New Findings in Simple Molecular Systems Under Pressure

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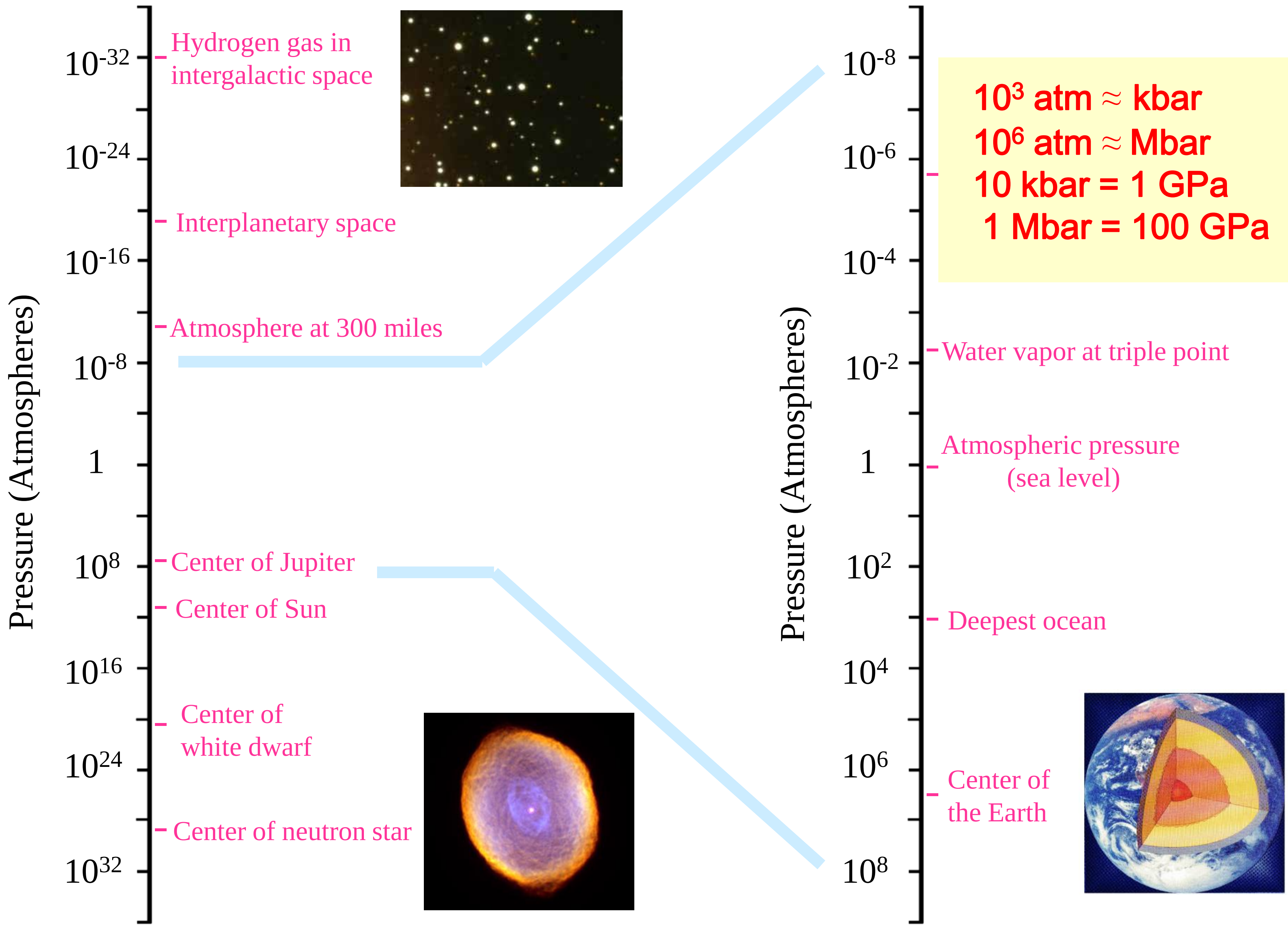
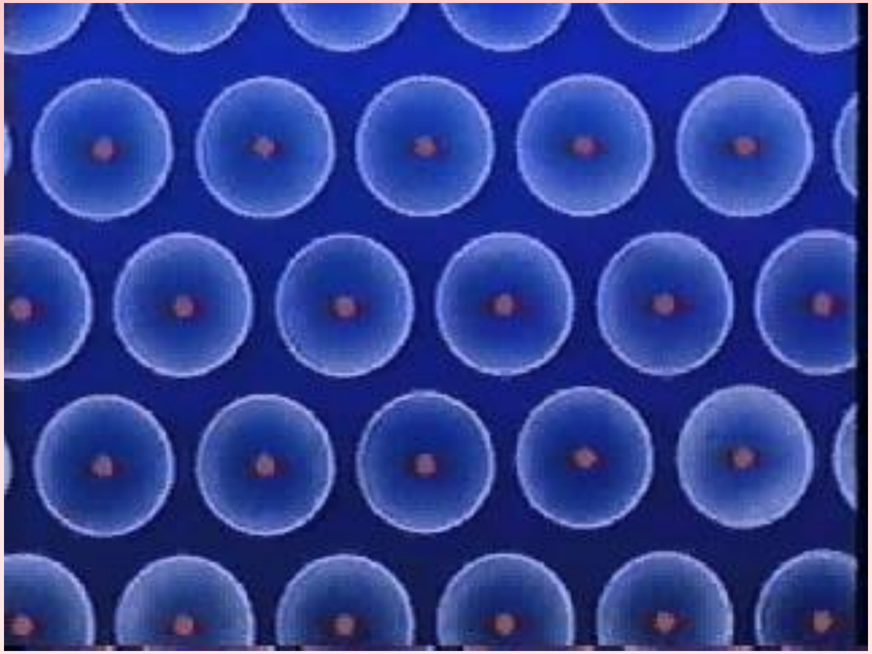
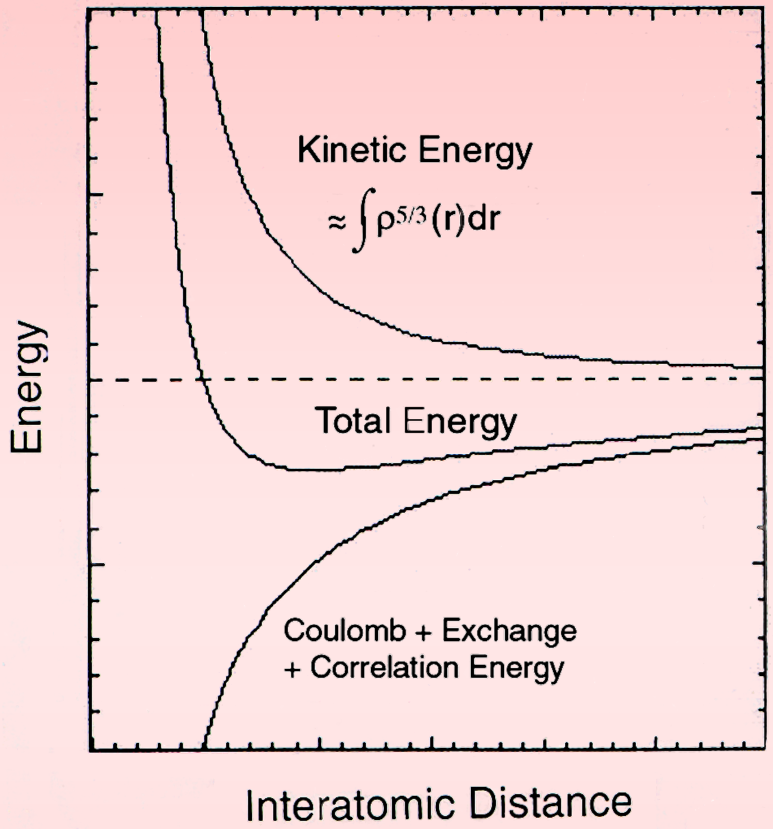
CC2010 “School for Young Scientists”
July 26, 2010

RANGE OF PRESSURE IN THE UNIVERSE



Compressing Atoms and Molecules





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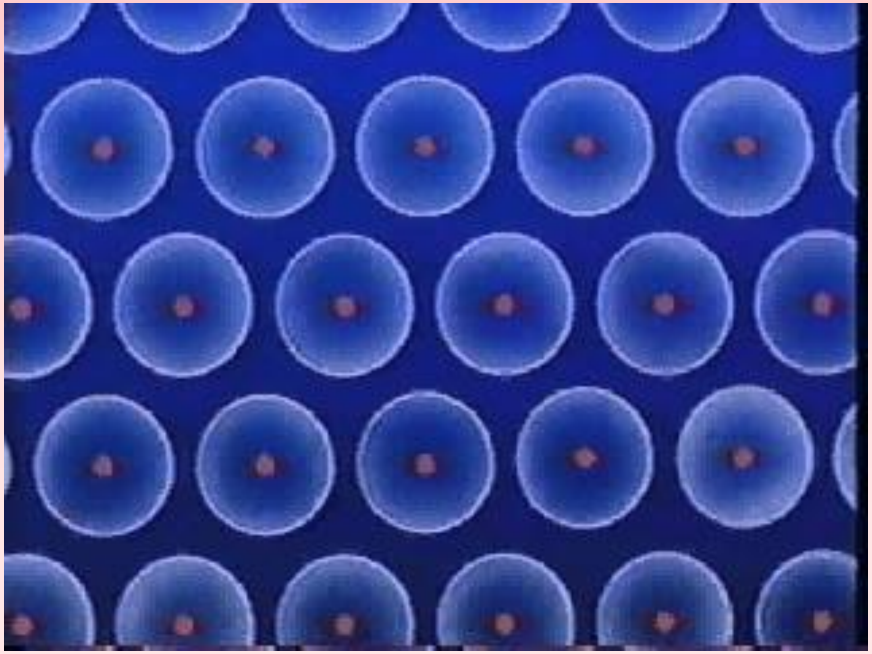
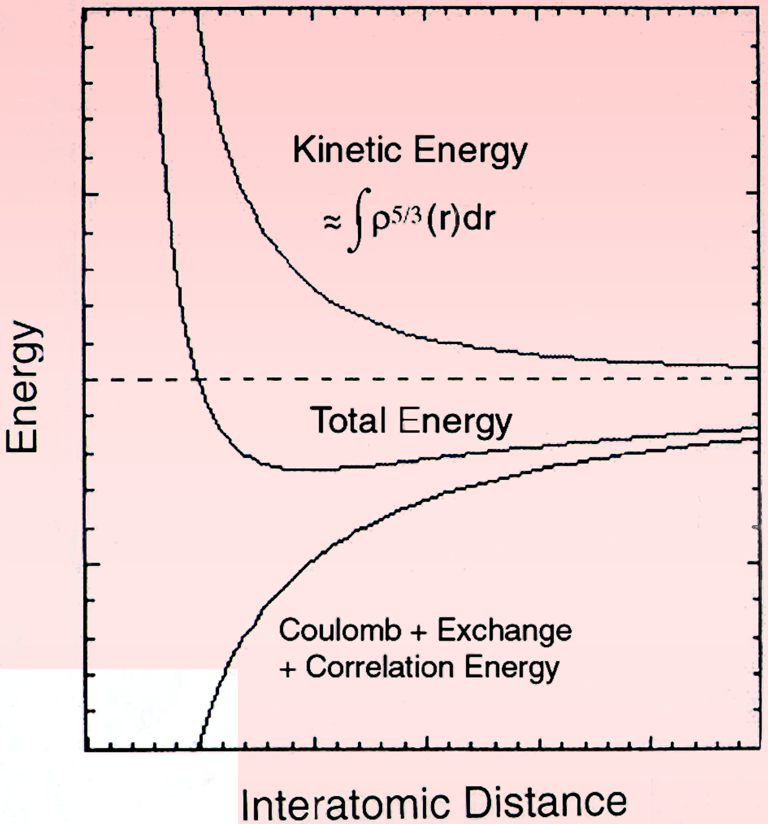
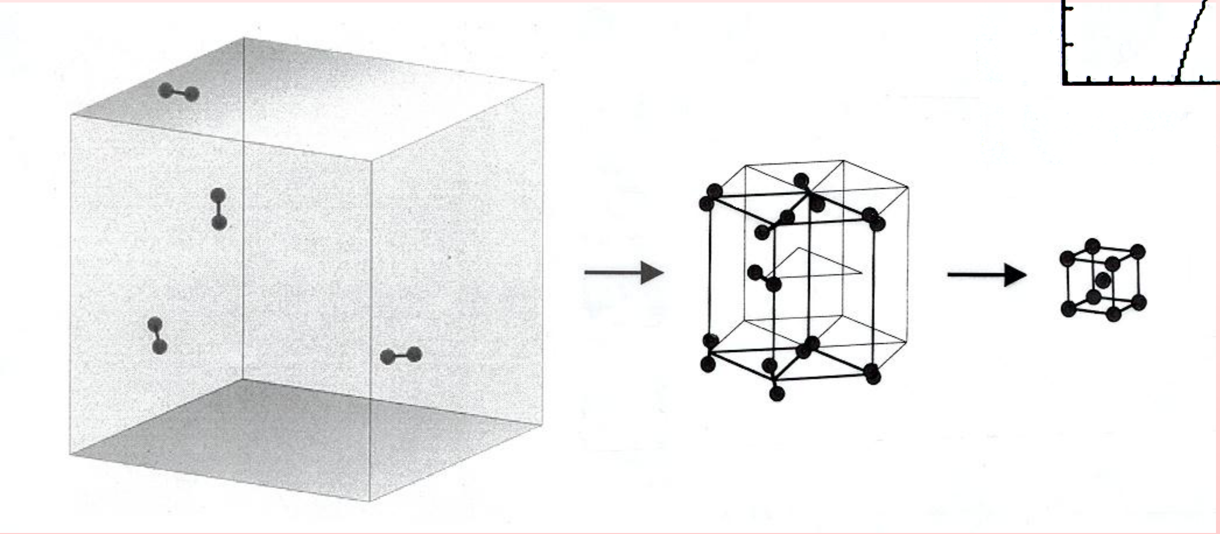




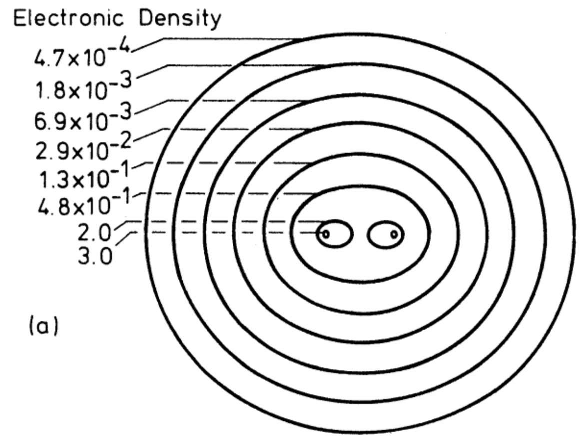


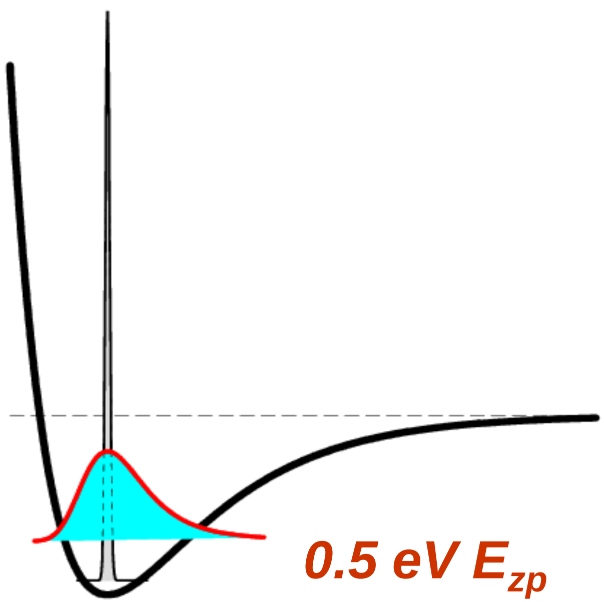
$$P = -\frac{\partial E}{\partial V}$$

Simple Molecular Systems Under Pressure

HYDROGEN

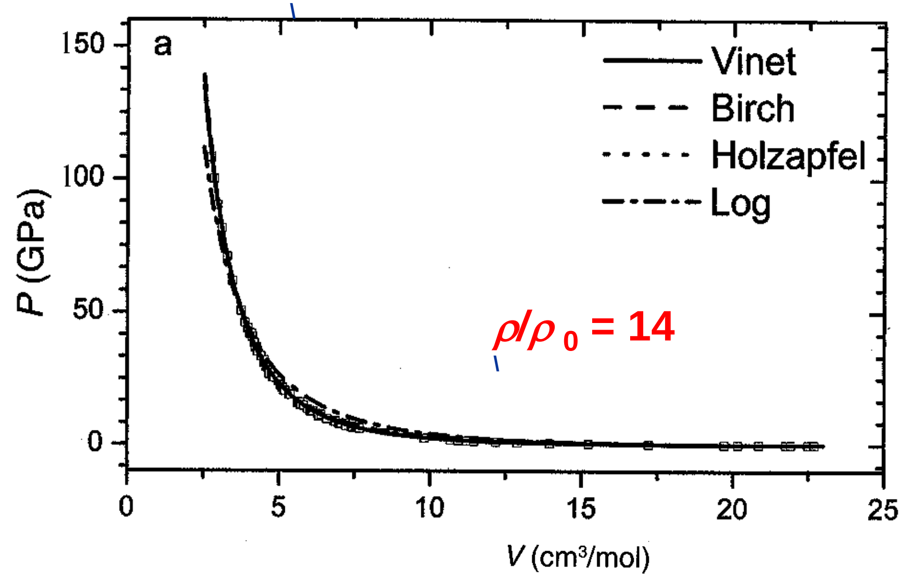
- *Nearly spherical charge distribution p-H_2*
- *E_b = 4.5 eV*





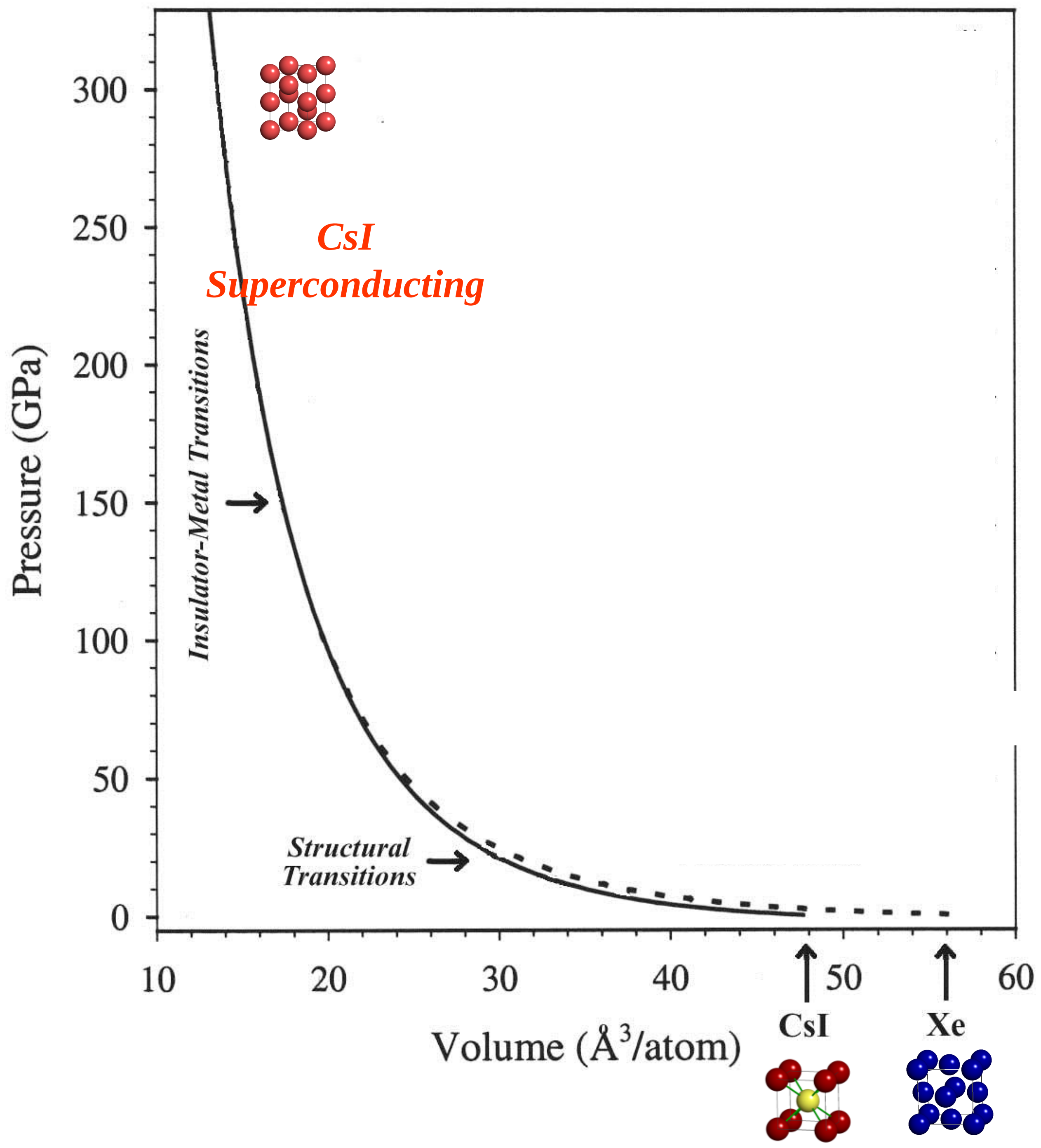
0.5 eV E_{zp}
Quantum Effects

Compressibility

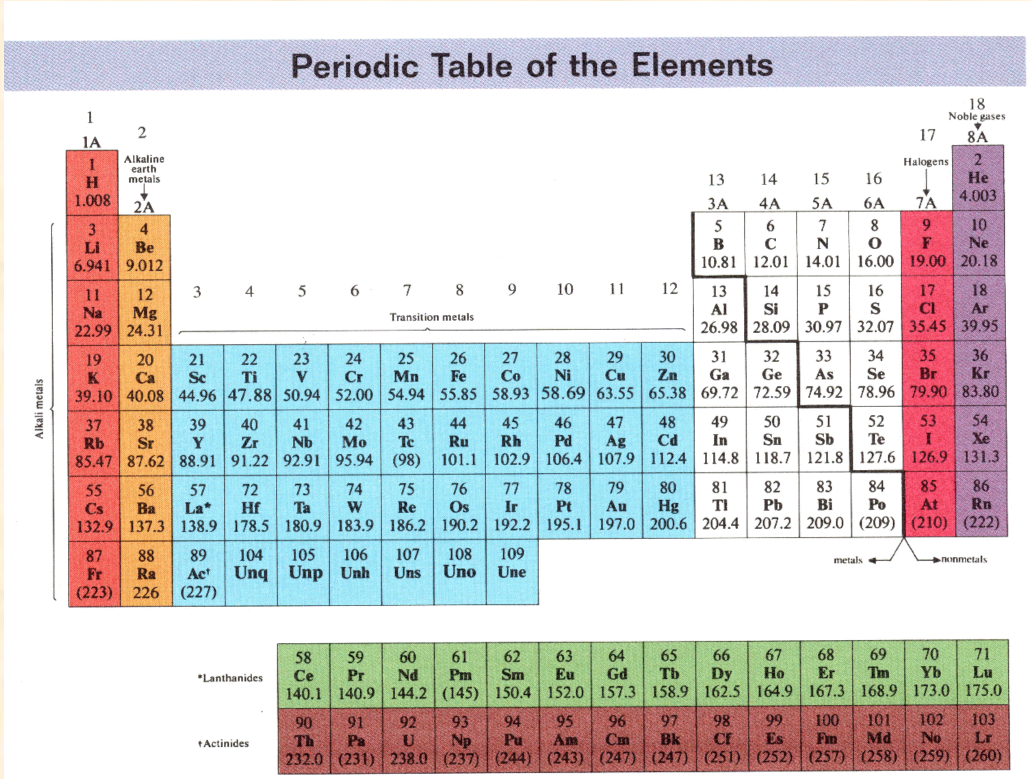


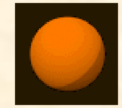
[Cohen *et al. Am. Mineral.* (2000)]

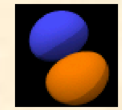
Free Energy Changes and Chemical Bonding

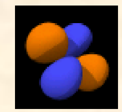


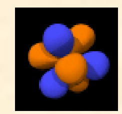
[Hemley and Ashcroft, *Physics Today* (1998)]



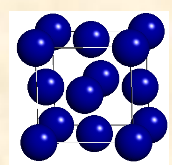


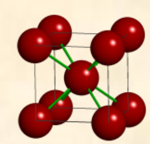


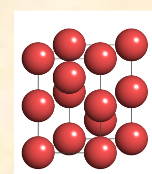


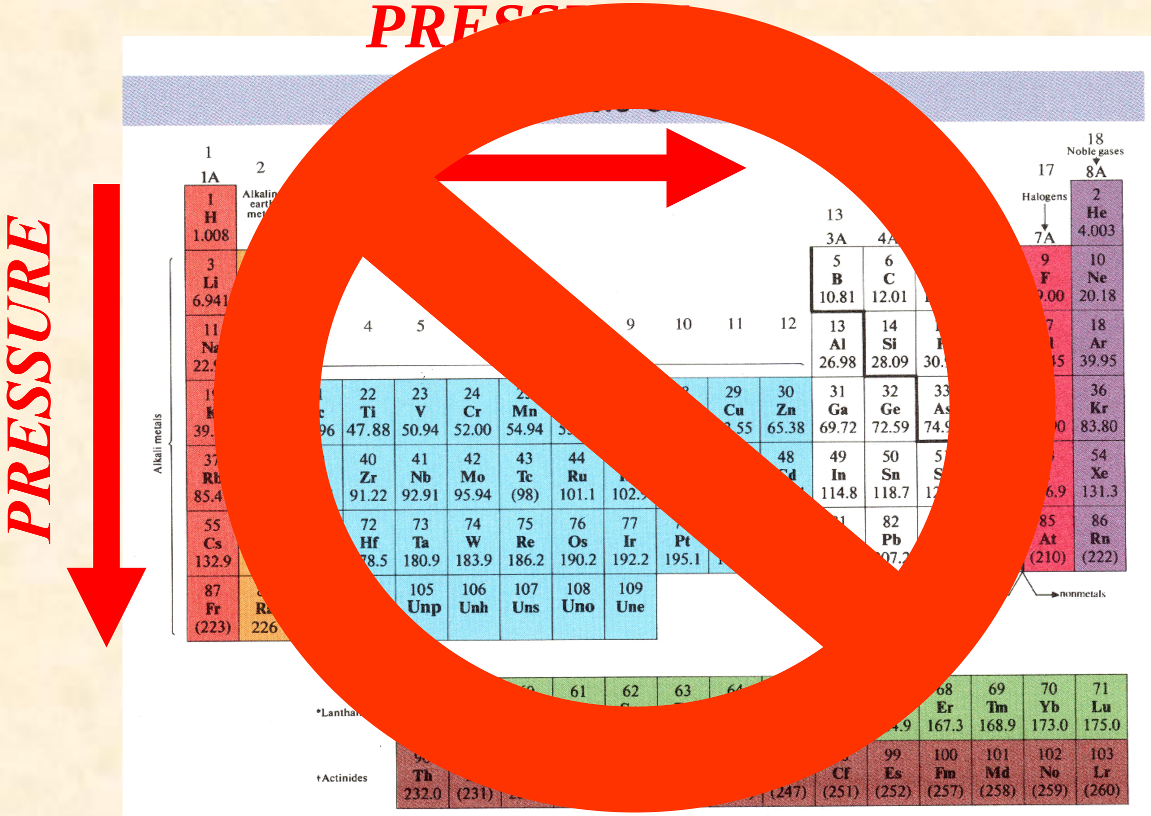


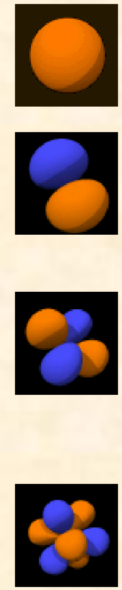
- **Filling of *s*, *p*, *d*, … orbitals**
- **Simple structures**



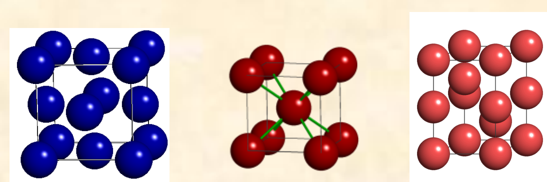






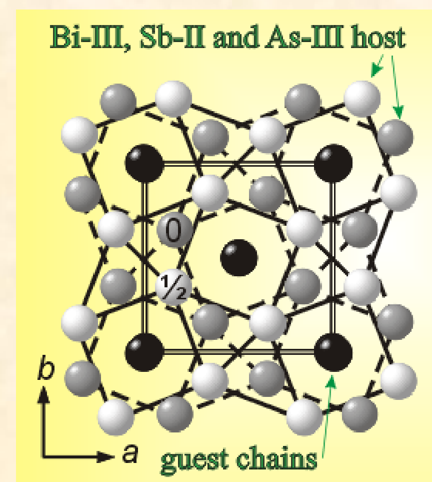


- **Filling of *s*, *p*, *d*, … orbitals**
- **Simple structures**

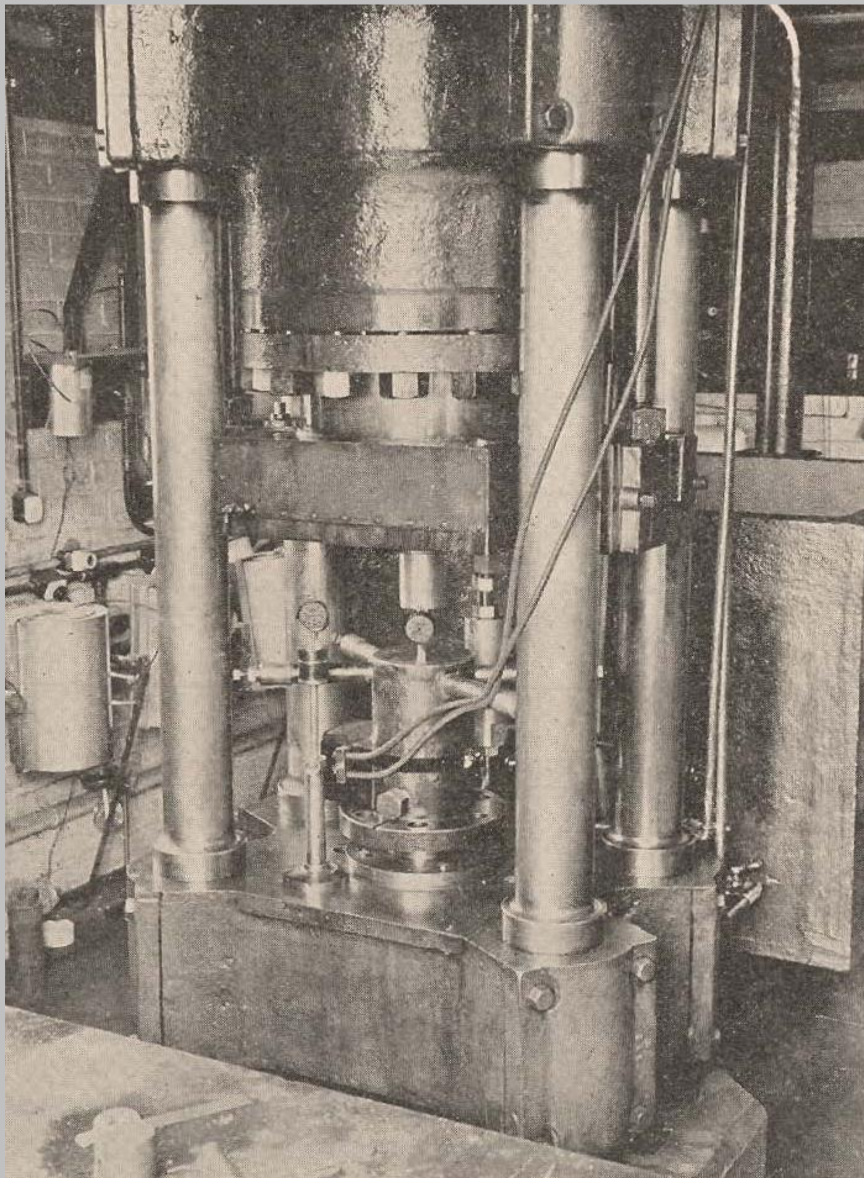


Under Pressure

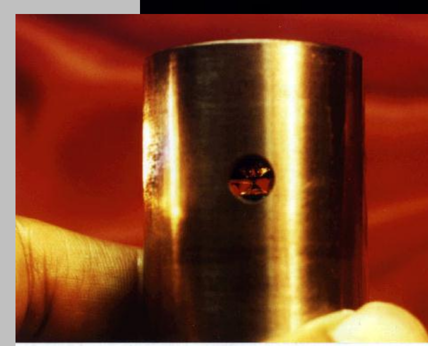
- **Orbital hybridization (*e.g.*, *s*->*d*)**
- **Complex structures**



DIAMOND ANVIL CELL

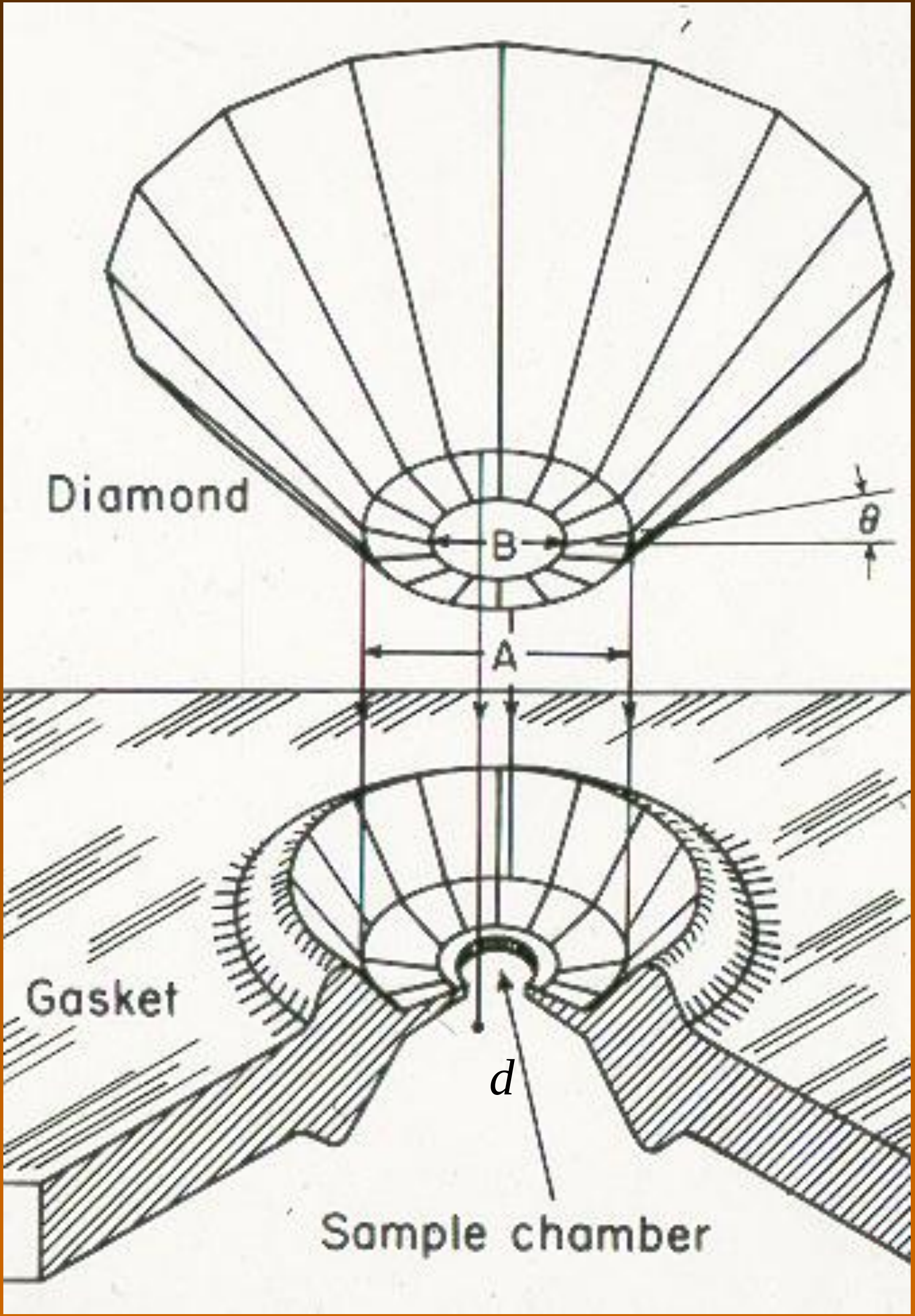


[E. D. Williamson, *J. Franklin Inst.* (1922)]



