

Solid Helium: An Unusual „Liquid“ or even a Superfluid?

Giorgio Benedek and J. Peter Toennies

With contributions from Robert Grisenti, Pablo Nieto, Manuel Kaez, and Anton Kalinin

Max Planck Institut für Dynamik und Selbstorganisation

jtoenni@gwdg.de

Göttingen, Germany

IMAGING

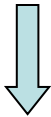
IMAGINING

IMAGINE A SOLID
WHICH IS A SUPERFLUID

The Long Search for the Superfluid Phase of Helium: From Conjecture to Experimental Evidence

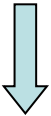
1969

Andreev & Lifshitz



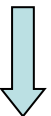
1970

Chester → Leggett



1973- present

Suzuki and many
others



2004

Kim & Chan

Success at last!?

SOVIET PHYSICS JETP

VOLUME 29, NUMBER 6

DECEMBER 1969

QUANTUM THEORY OF DEFECTS IN CRYSTALS

A. F. ANDREEV and I. M. LIFSHITZ

Institute of Physical Problems, U.S.S.R. Academy of Sciences

Submitted January 15, 1969

Zh. Eksp. Teor. Fiz. 56, 2057-2068 (June, 1969)

Can a Solid Be "Superfluid"?

A. J. Leggett

School of Mathematical and Physical Sciences, University of Sussex, Falmer, Brighton, Sussex, England

(Received 15 September 1970)

It is suggested that the property of nonclassical rotational inertia possessed by superfluid liquid helium may be shared by some solids. In particular, nonclassical rotational inertia very probably occurs if the solid is Bose-condensed as recently proposed by Chester. Anomalous macroscopic effects are then predicted. However, the associated superfluid fraction is shown to be very small (probably $\lesssim 10^{-4}$) even at $T=0$, so that these effects could well have been missed. Direct tests are proposed.

Search for superfluidity in solid ^4He

D. S. Greywall

Bell Laboratories, Murray Hill, New Jersey 07974

(Received 5 April 1977)

A small pressure difference between two sample chambers filled with solid ^4He and joined by a capillary was measured as a function of temperature. For temperatures greater than 30 mK and for pressures between 25 and 50 bar there were no indications of "superfluid flow" in the capillary.

letters to nature

Probable observation of a supersolid helium phase

E. Kim & M. H. W. Chan

Department of Physics, The Pennsylvania State University, University Park,
Pennsylvania 16802, USA

high- Q oscillator shown in Fig. 1 is given by $2\pi\sqrt{I/G}$, where I is the moment of inertia of the torsion bob, which contains helium, and G is the torsional spring constant of the Be-Cu torsion rod. A small hole drilled through the centre of the torsion rod allows the introduction of helium into the torsion bob. The oscillator is driven and maintained at resonance by a pair of electrodes. The onset of superfluidity in the helium inside the torsion bob decreases I , and hence decreases the resonant period. Bishop *et al.*³ made measurements of solid helium from 25 to 48 bar, and concluded that if there is a supersolid state, then either the supersolid fraction (the fraction of ^4He atoms

Outline

I. What is a Superfluid?

II. What is a Supersolid?

III. Recent Controversial Evidence for Supersolid ^4He

IV. The Geyser Phenomenon

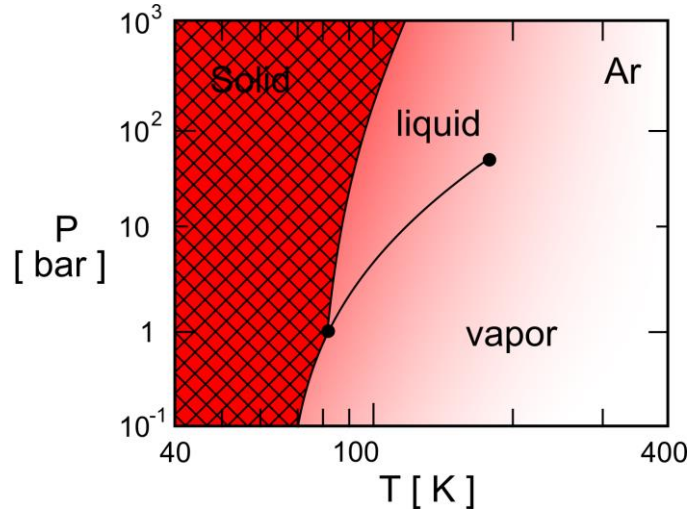
V. Geyser Anomalies

VI. Minigeysers Inside Capillaries

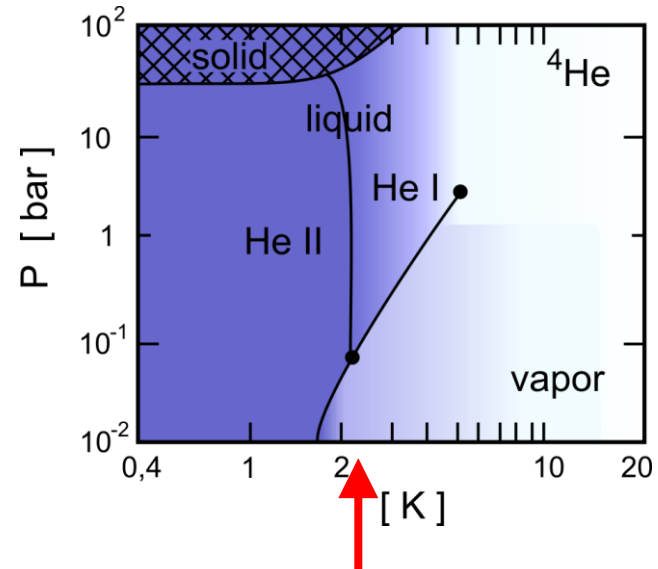
VII. Summary

Helium has a Uniquely Different Phase Diagram

All other matter
except the helium isotopes
e. g. Ar



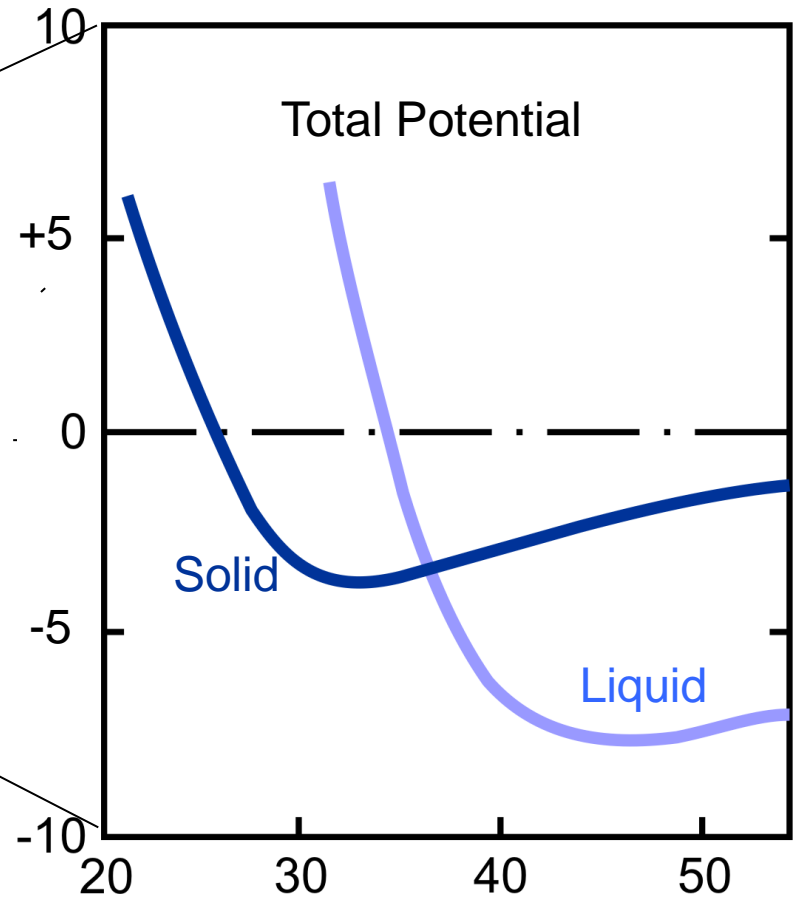
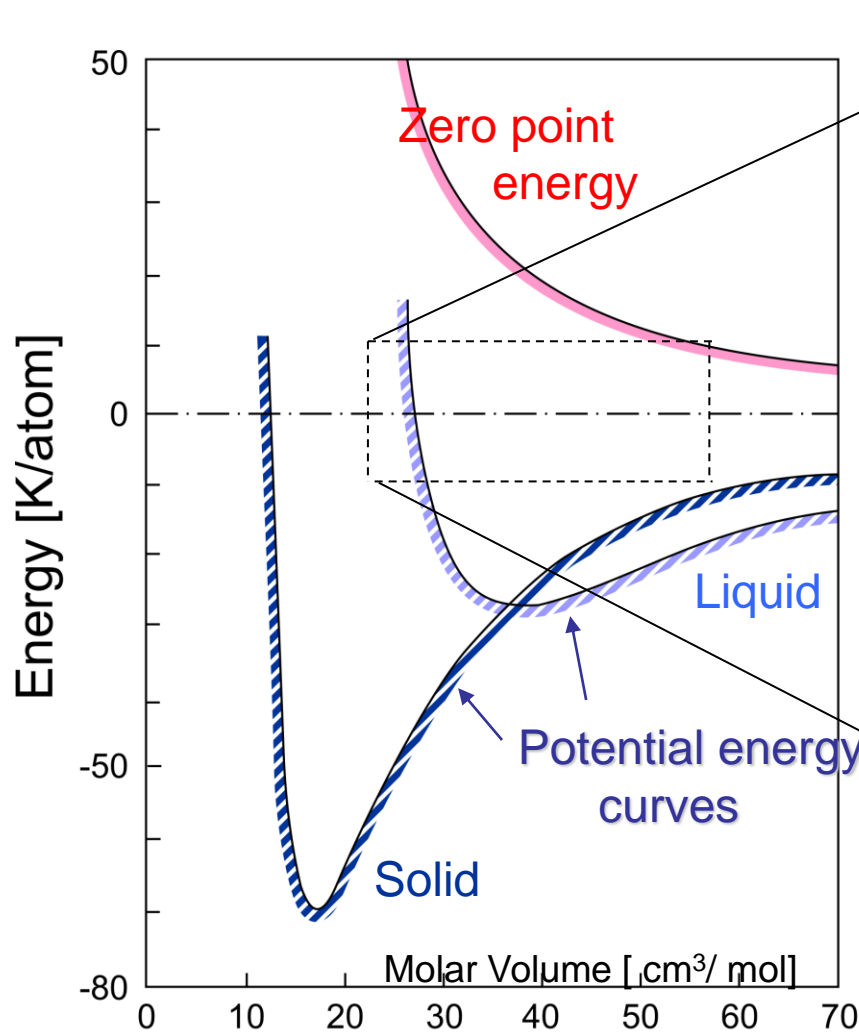
Helium, e. g. ⁴He



