond ω_D =1860 K,

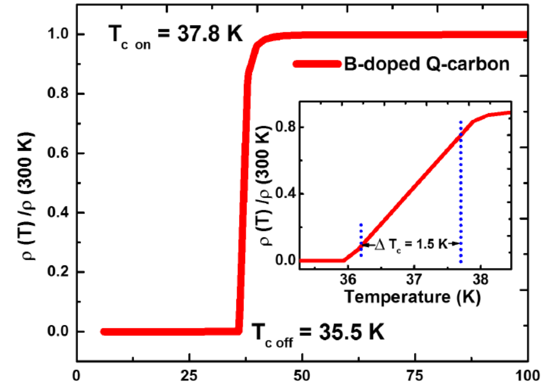
T_c>100 K but doping

Moussa, J. E. & Cohen, M. L *Phys. Rev. B* **77**, 064518 (2008)

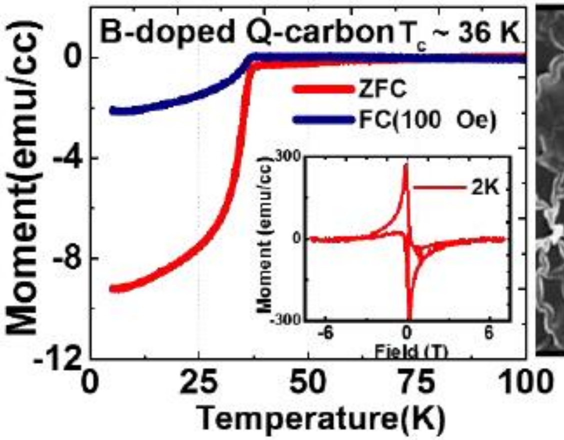
High-Temperature Superconductivity in Boron-Doped Q-Carbon

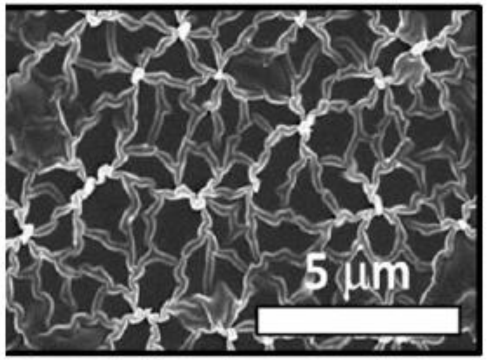
A. Bhaumik, R. Sachan, J. Naraya

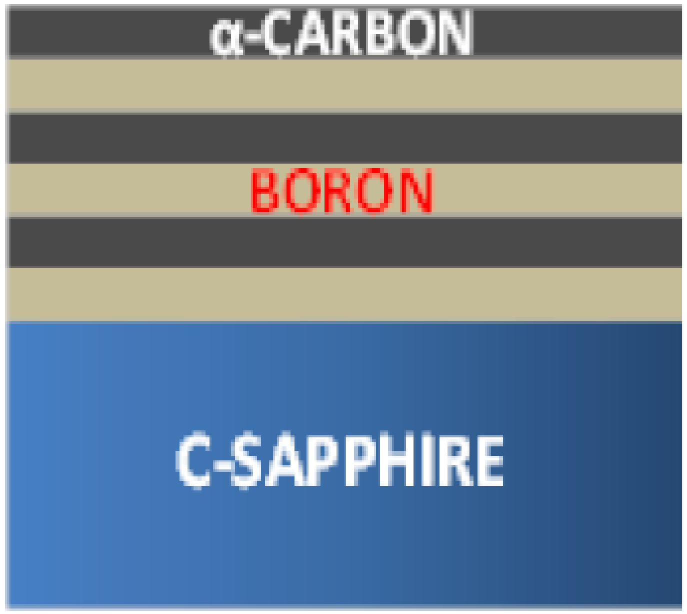
ACS Nano 2017, and Appl.Phys.