Diamond

- **Strength**
- **Transparency**

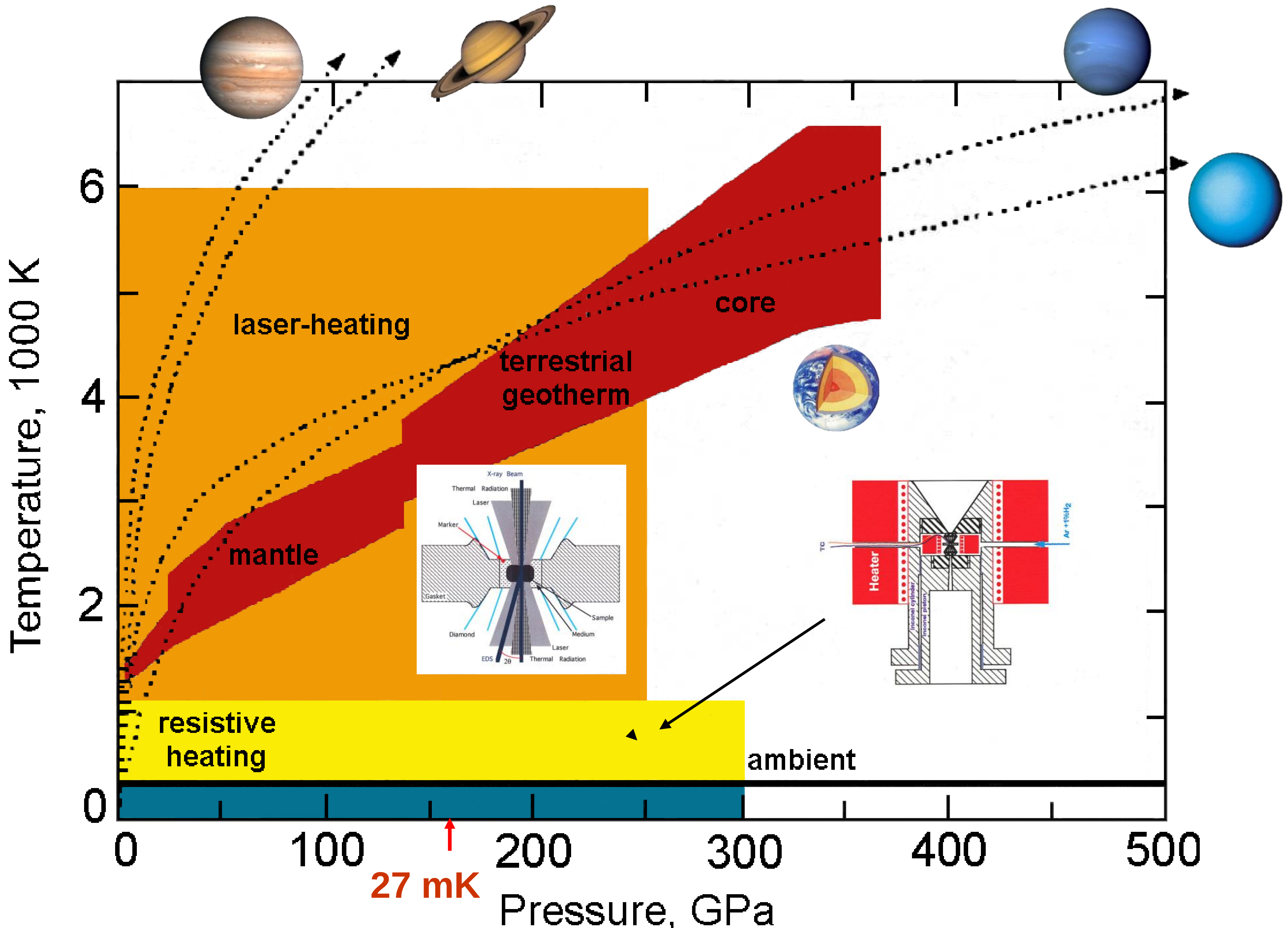


MEGABAR DIAMOND ANVIL CELL

$P = F/A$

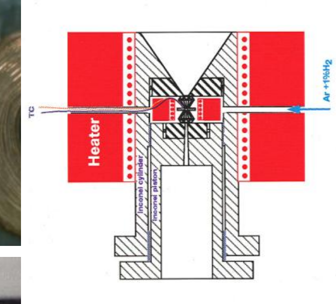
P	*d*	*Volume*
50 GPa	~200 μm	~10 nl (10^{-9} l)
200 GPa	~20 μm	~1 pl (10^{-12} l)

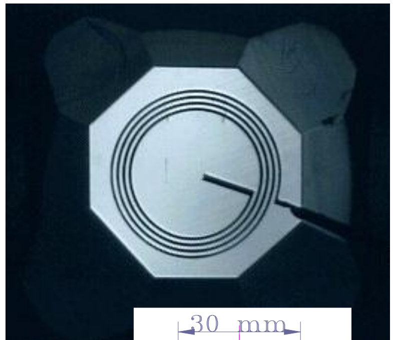
EXTREME STATIC PRESSURES *AND* TEMPERATURES

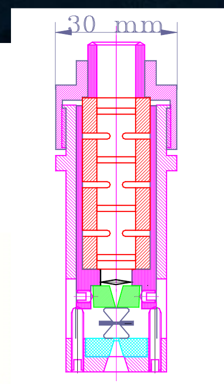


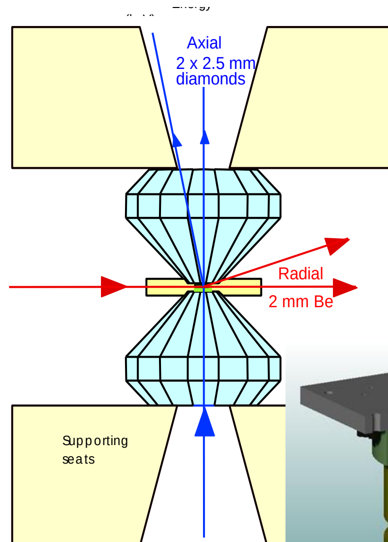
High-Pressure Technology:

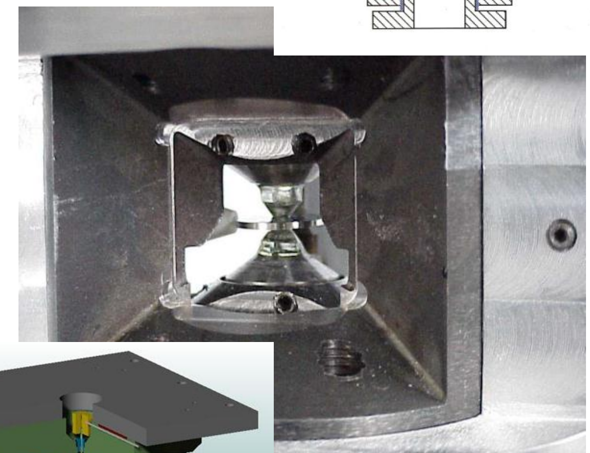
TOOLS FOR IN SITU MEASUREMENTS

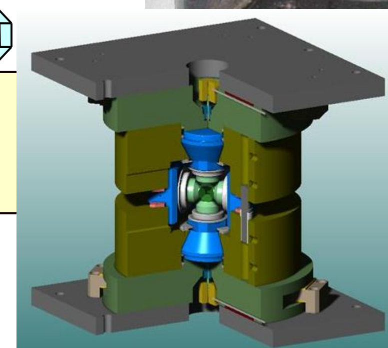


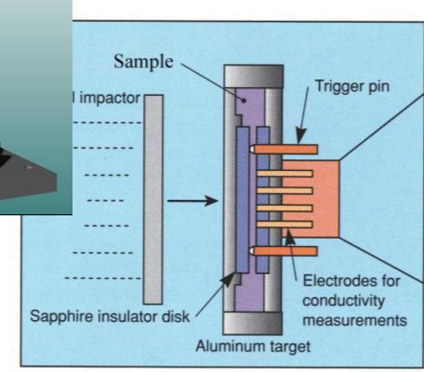


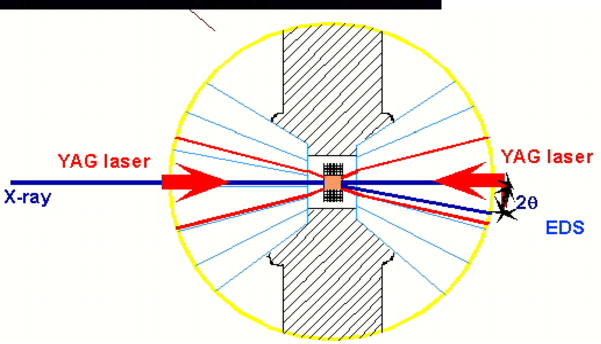


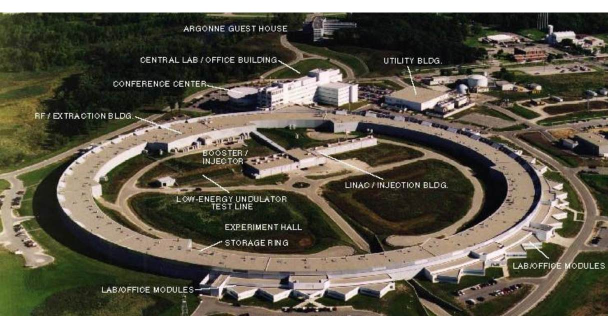


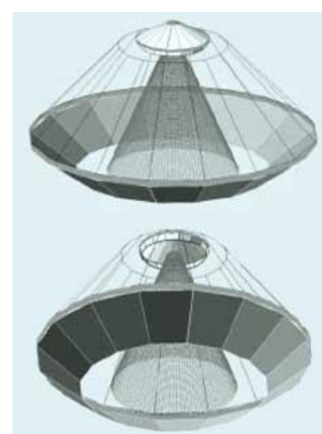


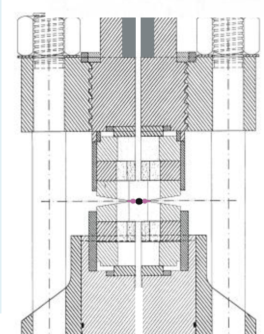






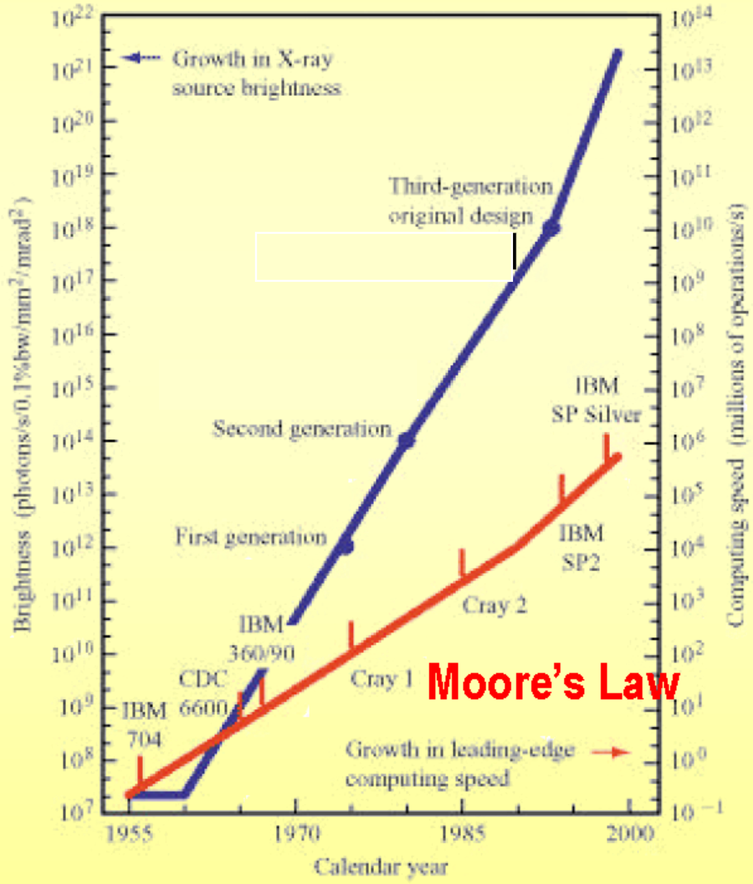




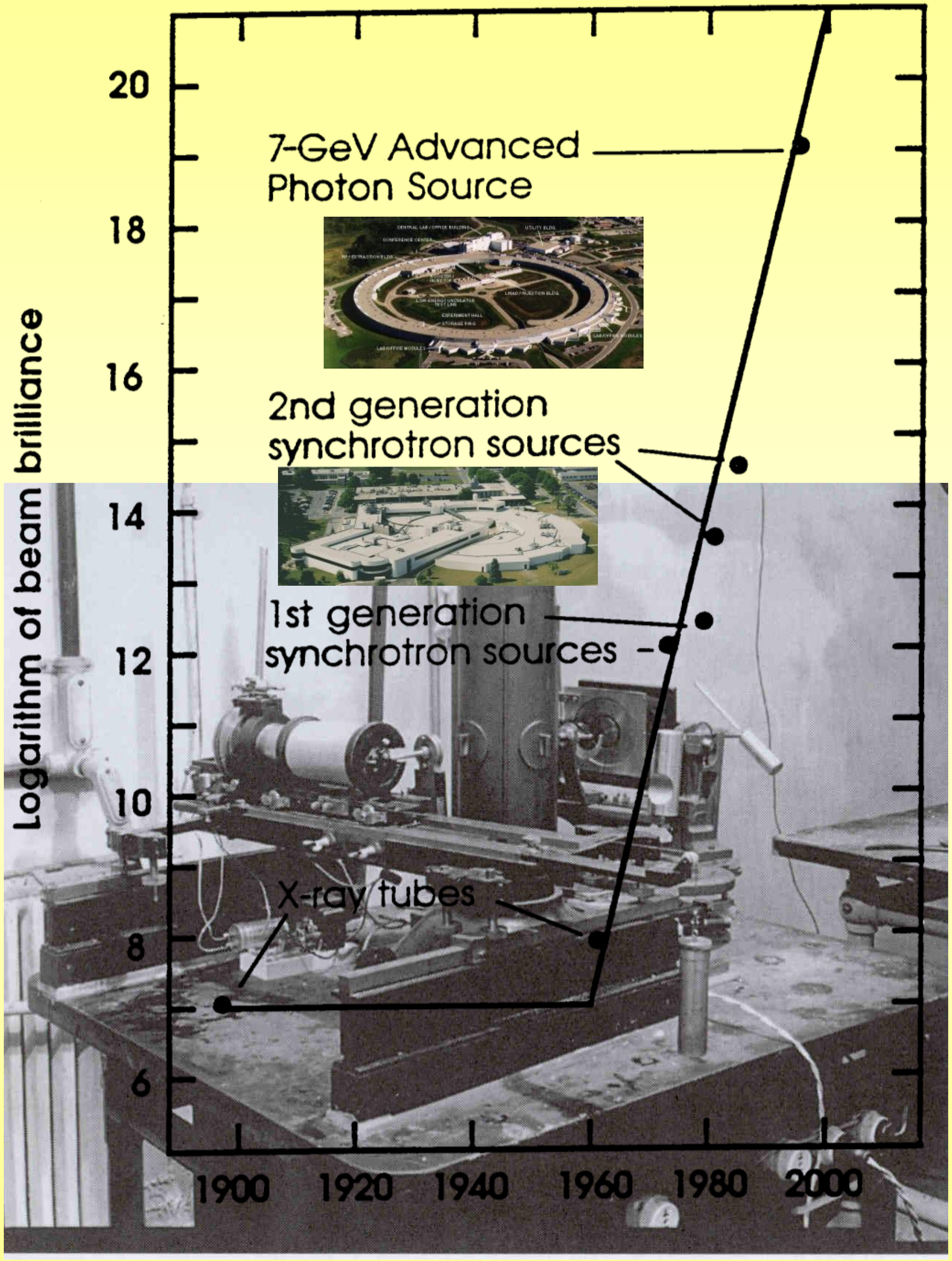


Evolution of Light Sources

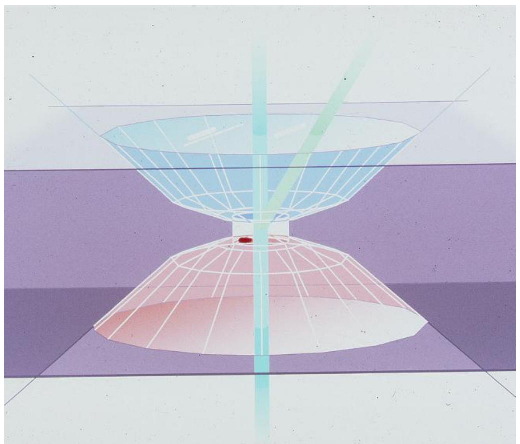
- *X-ray to infrared (diffraction limited)*



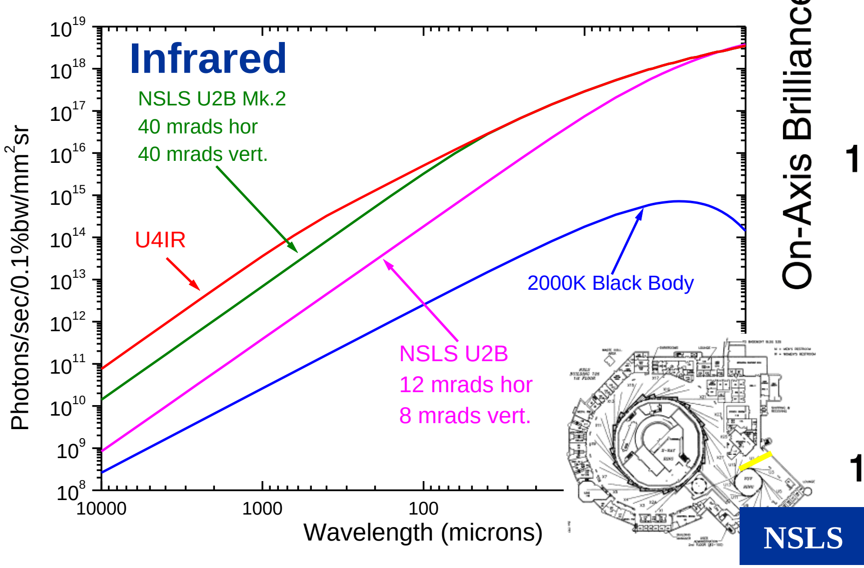
History of X-ray Sources

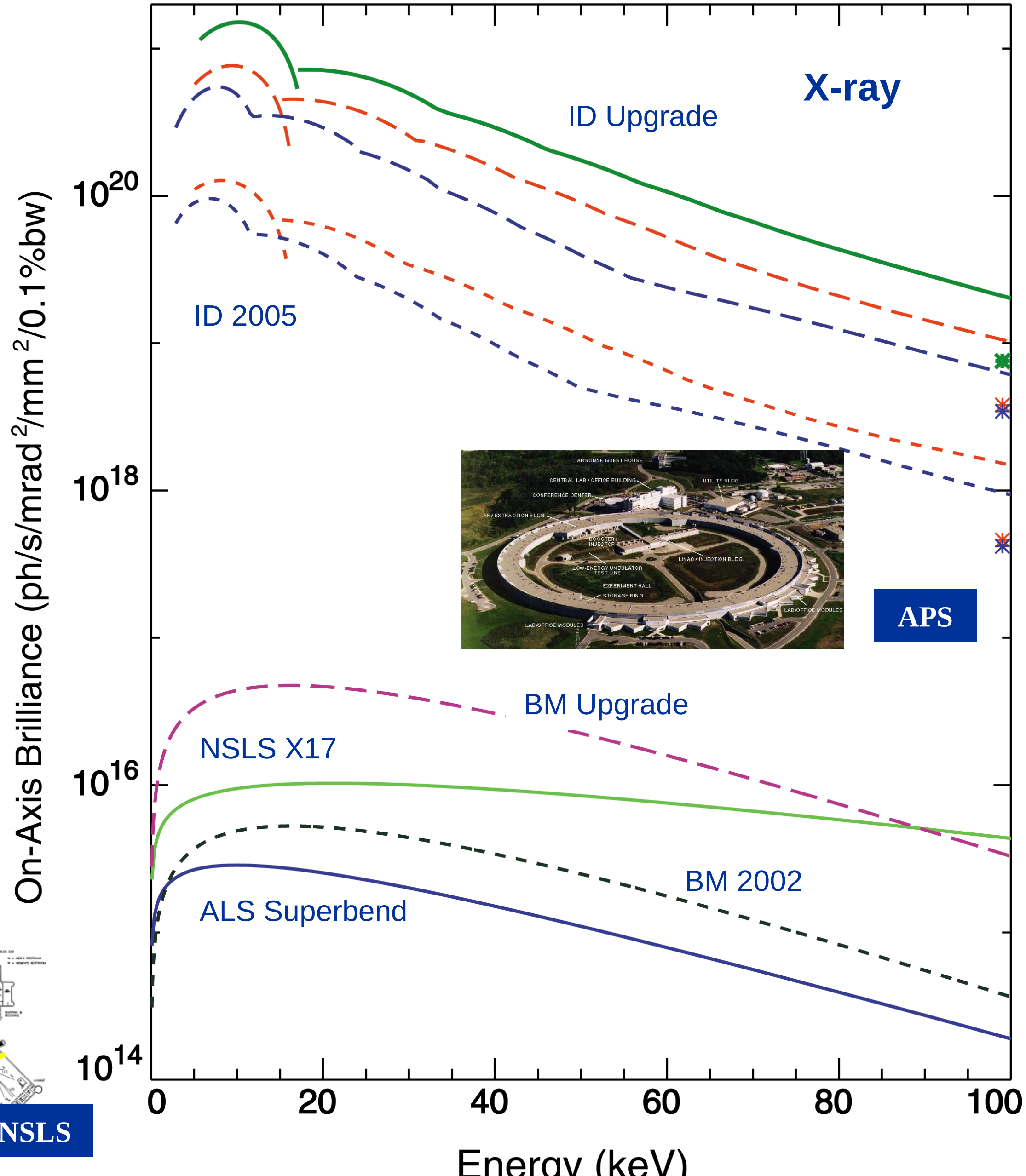


Need for High Brightness Microbeams



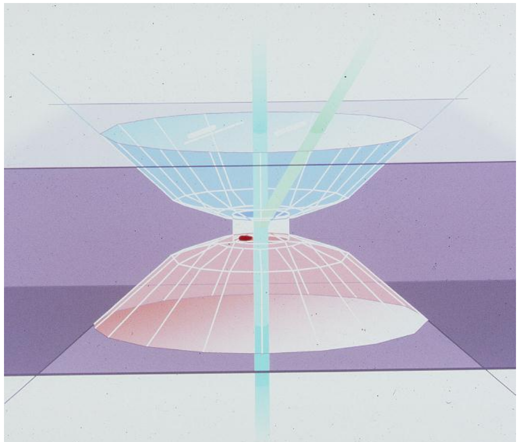
- ***X-ray focused to < 1 μm***
- ***Infrared (diffraction limited)***





Need for High Brightness Microbeams

Diamond opaque at >5 eV to ~10 keV



- ***X-ray focused to < 1 μm***
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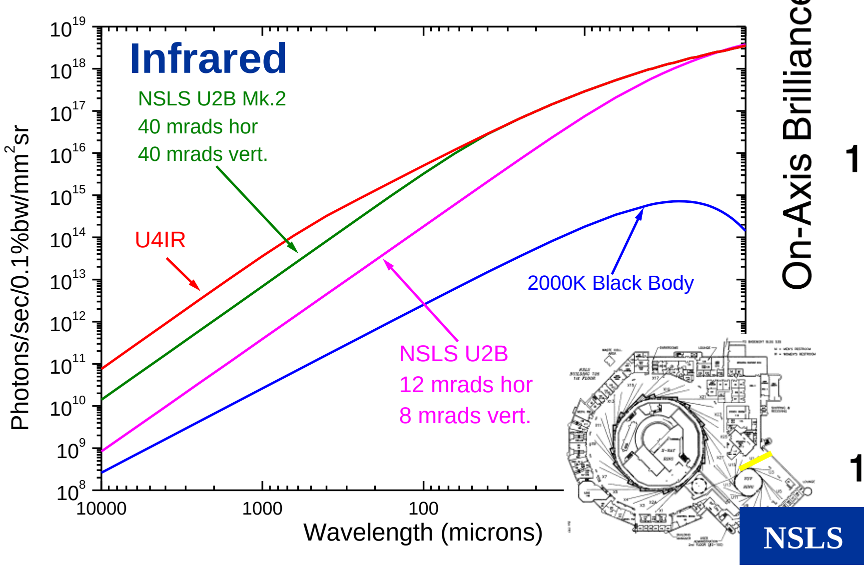
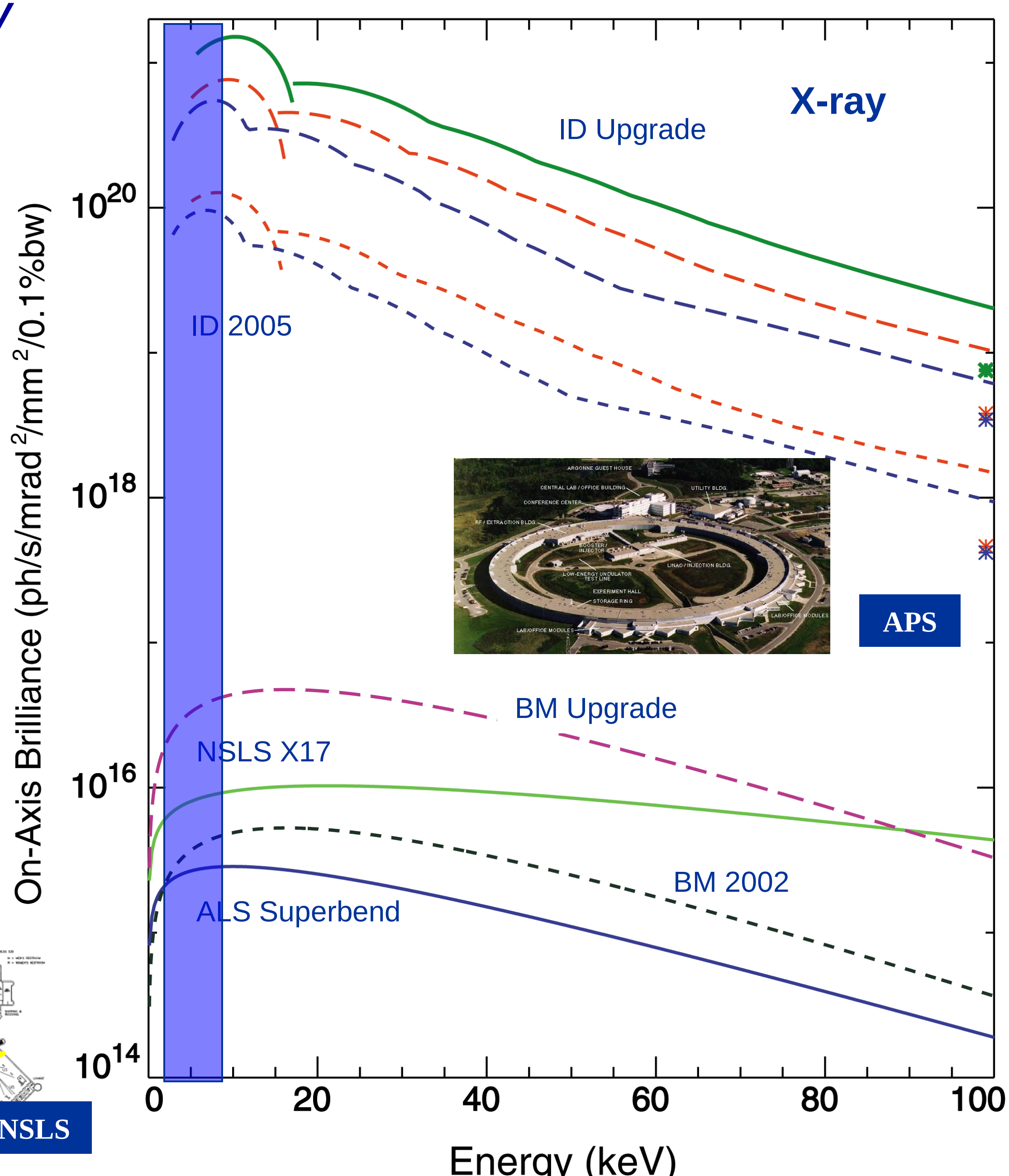




HOW DO KNOW THE PRESSURE?

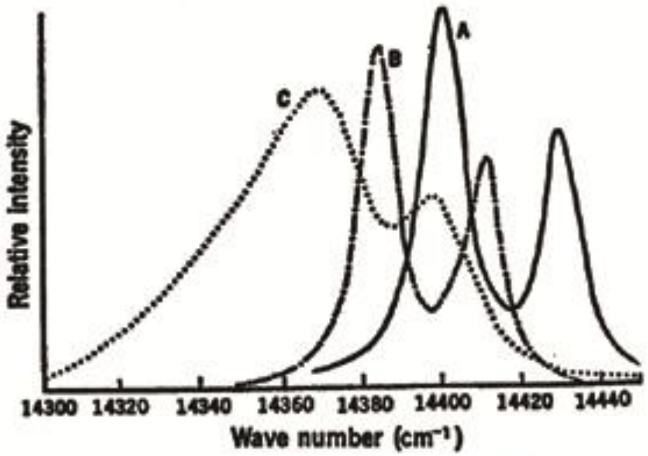


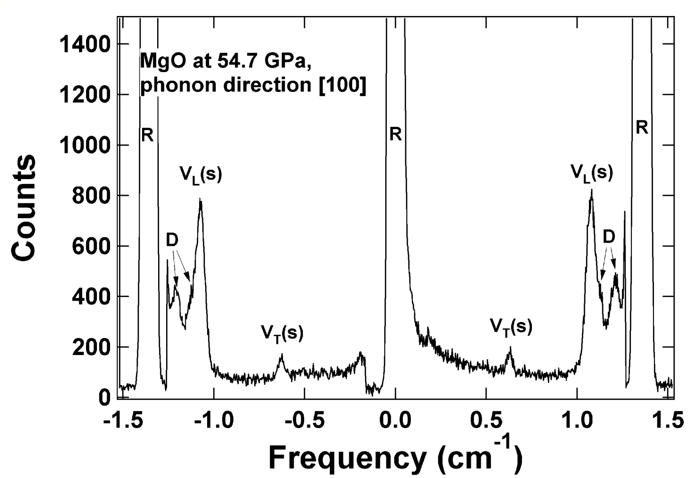
Fig. 1. The *R*-line luminescence spectra of a crystal of ruby in the diamond cell: curve A, ruby sample at ambient atmospheric pressure; curve B, ruby sample in a mixture of ices VI and VII at approximately 22.3 kbar; and curve C, ruby sample in a mixture of CCl_4 III and IV at an average pressure of 40 kbar (nonhydrostatic environment). (Peak heights are arbitrary.)

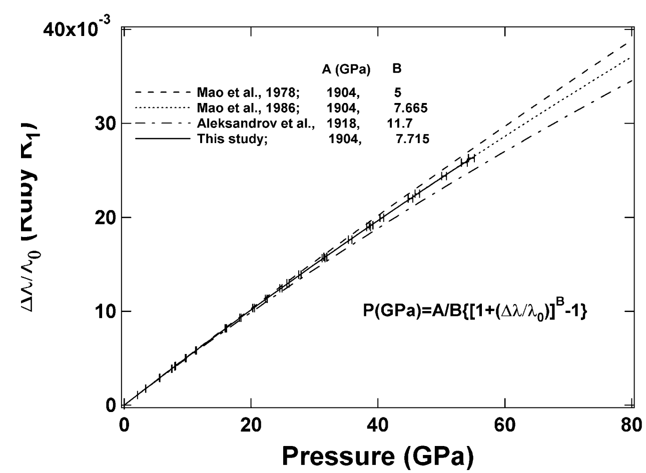
- **Original ruby scale to 10 GPa produced in 1972 (NBS).**
- **Volume of metals from diffraction using shock-wave equations of state; pressure scales to >200 GPa in 1978 (Carnegie)**
- **<u>Primary</u> pressure scales measuring volume and bulk modulus in 2000.**

Brillouin scattering combined with x-ray diffraction; confirms quasihydrostatic ruby scale (1%)

[Forman et al., *Science* (1972); Piermarini et al., *J. Appl. Phys.* (1975)].

[Zha et al., *Proc. Nat. Acad, Sci.* (2003)].





Brave New World Under Pressure

- Novel transformations: solids, liquids, glasses
- Structures: unexpected complexity
- Molecules break down, but new ones form
- Novel electronic and magnetic phenomena
- New recoverable materials
- Materials basis for understanding planets
- Structure-function in biological systems

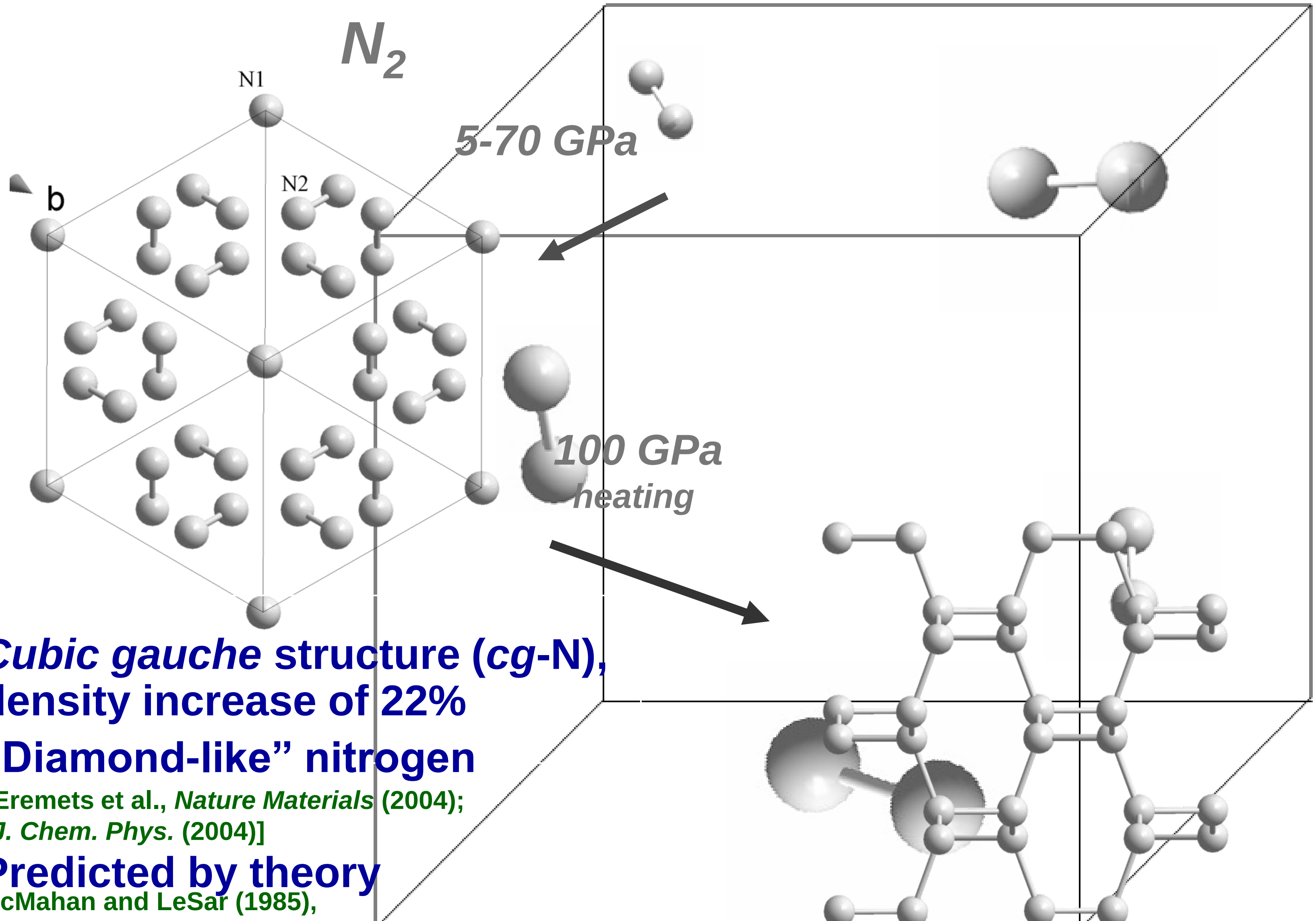
THEMES

- *Surprising structures and bonding*
- *Novel transitions*
- *New techniques*
- *Theory and experiment*
- *Future developments*

EXAMPLES:

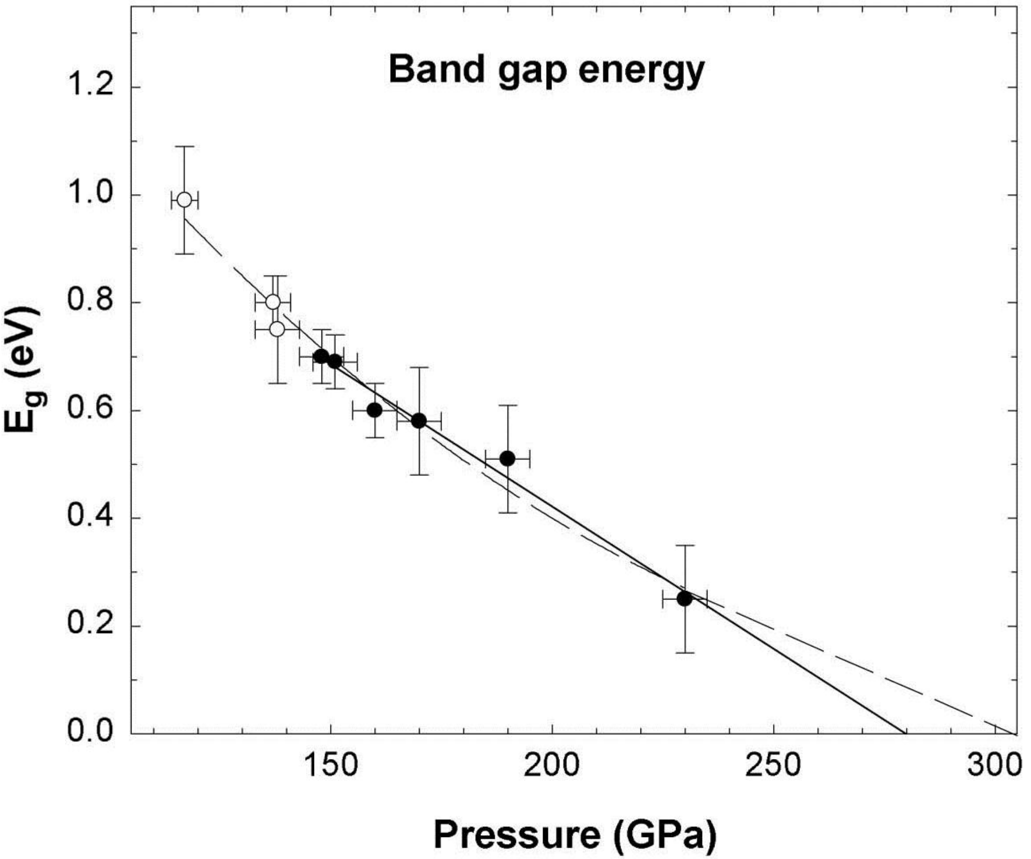
1. ‘Simple’ diatomics
2. Dense hydrogen
3. Elemental metals
4. Polyatomic systems
5. Van der Waals compounds
6. Transforming carbon