Below 2.2 K ⁴He is a superfluid

- Helium is the only substance which remains liquid down to the lowest achievable temperatures!
- Helium is the only substance known to be superfluid:
⁴He below 2.2 K; ³He below 3×10^{-3} K

In Solid and Liquid Helium the **Potential Energy** is Largely Compensated by the Large **Zero Point Energy**



The difference accounts for the very weak binding making **He the most tenuous of all liquids and solids**

Estimation of the Effect of Zero-Point Energy in a Quantum Solid

Condition for Stability:

$$|E_{pot}| \geq E_{kin}$$

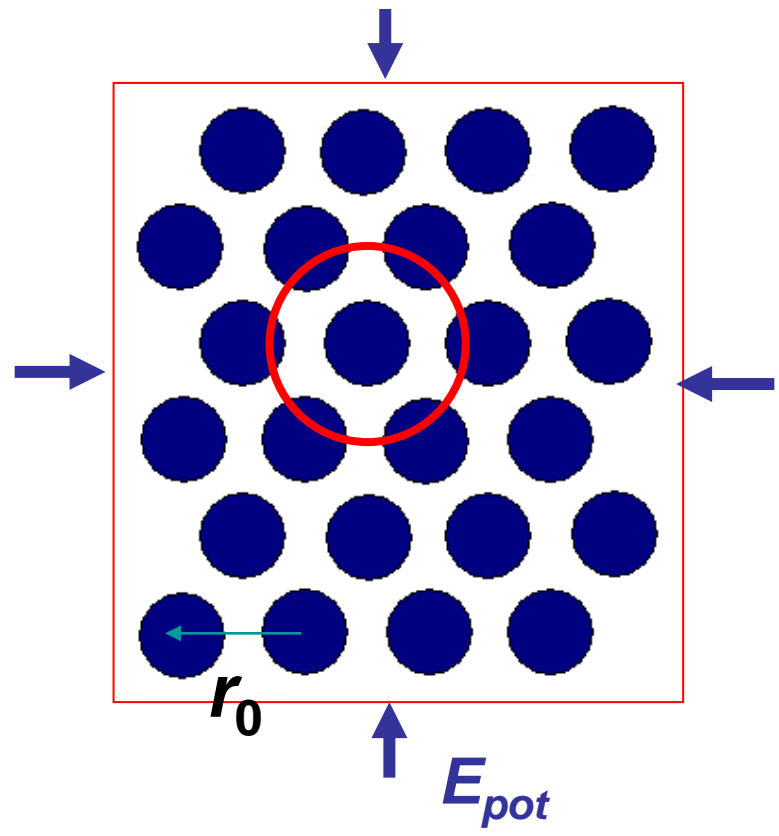
Estimate E_{kin} from Heisenberg's Uncertainty

$$\Delta r \Delta p \geq \frac{1}{2} \hbar$$

$$\Delta r \approx r_0$$

$$\Delta p \approx \sqrt{\langle p^2 \rangle} = \sqrt{2mE_{kin}}$$

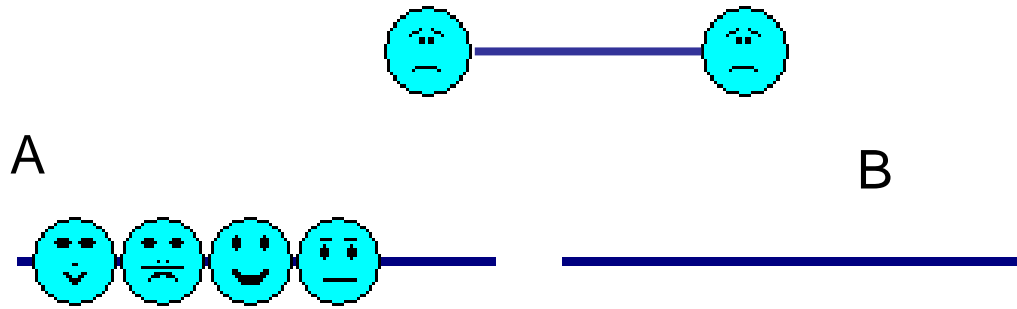
$$|E_{pot}| > E_{kin} \geq \frac{\hbar^2}{8mr_0^2}$$



Solid Helium is Barely Stable:

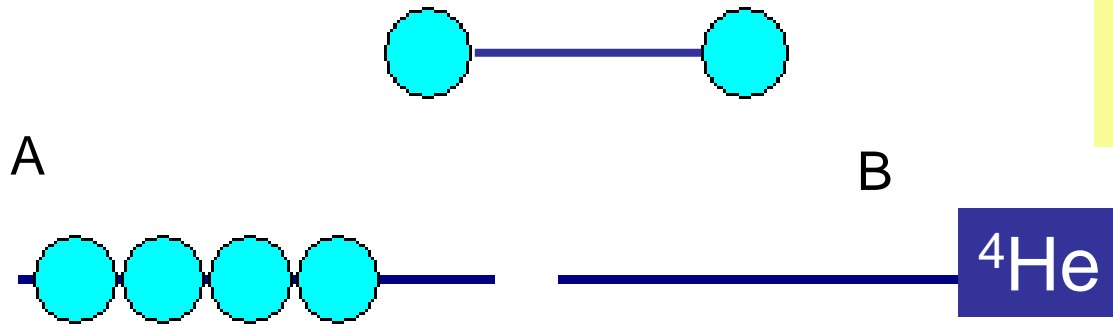
- attractive forces (E_{pot}) are weak
- both m and r_0 are small

A Simple Simulation Illustrating the 3 Basic Symmetries in Nature



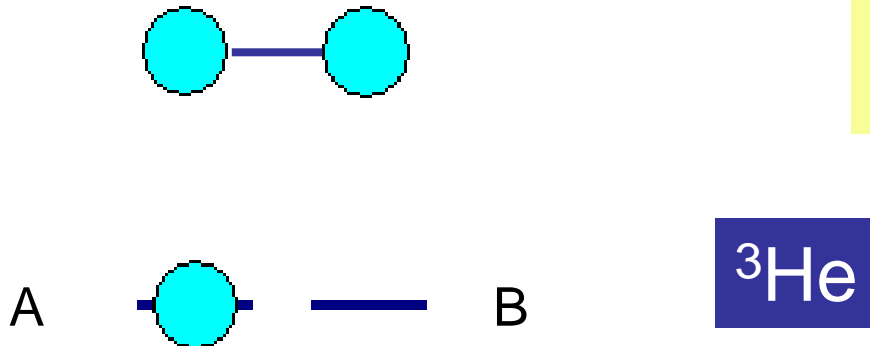
Classical (Maxwell-Boltzmann) statistics

$$P_A = P_B$$



Quantum Bose-Einstein statistics

$$P_A = 5P_B$$

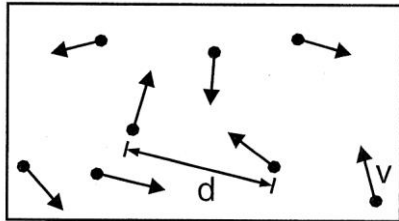


Quantum Fermi-Dirac statistics

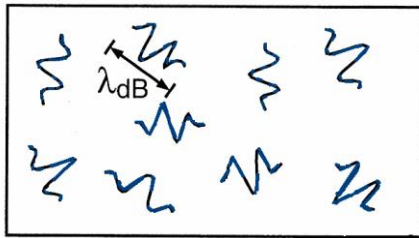
$$P_A = 0$$

Fermionic ${}^3\text{He}$'s are also repelled by Pauli exclusion!

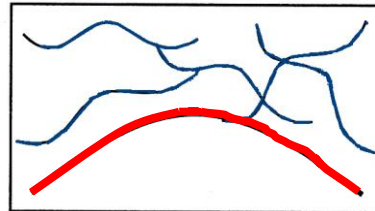
A Bose-Einstein Condensate (BEC) is a Macroscopically Coherent Quantum System



High Temperature T:
 thermal velocity v
 density d^{-3}
 "Billiard balls"

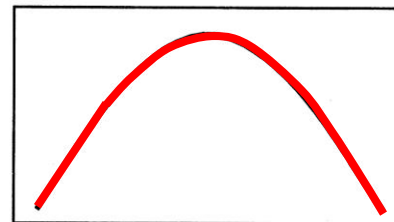


Low Temperature T:
 De Broglie wavelength
 $\lambda_{dB} = h/mv \propto T^{-1/2}$
 "Wave packets"

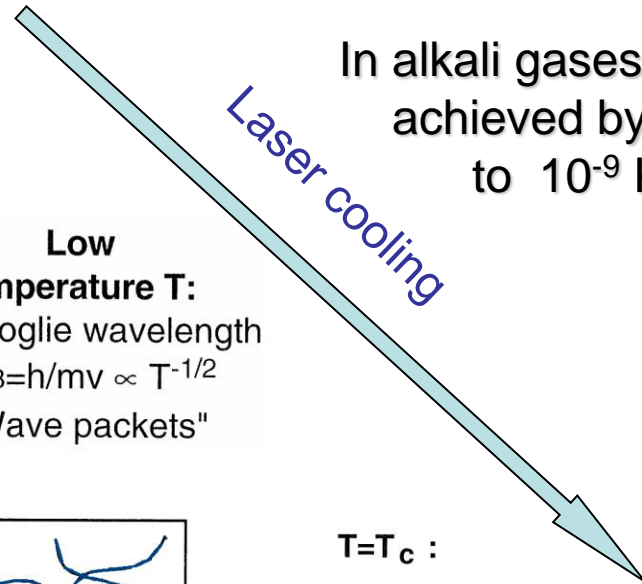


$T = T_c$:
BEC
 $\lambda_{dB} \approx d$
 "Matter wave overlap"