T_c=56 K

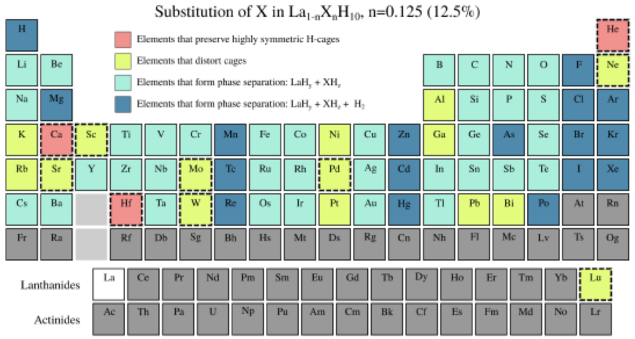


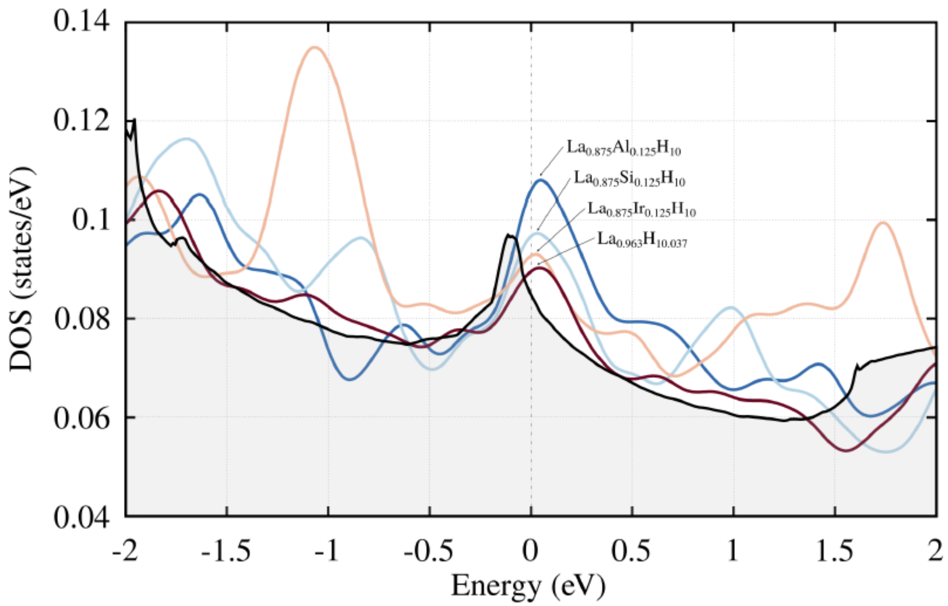




Nonequilibrium doping
nanosecond melting and recrystallization

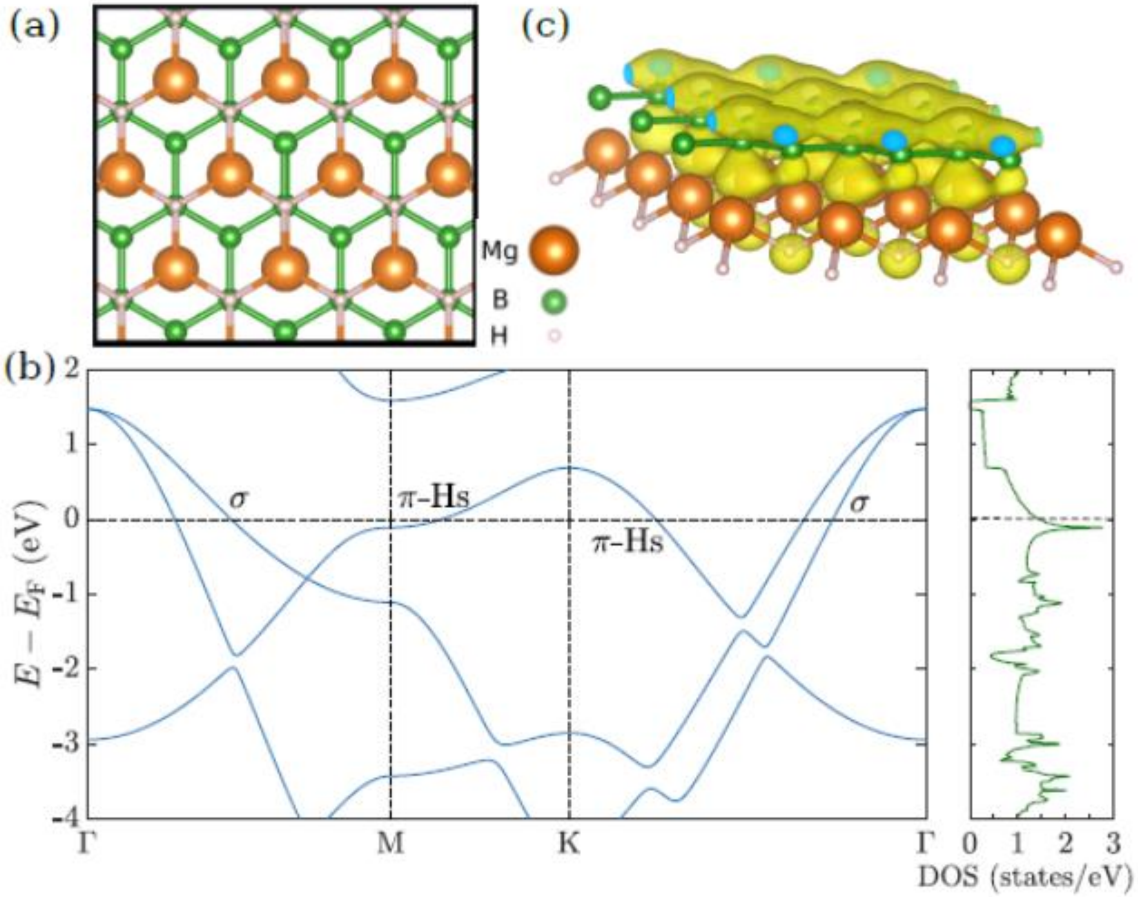
Reaching room temperature superconductivity by optimizing doping in LaH_{10}?
José A. Flores-Livas et al 2020 arXiv:2010.06446