‘Simple’ diatomics: high-pressure behavior of nitrogen



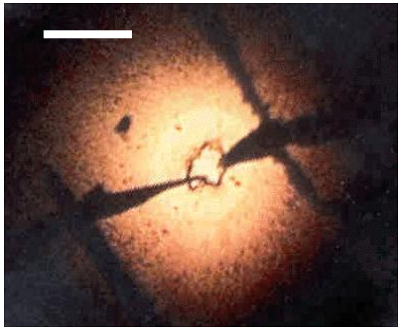
- ***Cubic gauche*** **structure (*cg*-N), density increase of 22%**
- **“Diamond-like” nitrogen**
  [Eremets et al., *Nature Materials* (2004); *J. Chem. Phys.* (2004)]
- **Predicted by theory**
  [McMahan and LeSar (1985), Martin & Needs (1986); Mailhiot et al. (1992)]

Non-molecular 'polymeric nitrogen' is semiconducting above 230 GPa

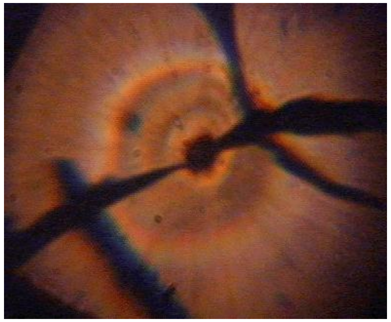


50 μm

75 GPa



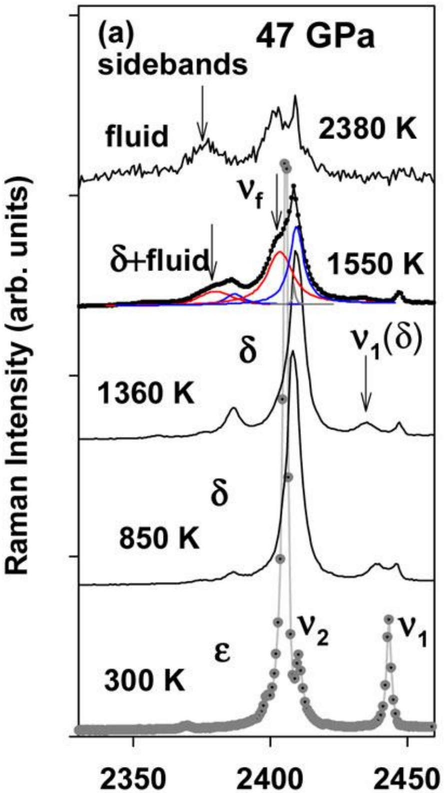
193 GPa

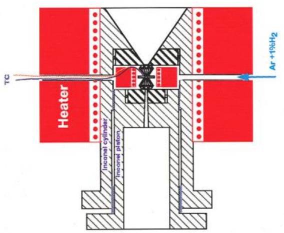


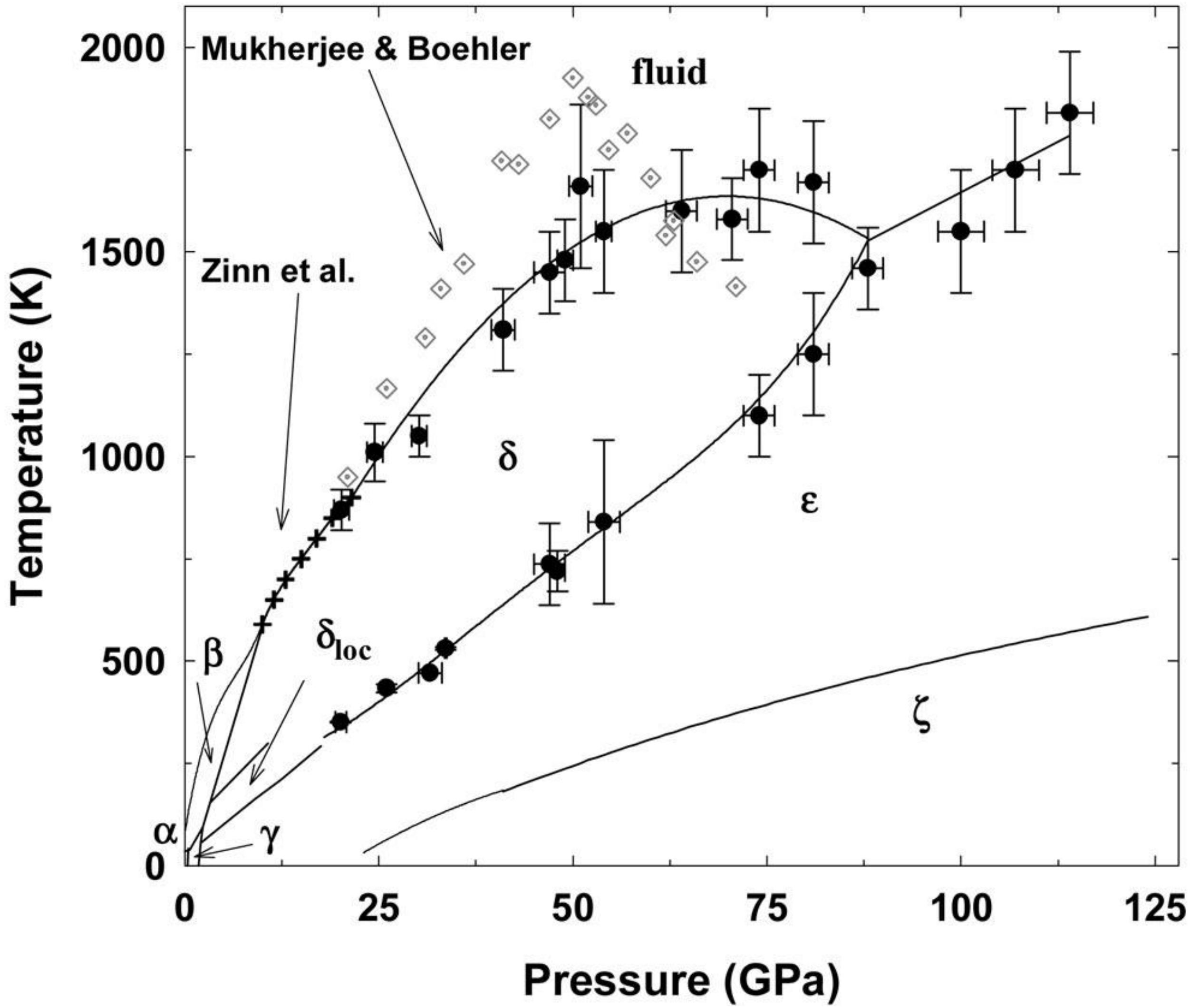
- **Optical (IR) absorption and electrical conductivity**
- **Possible band gap closure at 270 GPa**

[Goncharov *et al., Phys. Rev. Lett.* (2000);
Eremets *et al., Nature* (2001)]

New observations of the phase and reaction diagram of nitrogen

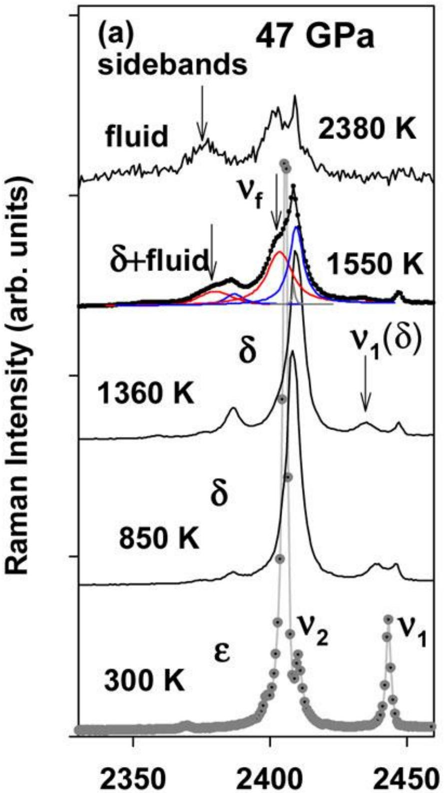


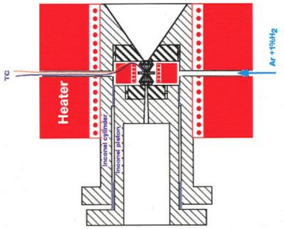


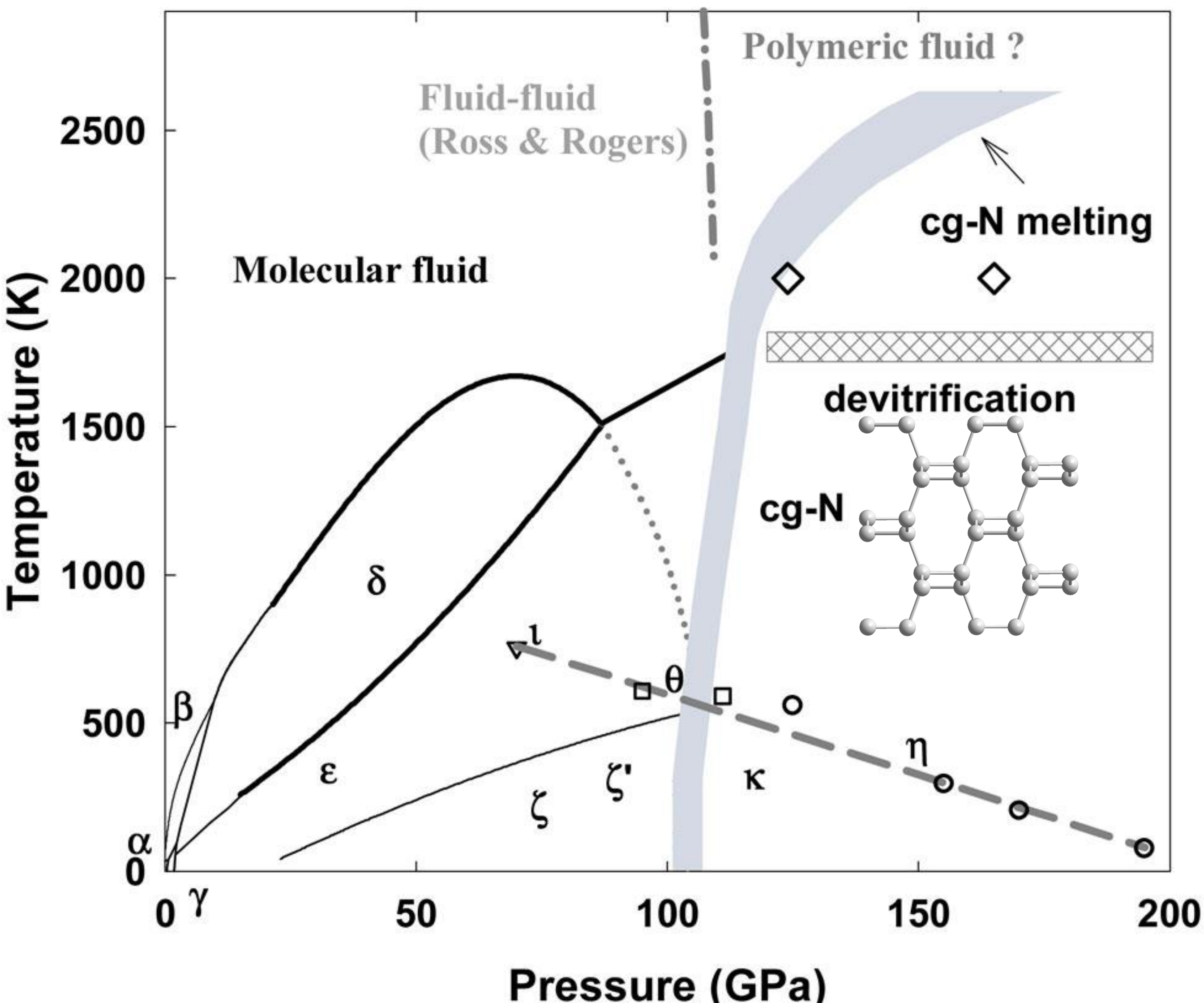


[Goncharov *et al.*, *Phys. Rev. Lett.* (2008)]

New observations of the phase and reaction diagram of nitrogen

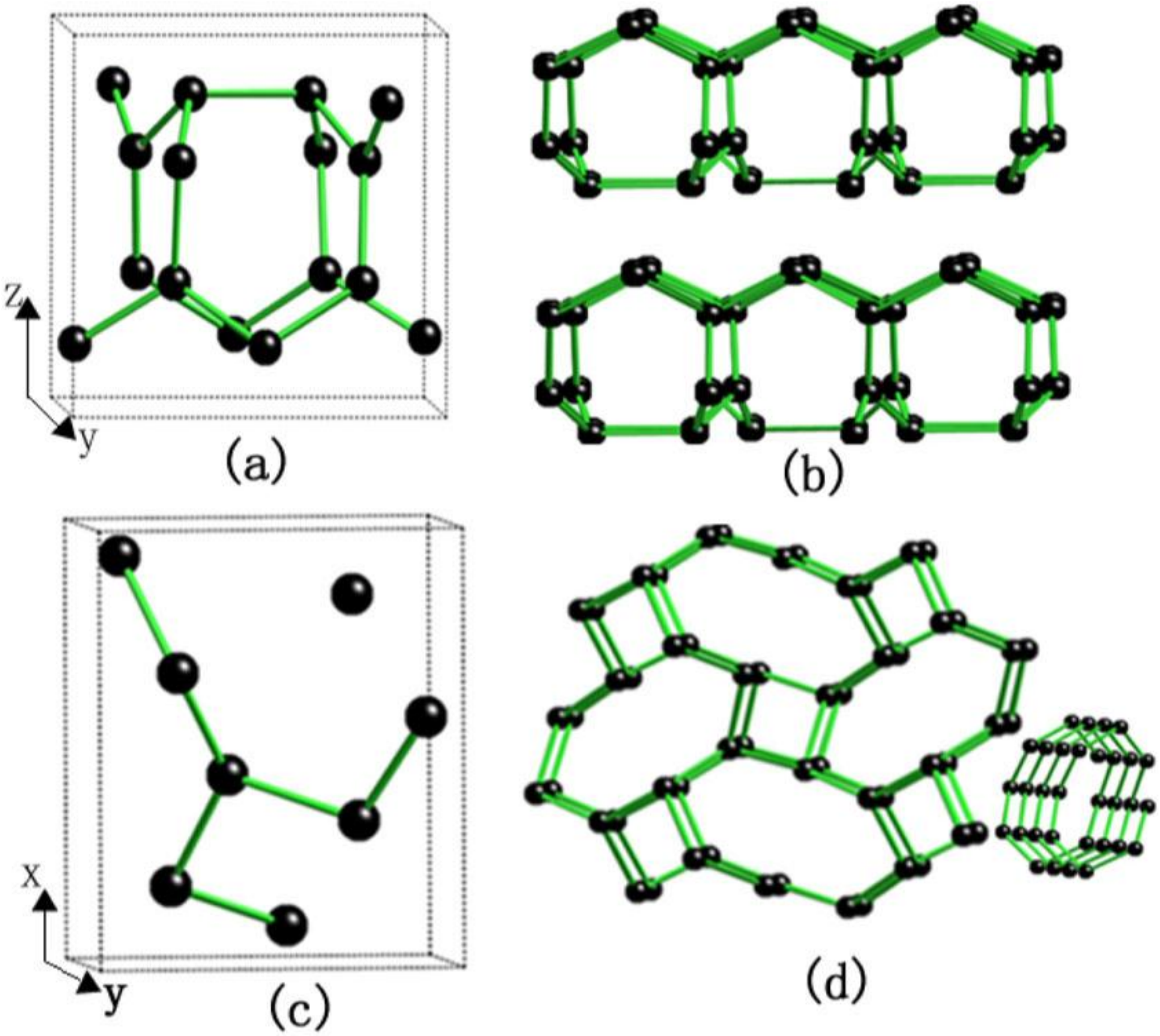






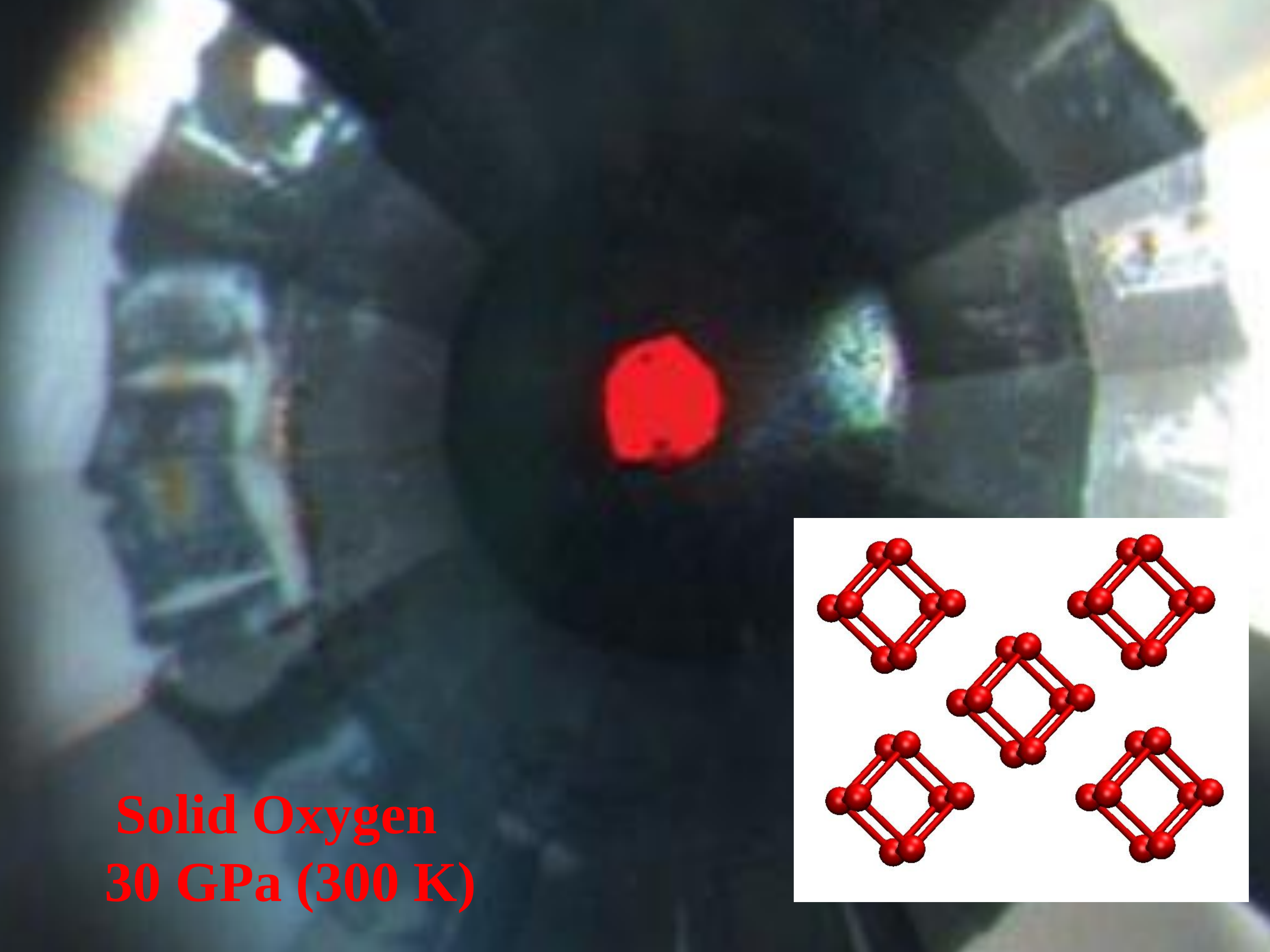
[Goncharov *et al.*, *Phys. Rev. Lett.* (2008)]

Theoretical predictions of higher pressure behavior of nitrogen

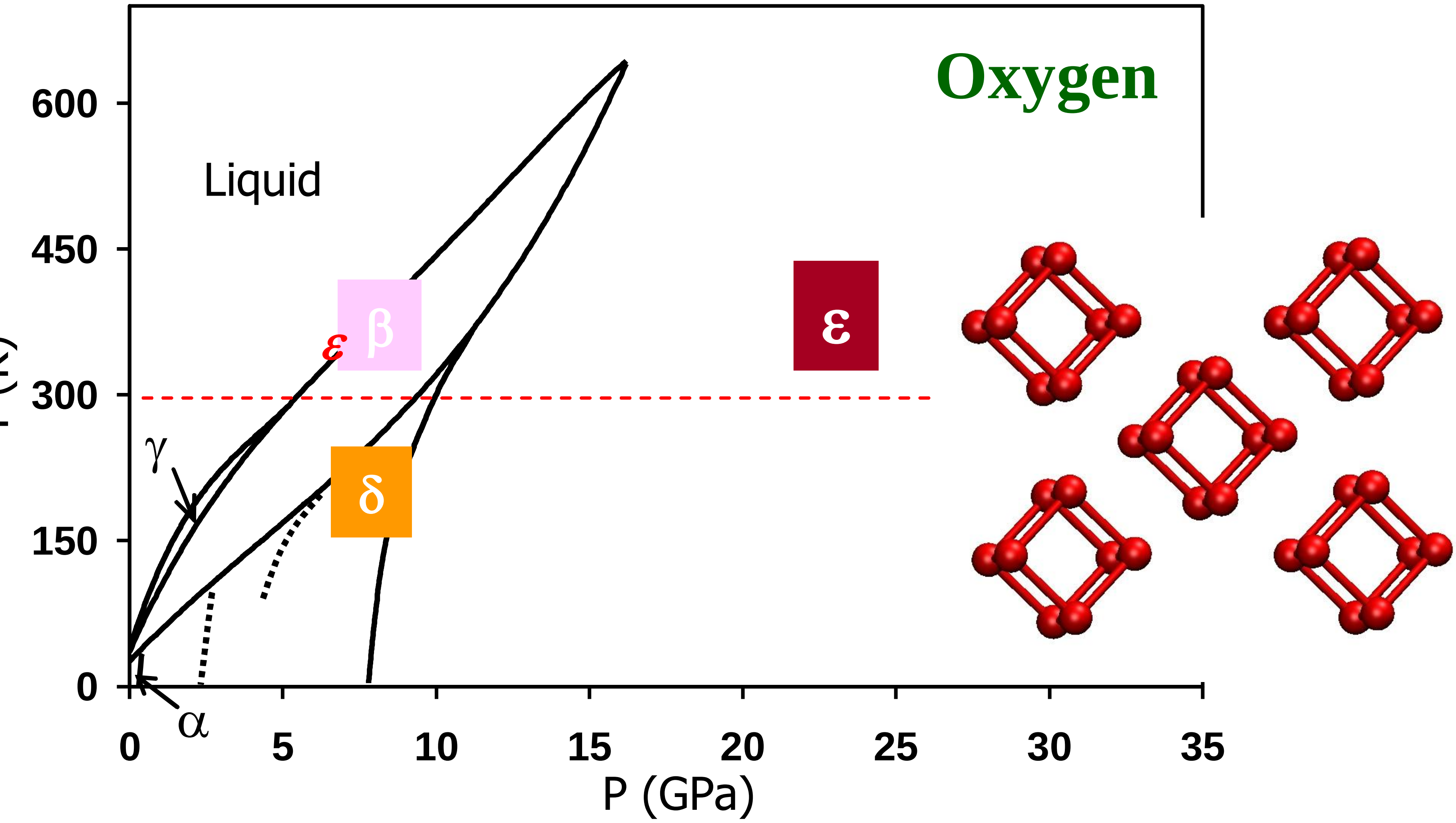


[Ma et al., *Phys. Rev. Lett.* (2009)]

[*see also*, Bonev *et al., Phys. Rev. Lett (2008)*]

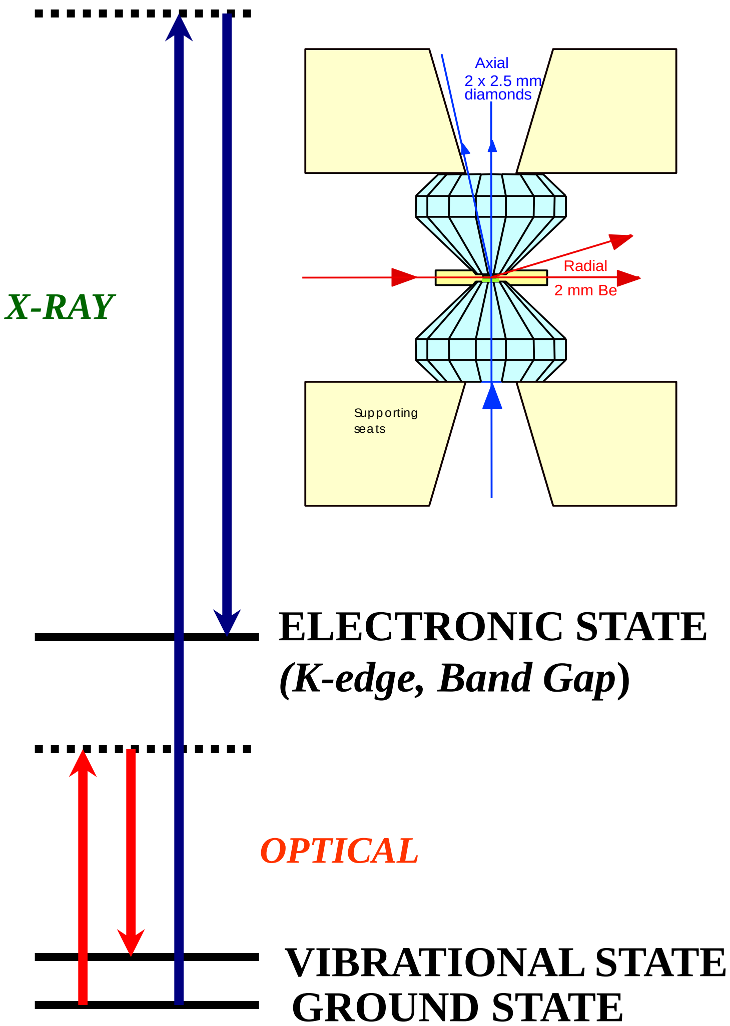

Solid Oxygen
30 GPa (300 K)

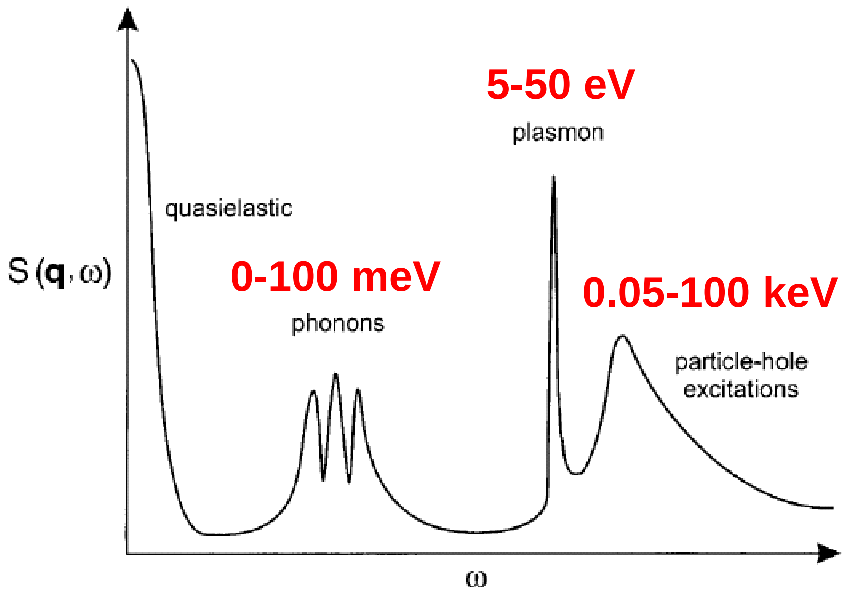
Origin of stability of ε-oxygen structure



[Lundegaard et al., *Nature* (2006*);*
Fujihishi *et al., Phys. Rev. Lett*. (2006)]

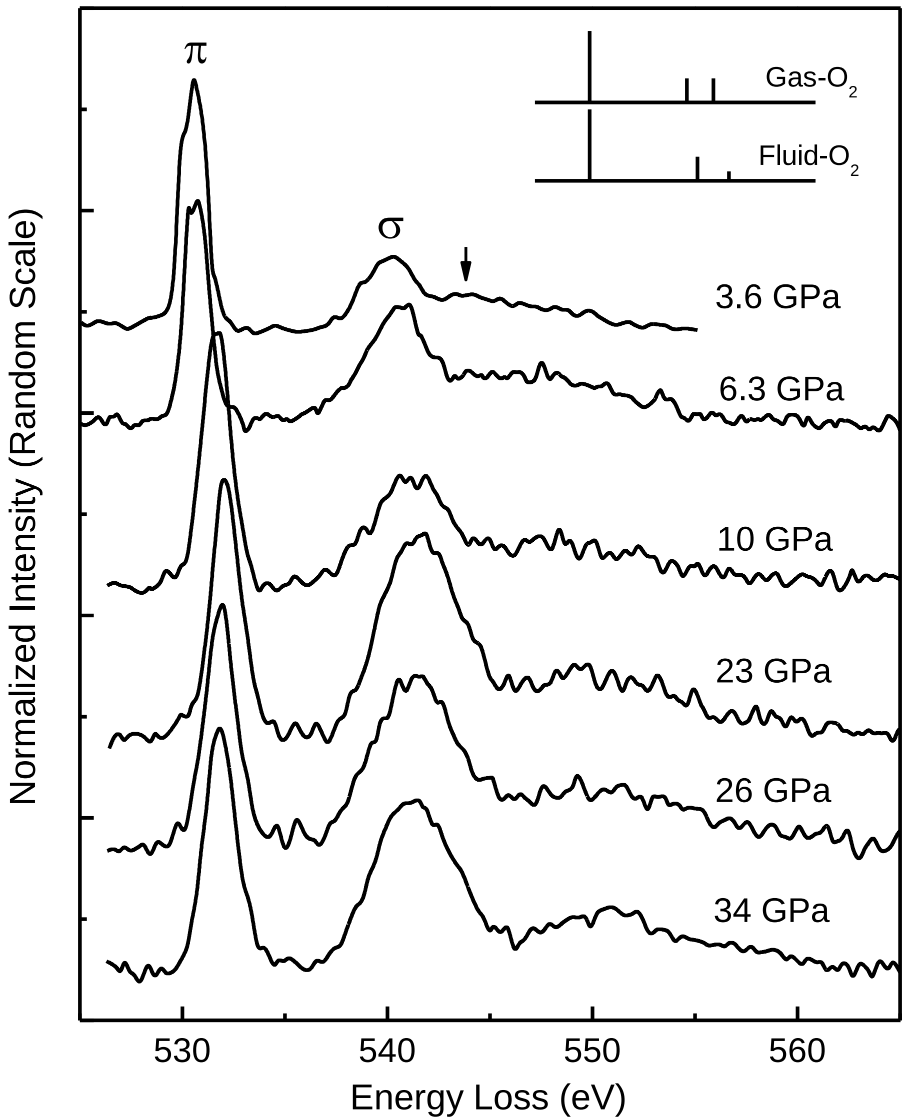
Pressure dependence of bonding and electronic structure from inelastic x-ray scattering



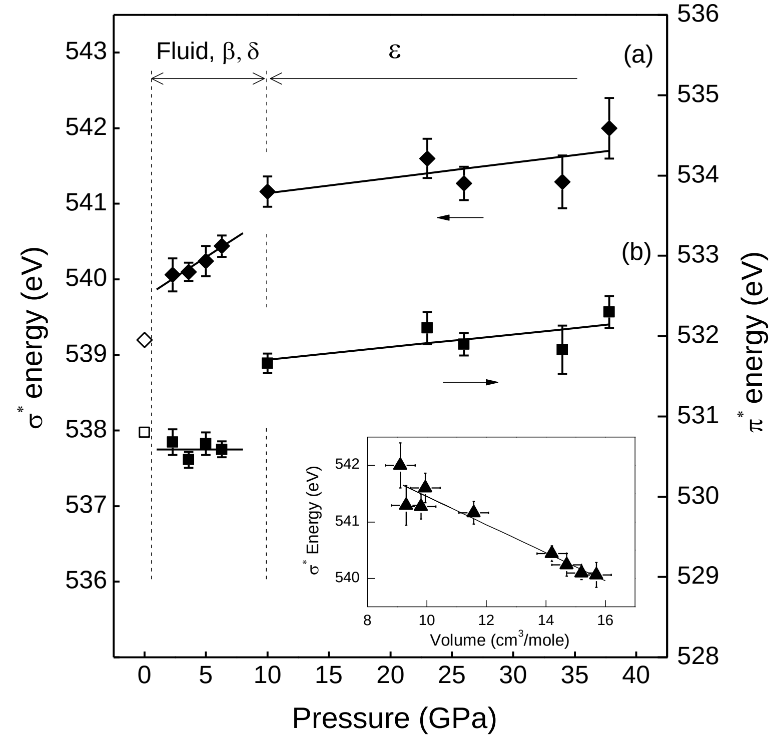


- Diamond window opaque above 5 eV
- Q dependence
- Scatter into excited states

X-ray Raman reveals the origin of unusual bonding in dense oxygen



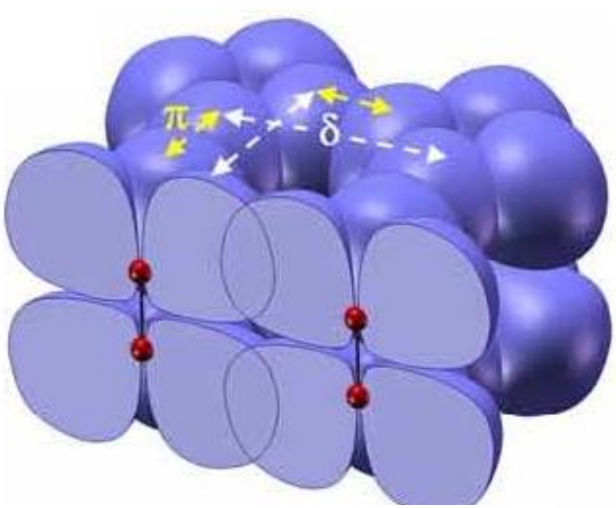
[Meng et al., *PNAS* (2008)]

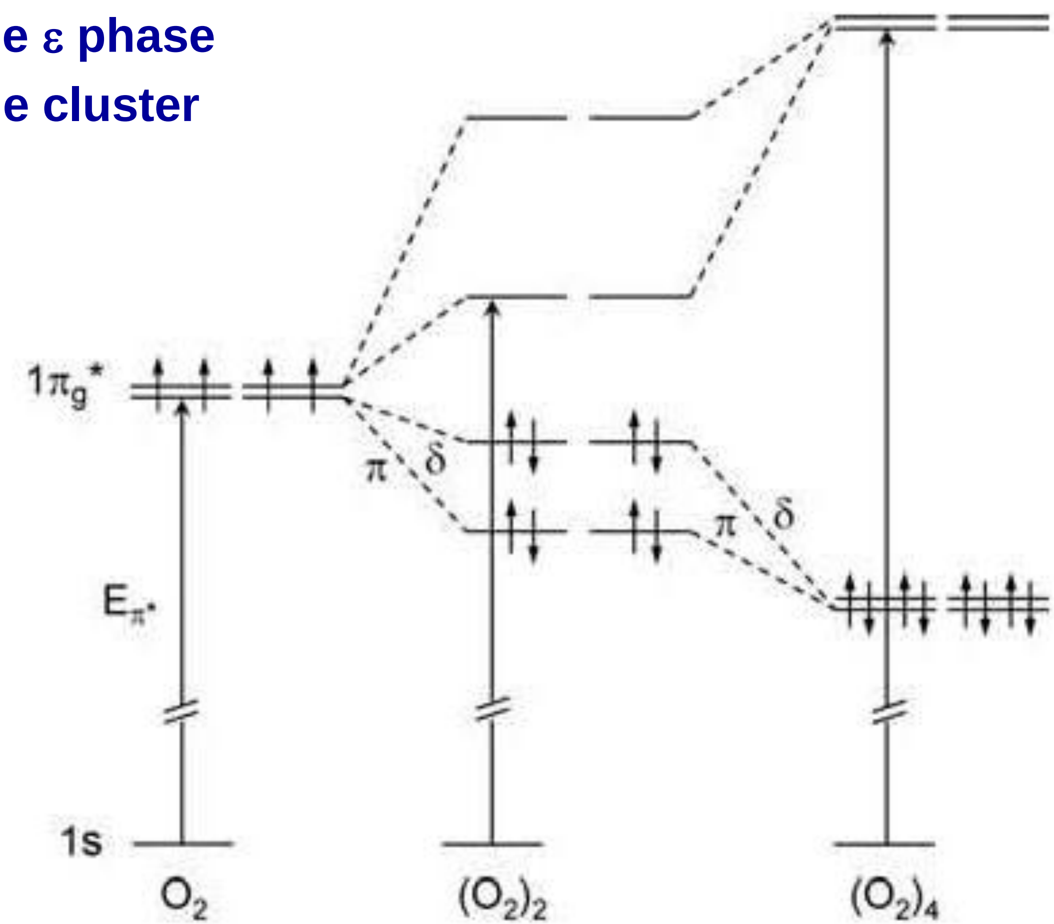


- **Molecules interact through half-filled $1\pi_g^*$ orbital in the low-pressure phases**