In the Bose-Einstein condensed gases the condensate fraction is 100%



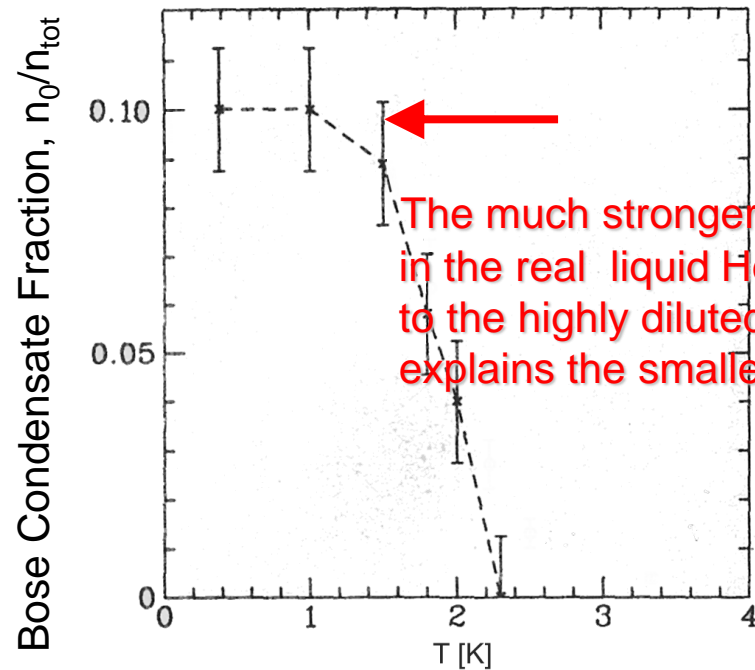
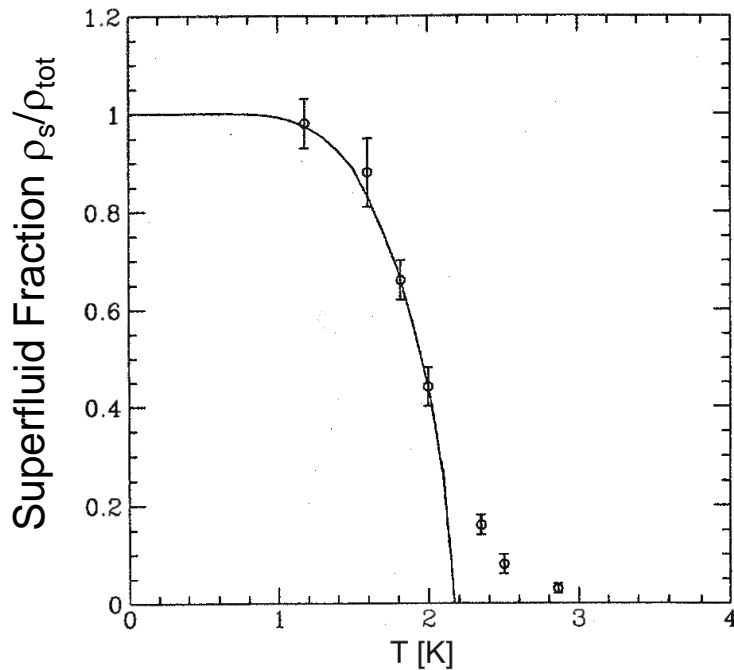
$T=0$:
Pure Bose condensate
 "Giant matter wave"



In alkali gases BEC is achieved by cooling to 10^{-9} K

What is a Superfluid?

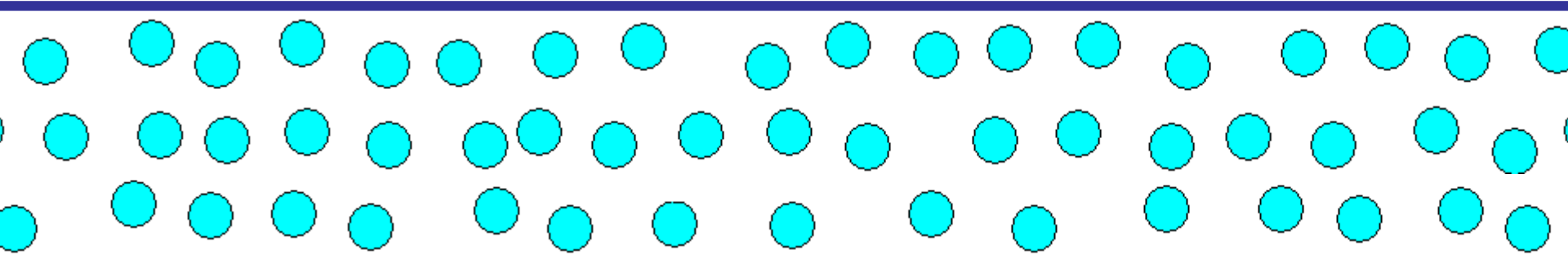
The Superfluid Fraction and the Bose Condensate Fraction are not the Same in Superfluid Helium



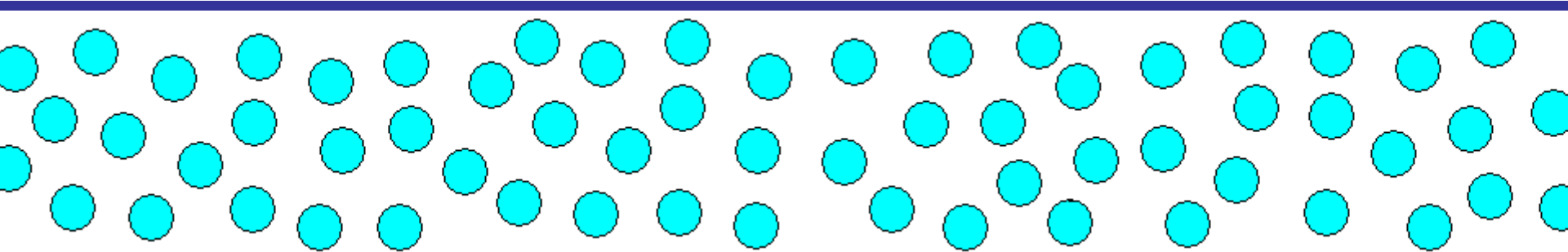
The much stronger interactions in the real liquid He compared to the highly diluted alkali gases explains the smaller n_0

The superfluid fraction is a model quantity whereas the Bose condensate fraction is physically defined, but hard to measure

Two-fluid model of the superfluid state (L. Tisza)



a normal (viscous) component with atoms having different excited-state velocities

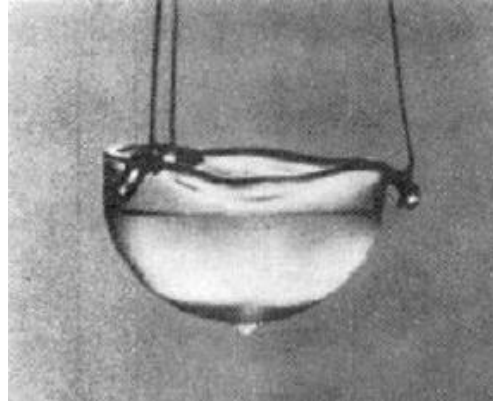


a superfluid component with all atoms having the same ground state velocity (BEC \Rightarrow no dissipation \Rightarrow zero viscosity)

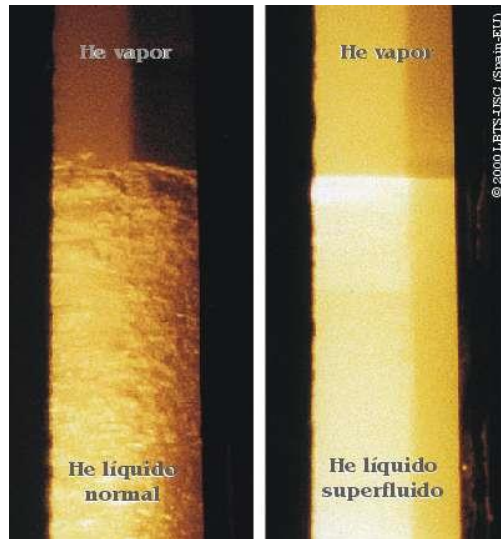
Some Macroscopic Manifestations of Superfluidity in ^4He

Creep:

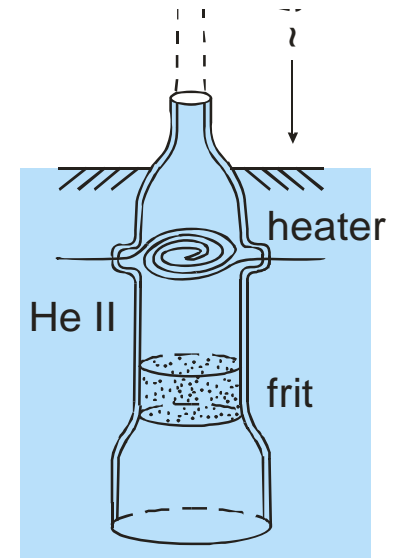
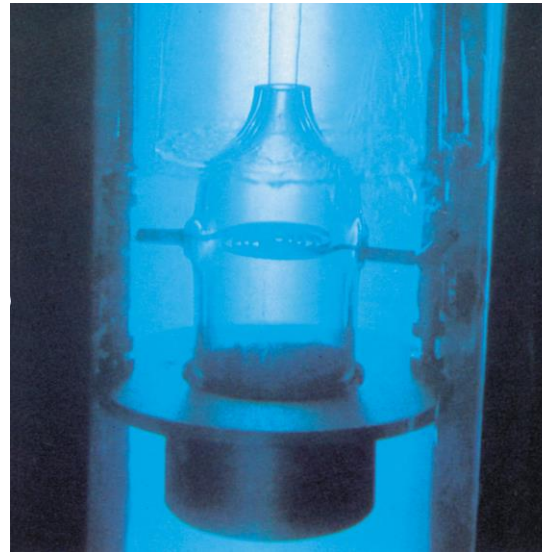
Superfluid helium can climb up the walls and go over the rim of a beaker and collect and drop off the bottom



Superfluid doesn't Boil



Fountain Effect



Microscopic Manifestations:

- frictionless translations $v \leq 58$ m/sec
- free rotations

Theory of Bose-Einstein condensation in trapped gases

Franco Dalfovo and Stefano Giorgini · Lev P. Pitaevskii · Sandro Stringari

Dipartimento di Fisica, Università di Trento and Istituto Nazionale per la Fisica della Materia, I-38050 Povo, Italy

VI. SUPERFLUIDITY AND COHERENCE PHENOMENA

Superfluidity is one of the most spectacular consequences of Bose-Einstein condensation. However, the explicit connection between superfluidity and BEC is not trivial and has been the object of a longstanding and deep investigation in the last decades, mainly for its importance in understanding the physics of liquid helium. In macroscopic bodies superfluidity shows up with many peculiar features: absence of viscosity, reduction of the moment of inertia, occurrence of persistent currents, new collective phenomena (second sound, third sound, etc.), quantized vortices, and others. Several properties