aluminium to increase the occupation at the Fermi level by more than 30 %
Increase of Tc ~15%

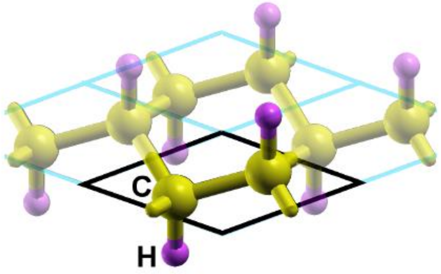
Hydrogen doping



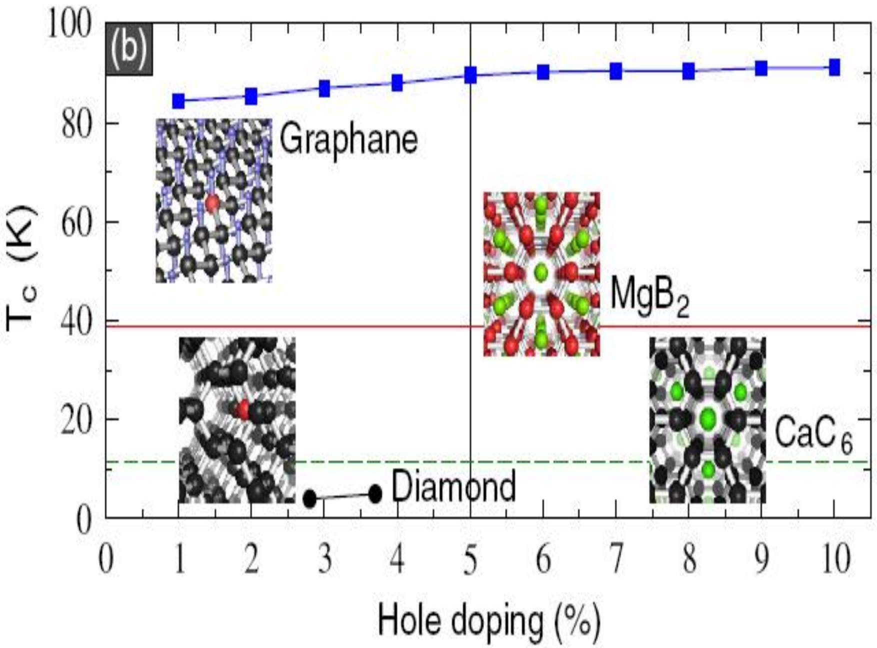
Hydrogen-induced high-temperature superconductivity in two-dimensional materials: Example of hydrogenated monolayer MgB_2