X-ray Raman reveals the origin of unusual bonding in dense oxygen

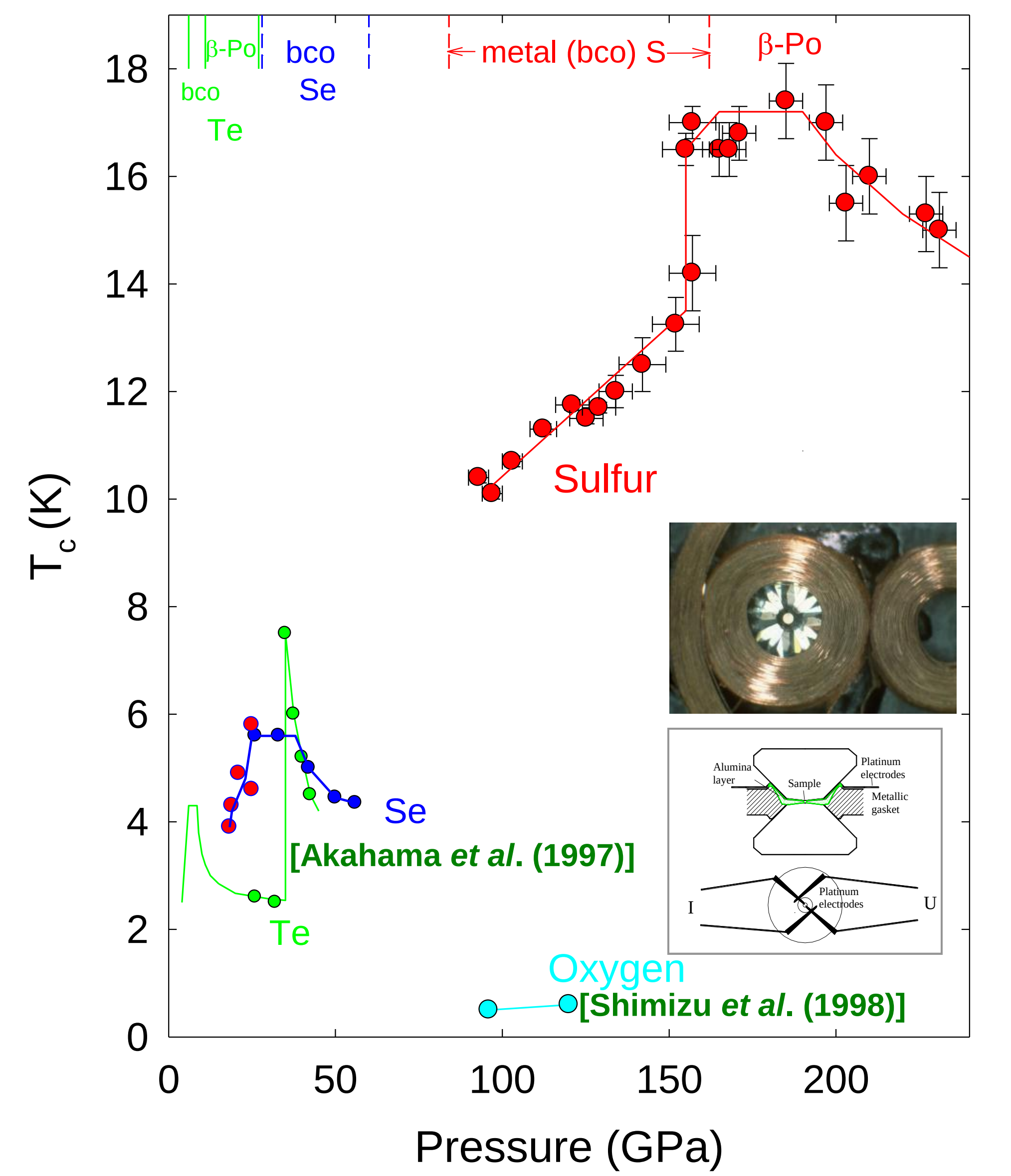
- **Increasing orbital overlap with pressure**
- **Intermolecular π^*-bonding in $(O_2)_4$ cluster**
- **Closed-shell interactions in the ε phase**
- **Stabilization of a four-molecule cluster**



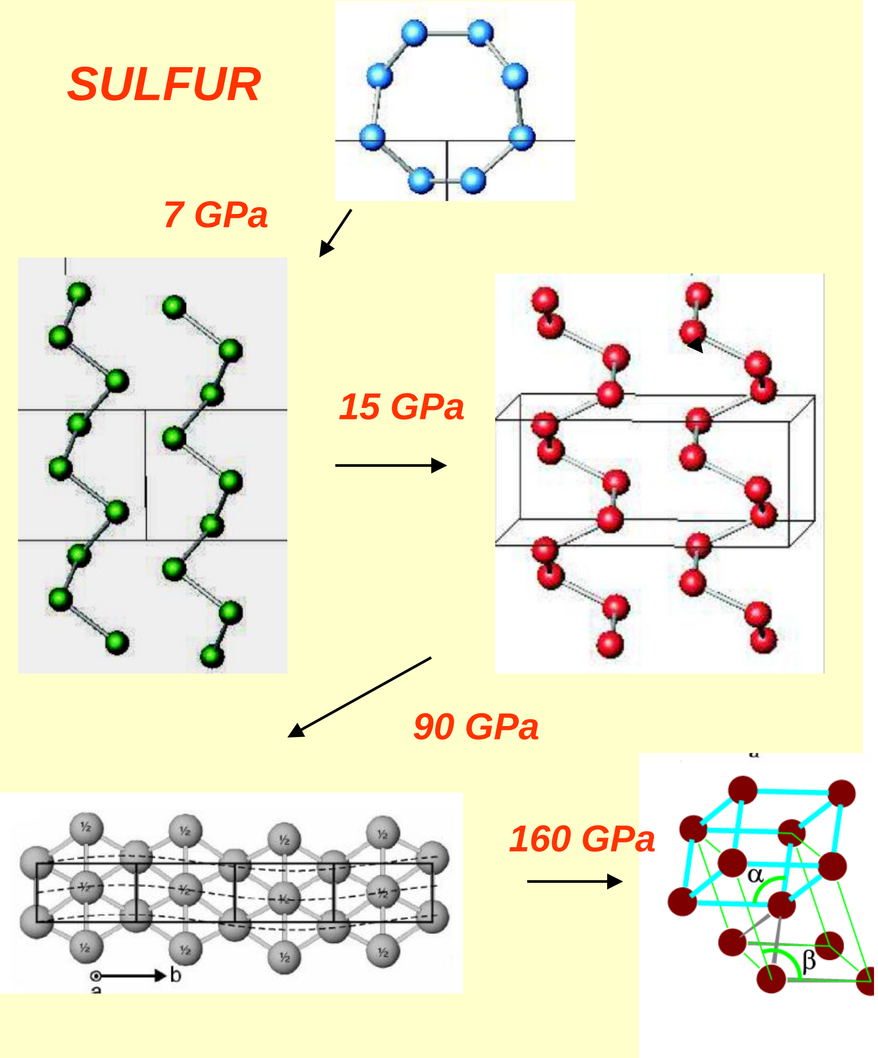


[Meng et al., *PNAS* (2008)]

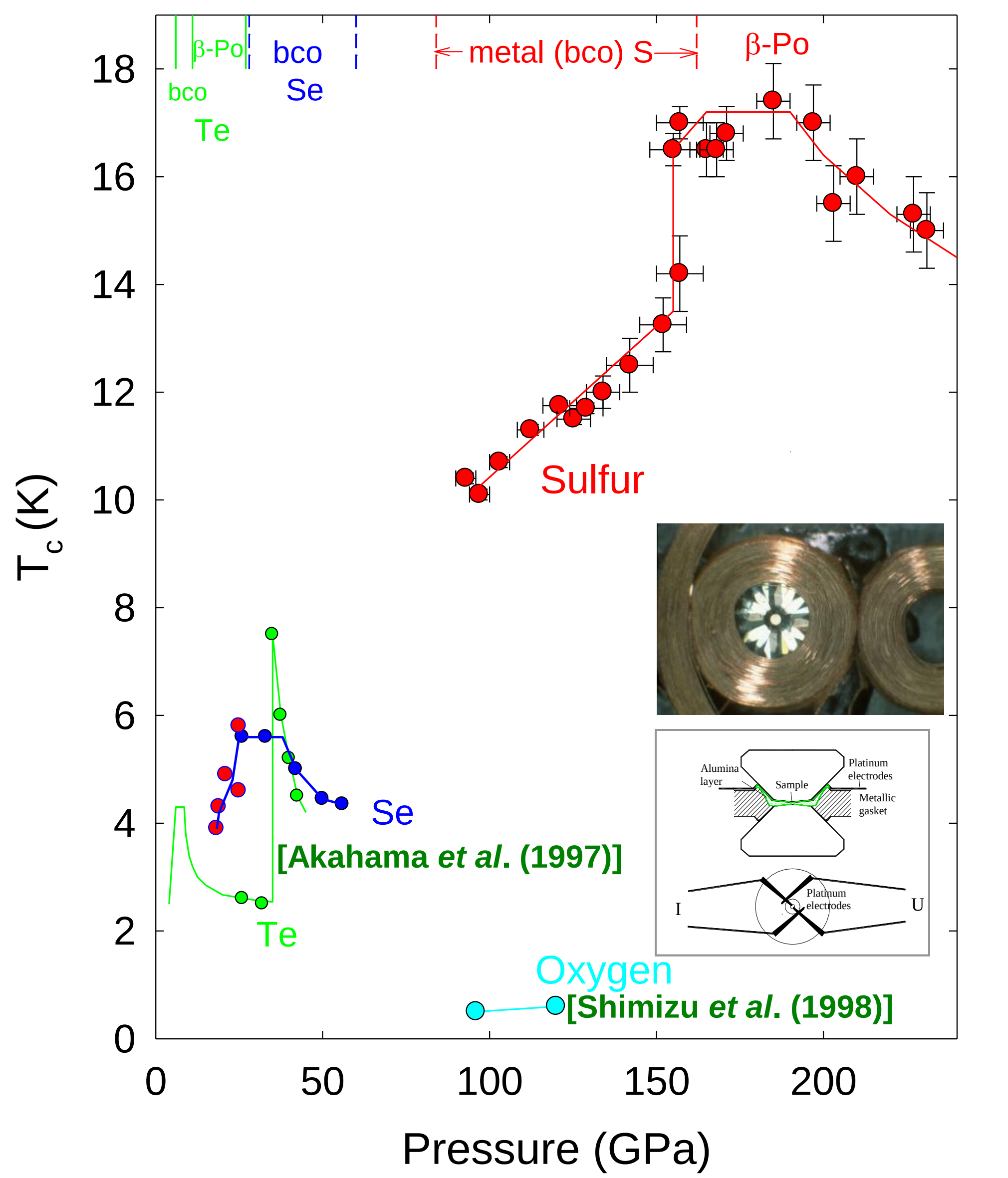
Structures and superconductivity in Group VI elements under pressure



Structures and superconductivity in Group VI elements under pressure



[Degtyareva *et al.*, *Nature Materials*, (2005)]
[Fujihishi *et al.*, *Phys. Rev.* (2004)]

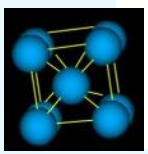


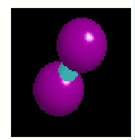
Hydrogen occupies a unique position in the Periodic Table

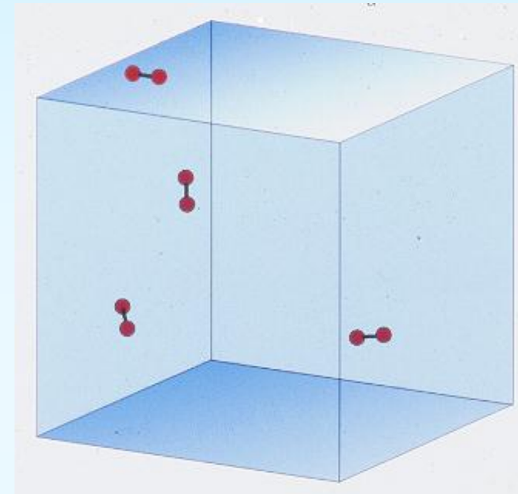
Discovered by Henry Cavendish in 1766

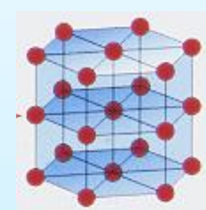
Alkalis *Halogens*

1 H								?								1 H	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Ru	105 Ha	106 Unh	107 Uns	108 Uno	109 Une	110 Unf								
	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu			
	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr			









>25 GPa

DECEMBER, 1935 JOURNAL OF CHEMICAL PHYSICS VOLUME 3

On the Possibility of a Metallic Modification of Hydrogen

E. WIGNER AND H. B. HUNTINGTON, *Princeton University*

(Received October 14, 1935)

Any lattice in which the hydrogen atoms would be translationally identical (Bravais lattice) would have metallic properties. In the present paper the energy of a body-centered lattice of hydrogen is calculated as a function of the lattice constant. This energy is shown to assume its minimum value for a lattice constant which corresponds to a density many times higher than that of the ordinary, molecular lattice of solid hydrogen. This minimum—though negative—is much higher than that of the molecular form. The body-centered modification of hydrogen cannot be obtained with the present pressures, nor can the other simple metallic lattices. The chances are better, perhaps, for intermediate, layer-like lattices.

Later predictions indicated even more exotic behavior of hydrogen at high density

• ***Superconductivity***

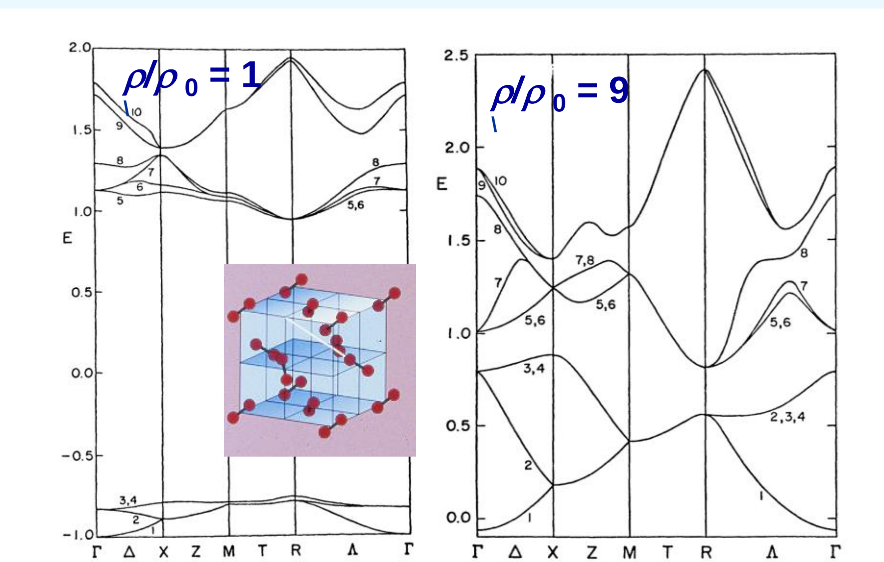
VOLUME 21, NUMBER 26 PHYSICAL REVIEW LETTERS 23 DECEMBER 1968

METALLIC HYDROGEN: A HIGH-TEMPERATURE SUPERCONDUCTOR?

N. W. Ashcroft
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850
(Received 3 May 1968)

Application of the BCS theory to the proposed metallic modification of hydrogen suggests that it will be a high-temperature superconductor. This prediction has interesting astrophysical consequences, as well as implications for the possible development of a superconductor for use at elevated temperatures.

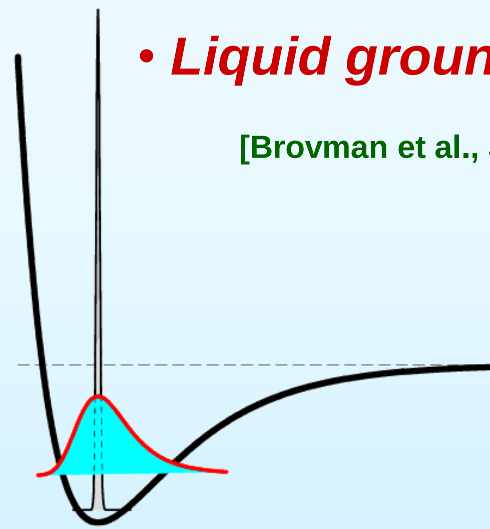
• ***Band overlap***



[Friedli & Ashcroft, *Phys. Rev. B* (1977);
[Ramaker et al., *Phys. Rev. Lett*. (1975)]

• ***Liquid ground state***

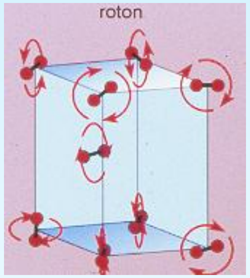
[Brovman et al., *JETP* (1974)]



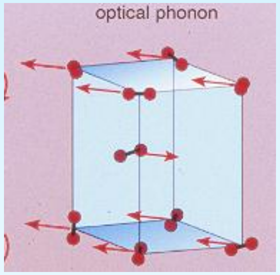
Fully quantum mechanical system: 'The Element of Uncertainty'

Vibrational spectroscopy has been an important probe of the high-pressure behavior of hydrogen

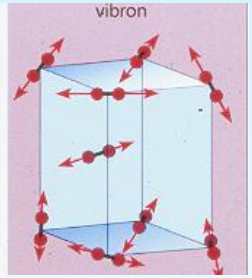
Rotons



Lattice Modes



Vibrons



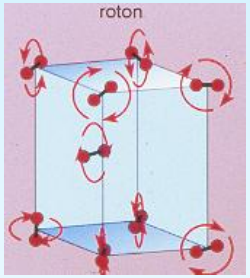
$S_0(J)$ $Q_{\Delta v}(J)$; *e.g.*, $Q_1(1)$

PRESSURE EFFECTS

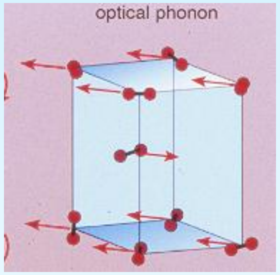
- **Rotational ordering**
- **Molecular stability**
- **Molecular interactions**

Vibrational spectroscopy has been an important probe of the high-pressure behavior of hydrogen

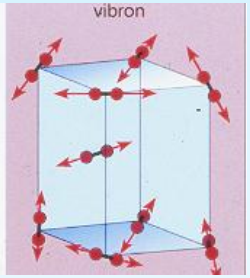
Rotons



Lattice Modes



Vibrons



$S_0(J)$ $Q_{\Delta v}(J)$; e.g., $Q_1(1)$

PRESSURE EFFECTS

- Rotational ordering
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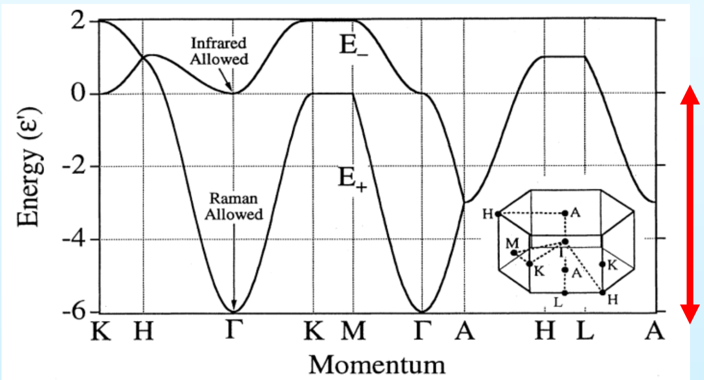


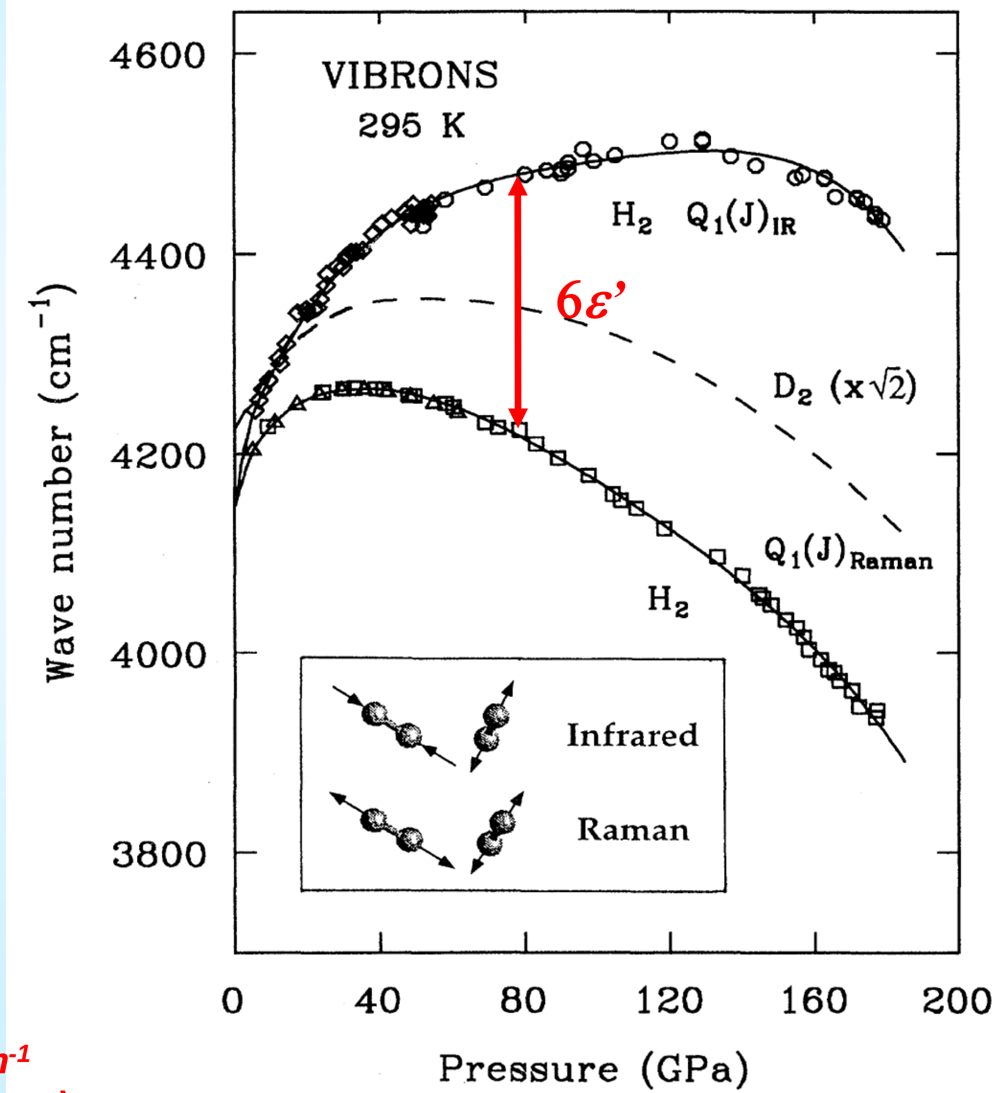
$6\varepsilon'$

$$H_{JK} = \sum_m W'_m \, |m\rangle\langle m| - \frac{1}{2} \sum_{m,n \neq m} \epsilon'_{m,n} \, |m\rangle\langle n|$$

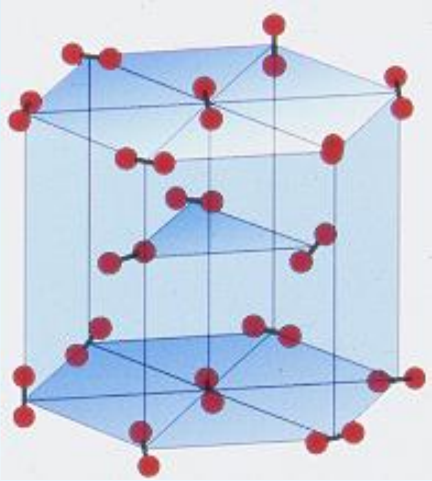
On-site term

Coupling ~ $1/r^6$

$6\varepsilon' = 3$ cm^{-1} (zero pressure)



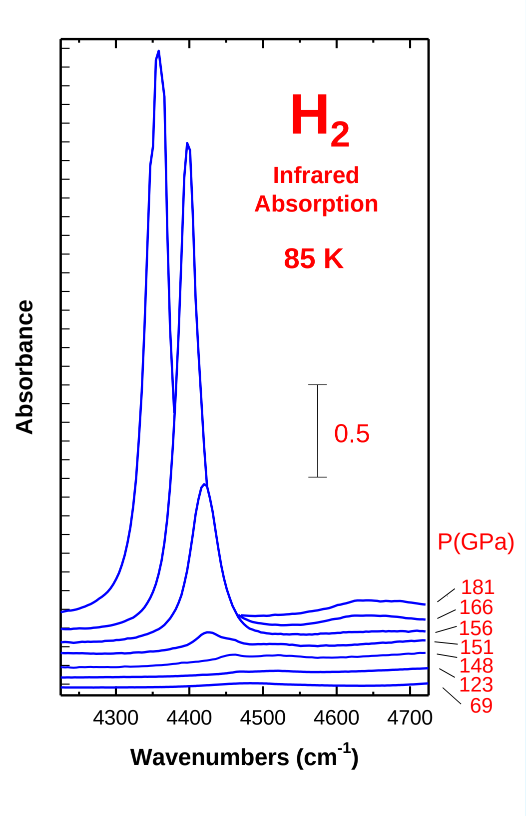
Solid hydrogen at megabar pressures

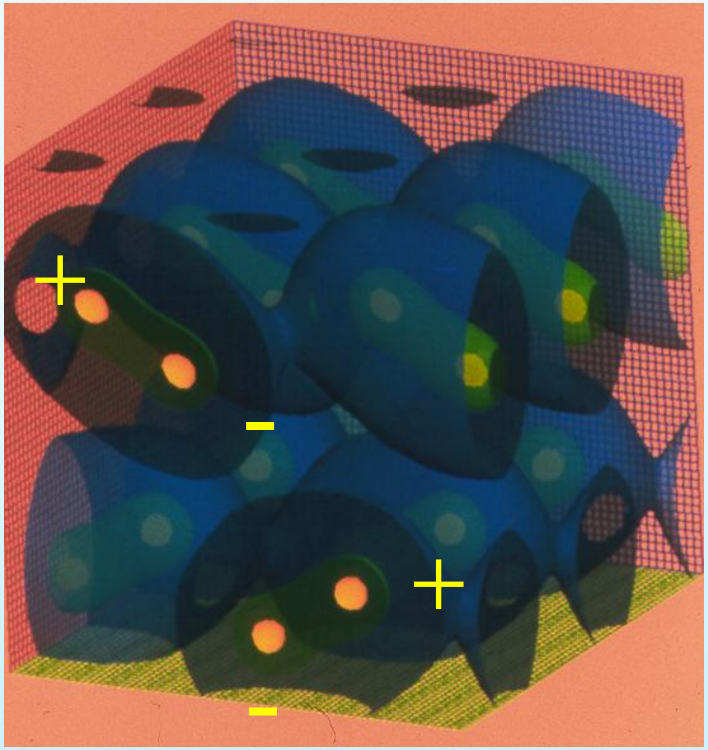


[Glazkov *et al., JETP Lett*. (1988); Mao *et al., Science* (1988); Loubeyre *et al . Nature* (1996)]

High Pressure Structure (Phase I)

- Molecules stable to ~300 GPa in solid
- ρ/ρ_0 ~ 14 at 300 GPa from x-ray eos

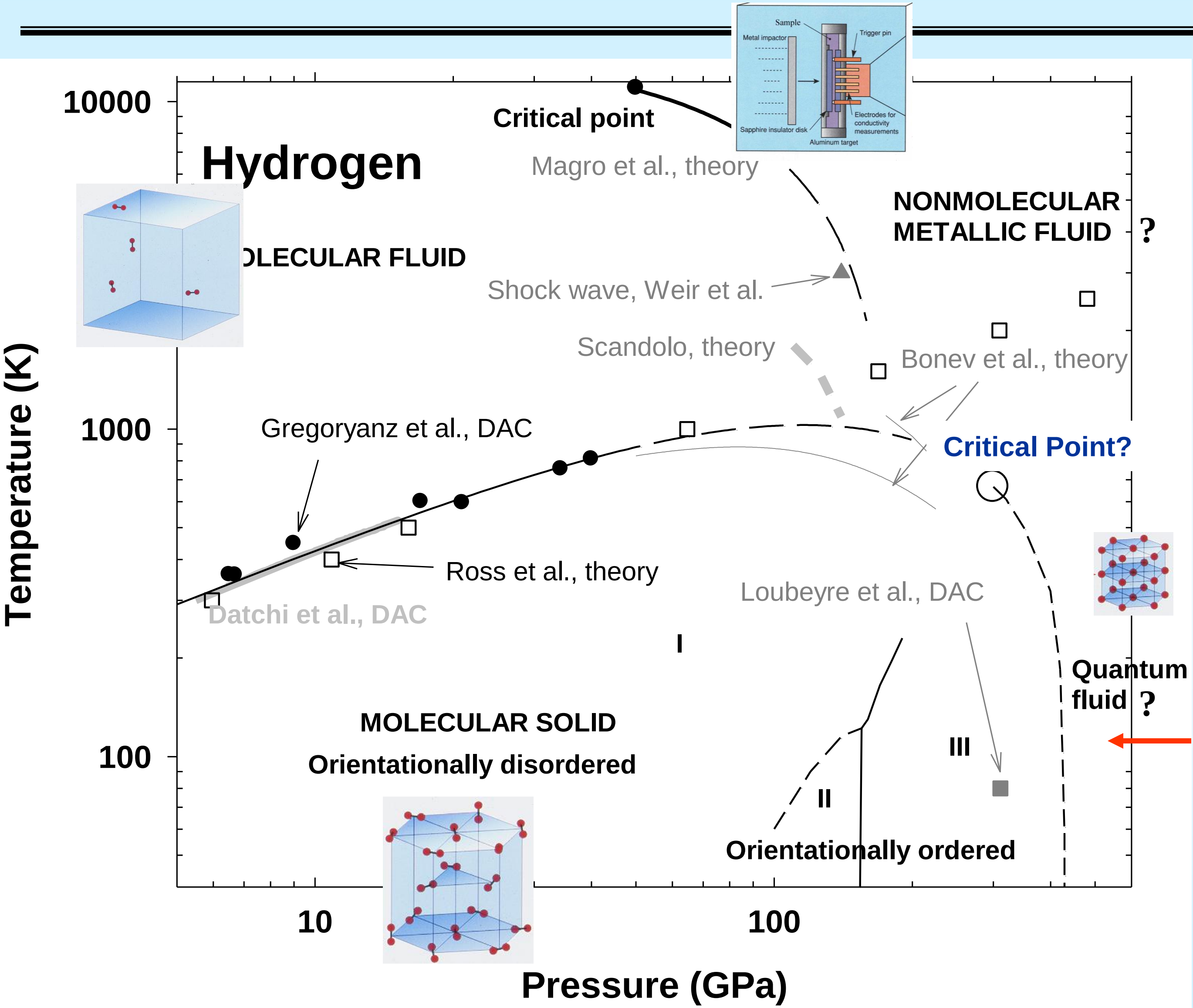


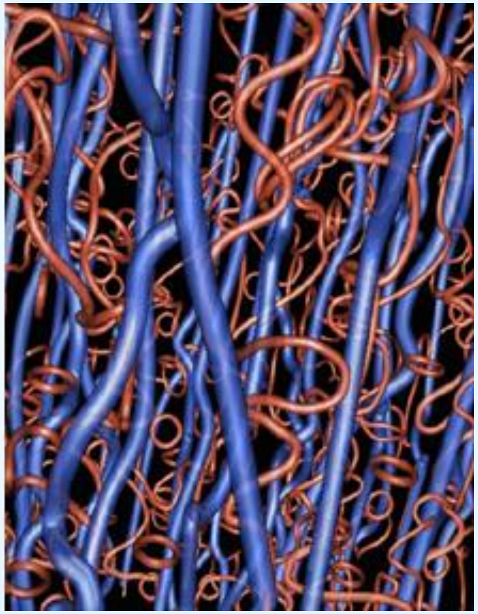


"Ionic" charge-transfer state forms at 150 GPa; stable to >300 GPa

[Hemley *et al. Nature* (1994); Goncharov et al. *Proc. Nat. Acad. Sci.* (2002); Loubeyre et al., *Nature* (2002)]

Phase diagram of dense hydrogen



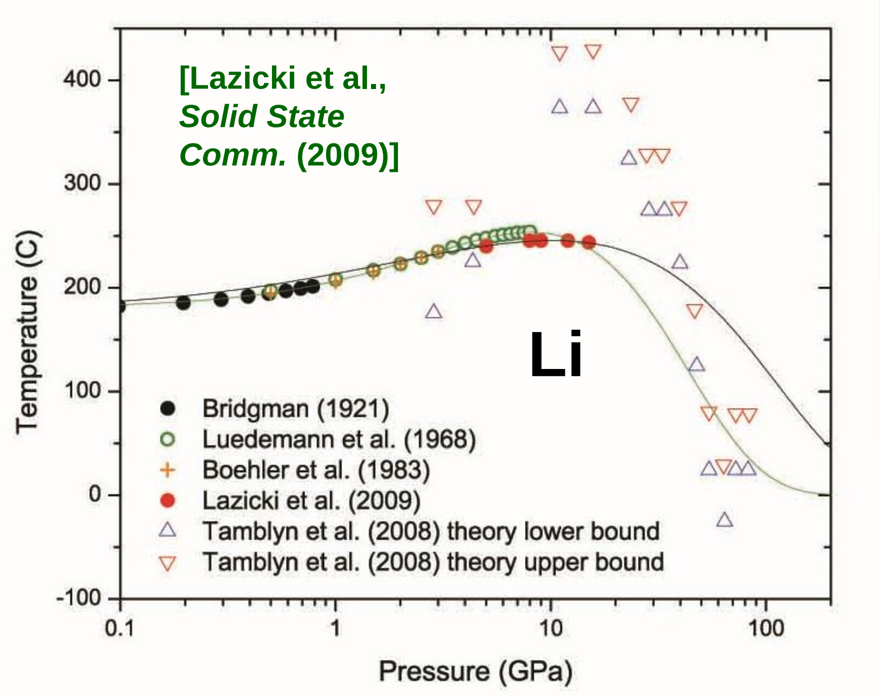


Combined superfluidity and superconductivity >400 GPa predicted

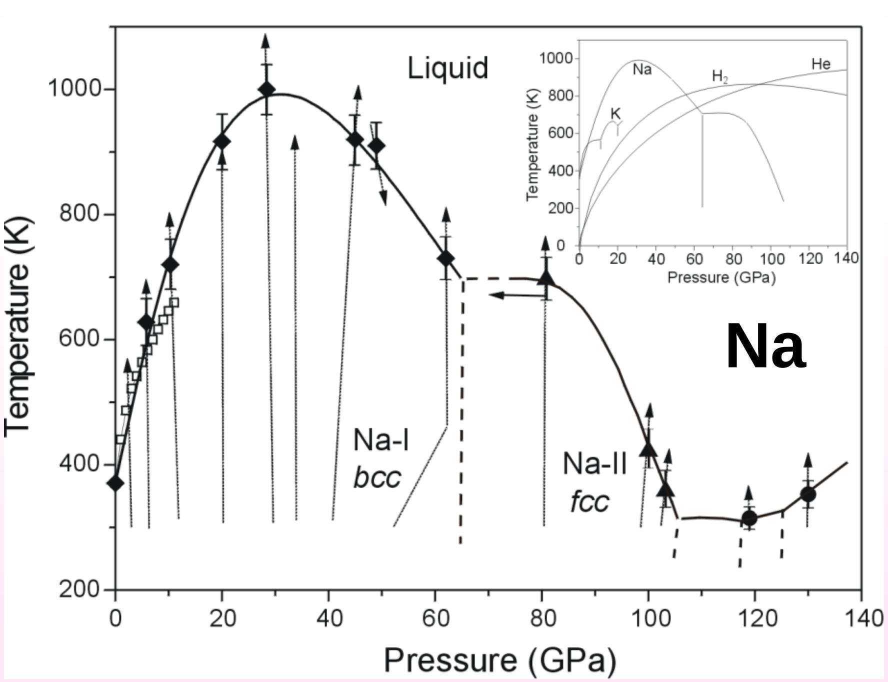
[Goncharov and Crowhurst, *Phase Transitions* (2007)]

[Babaev et al., *Phys. Rev. Lett.* (2005)]

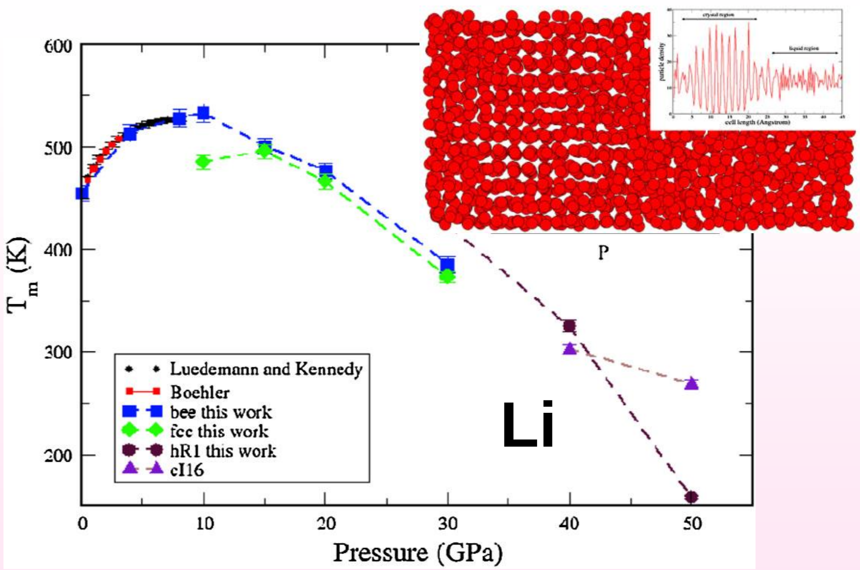
Alkali metals at megabar pressures



[Lazicki et al., *Solid State Comm.* (2009)]