Fritz London in his famous book

SUPERFLUIDS

Volume II

Macroscopic Theory of Superfluid Helium

wrote in the Preface:



„ Superfluid helium, also called liquid helium II, is the only representative of a particular „fourth“ state of aggregation beside the solid, liquid, and gaseous states.“

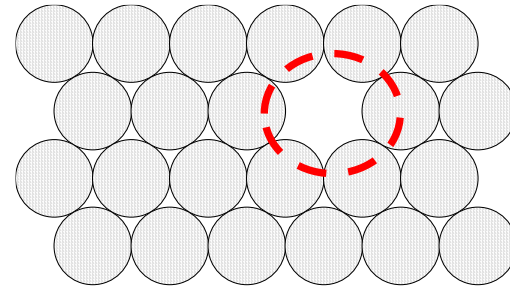
Solid Properties: ^4He Compared to Ar

Solid ^4He like Ar has a well defined lattice structure (X-rays) and well-defined phonon dispersion curves (neutron diffraction)

Property	Ratio with respect to Ar
Elastic Constants \mathbf{C}_{11}	$\approx 1-2 \cdot 10^{-2}$
Compressibility $K = \frac{1}{V} \frac{dV}{dP}$	≈ 10
Thermal conductivity λ	≈ 60
Reduced molar volume: $\nu = V / R_0^3$	≈ 2
Lindemann ratio L the ratio of the root mean squared vibrational amplitude to the interatomic distance	≈ 2

Vacancies in Solids

A vacancy is an empty lattice site



Vacancies are always present in a crystal because of the corresponding increase in entropy

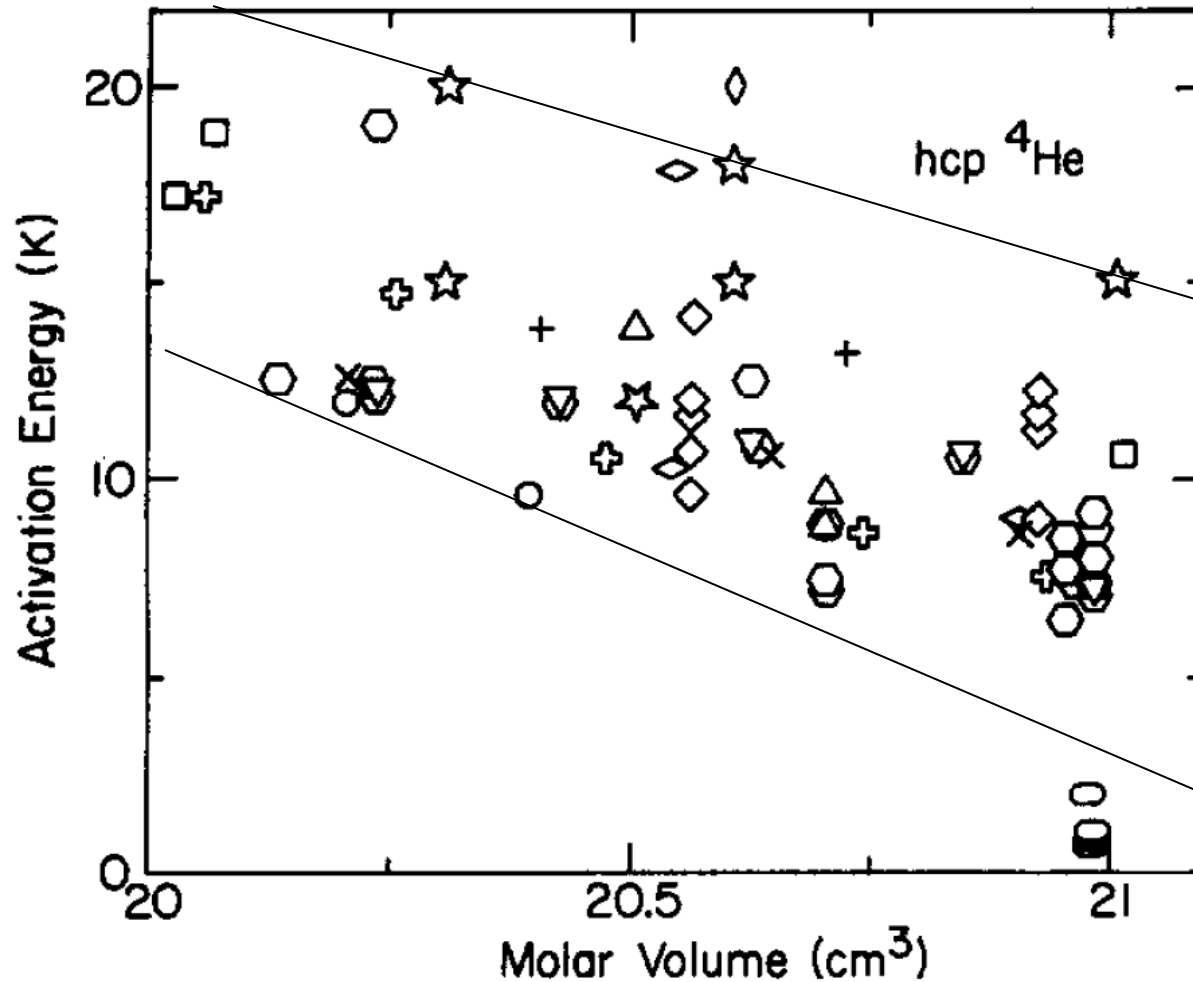
Their concentration is given classically by

$$x_v \propto \exp(-\phi/T)$$

Activation (formation) energies ϕ in solid ^4He are very small and rather uncertain: $\phi \approx 10$ K. $x_v = 0$ at $T = 0$ K

Vacancies in a quantum crystal are predicted to form delocalized bands even at $T = 0$ K. Expt's ??

The Uncertainty in the Activation Energy for Vacancy Formation is Large

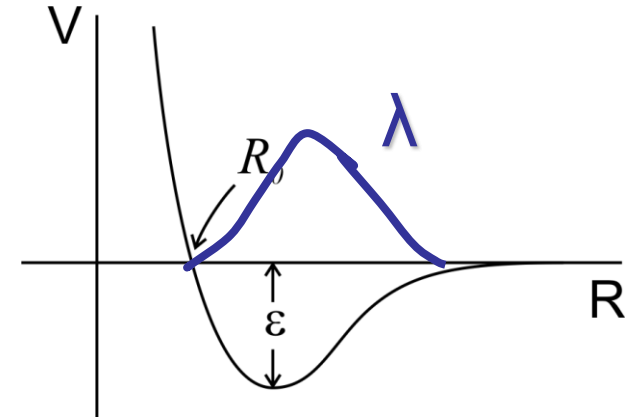


What is a Supersolid? I.

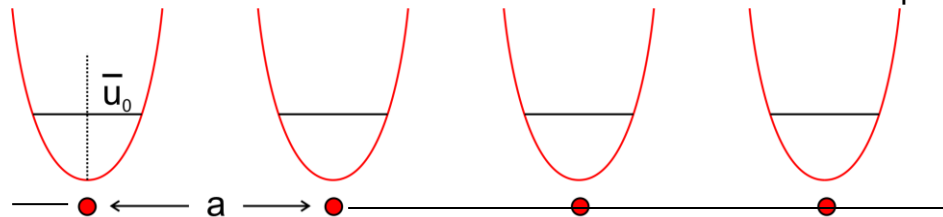
Andreev-Lifshitz Theory

The de Boer parameter Λ is used to account for quantum effects

$$\Lambda \left(= \frac{h\sqrt{m\varepsilon}}{R_0} \right) \approx \frac{\bar{u}_0^2}{a^2}$$

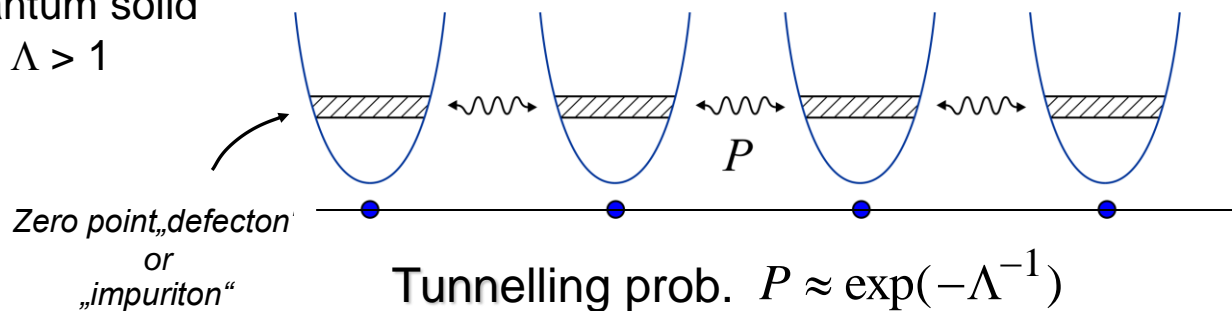


Classical solid
 $\Lambda < 1$



e.g. Ar $\Lambda = 0.2$

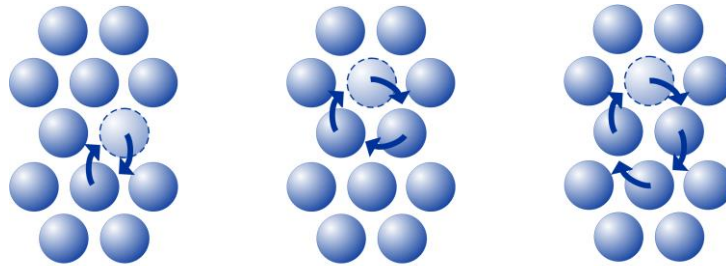
Quantum solid
 $\Lambda > 1$



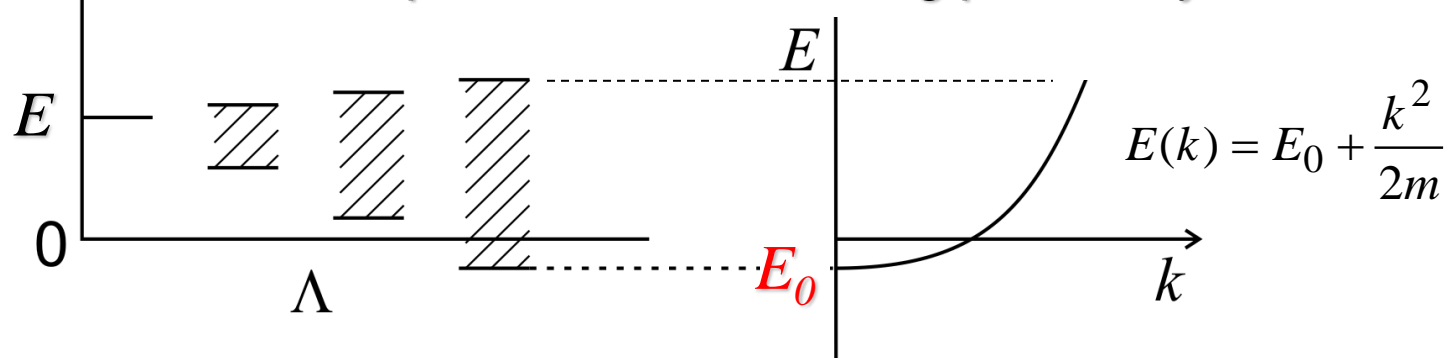
e.g. ${}^4\text{He}$ $\Lambda = 2.87$

Andreev-Lifshitz Theory, Continued

Tunnelling is thought to Involve the exchange of particles



The width of the band depends on the tunneling probability



$E_0 < 0 \Rightarrow$ a new lower energy „incommensurate“ vacancy state
(no. lattice sites \neq no. atoms) appears