J. Bekaert,[1,*] M. Petrov,[1] A. Aperis,[2] P. M. Oppeneer,[2] and M. V. Milošević[1,†]

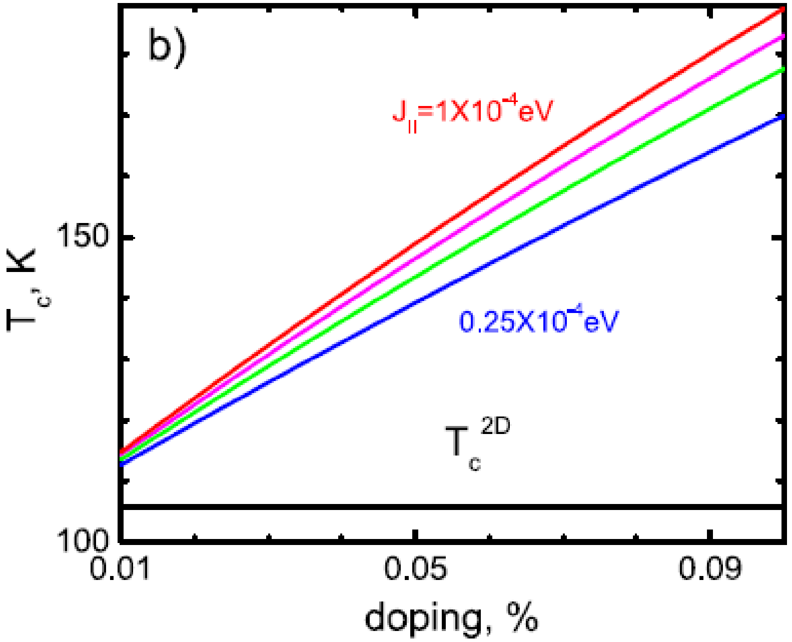
[1] *Department of Physics, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*
[2] *Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden*
(Dated: February 12, 2019)