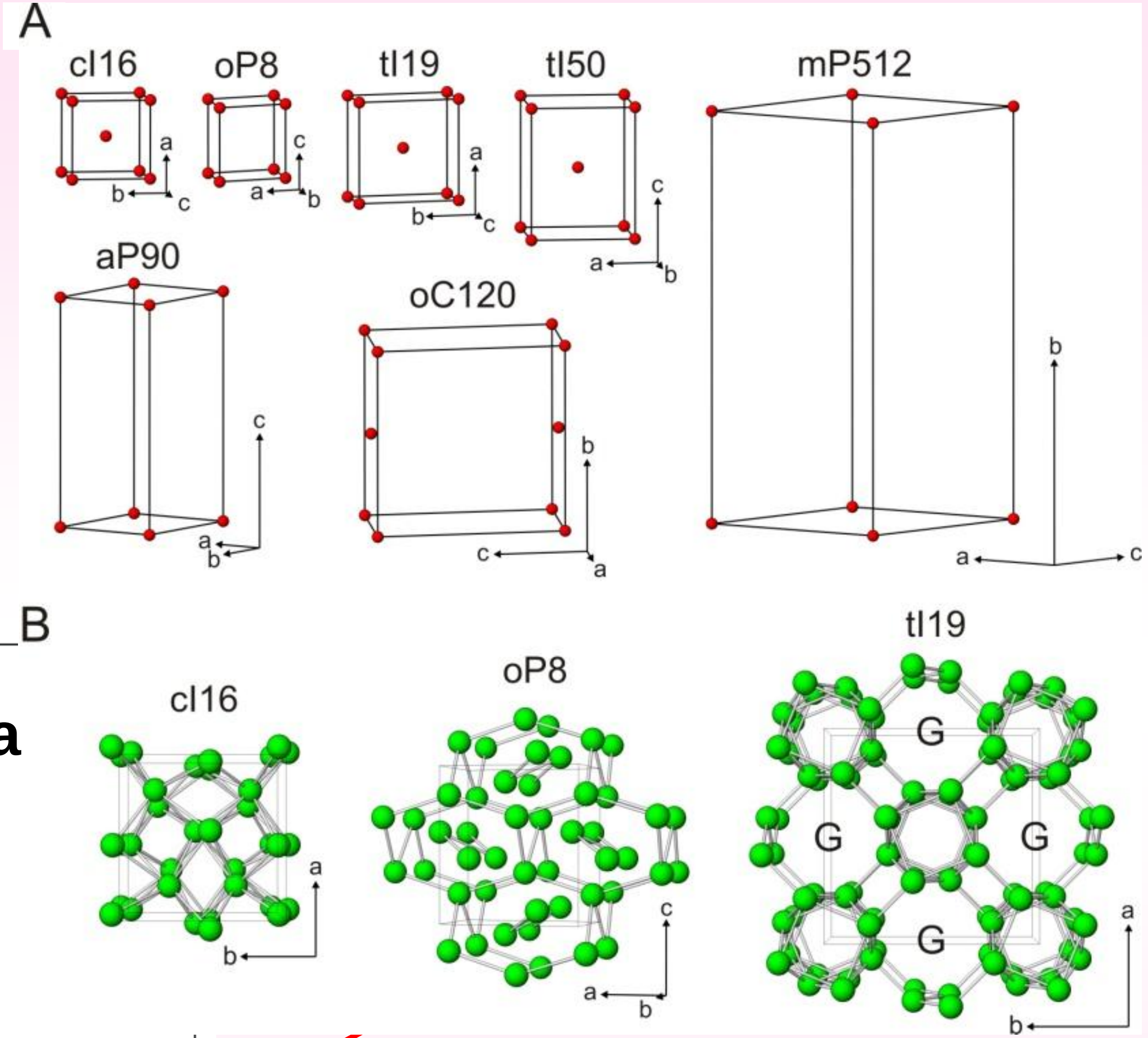


[Gregoryanz et al., *Phys. Rev. Lett.* (2005)]

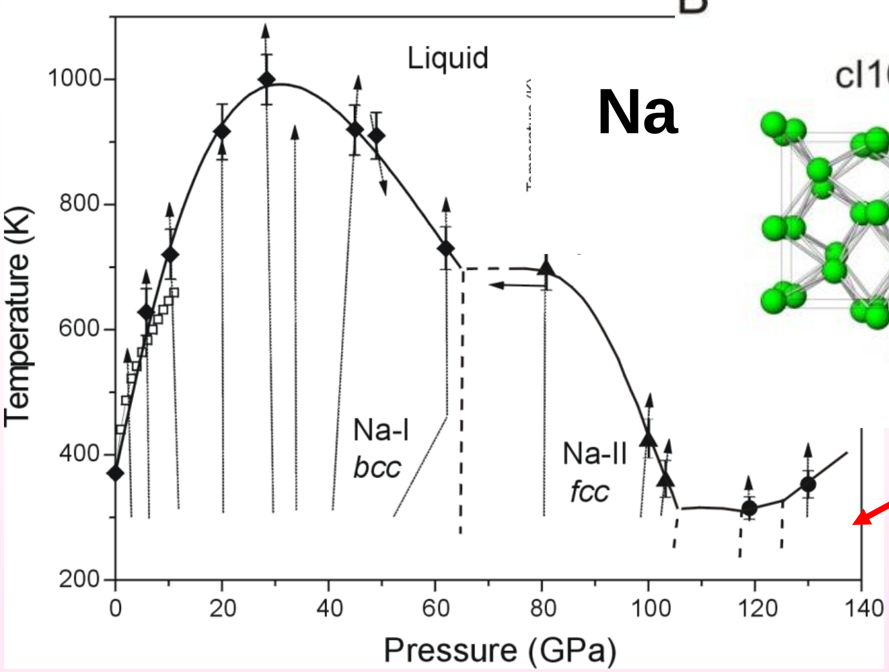


[Hernandez et al., *Phys. Rev. Lett.* (2010)]

Alkali metals at megabar pressures

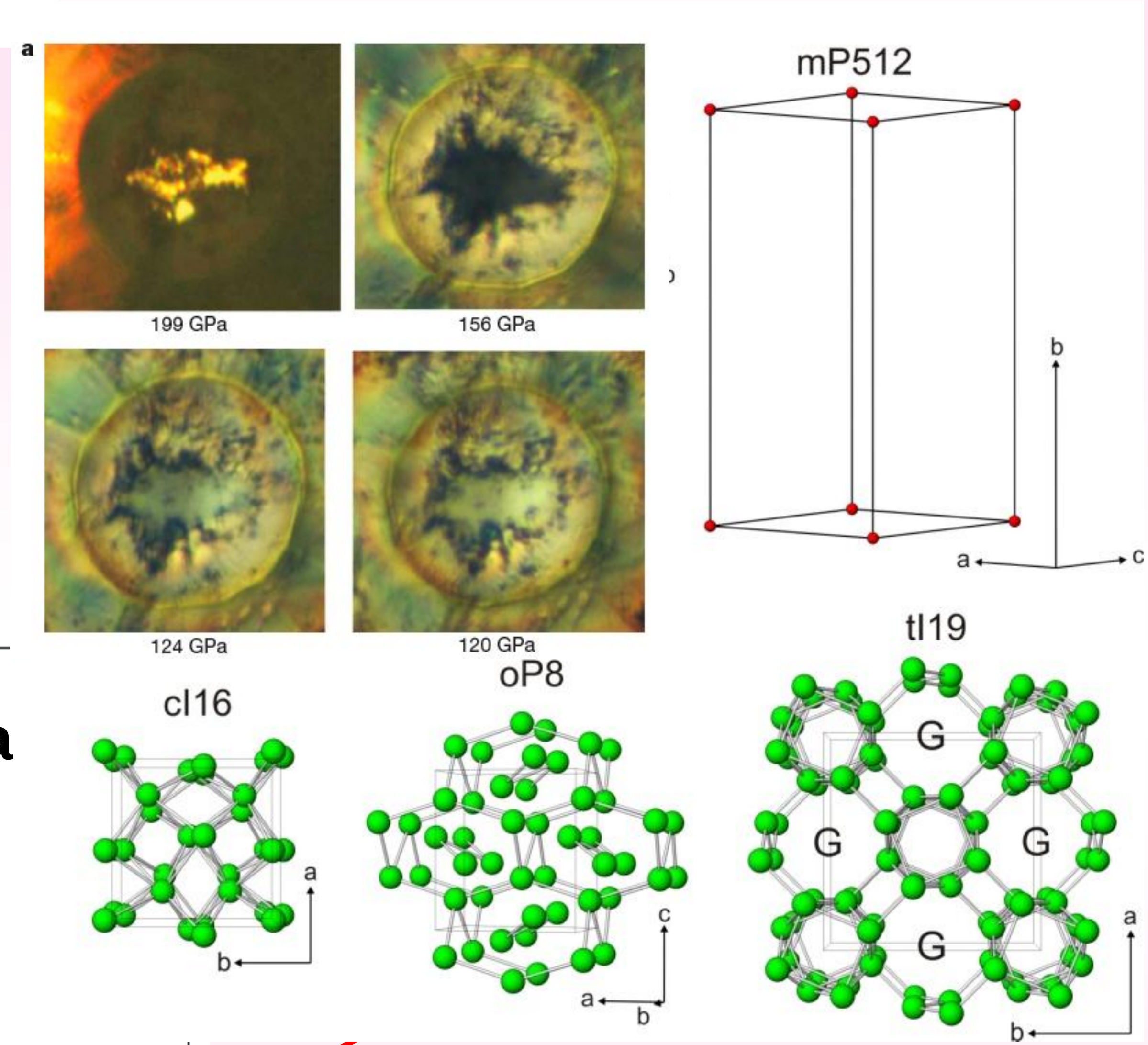


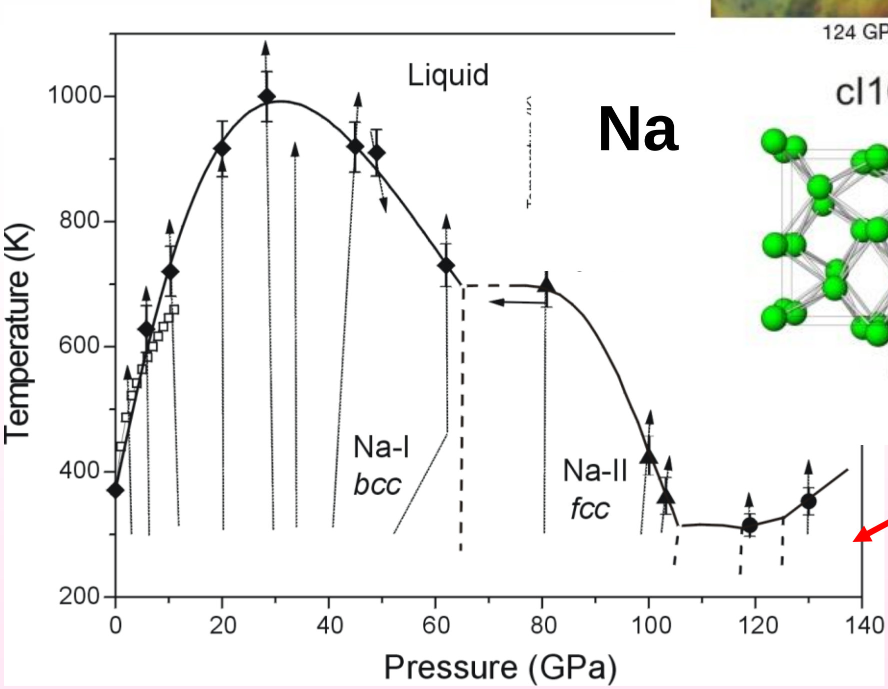
[Gregoryanz et al., *Science* (2008)]



[Gregoryanz et al., *Phys. Rev. Lett.* (2005)]

Alkali metals at megabar pressures



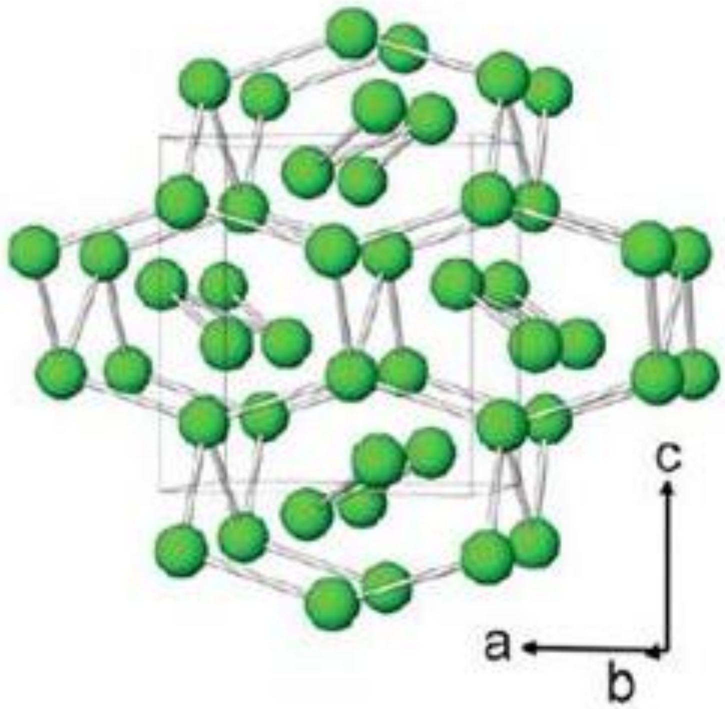


[Gregoryanz et al., *Phys. Rev. Lett.* (2005)]

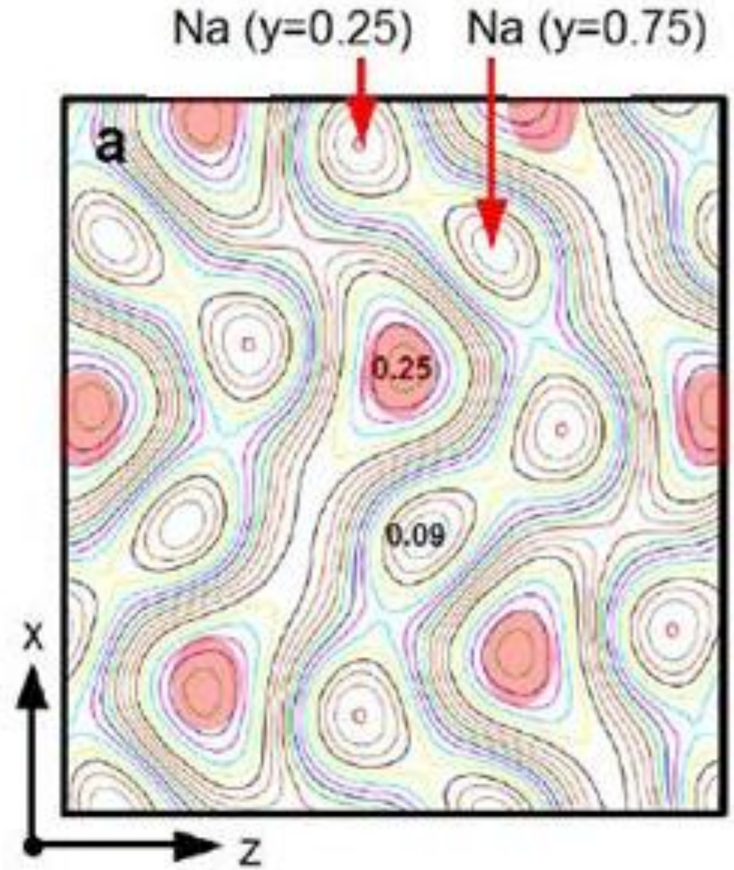
[Ma et al., *Nature* (2009);]

fcc - cI16 - tI19 - hP4 (transparent)
METAL TO INSULATOR TRANSITION!

Origin of the phenomena: *interstitial charge densities*



[Lazicki et al., *PNAS* (2009);
see also, Ma et al., *Nature* (2009)]



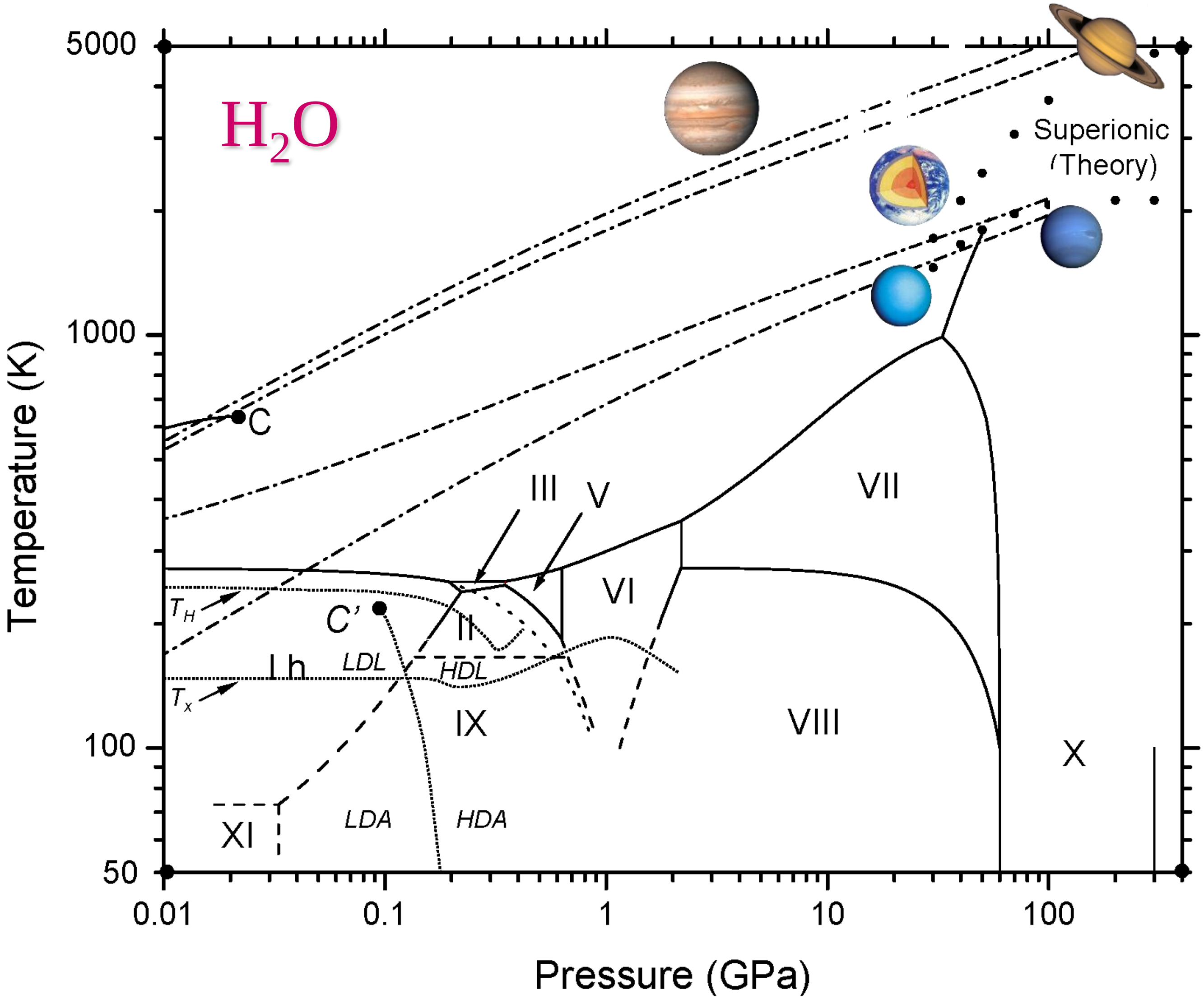
"Dimerized" and insulating Li

[Neaton & Ashcroft, *Nature* (2002)]

- ***Altogether new bonding type***
- ***"Re-entrant" molecular solid***
- ***Other systems?***

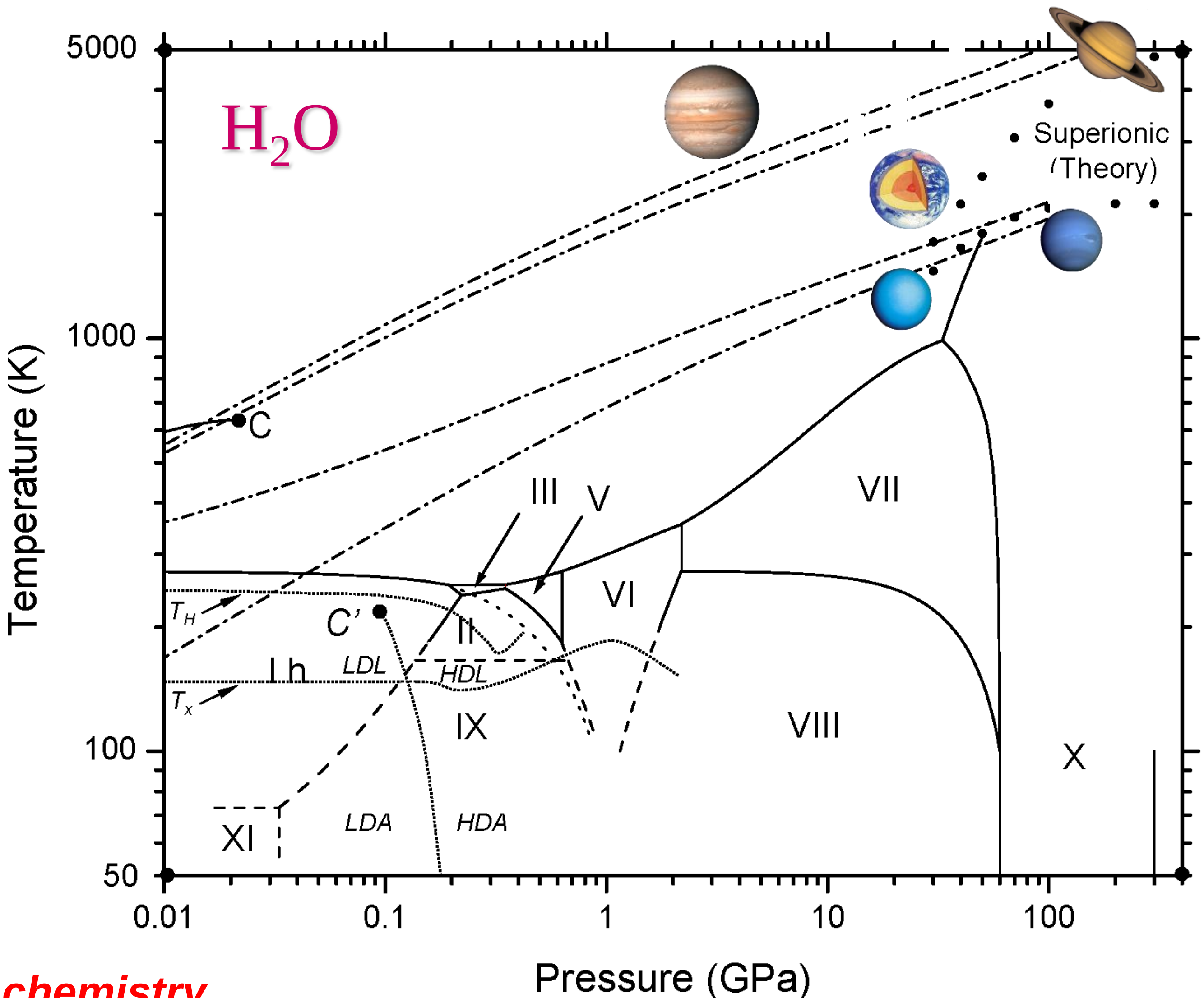
The high-pressure behavior of water continues to present new questions and surprises

The high-pressure behavior of water continues to present new questions and surprises



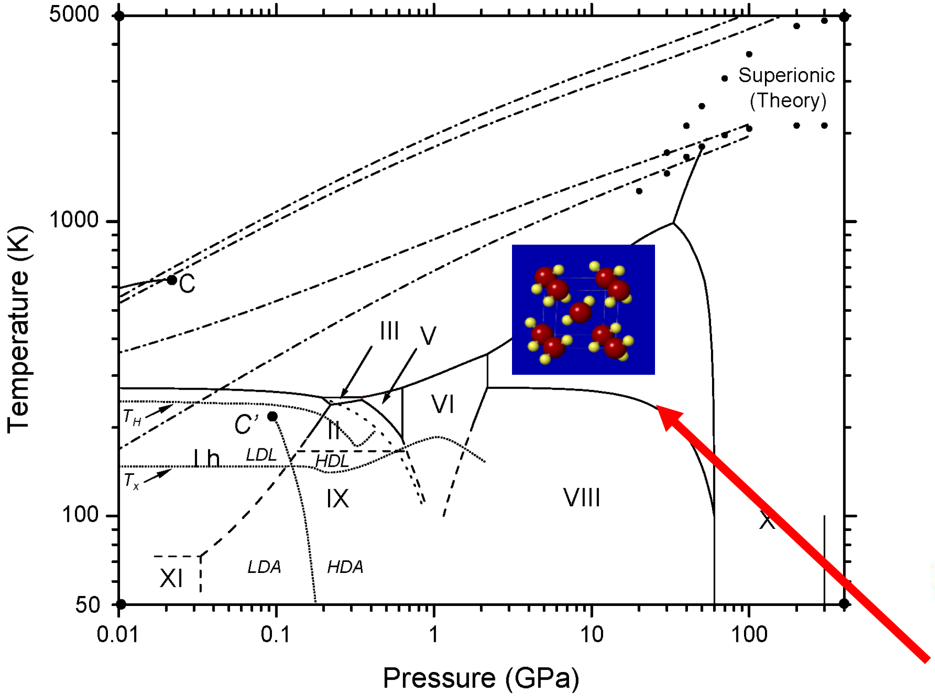
The high-pressure behavior of water continues to present new questions and surprises

- ~20 stable and metastable phases
- Novel transitions
  - non-molecular
  - amorphization
  - liquid/liquid trans
- Nature of the hydrogen bond



➢ ***Radiation-induced chemistry***
➢ ***Higher pressure behavior***

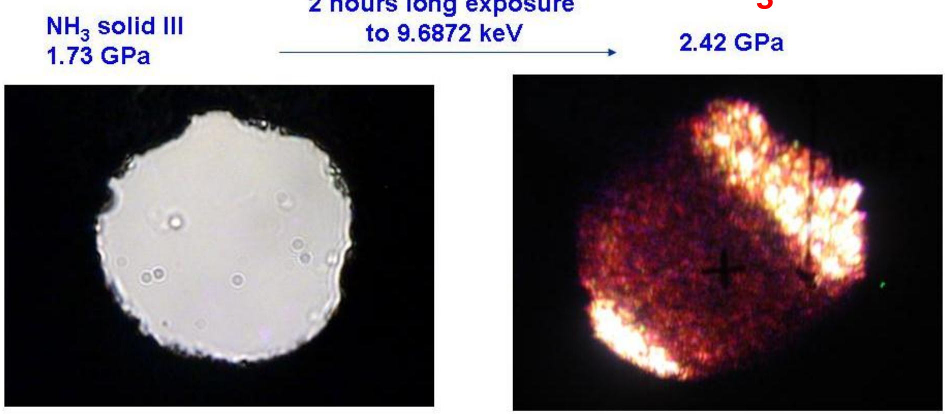
Radiation-induced chemistry under pressure



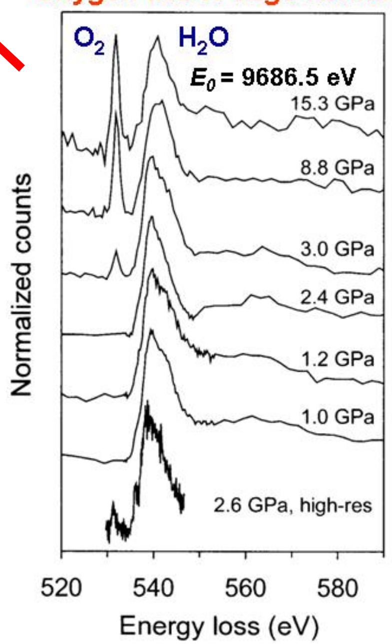
- **Molecular alloy of H_2-O_2**
- **High-pressure van der Waals compound**
- **Metastable energetic material**

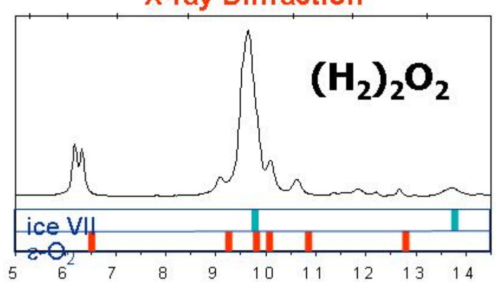
➢ ***High density excited-state chemistry***

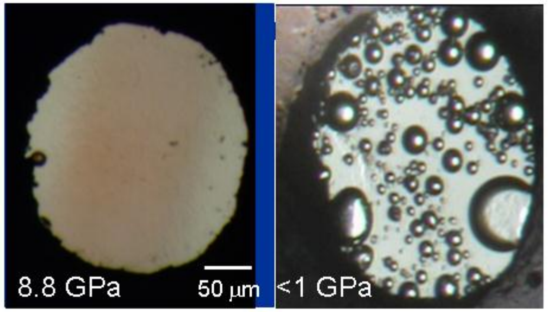
Similar breakdown of NH_3



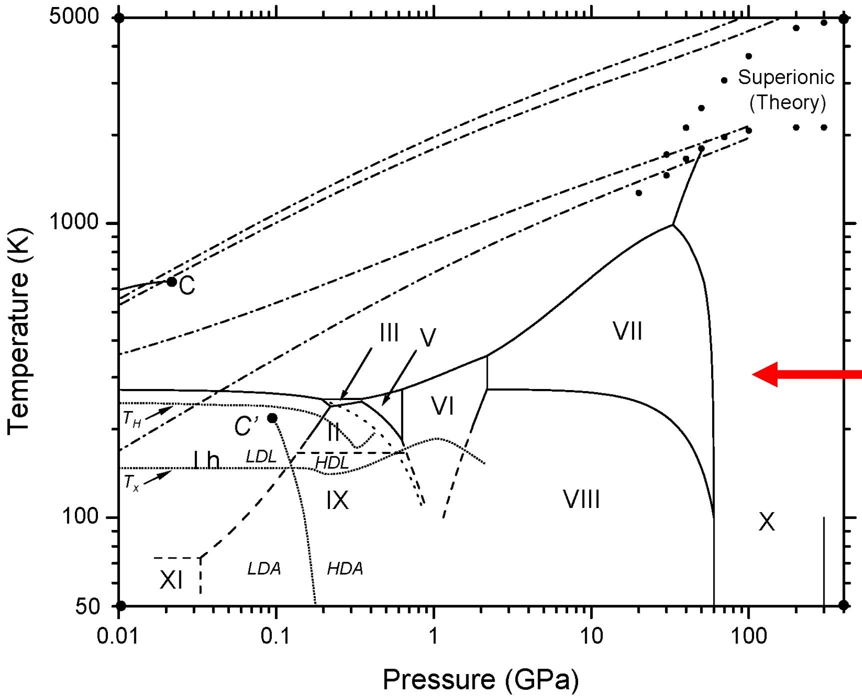
[W. Mao *et al*., *Science* (2006)]

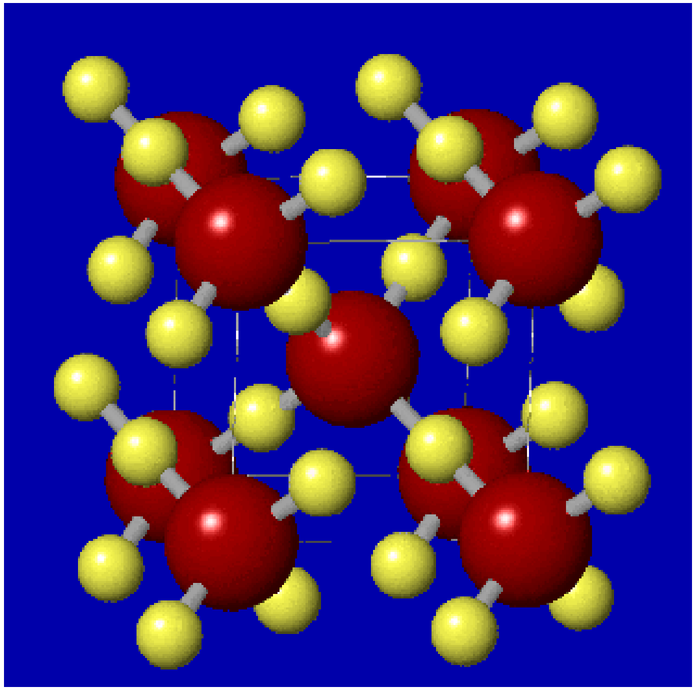






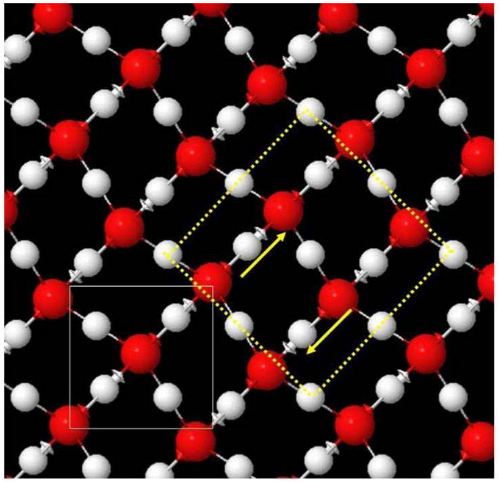
H_2O at multimegabar pressures





- Non-molecular ice X
- Ionic solid

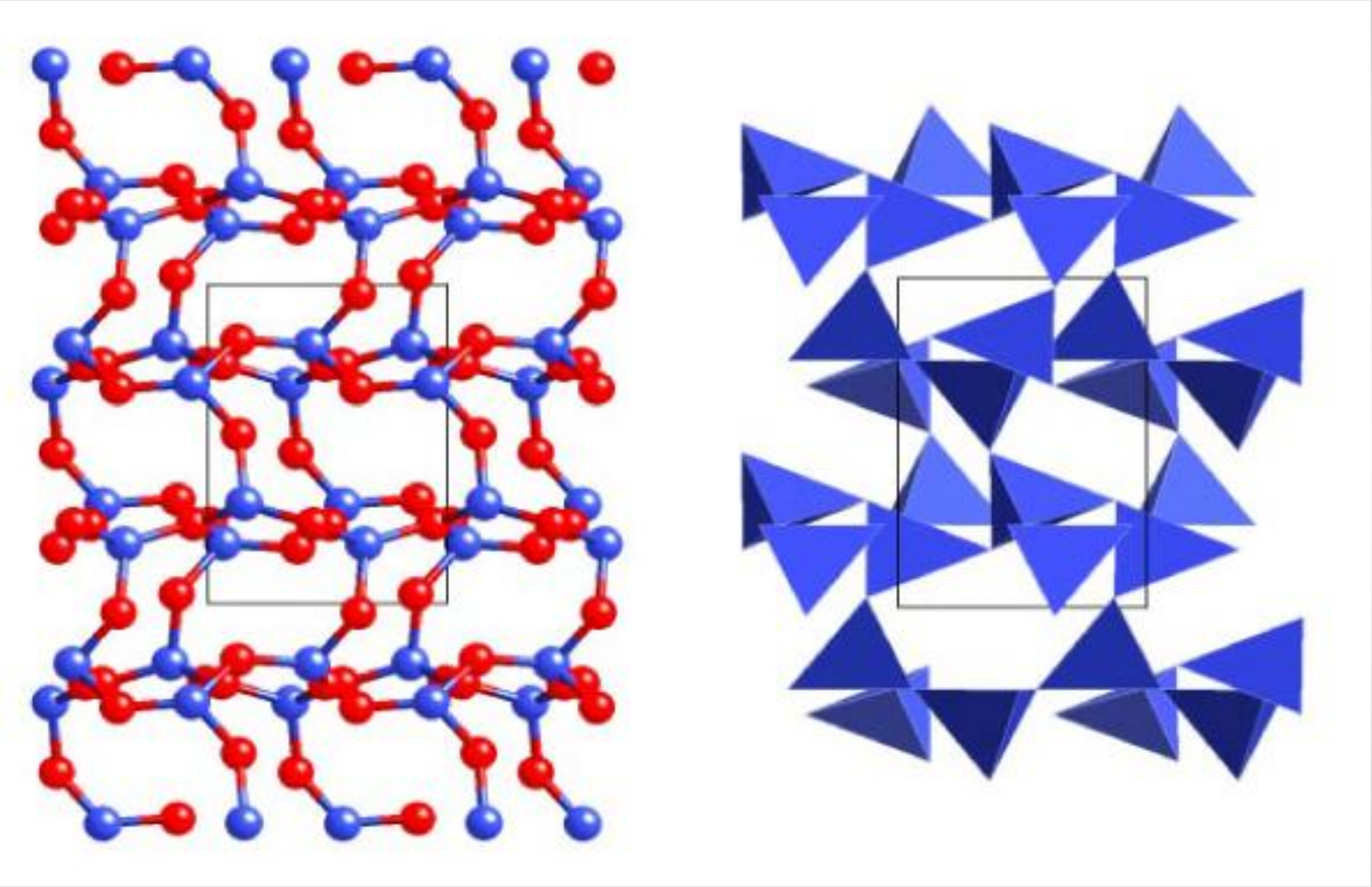
[Goncharov *et al., Science* (1996);
suggested by Kamb & Davis, *PNAS* (1964)]



- Post-ice X at 400 GPa predicted
- M-point phonon instability (ice X)

[Caracas, *Phys. Rev. Lett.* (2008)]

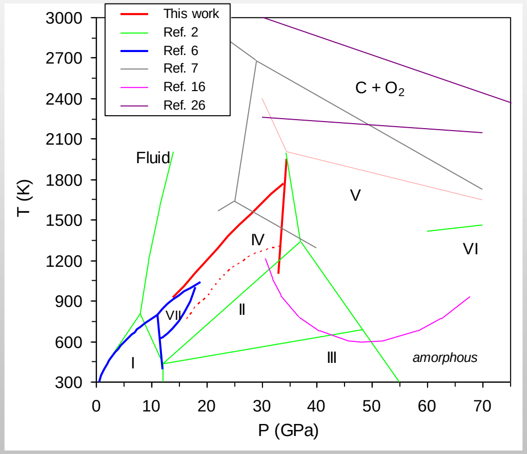
Novel high *P-T* transformations of CO_2



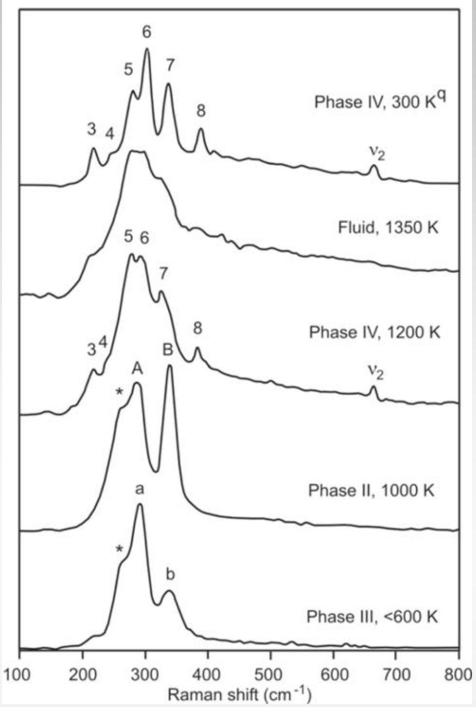
[Iota et al ., *Science* (1999);
Lipp et al., *Nature Mat.* (2005)].