Being incommensurate this state can support mass transport

**Bose-Einstein condensation of $E_0 < 0$ zero-point vacancies (Bosons!)
leads to superfluid flow**

How Does a Supersolid Compare to a Superfluid?

	Superfluid helium	Supersolid helium
	Well established!	Estimates ¹⁾
Transition Temperature:	$T_c = 2.2 \text{ K}$	$T_c \leq 0.1 \text{ K}$
Superfluid Fraction:	$\rho_s / \rho_{\text{tot}} = 1.0$	$\rho_s / \rho_{\text{tot}} \leq 3 \times 10^{-3}$
Critical velocities:	$v_{\text{crit}} \approx 58 \text{ m/sec}$	$v_{\text{crit}} \leq 10^{-4} \text{ cm/sec}$

¹⁾ From the review by Meisel, Physica B178, 121 (1992)

Below T_c and below v_{crit} the flow of the solid should exhibit reduced friction.

The Idea Behind the Experiment of Kim and Chan

In 1970 Leggett suggested that *nonclassical rotational inertia (NCRI)* found in superfluid liquid helium may also occur in solid helium

The free energy of N helium atoms in a crystalline annulus of internal radius R and thickness d , rotating about the axis of the cylinders at constant angular velocity ω is

$$F(\omega) = F_0 + \frac{1}{2} I_0 \omega^2 + \Delta F(\omega)$$

where F_0 = Free energy for $\omega = 0$

and I_0 = Classical moment of inertia, $I_0 = Nm/2 \cdot (R^2 + (R+d)^2)$

$$\text{and } \Delta F(\omega) = -\frac{1}{2} (\rho_s / \rho) I_0 \omega^2$$

↑
Superfluid Fraction

SUPERFLUIDITY AND THE MOMENTS OF INERTIA OF NUCLEI

A. B. MIGDAL

Submitted to JETP editor February 13, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) 37, 249-263 (July, 1959)

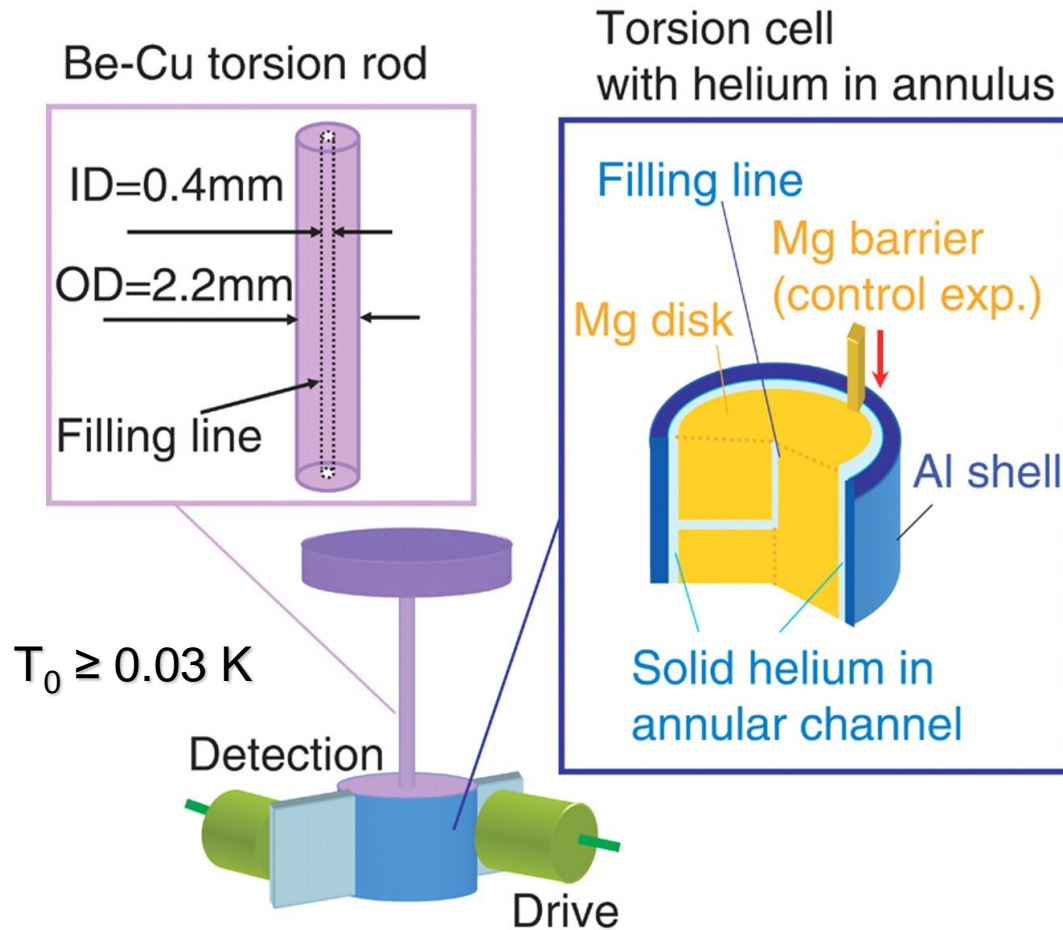
A method is developed for the treatment of superfluidity of nuclei. A formula which agrees satisfactorily with experiment is obtained for the moment of inertia of a nucleus. An expression is found for the change in the energy of "pairing" in the transition from an even-even to an even-odd nucleus, and also for the change in the moment of inertia associated with this transition.

The existence of correlated pairs and superfluidity is evidenced most clearly in nuclear moments of inertia. The moments of inertia of nuclei are two or three times smaller than those computed from the formula for the moment of inertia of a solid, and this is the most direct evidence for the superfluidity of nuclear matter.

Therefore, there is fundamental interest in the calculation of moments of inertia of nuclei on the basis of the modern theory of superfluidity of Fermi-systems. The formalism of this theory has been developed for homogeneous, unbounded systems.⁴ However, in the case of a nucleus, the finite dimensions of the system are found to be very important.

The Kim and Chan Experiment 2004

The Torsional Oscillator Commonly Used to Detect Superfluidity



The torsional Frequency is measured

$$\tau_0 = 2\pi \sqrt{\frac{I}{\kappa}}$$

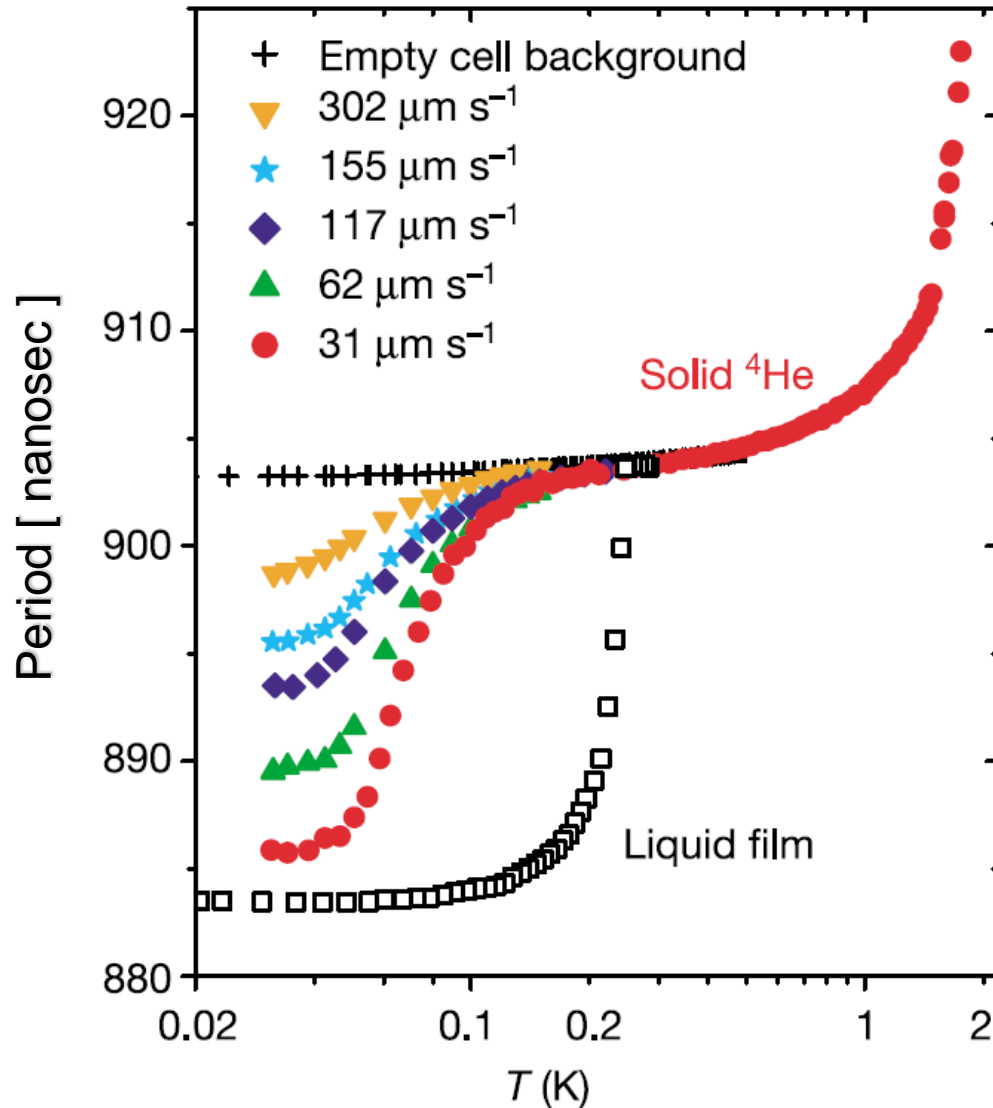
Where I is the moment Of inertia, κ is the spring constant