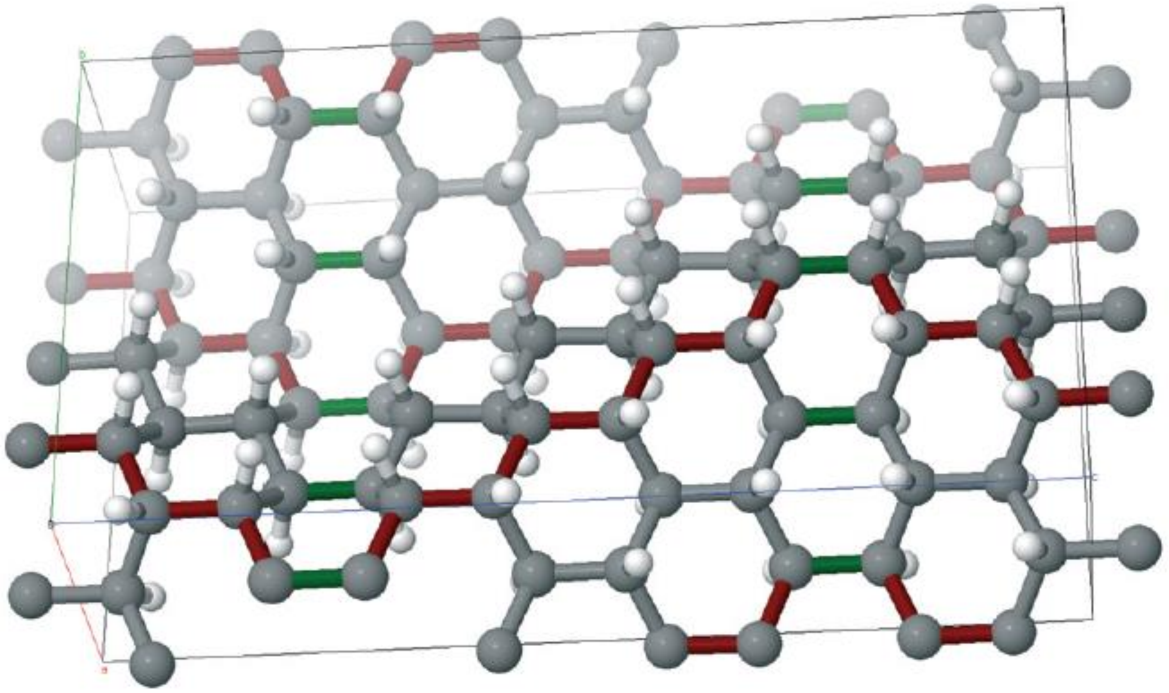
Graphane C-H ambient pressure

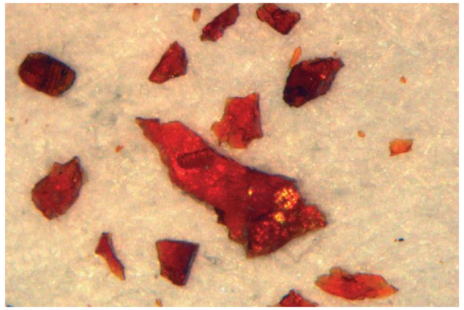


G. Savini, A. C. Ferrari, and F. Giustino, PRL, 105, 037002 (2010)



V.M. Loktev · V. Turkowski 2011

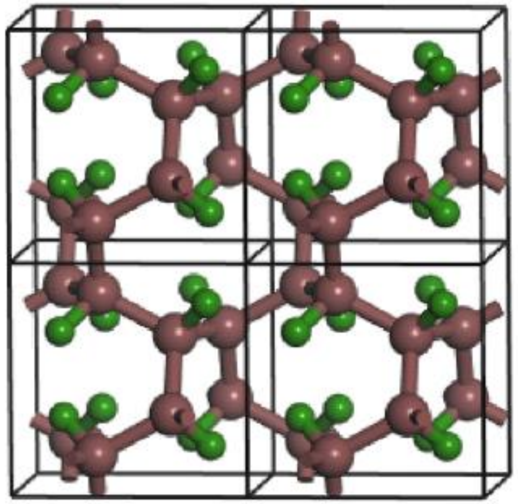




200 µm

Kondrin, M. V. *et al.* Bulk graphanes synthesized from benzene and pyridine. *CrystEngComm* **19**, 958–966 (2017)