- **CO_2 behaves like SiO_2 in lower mantle**
- **Phase diagram?**

High P-T CO_2 melting and dissociation

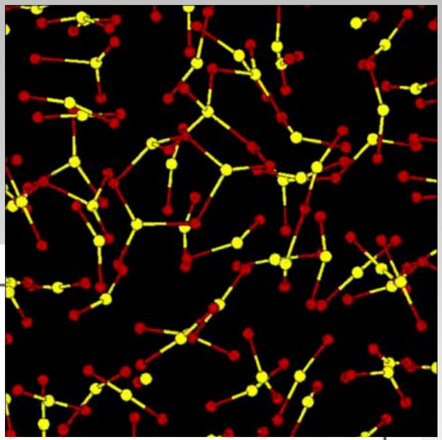


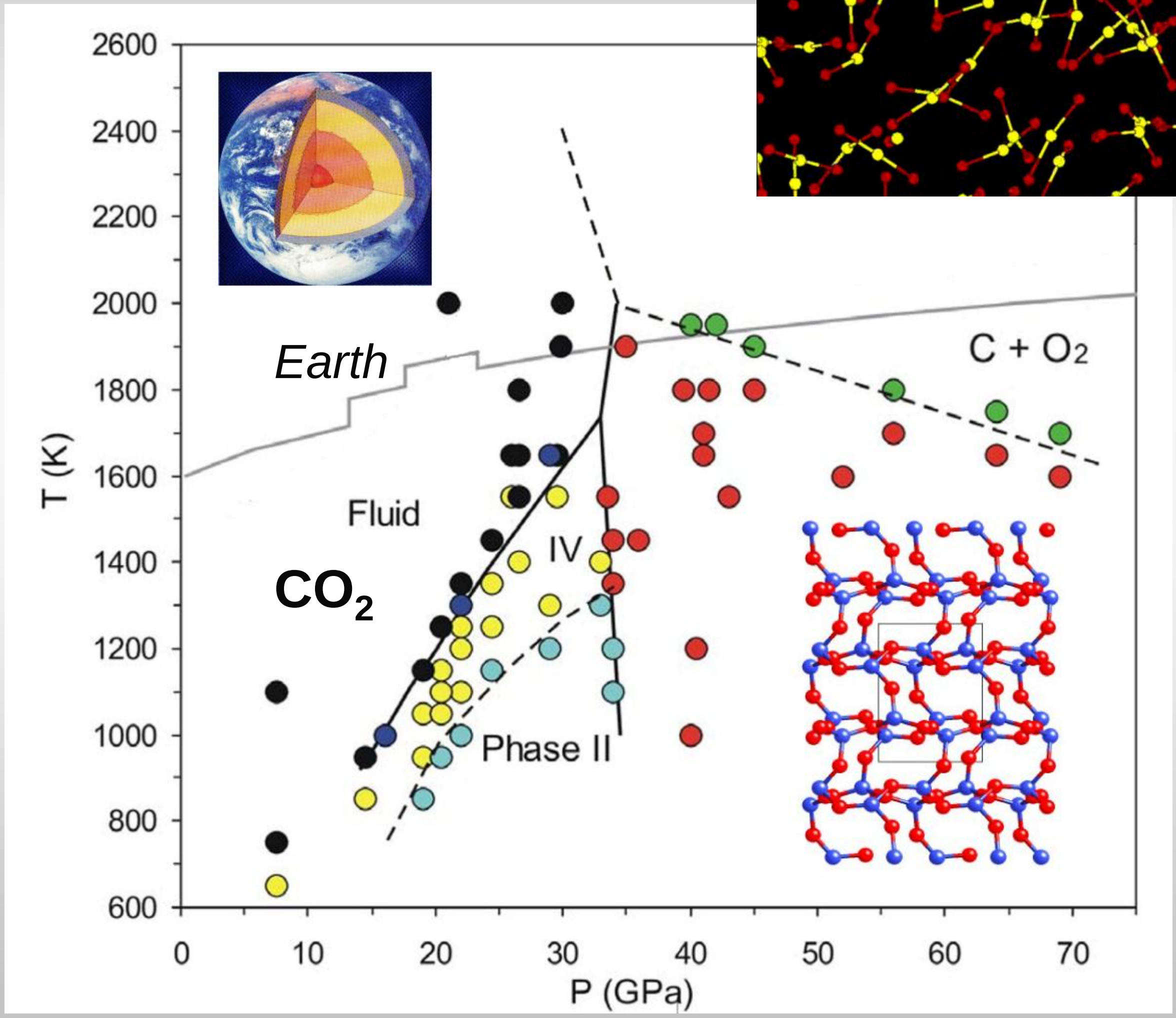
High P-T CO_2 melting and dissociation

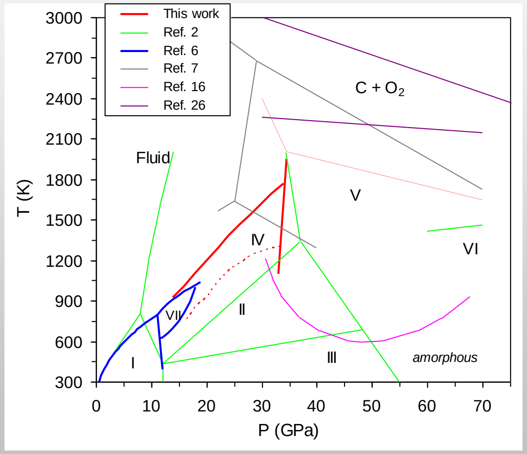


THEORY

[Montoya et al., *submitted*]



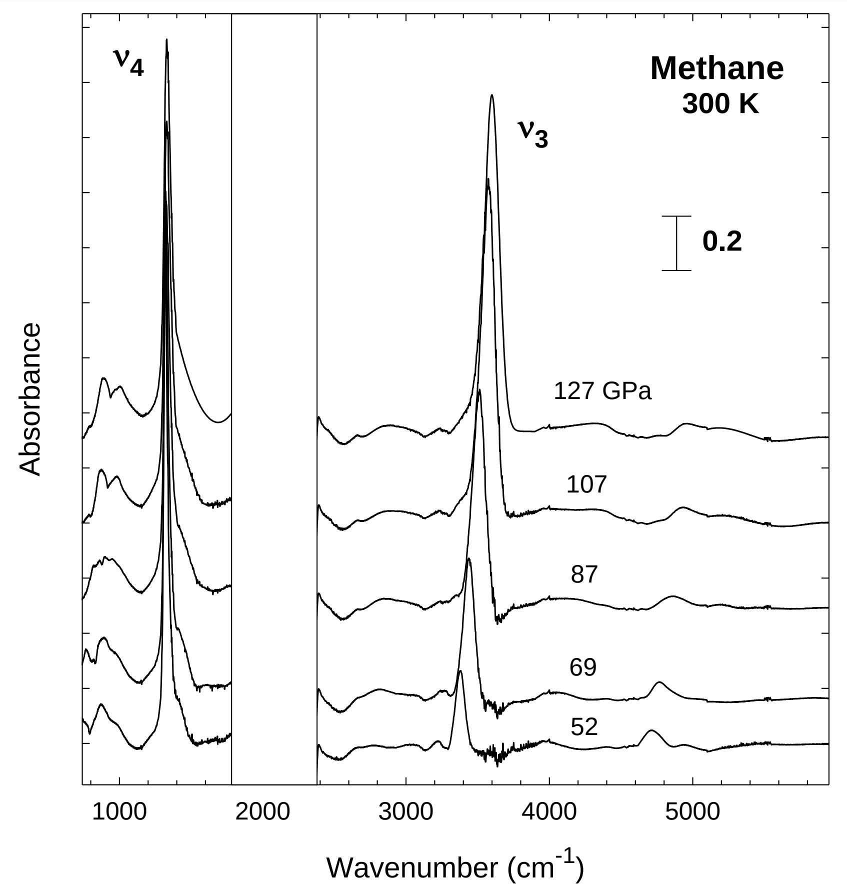




[Litasov et al., *submitted*]

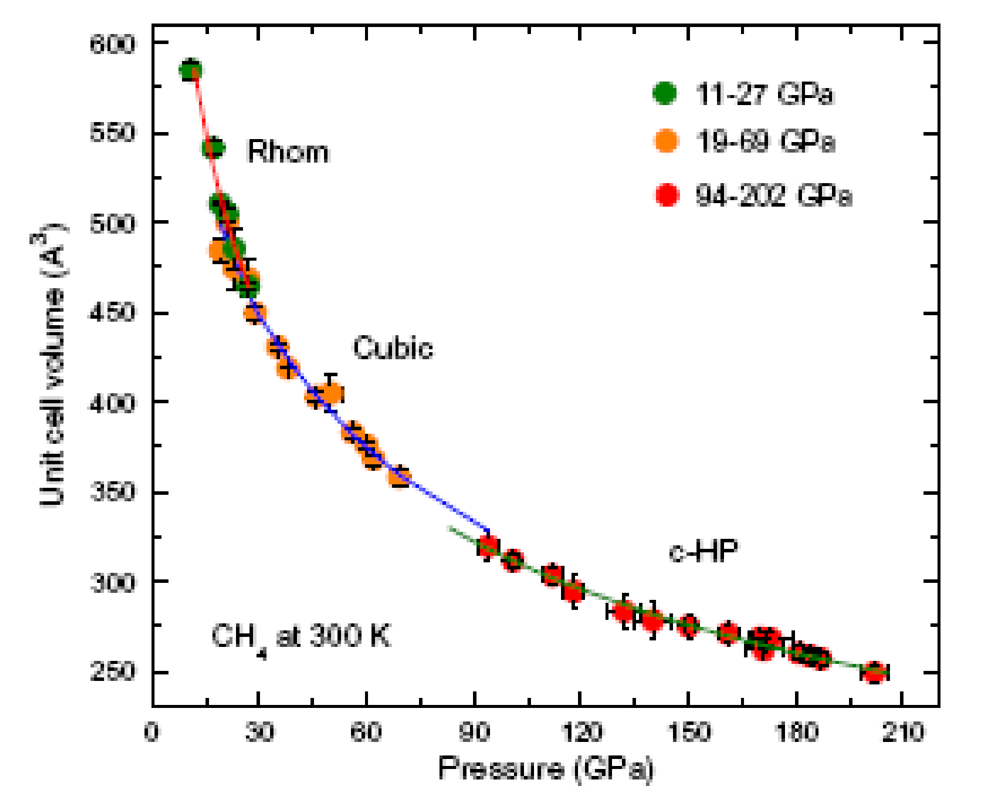
Methane is stable to megabar pressures at 300 K

Infrared



[Badro *et al., to be published*]

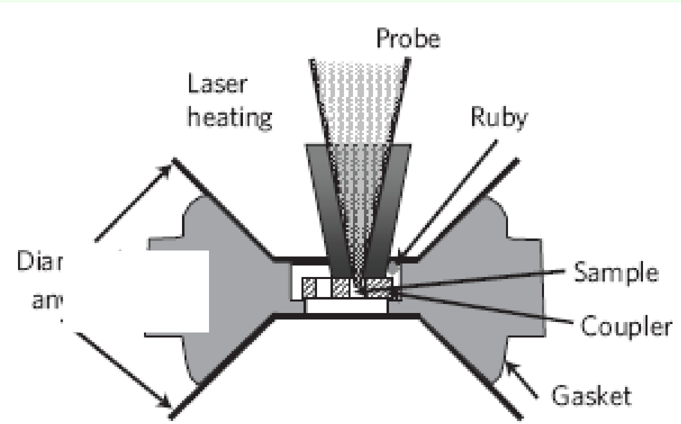
X-ray

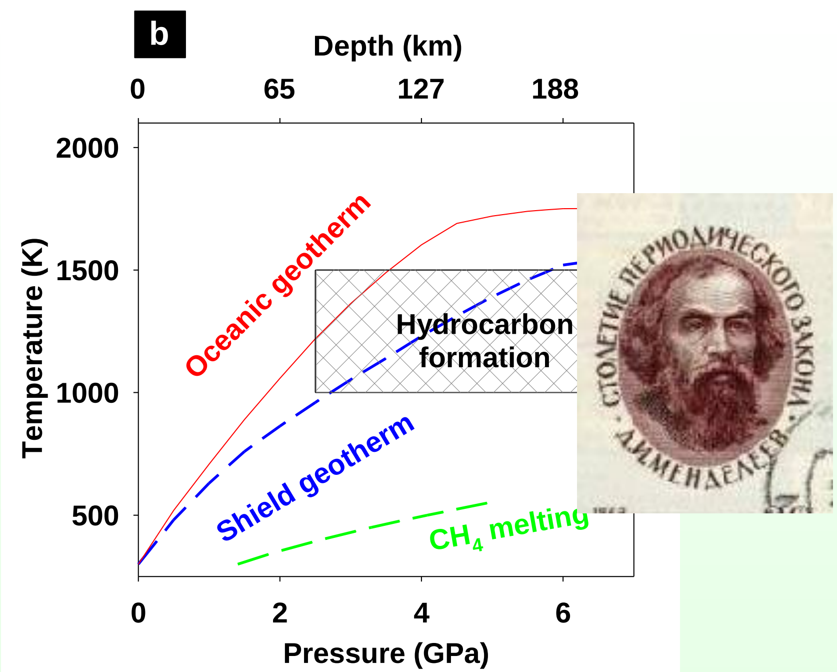


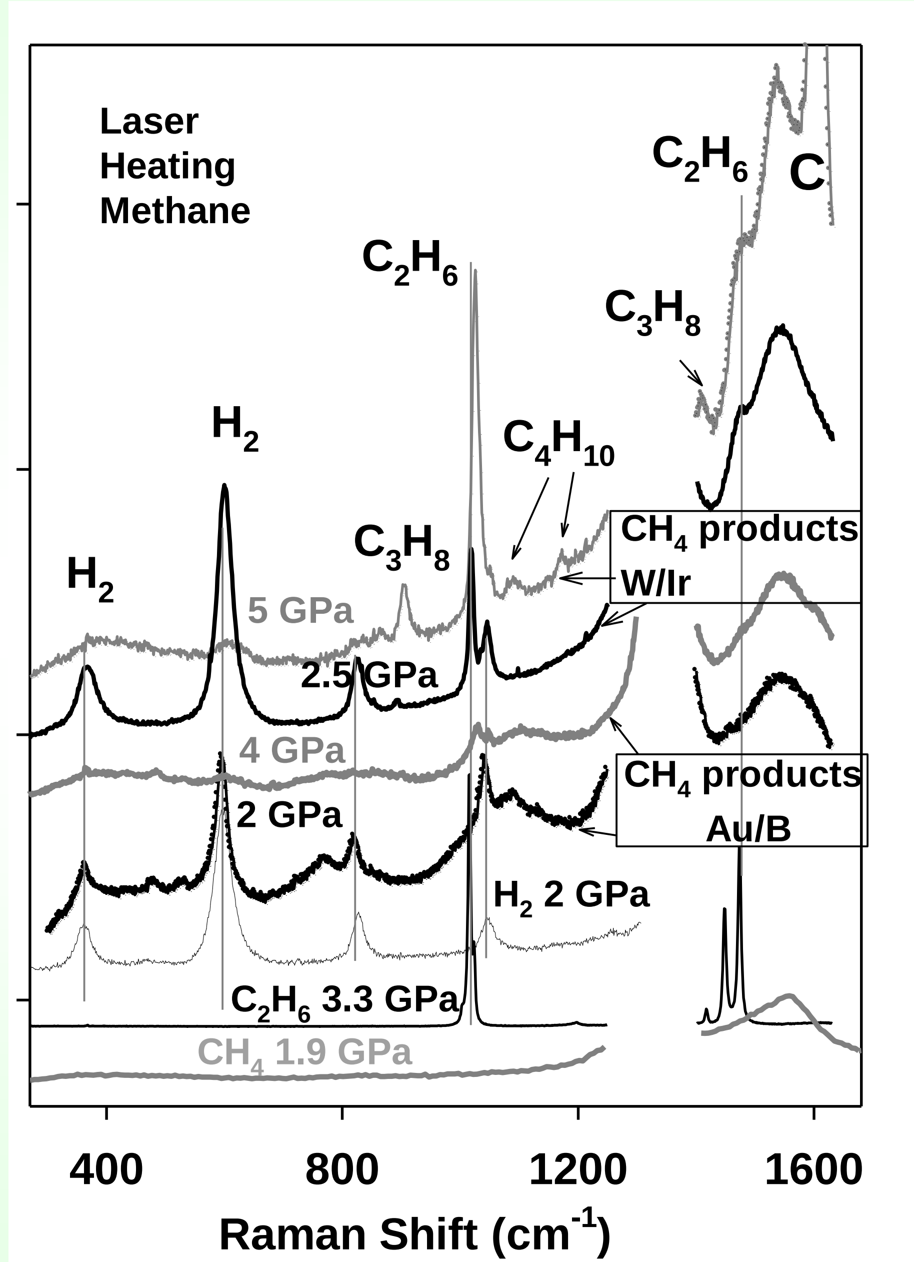
[Sun *et al., Chem. Phys. Lett.* (2009)]

- ***Large metastability***
- ***Remains insulating***
- ***Equilibrium phases?***

Higher hydrocarbons are produced from laser heating pressurized methane







[Kolesnikov *et al.*, *Nature Geoscience* (2009)]

Metallization of Group IVA molecular hydrides?

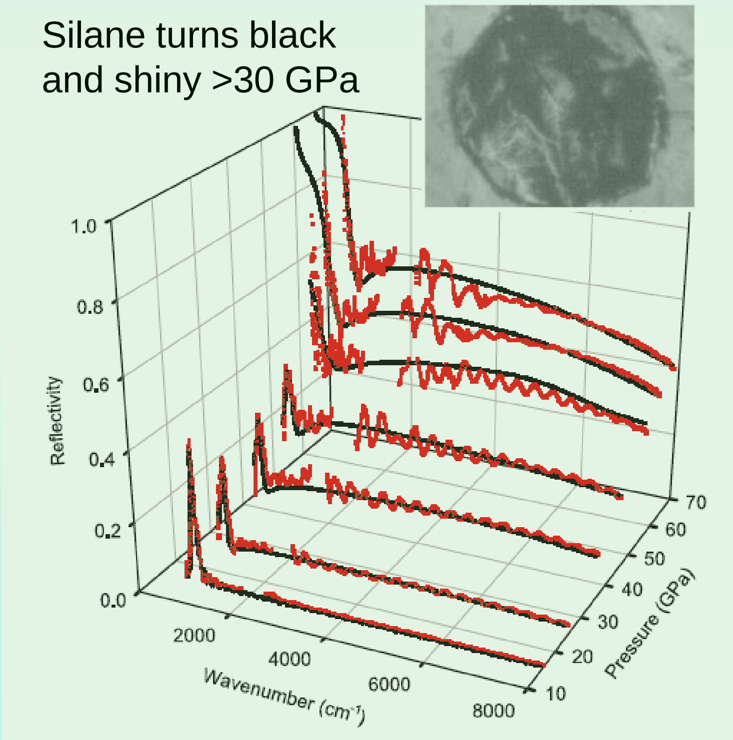
VOLUME 92, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 7 MAY 2004

Hydrogen Dominant Metallic Alloys: High Temperature Superconductors?

N.W. Ashcroft

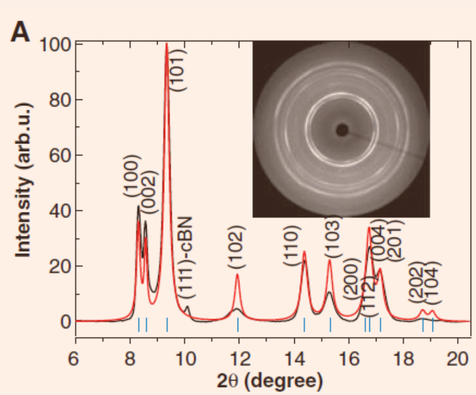
Infrared reflectivity indicates metallization of silane at 60 GPa.

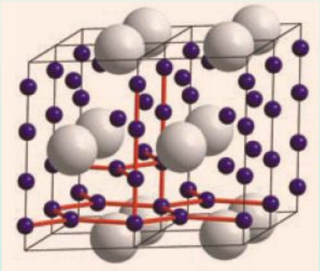
Silane turns black and shiny >30 GPa



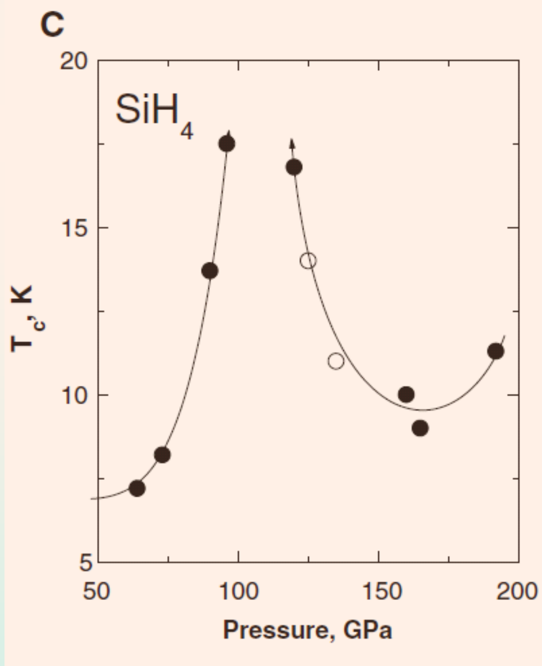
Chen *et al*. *Proc. Natl. Acad Sci.* **105**, 211 (2008)

Metallization via electrical resistance at 50-65 GPa. Superconductivity : 17 K @ 100 GPa.





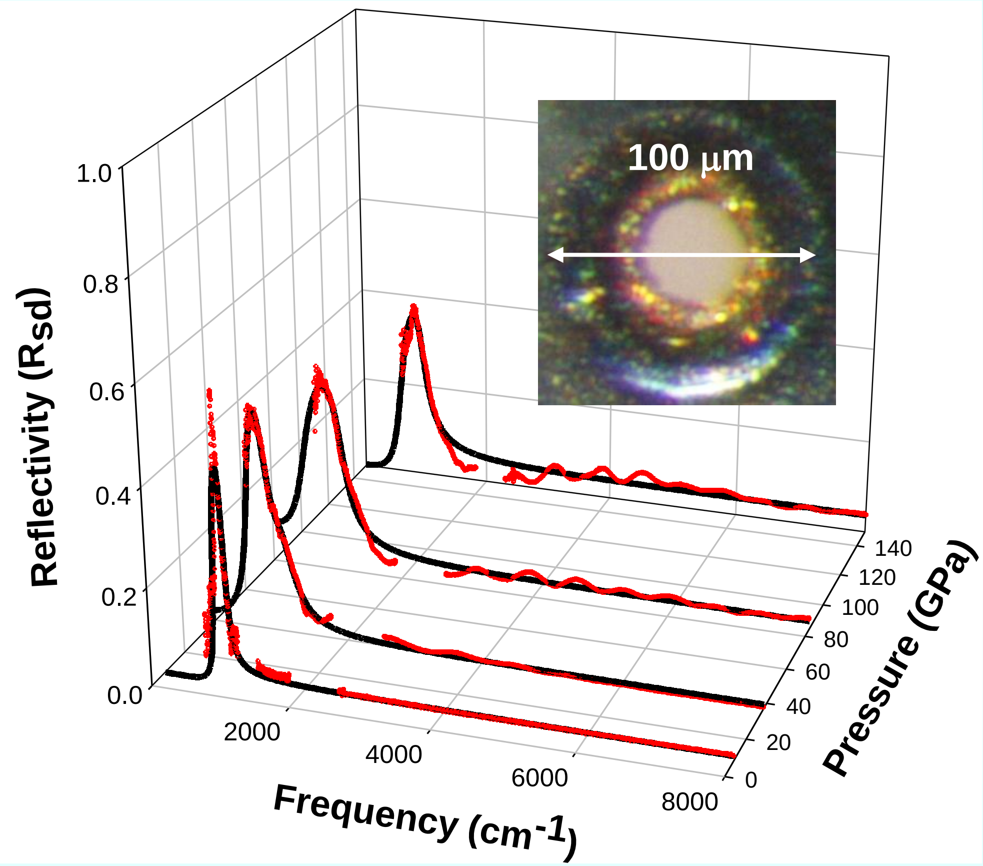
Metallic $P6_3$ Structure



Eremets *et al*. *Science* **319**, 1506 (2008)

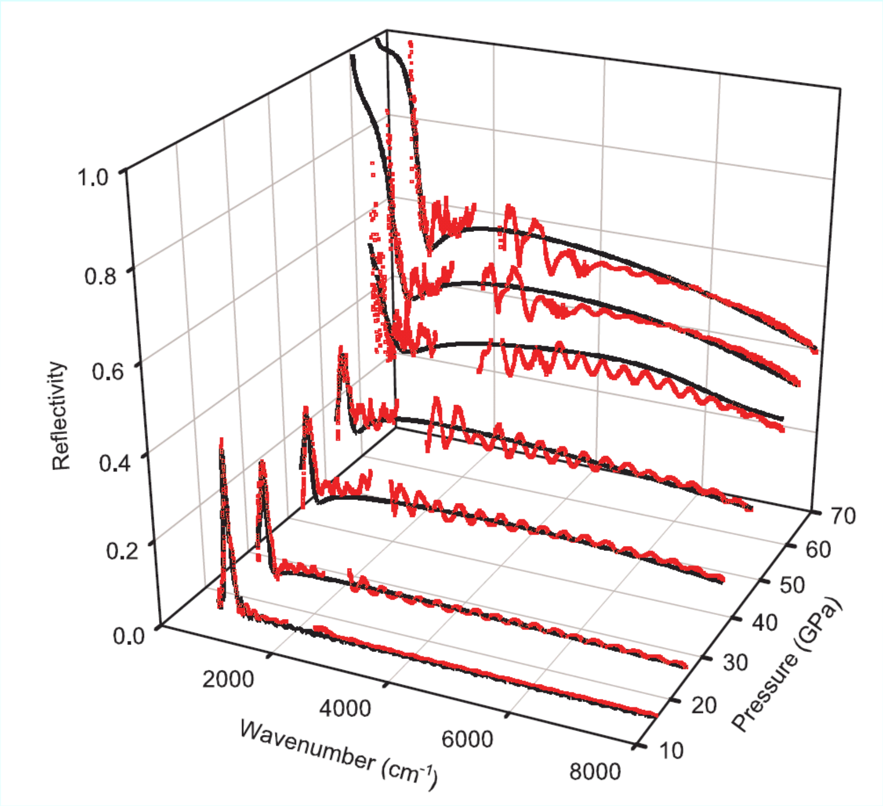
The metallization of silane has been revisited

Gold-lined gasket –
non-metallic behavior



[Strobel *et al.*, *to be published*]

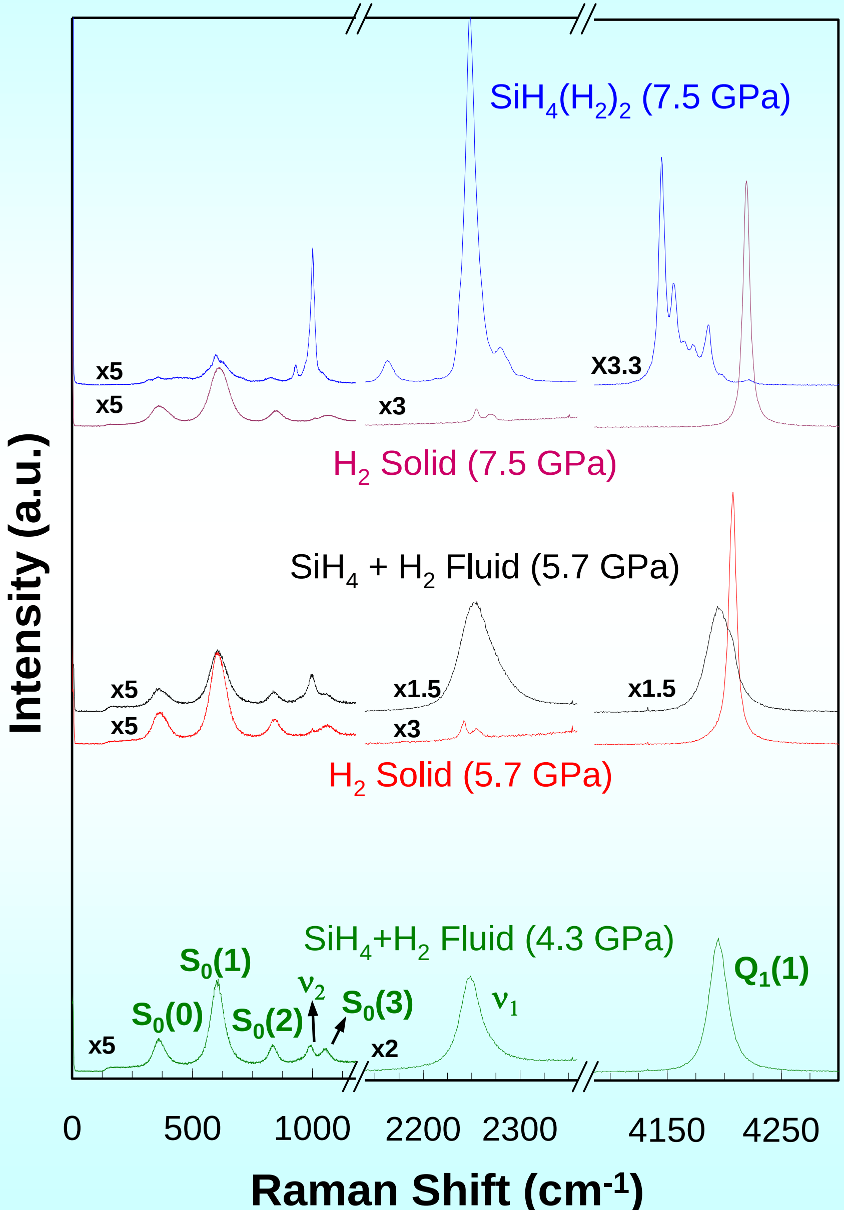
Rhenium gasket

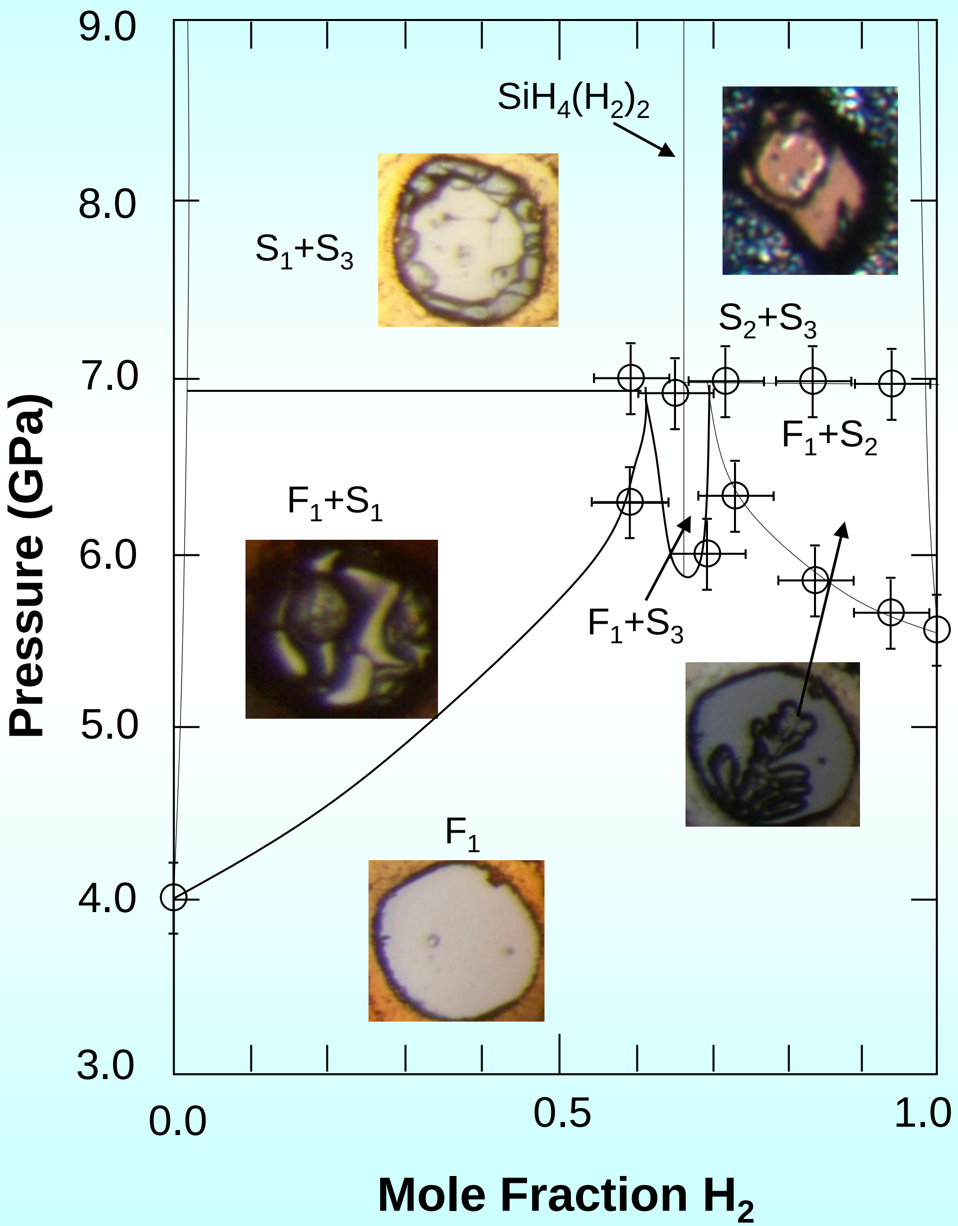


Chen *et al*. *Proc. Natl. Acad Sci.* **105**, 211 (2008)

- **Silane decomposes to metallic Si and amorphous Si:H above ~30 GPa.**
- **Previously reported metallization is likely related to a combination metal hydride formation and gasket/laser/x-ray catalyzed decomposition.**
- **Mixing SiH_4 with H_2?** [*see also*, Degtyareva *et al.*, *Solid State Comm.* (2009)]

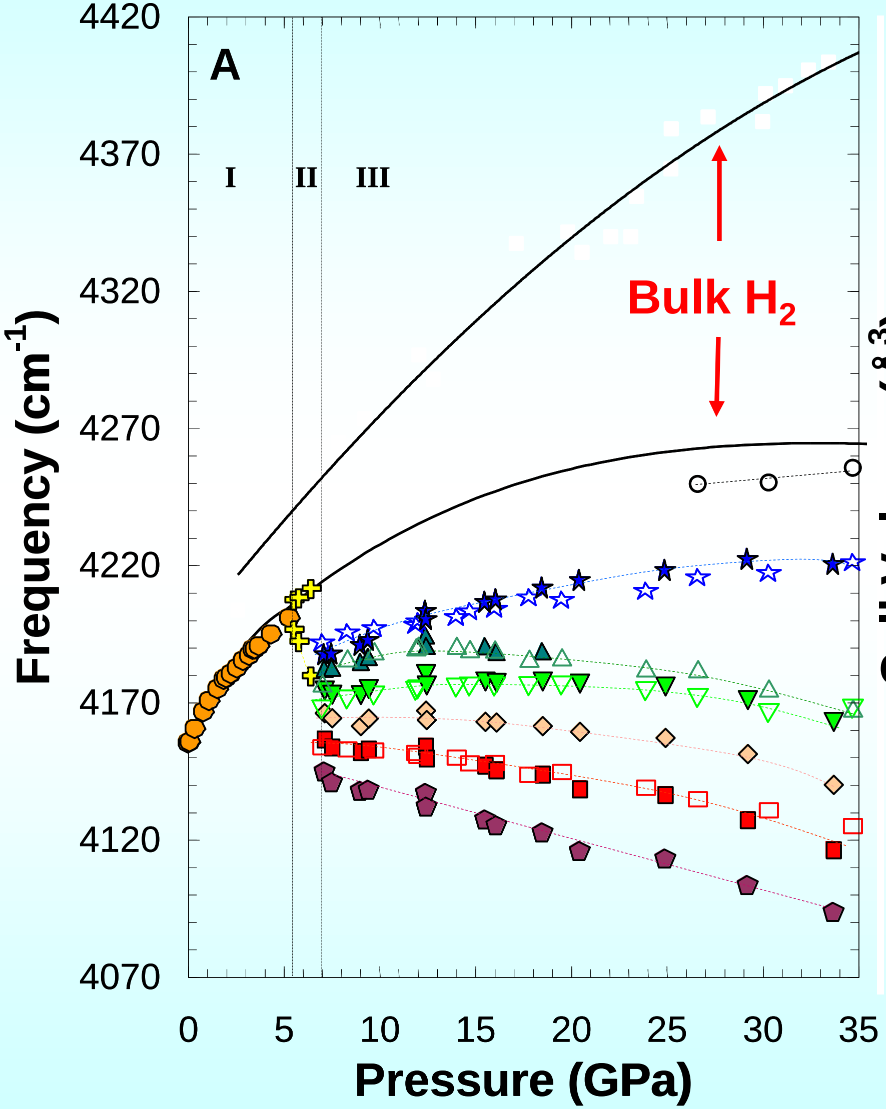
The SiH_4-H_2 system exhibits rich high-pressure behavior