The resolution is very good

$$\frac{\delta\tau}{\tau_0} = 5 \times 10^{-7}$$

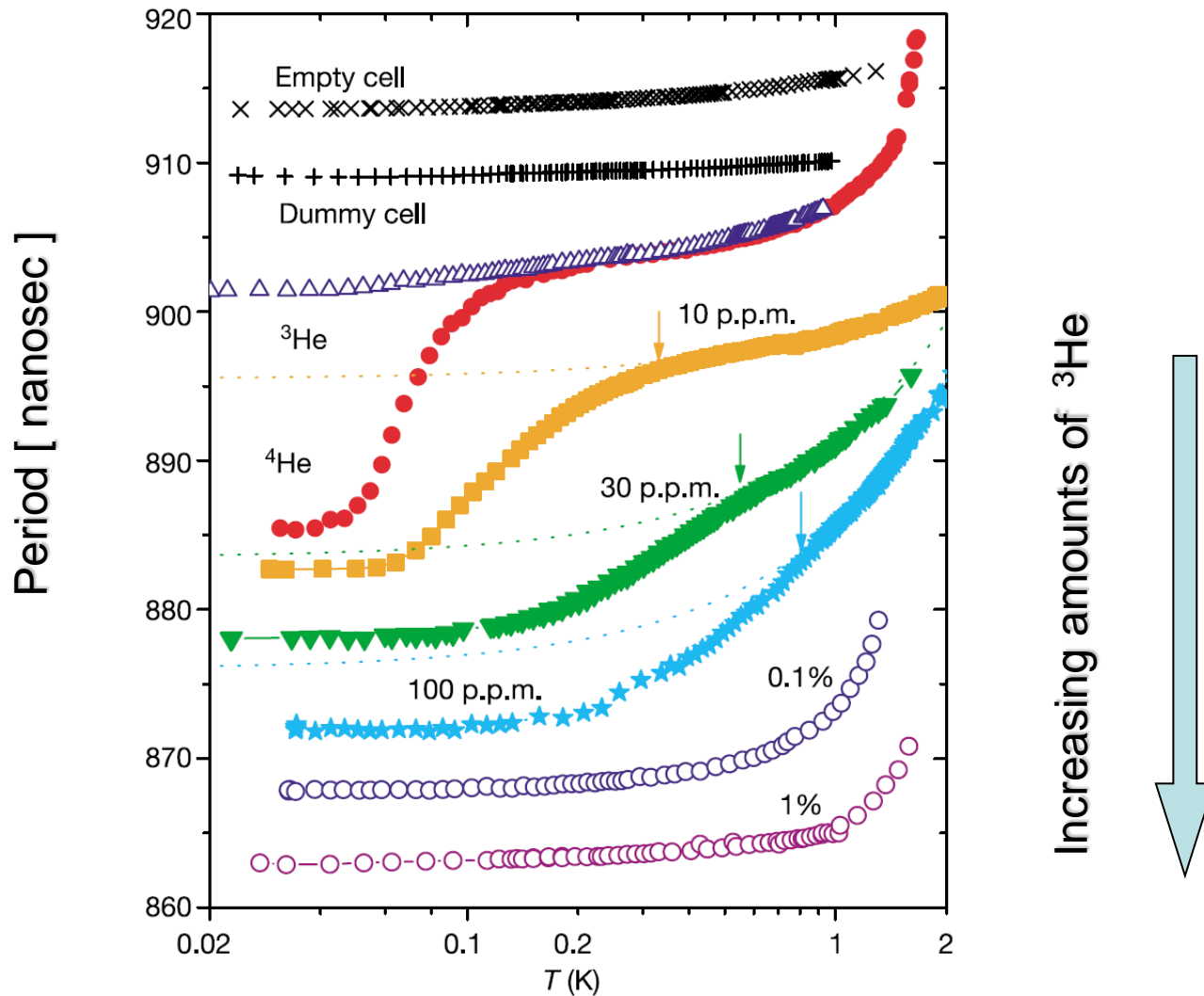
Method: Berthold, Bishop and Reppy, Phys. Rev. Lett. 39, 348 (1977)

Change in Period Reveals Change in Moment of Inertia



E. Kim and M. H. W. Chan, Nature 427, 225 (2004); Science 305, 1941 (2004)

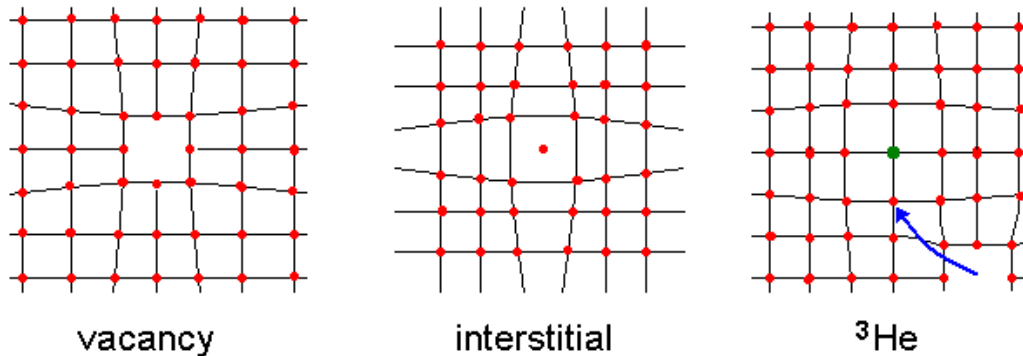
Small Amounts of ^3He Have a Big Effect



E. Kim and M. H. W. Chan, *Nature* **427**, 225 (2004); *Science* **305**, 1941 (2004)
 ^3He in ^4He

^3He in Solid ^4He

- Soluble in small concentrations
- Expected to annihilate a vacancy,
Binding energy is about 1 K ¹⁾

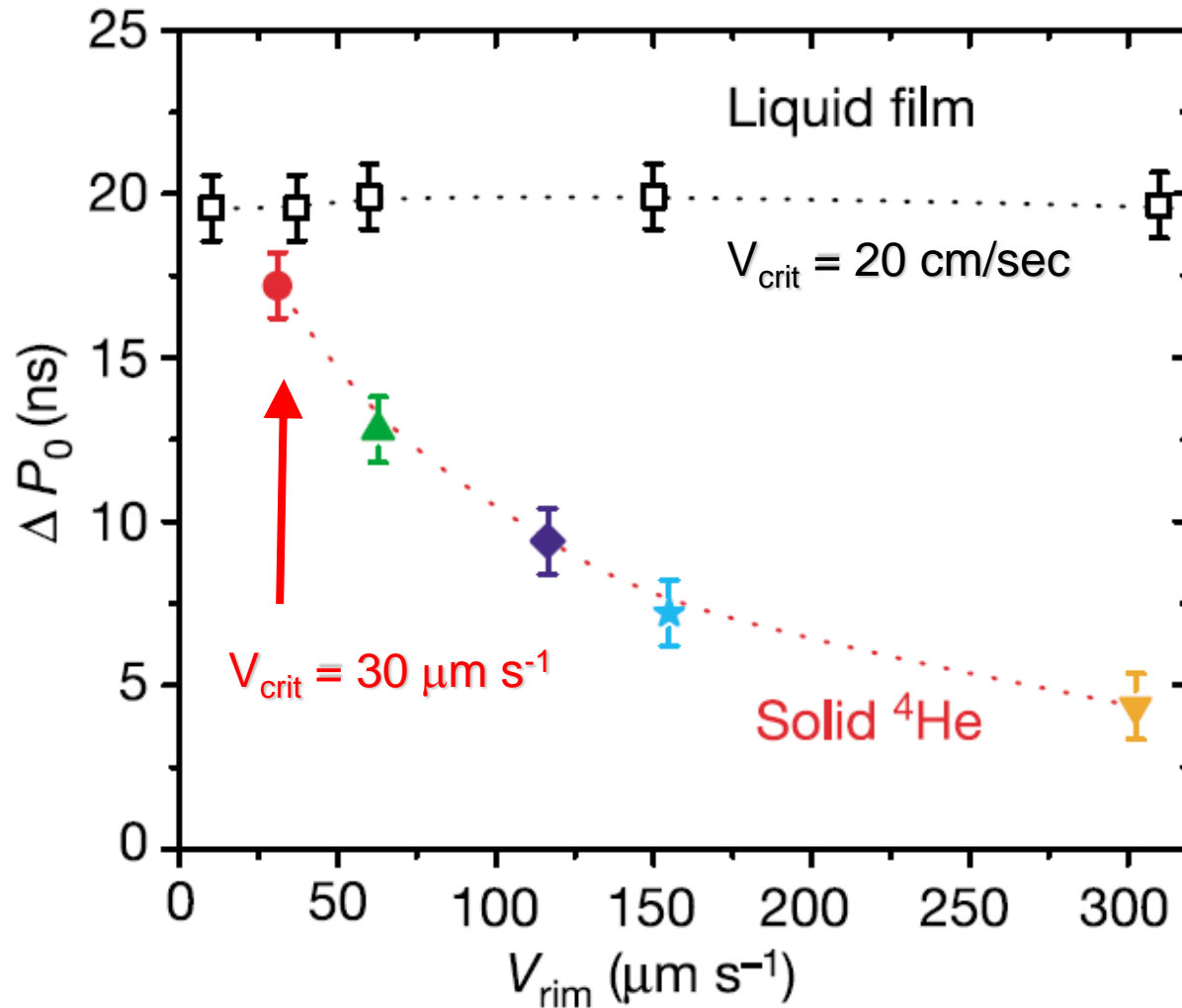


- Highly mobile delocalized Impuriton band
may also segregate to dislocations or interfaces ²⁾

1) Scuster, Swirsky, Schmidt, Polturak and Lipson, Europhys. Lett. 33, 623 (1996)