Increasing SC with hydrogen

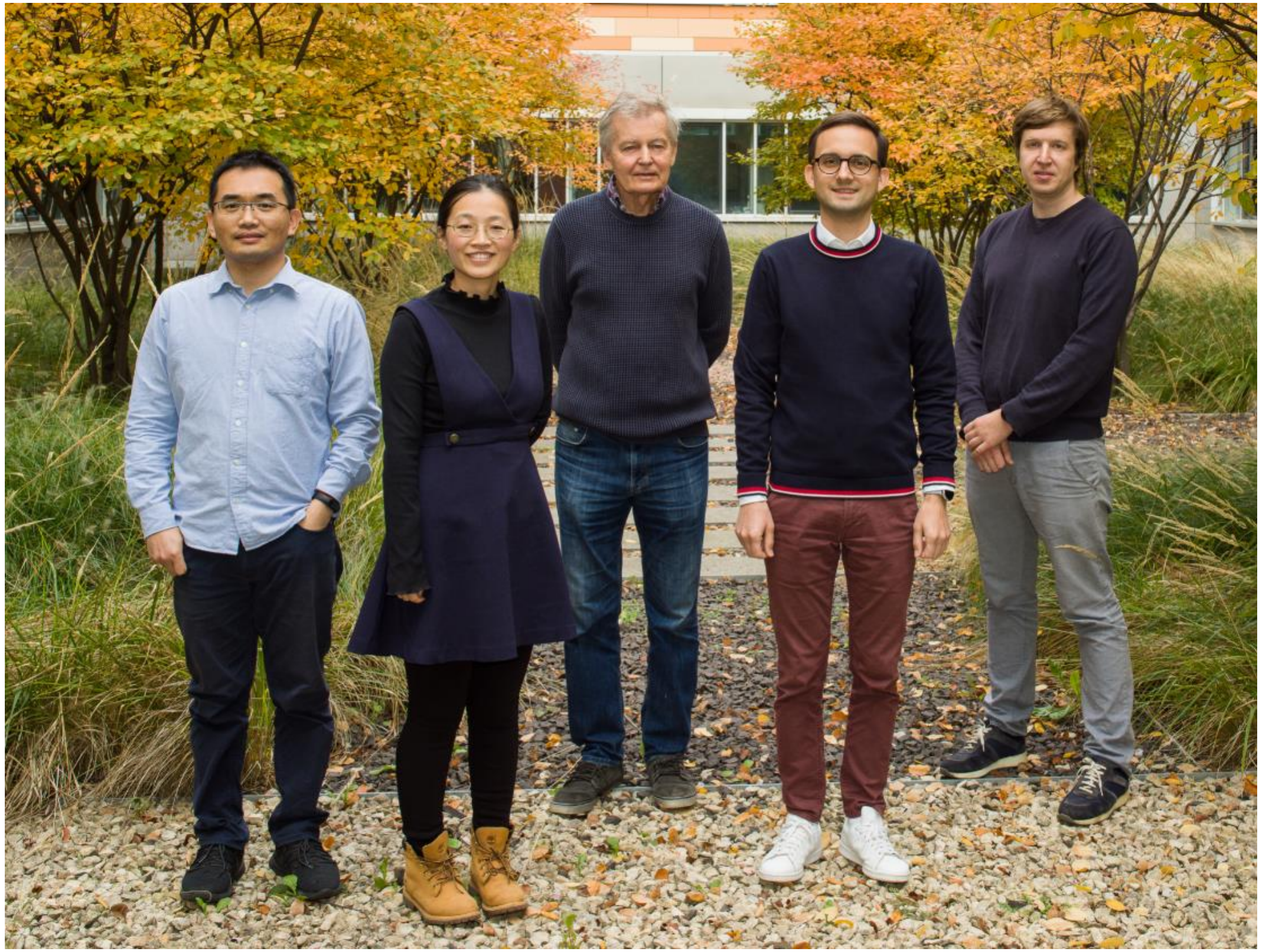


diamond-like cubic hydrocarbon K_4-CH
Tc ~80 K

Chao-Sheng Lian et al *Sci. Reports*, 7, *1464*

Acknowledgement

A. Drozdov
I. Troyan
P. Kong
V. Minkov
S. Besedin
M. Kuzovnikov
D. Knyazev
H. Wang
University of Mainz
V. Ksenofontov and S. Shylin
MagLab
S. Mozaffari, F. Balakirev, Dan Sun
I. Balicas, D. Graf
APS GeSCARS
V. Prakapenka and E. Greenberg
Polish Academy of Sciences
M. Tkacz
Osaka University
K. Shimizu and M. Einaga
Synchrotron SOLEIL
T. Timusk, P. Roy
W. Pickett,
Ch. Pickard, I. Errea, Y. Ma,
L. Boeri, J. A. Flores-Livas, A. Sanna, G. Profeta, R. Arita
Vladimir Kresin



Max Planck Institute for Chemistry,
U. Pöschl. Technical support.
The community of the Max Planck Society