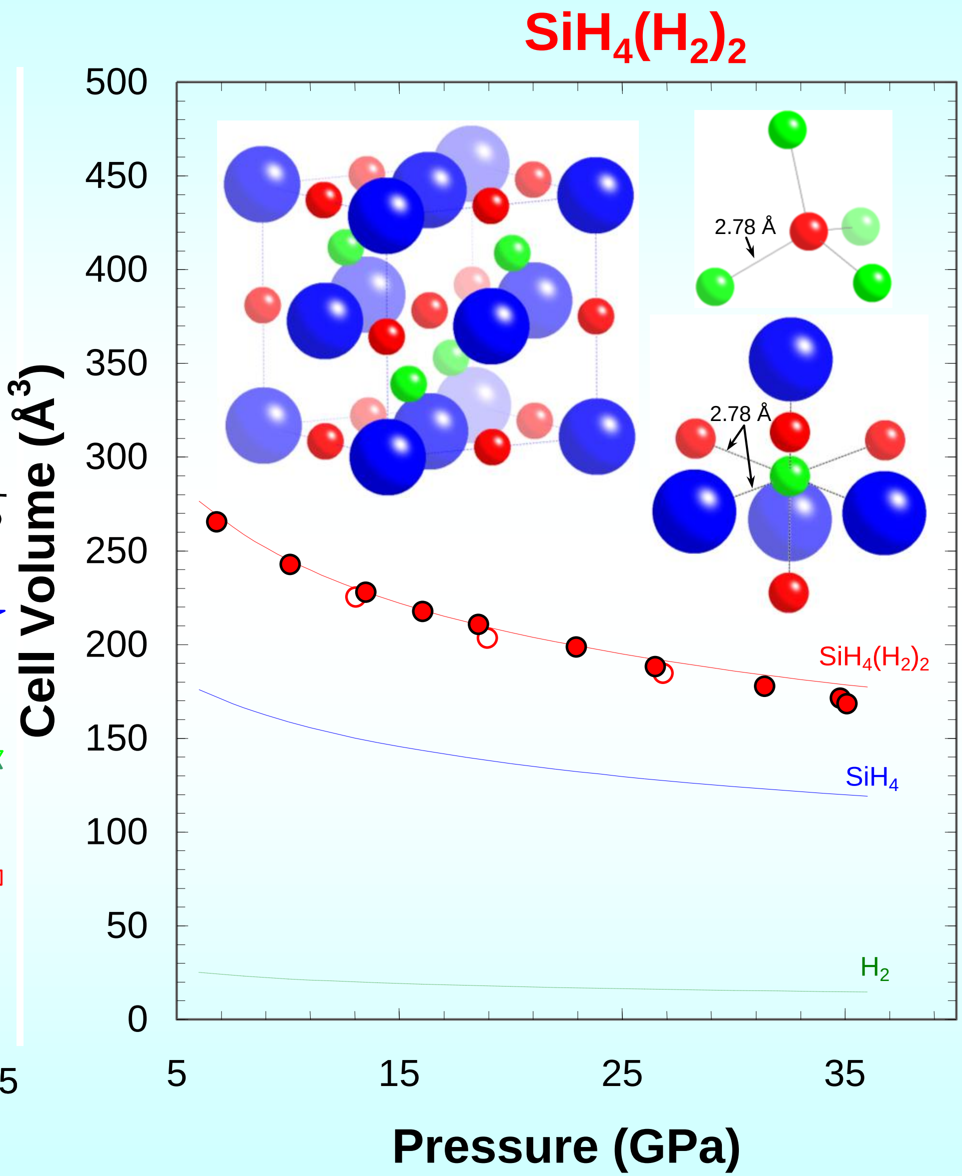




[Strobel et al. *Phys. Rev. Lett.* (2009)]

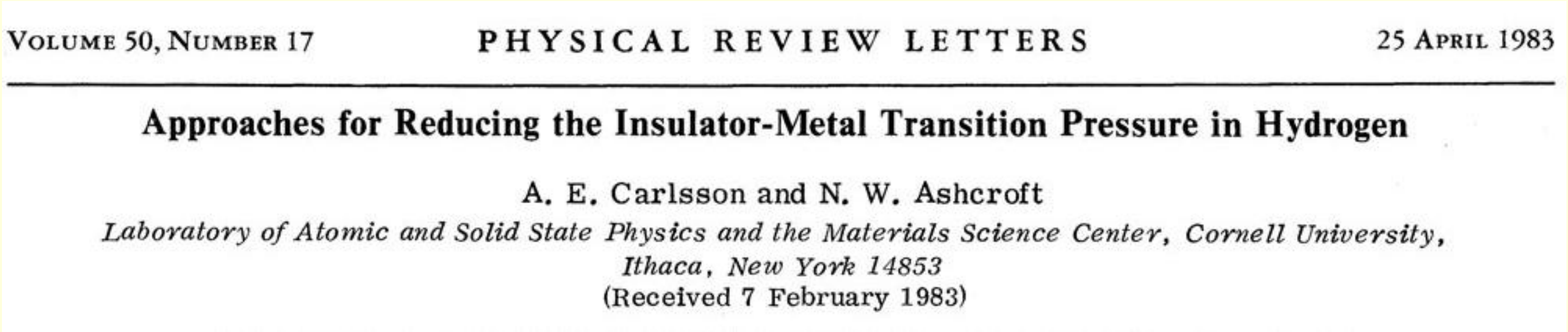
Novel interactions in SiH_4-H_2





[Strobel *et al.*, *Phys. Rev. Lett.* (2009)]

New hydrogen-xenon chemistry

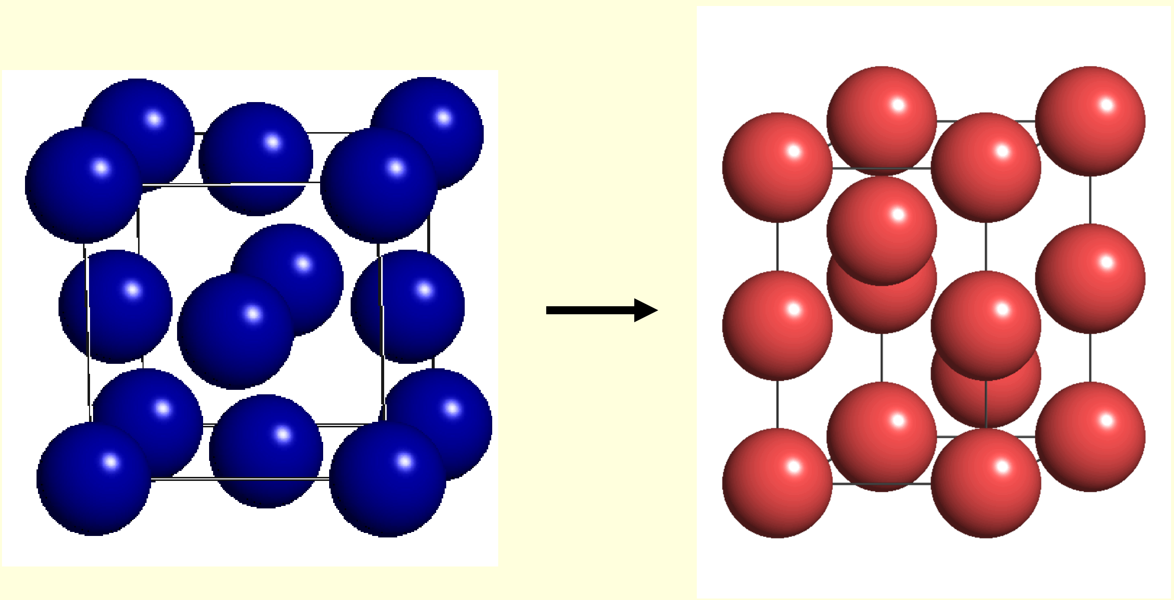

VOLUME 50, NUMBER 17 PHYSICAL REVIEW LETTERS 25 APRIL 1983

Approaches for Reducing the Insulator-Metal Transition Pressure in Hydrogen

A. E. Carlsson and N. W. Ashcroft
Laboratory of Atomic and Solid State Physics and the Materials Science Center, Cornell University, Ithaca, New York 14853
(Received 7 February 1983)

Xe fcc-hcp transition then becomes metallic at 140 GPa (300 K)

[Reichlin et al., *Phys. Rev. Lett*. (1986); *ibid.*, Goettel et al. (1986); Eremets et al., *ibid.* (2000)]

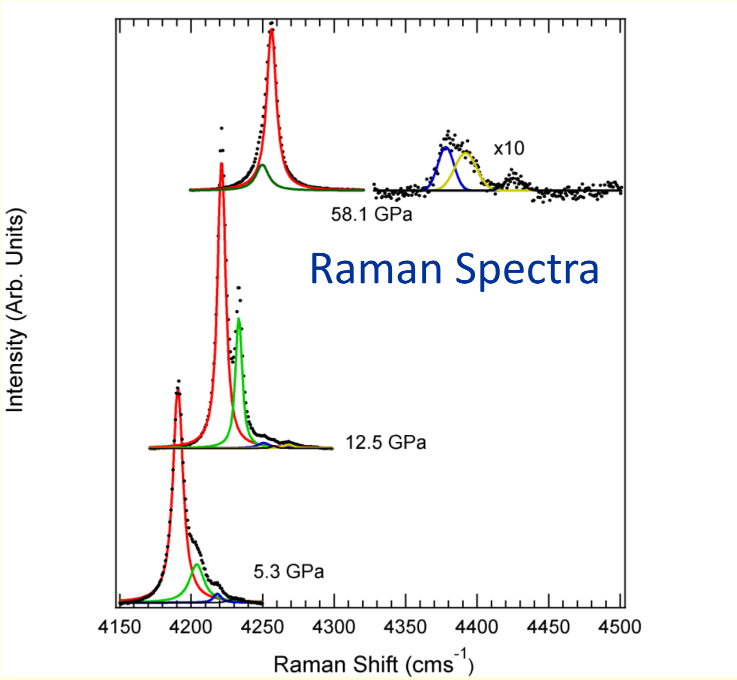


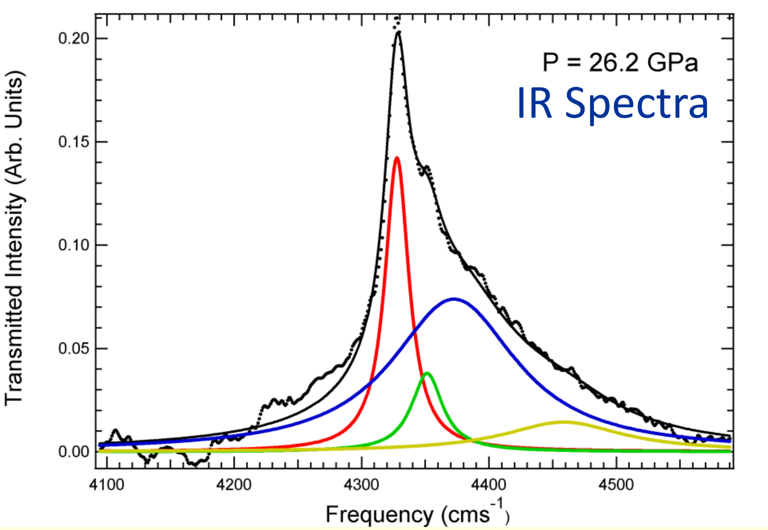
Pressure-ionize Xe atoms in H_2? Alloy stable?

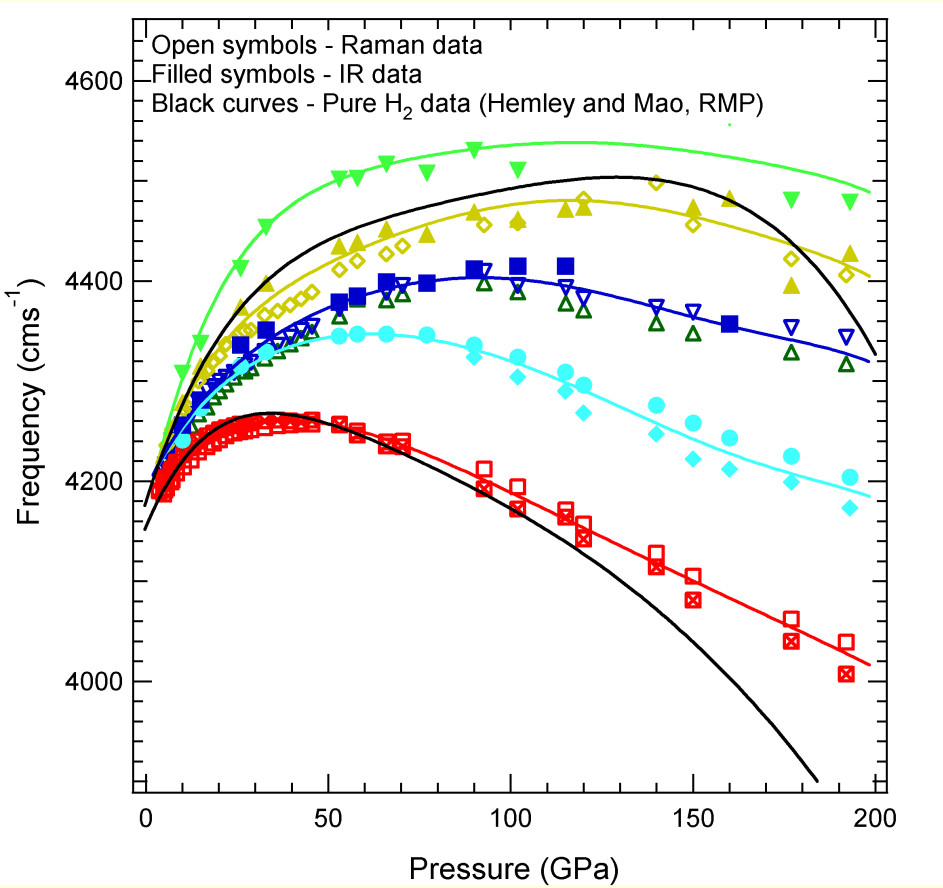
$$Xe + 2PtF_6 \longrightarrow XeF_2 + 2PtF_5$$

[Bartlett. *Proc. Chem. Soc*. (1962)]

Vibrational spectroscopy of Xe-H_2 to 250 GPa

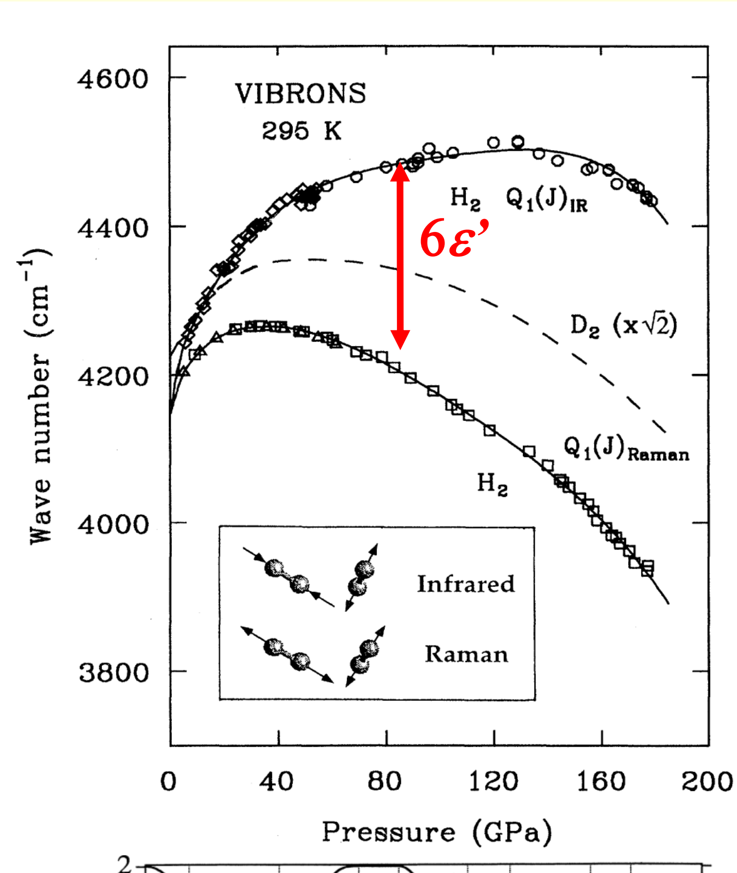


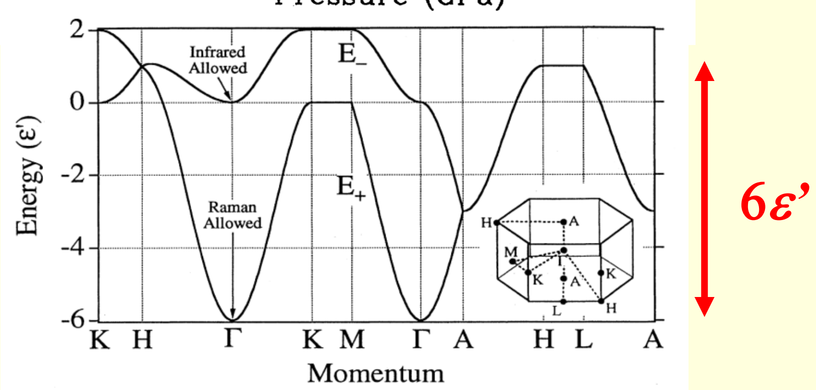


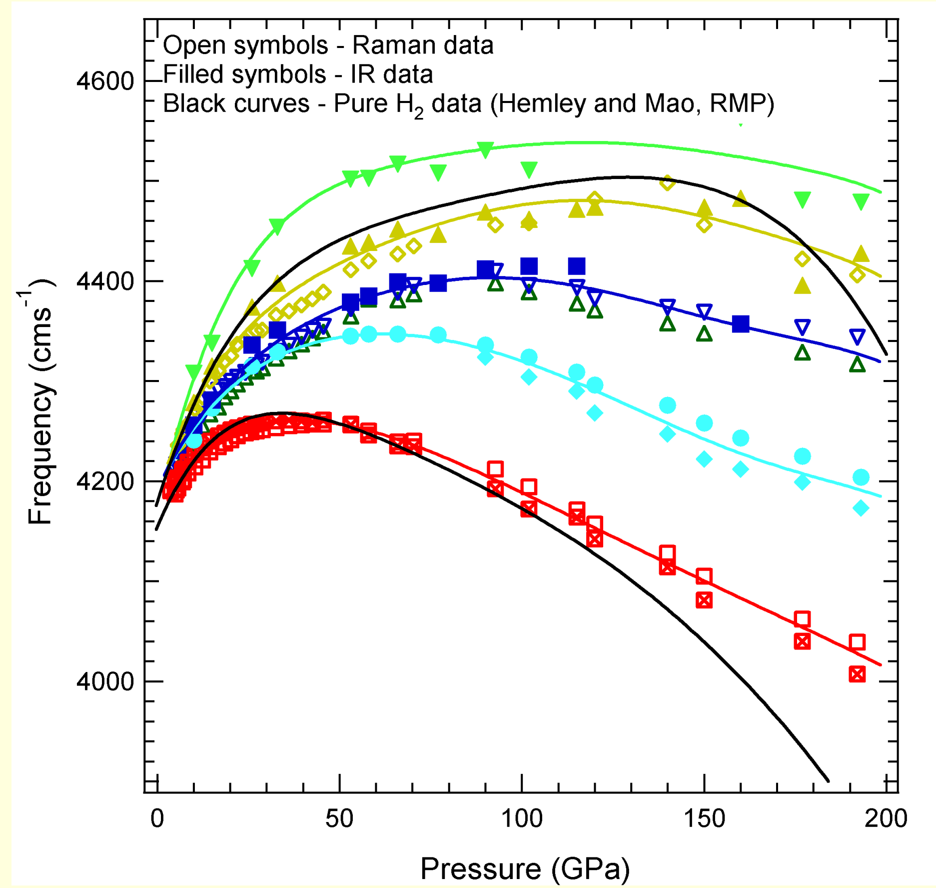


[Somayazulu et al.,
Nature Chem. **(2010)]**

Vibrational spectroscopy of Xe-H_2 to 250 GPa



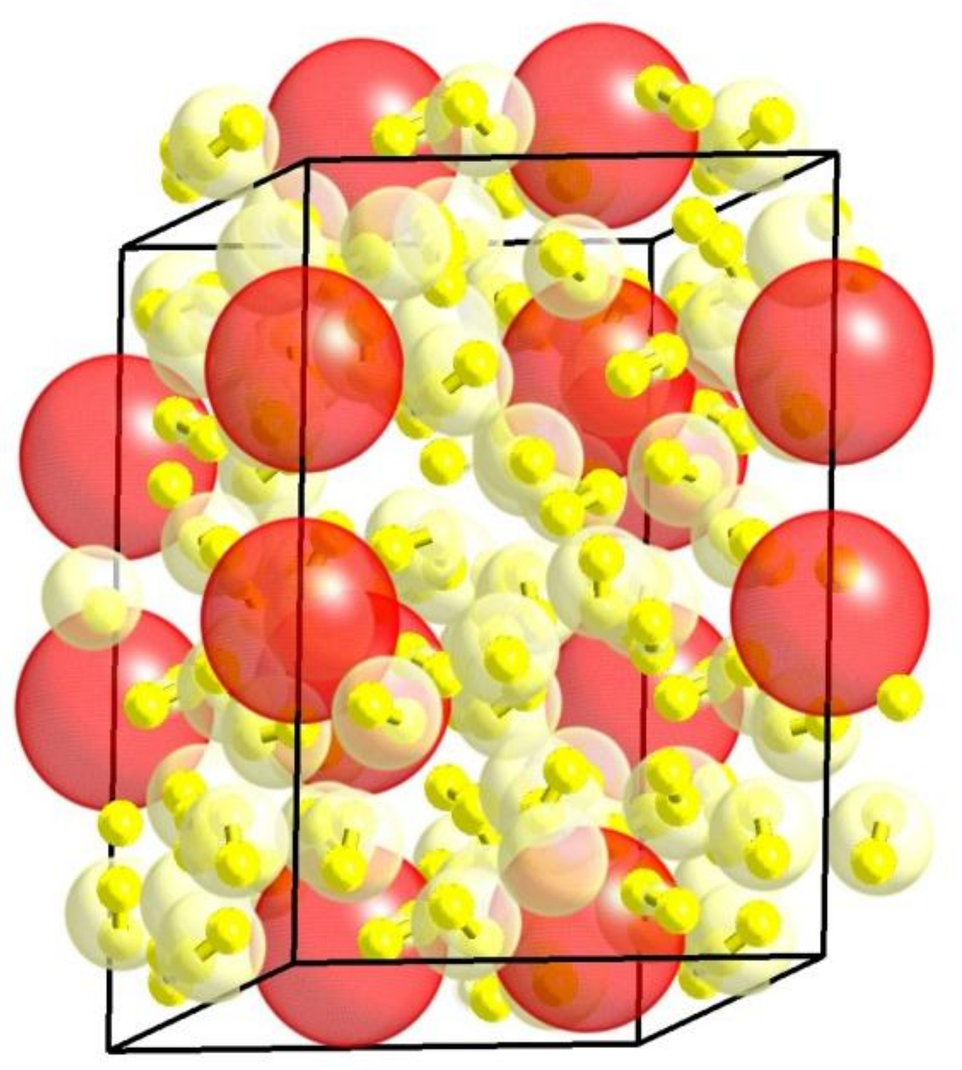


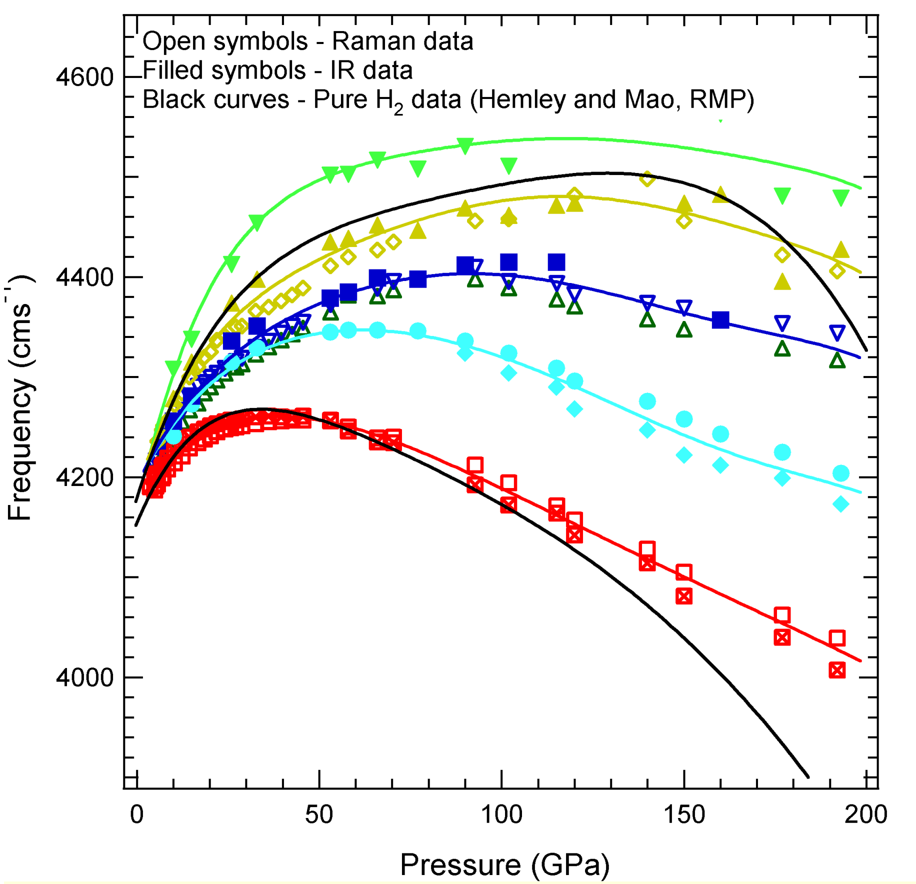


Vibrational Coupling Pure H_2

[Somayazulu et al., *Nature Chem.* (2010)]

Structure and stability of Xe-H_2

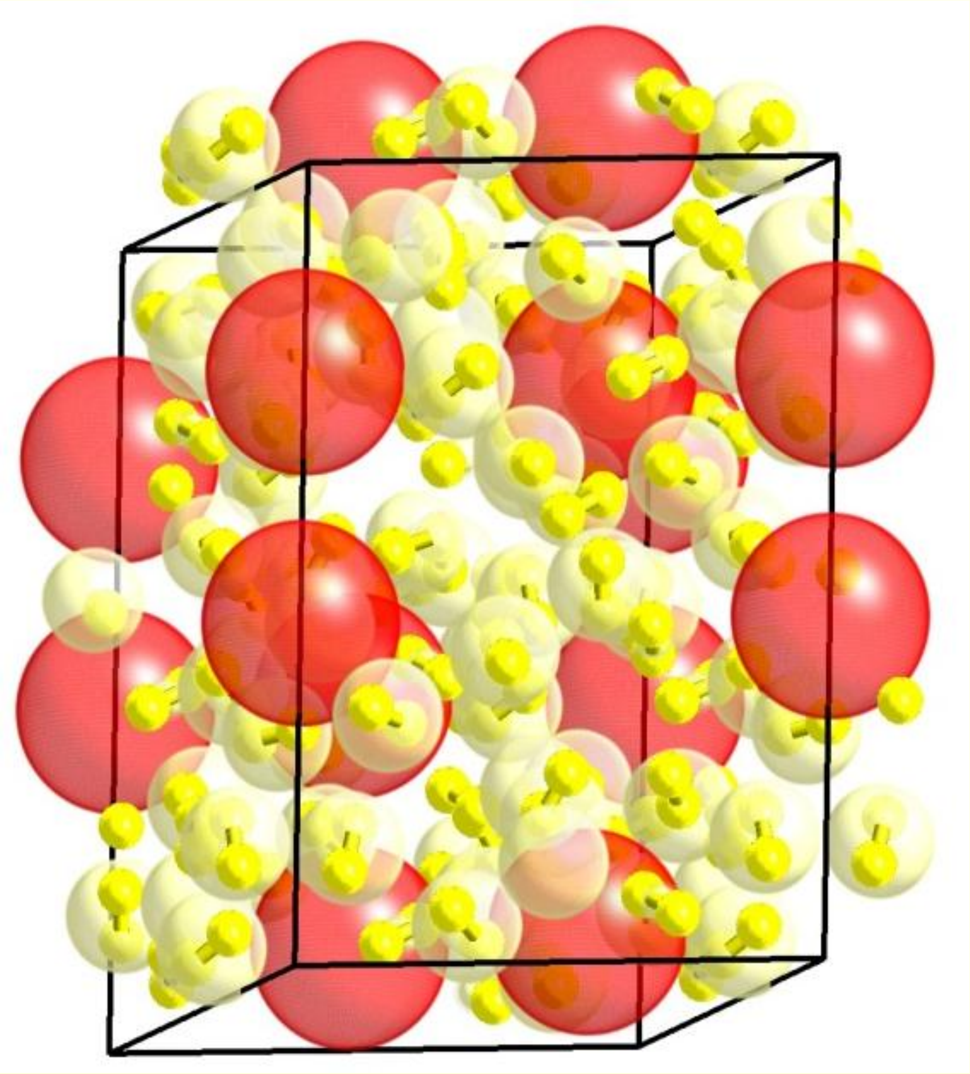


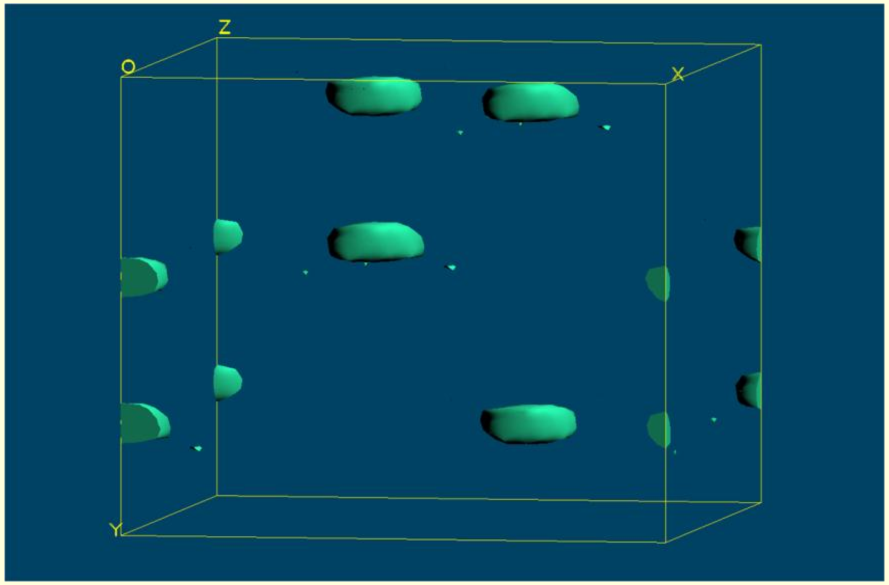


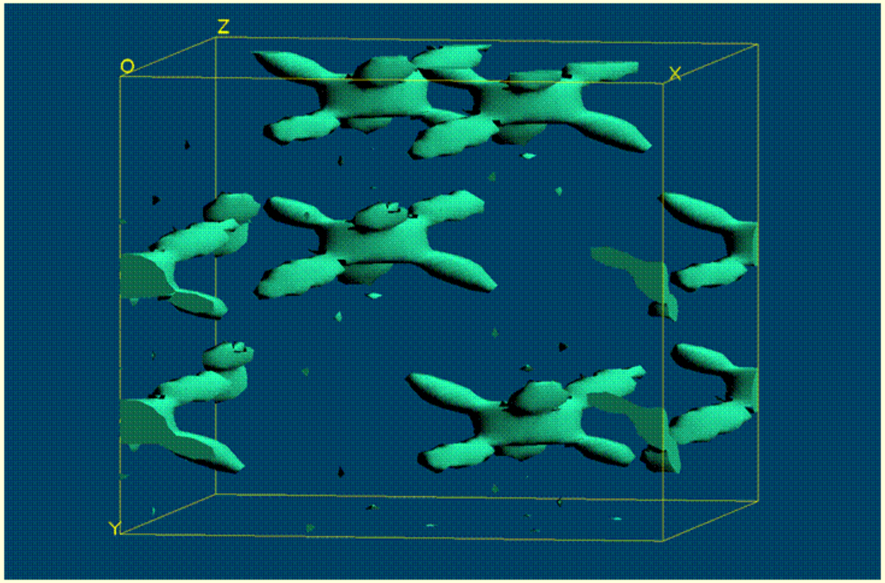
[Somayazulu et al., *Nature Chem.* (2010)]

- **Stoichiometry: $Xe(H_2)_7$**
- **H_2 molecules intact to 250 GPa**
- **Not metallic at 250 GPa (300 K)**
- **Potential hydrogen storage material**

Structure refinement reveals electron density spread into hydrogen

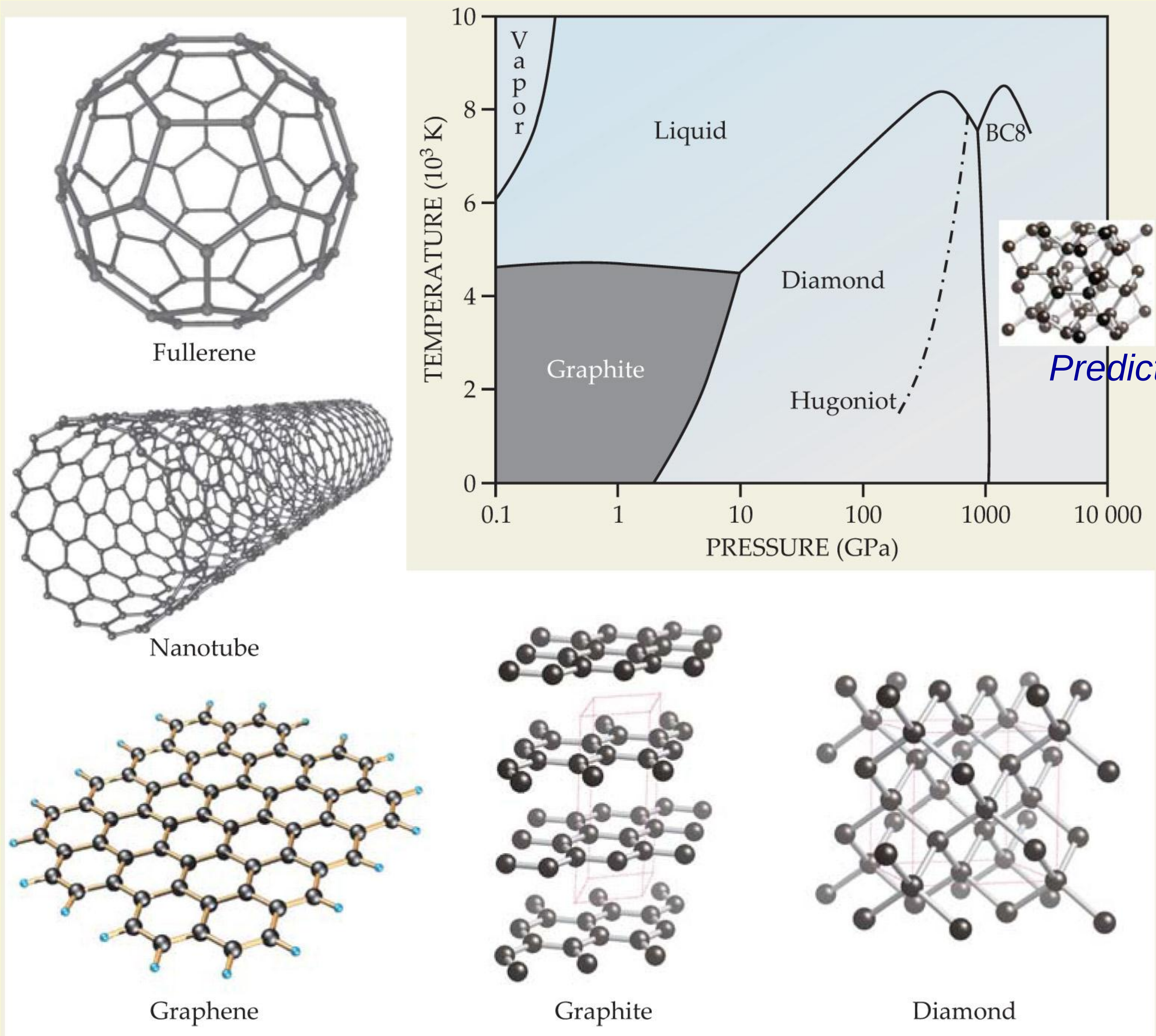






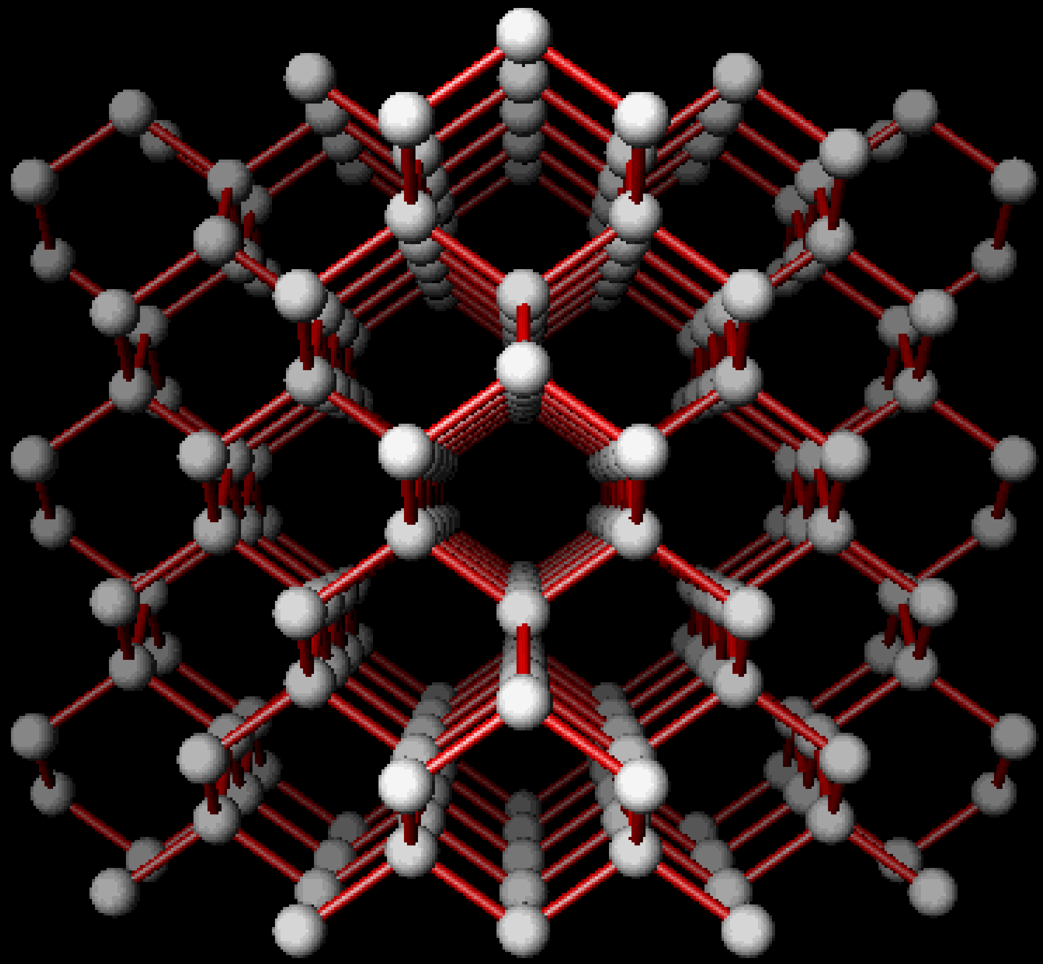
[Somayazulu et al., *Nature Chem.* (2010)]