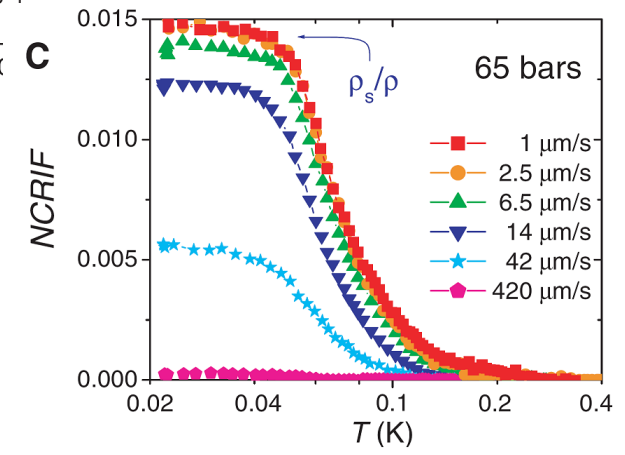
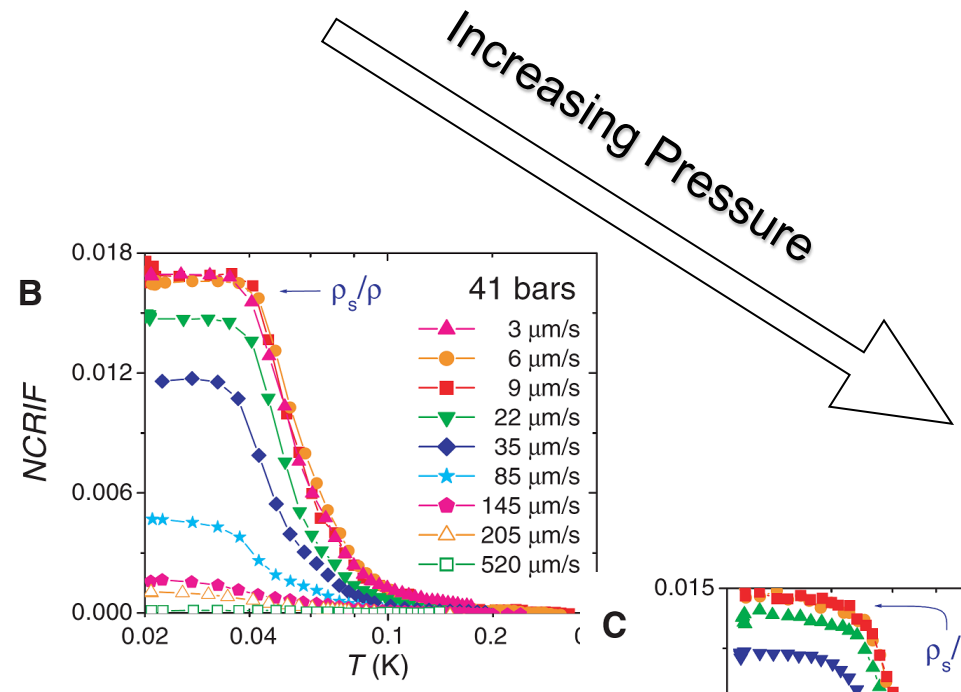
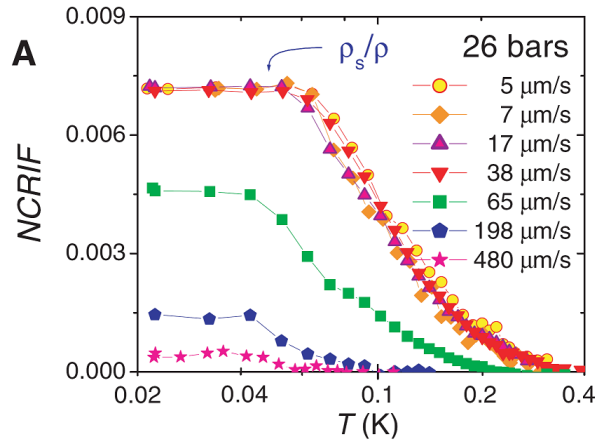
2) Carmi, polturak and Lipson, Phys. Rev. Lett. 62, 1364 (1989)

Change in Period has a Strong Velocity Dependence

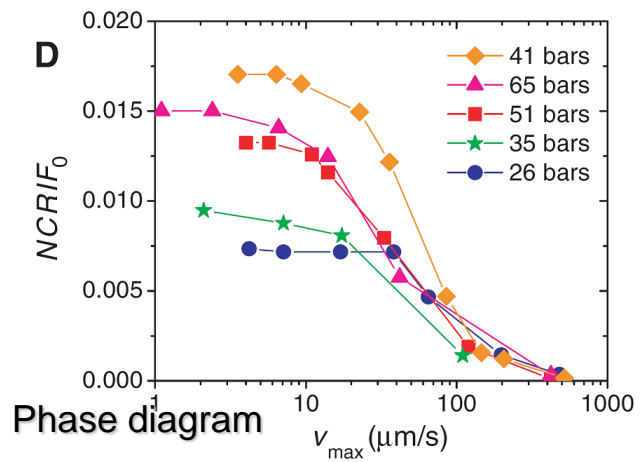


E. Kim and M. H. W. Chan, Nature 427, 225 (2004); Science 305, 1941 (2004)

Non-Classical Rotational Inertia Fraction as Function of Pressure

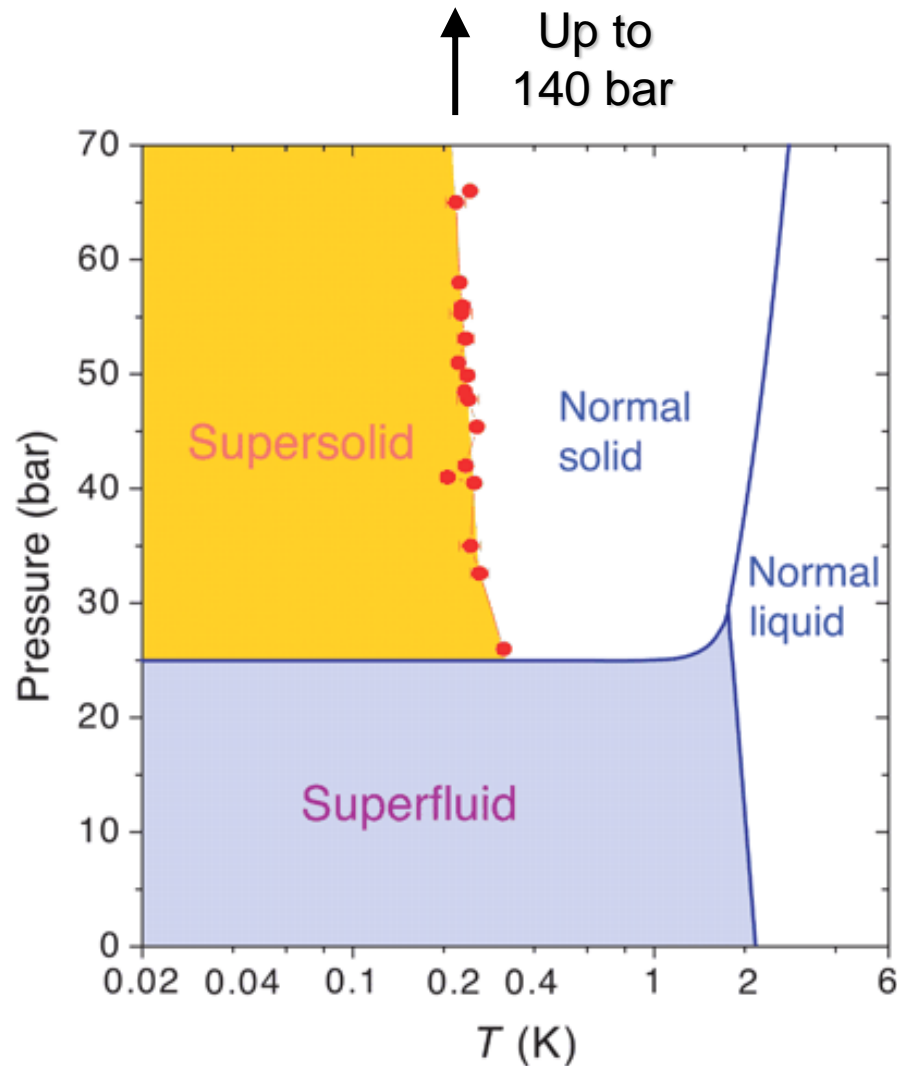


Velocity Dependence at Different Pressures



E. Kim and M. H. W. Chan, Nature 427, 225 (2004);
Science 305, 1941 (2004)

Phase Diagram: Pressure Dependence



E. Kim and M. H. W. Chan, *Nature* 427, 225 (2004); *Science* 305, 1941 (2004)

Some Alternative Explanations of Kim and Chan Expts:

2004

A. J. . Leggett: No. of atoms \neq no. of lattice sites: Solid is incommensurate and may have zero-point vacancies at $T = 0K$: BEC?

A. J. . Leggett: Sample contains large no. of large defects such as dislocations

2005

G. Dash: Grain boundary premelting to produce liquid at container walls. Slippage explains obs.

P.W. Anderson: Critical fluctuations (near some critical point) destroy supersolid by formation of vortex state or by other mechanism. Possibly $T_c \ll 50$ mk. BEC??