Rich polymorphism of carbon: *stable and metastable phases*



[Hemley, Crabtree & Buchanan, *Physics Today* (2009)]

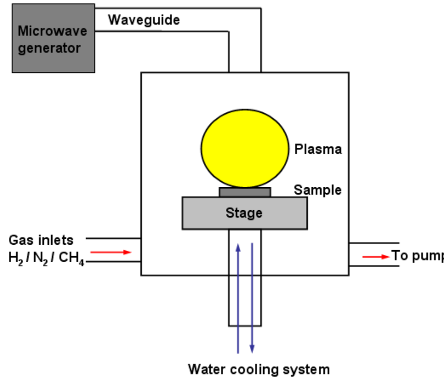
Diamond has unique physical properties:
ultimate material for extreme conditions



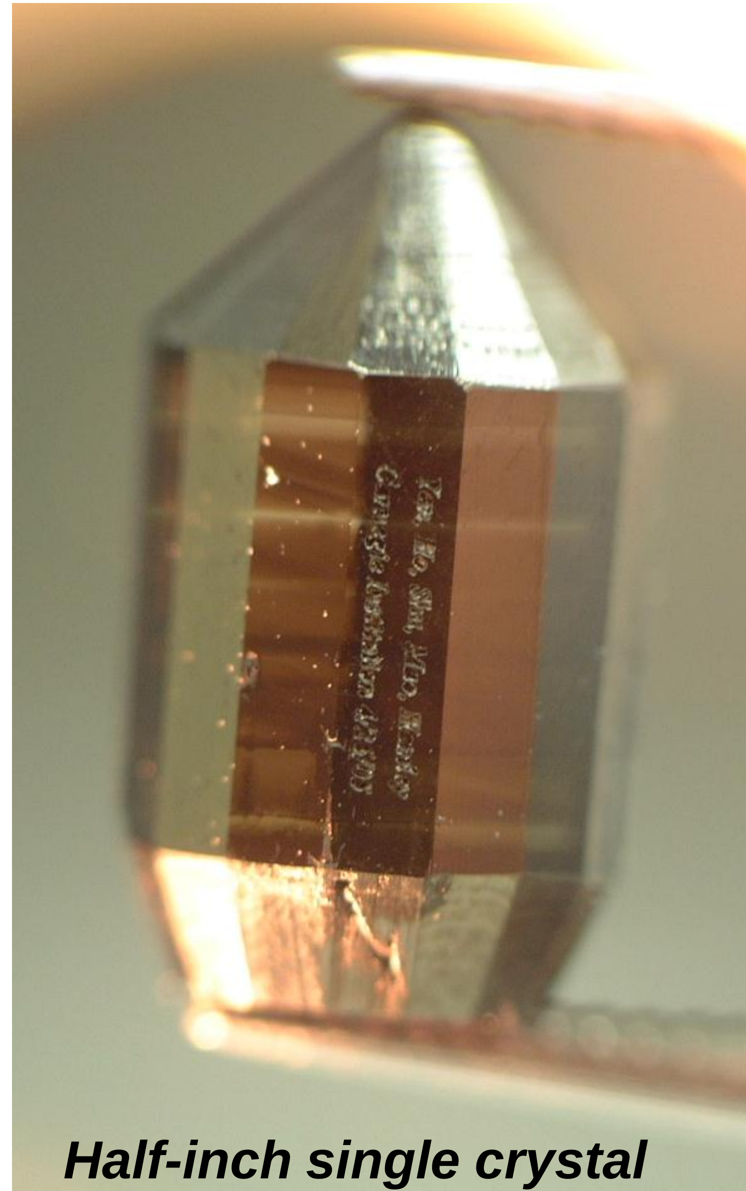
- High hardness/strength
- Transparency
- Low friction
- Low adhesion
- High thermal conductivity
- Low thermal expansion
- High refractive index
- Chemical inertness
- Biocompatibility
- Radiation hardness
- Electrical insulator
- Electronic properties

CVD techniques have enabled a new diamond technology

Synthesis of diamond
General Electric, Co. (1954)



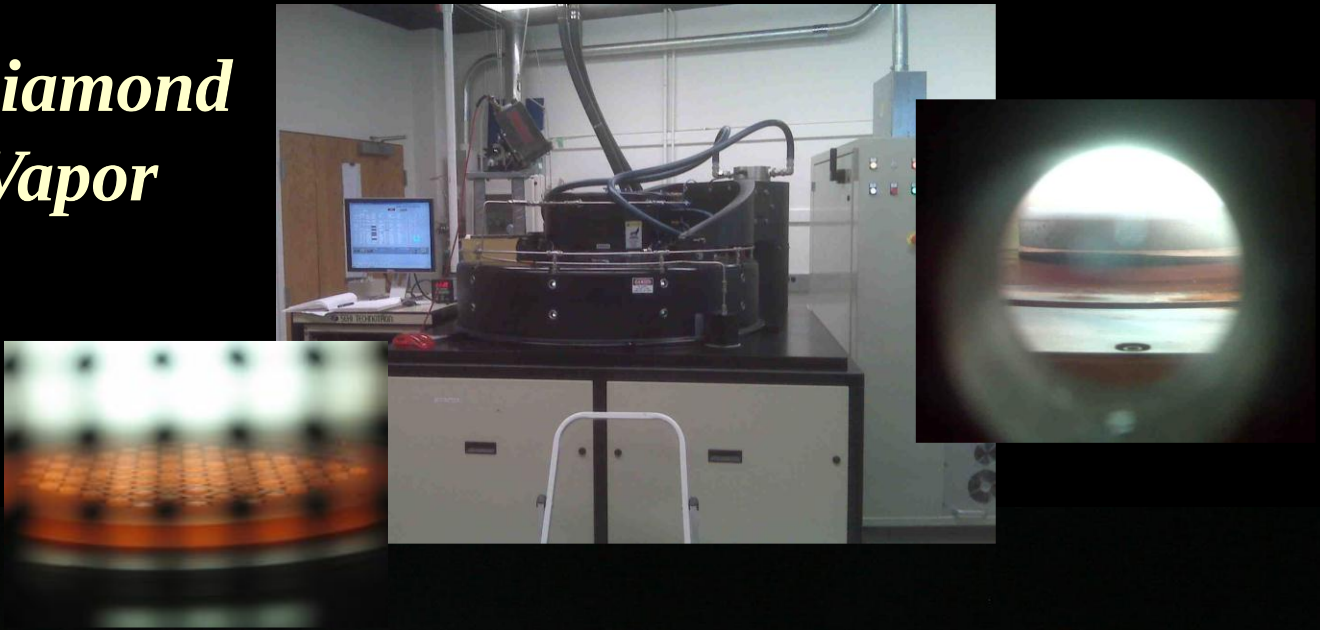
Microwave Plasma Chemical Vapor Deposition (CVD)



Half-inch single crystal

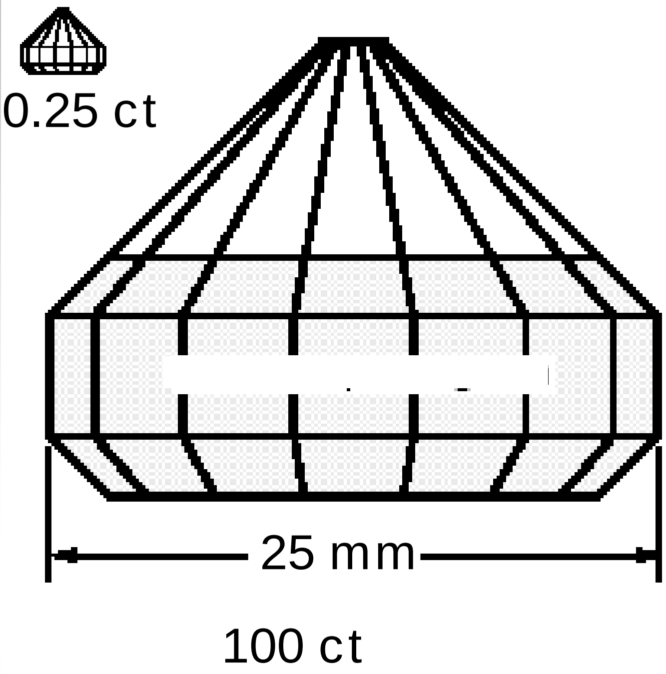
[Ho *et al.*, *Industrial Diamond Rev.* (2006)]

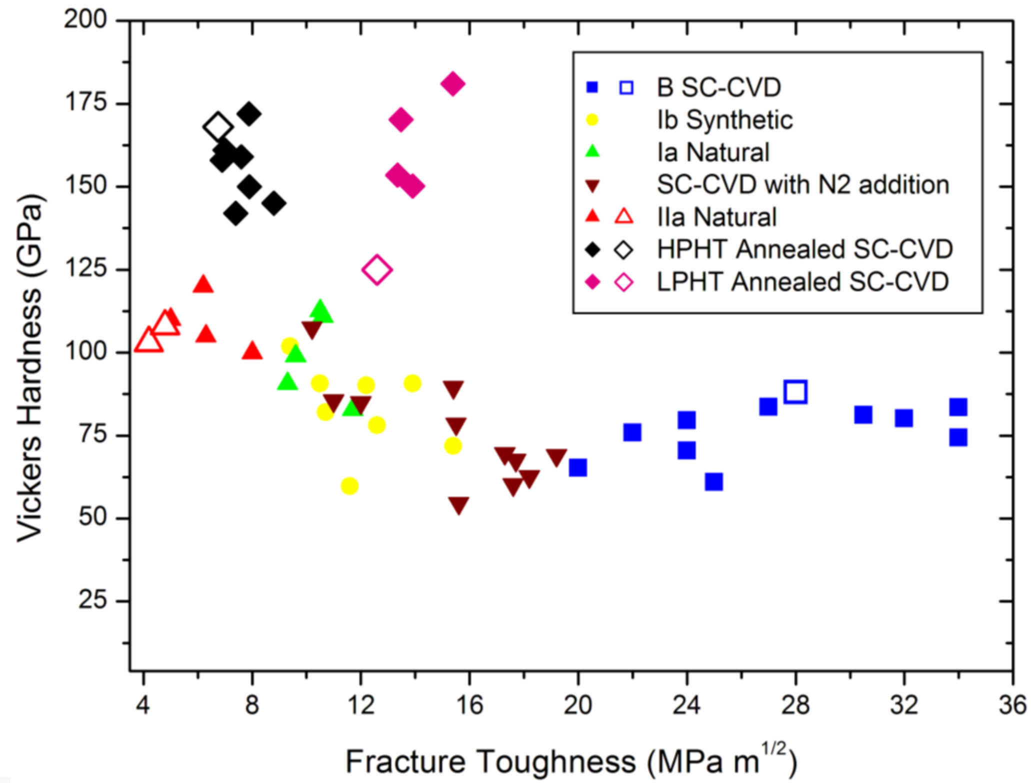
Single Crystal Diamond from Chemical Vapor Deposition

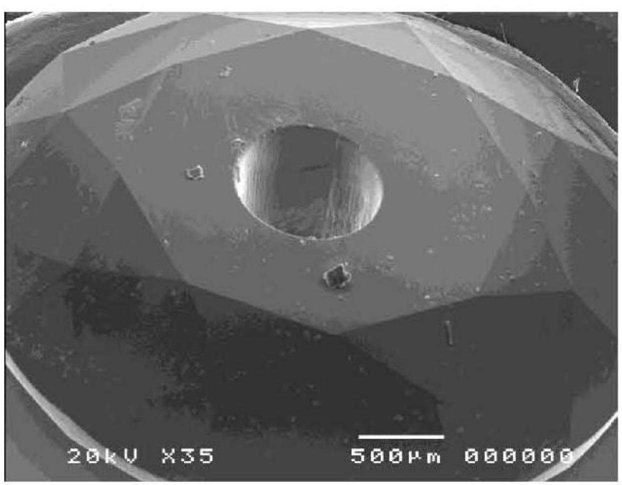


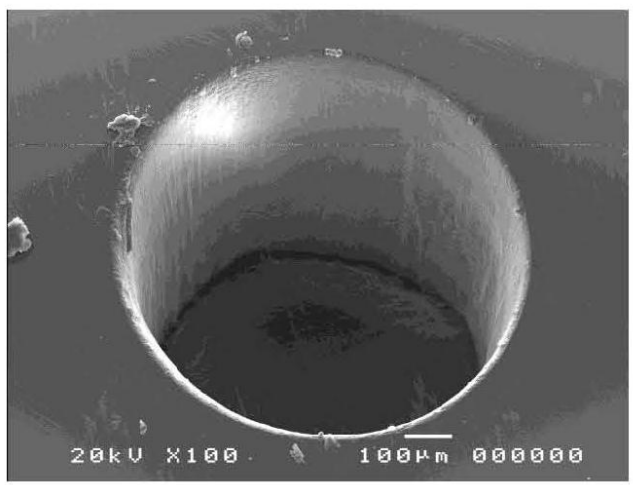
[Meng *et al.*, *PNAS* (2008)]

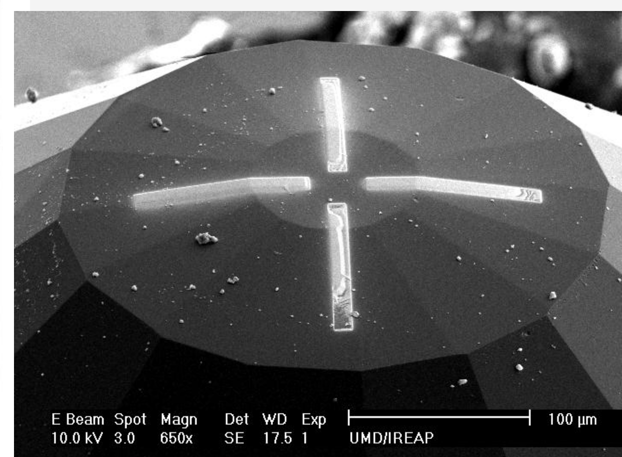
Next generation CVD diamond technology for high pressure



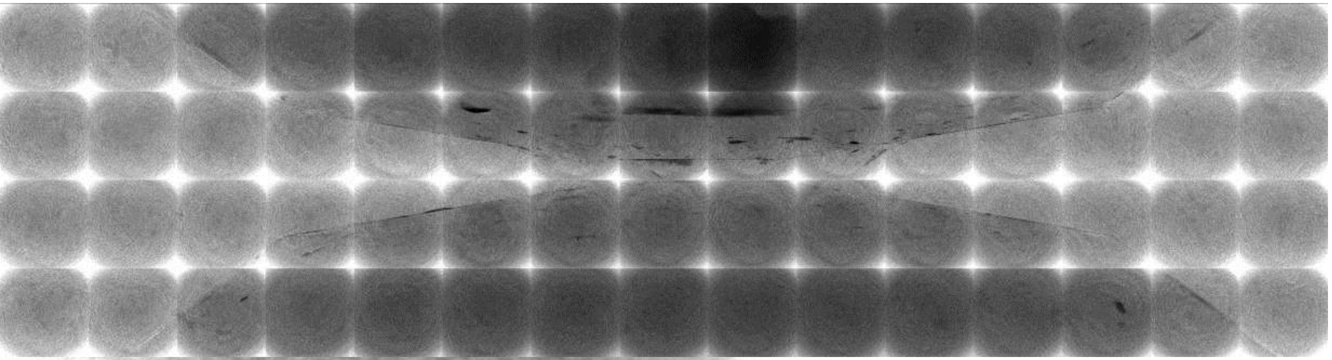




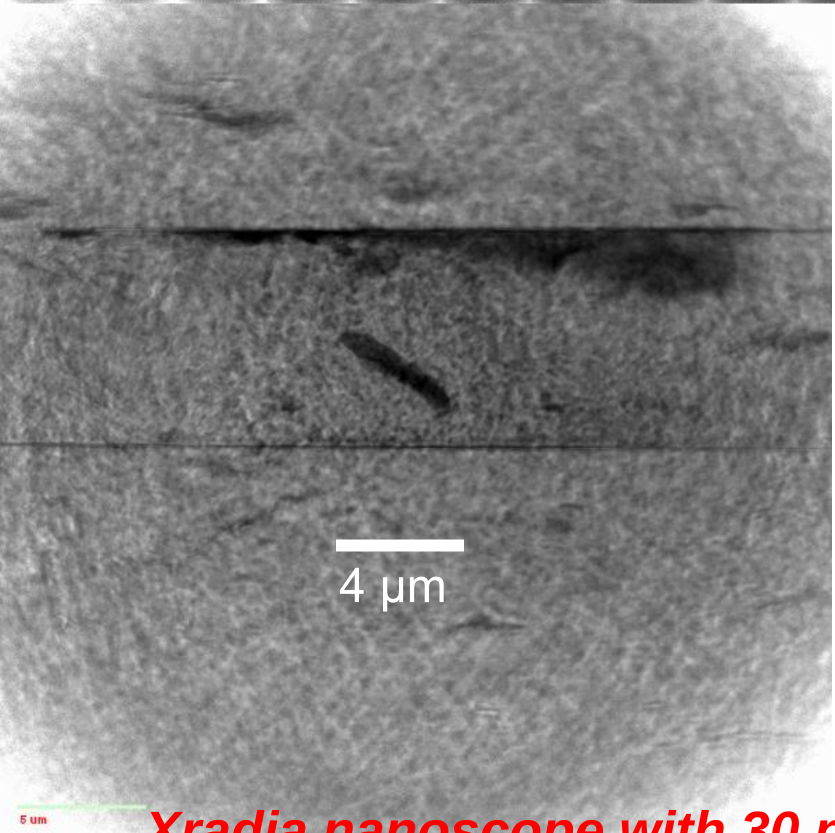




Using nanobeams to measure anvil nanostrains and optimize pressure

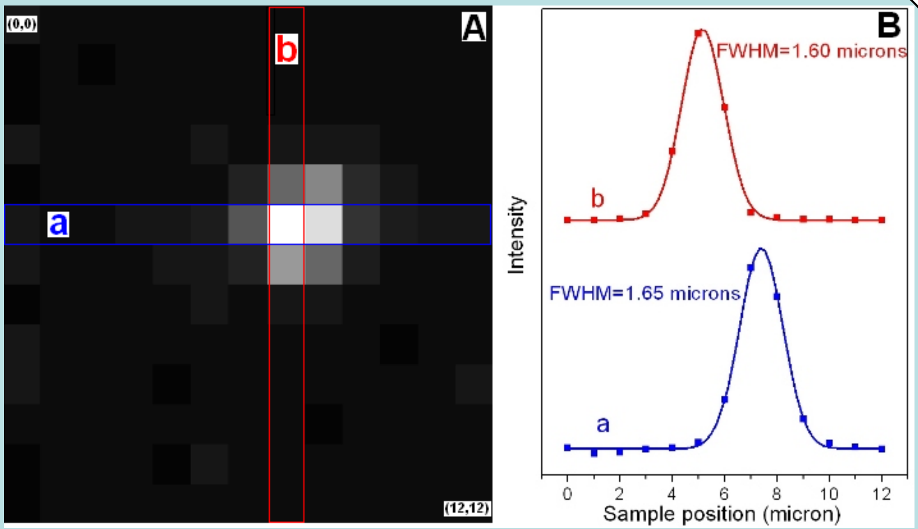


First submicron megabar x-ray measurements



30 nm resolution

[W. Mao



Grain size determination in a post perovskite with scanning nanoprobe (250 nm beam)

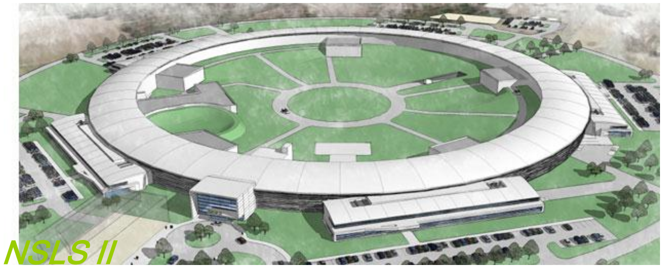
Xradia nanoscope with 30 nm resolution

SSRL Beamline 6-2

[Wang, et al. *PNAS* **(2010)**]

New generations of large facilities are coming on line

X-ray Sources

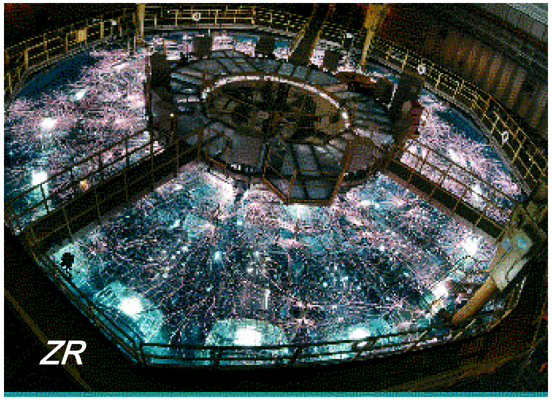


- *Higher brightness synch.*
- *Dynamic compression*
- *Energy Recovery Linacs*
- *Fourth Generation Sync.*

Neutron Sources

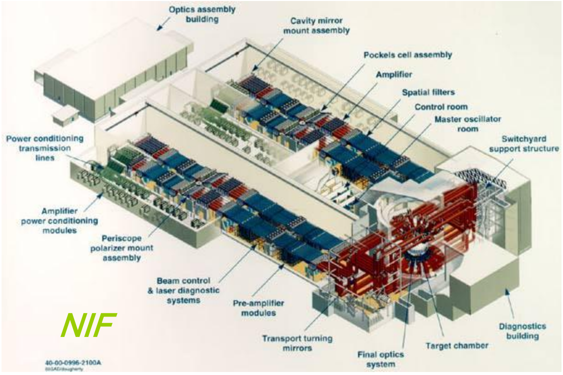
- *Dedicated beamlines*
- *>100 GPa neutron scattering*

Pulsed Power



- *Ultrahigh P-T conditions*
- *New diagnostics*
- *Static/dynamic*

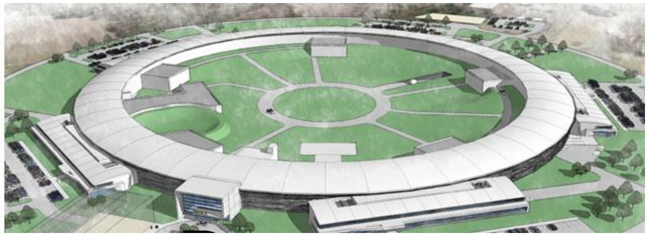
Laser Sources



- *10 Mbar-Gbar pressures*
- *New diagnostics*
- *Static/dynamic*

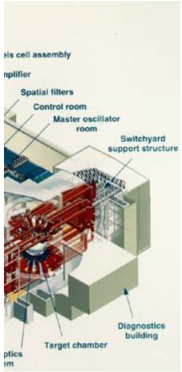
New generations of large facilities are coming on line

X-ray Sources



Neutron Sources

- ***New inelastic scattering in new domains***
- ***Time dependent (<ps-scale) diffraction/imaging***
- ***Heterogeneous/complex assemblages: nm-diffraction***
- ***Interfaces/grain boundaries***
- ***New domains of P-T-t***



- ***Static/dynamic***

- ***Static/dynamic***

CONCLUSIONS AND PERSPECTIVES

1. Exploring materials under extreme conditions is deepening our understanding of chemistry at a fundamental level.

2. Unexpected structures and bonding schemes are emerging through a combination of experiment and theory.

3. 'Simple' molecular and elemental systems provide a useful starting point for developing this new understanding.

4. Progress continues as a result of continued development of new techniques and materials.

ACKNOWLEDGEMENTS

Collaborators

CARNEGIE INSTITUTION

Ho-kwang Mao	Alexander Goncharov
Viktor Struzhkin	Ronald E. Cohen
Chih-shue Yan	M. Somayazulu
Changsheng Zha	Timothy Stobel
Joe Lai	Robert Hazen
Yufei Meng	Yingwei Fei
Yingwei Fei	Stephen Gramsch
Jinfu Shu	Qi Liang
Zhenxian Liu	Yue Meng
Guoyin Shen	Muhetaer Aihaiti
Anurag Sharma	Patrick Griffin
Yang Ding	Amy Lazicki
P. Ganesh	S. Krasnicki

OTHER INSTITUTIONS

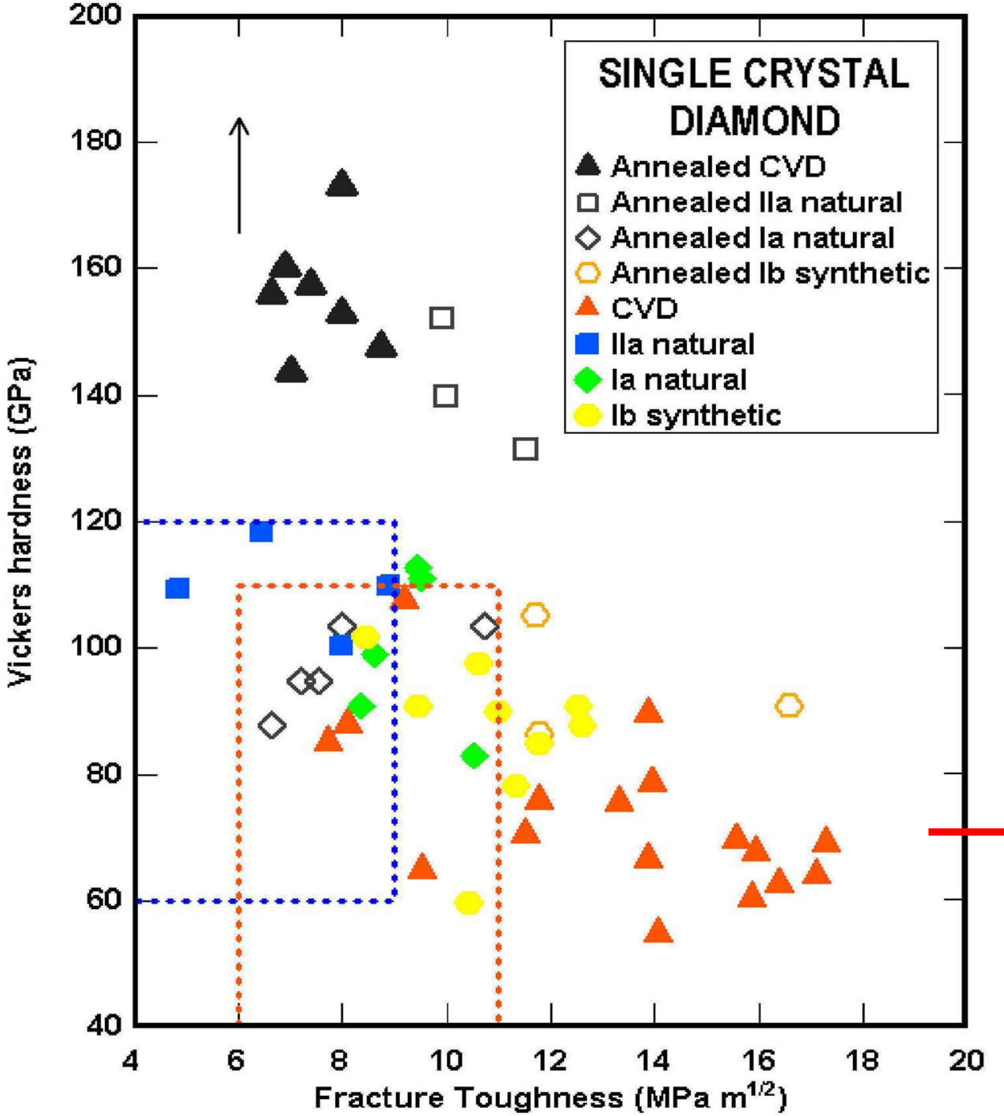
Pierre Toledano (Ameins)
K. Litasov (Tohoku)
(Chi-chang Kao (BNL)
Przemek Dera (GSECARS)
Jennifer Ciezak (ARL)
Tim Jenkins (NIST)
E. Gregoryanz (Edinburgh)
Mikhail Eremets (Mainz)
Wendy Mao (Stanford)
Yusheng Zhao (LANL)
Nick Sobolev (Novosibirsk)
G. Zou (Jilin)
Eric Shirley (NIST)
Paul Loubreyre (CEA)
Raymond Jeanloz (Berkeley)
G. W. Collins (Livermore)

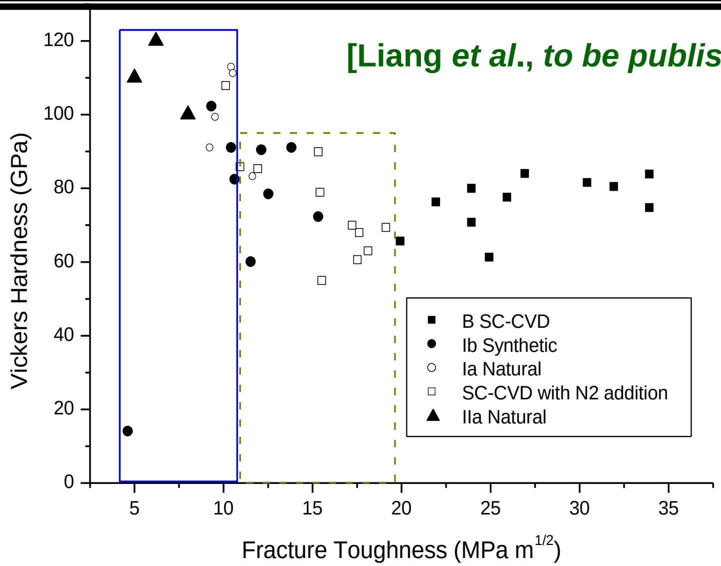
Financial Support

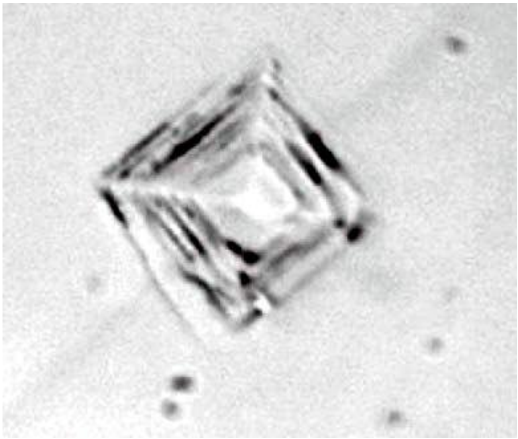
DOE/NNSA/SSAAP
DOE/OS/BES
NSF, Carnegie Institution


TIMEX

The mechanical properties can be tuned over a range of hardness and toughness

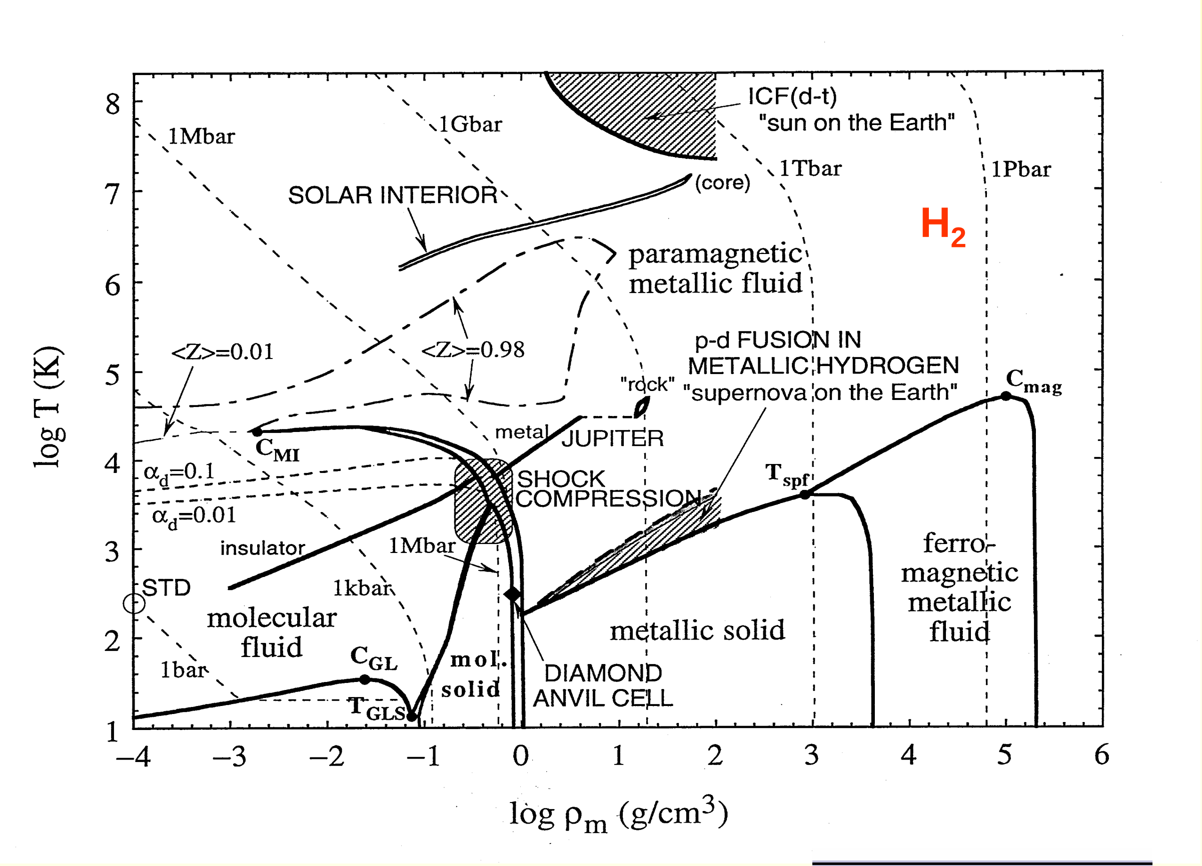


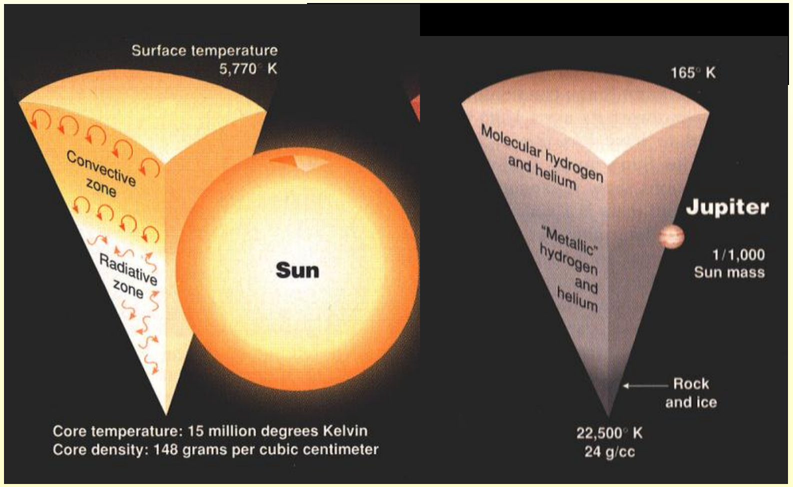




Ultratough Diamond:
No crack propagation
Kic > 30 MPa m$^{1/2}$

Uncharted Territory Beyond Conventional Materials Physics





- **Combined static/ dynamic compression**
- **Ultra-fast diagnostics**

[Loubeyre et al., *High Pres. Res.* (2004)]