2006

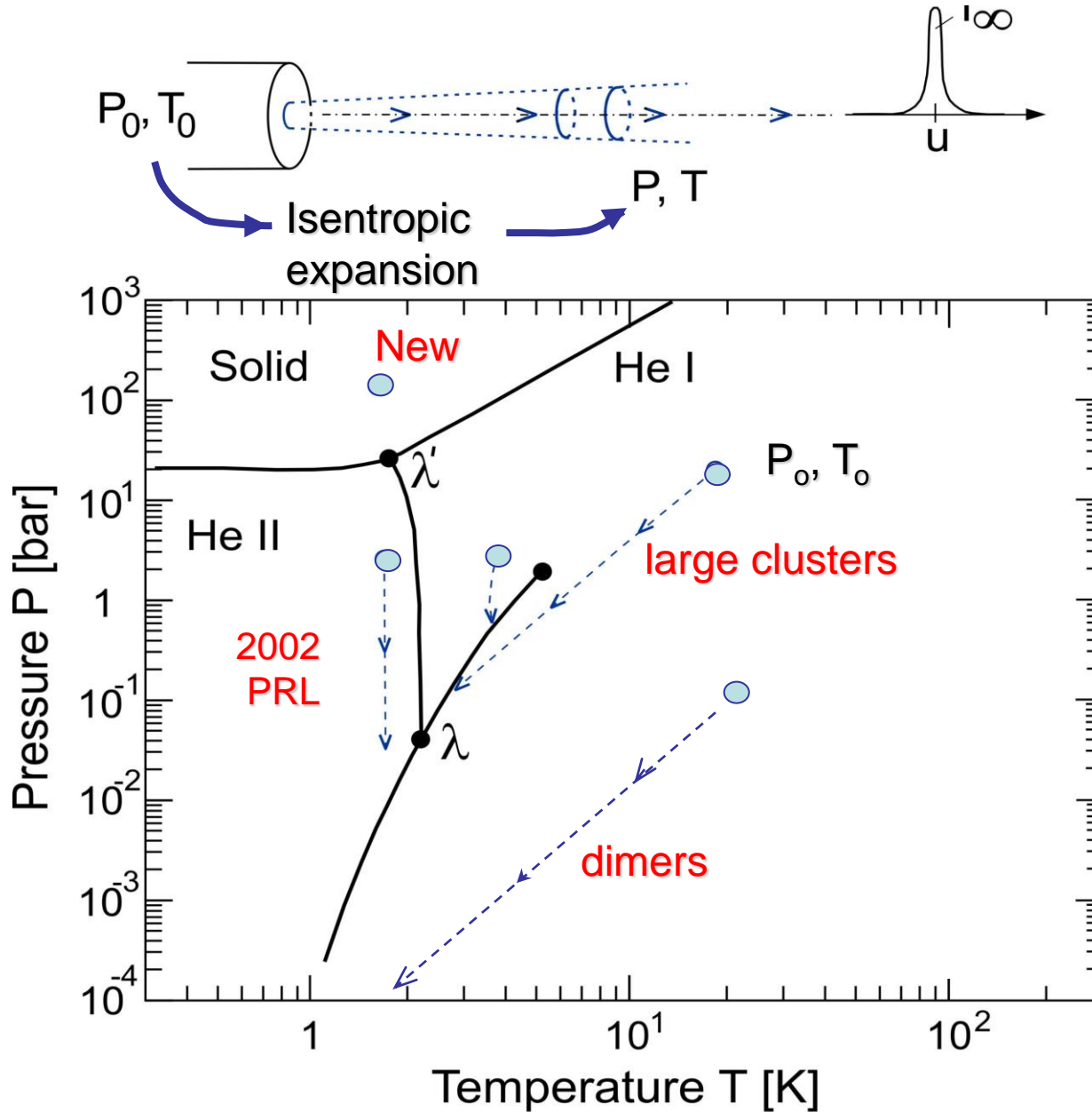
J. Reppy: BEC only in samples not sufficiently annealed: Disorder necessary!

J. Beamish
and
J. Goodkind: Ppb ^3He enhance/destroy BEC?

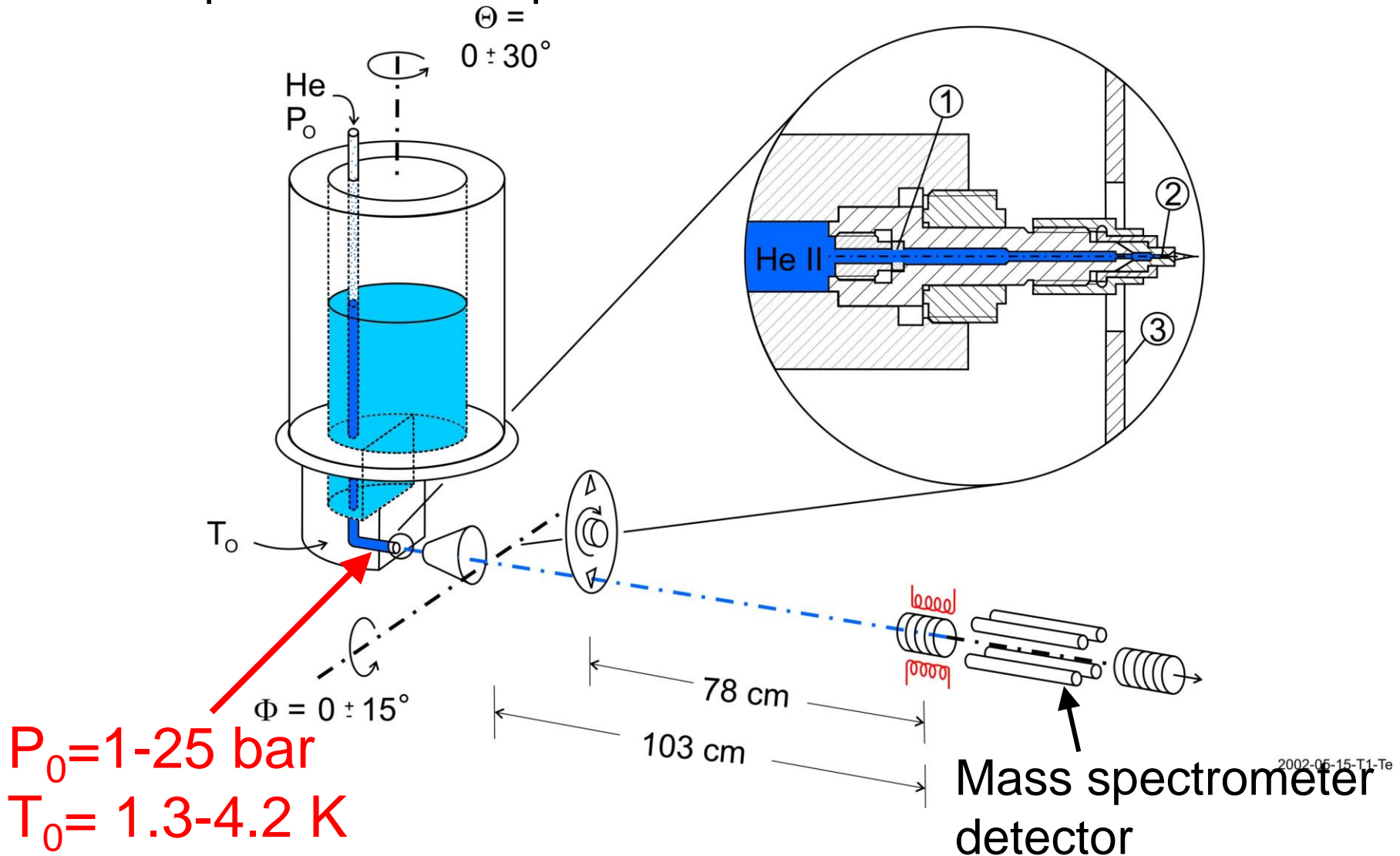
At present there is still no conclusive evidence for the supersolid state of helium!
geysers

The Geyser Phenomenon

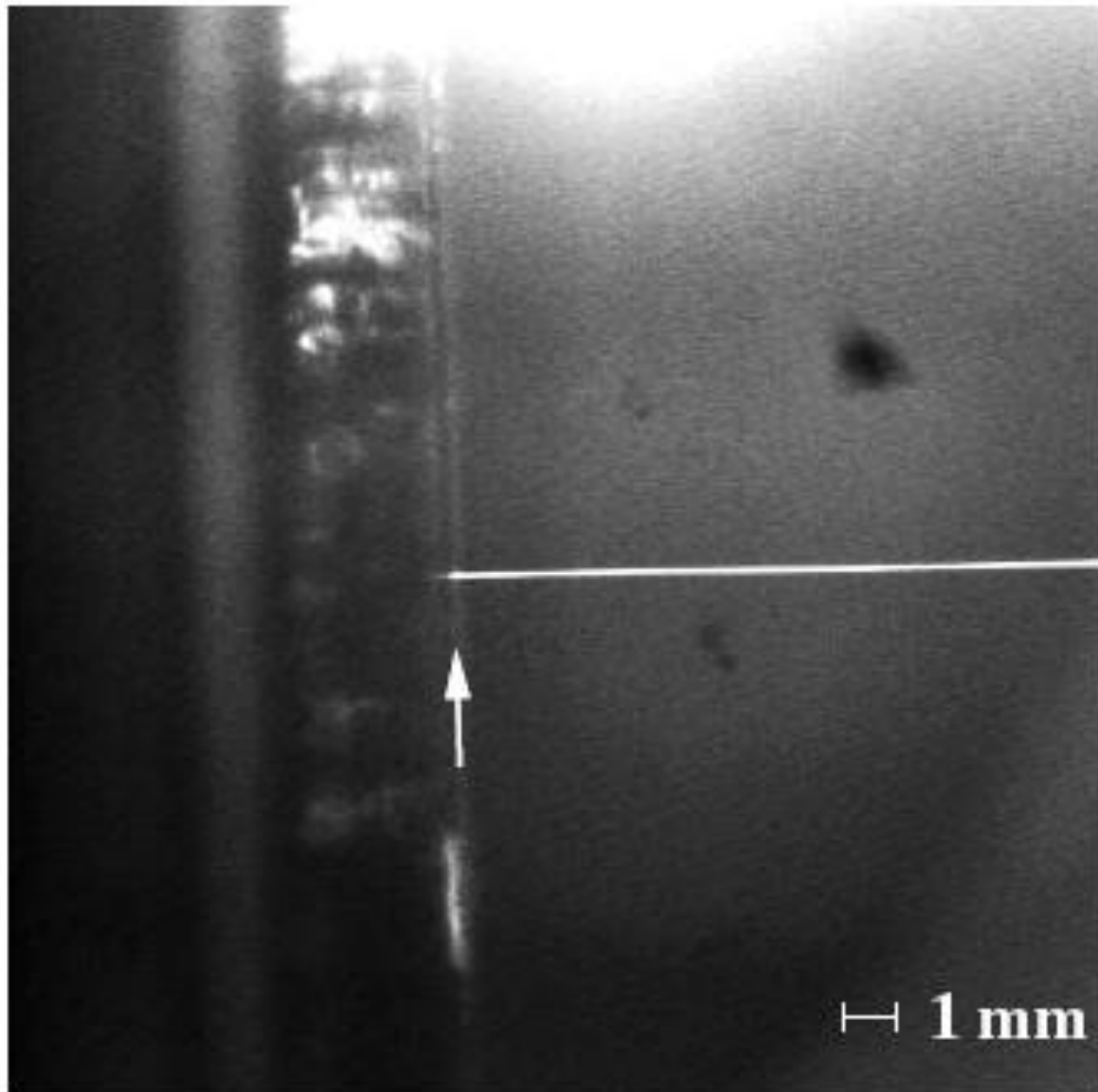
He Expansions: Initial Conditions and Isentropes



Starting 2001 Our Group Investigated Expansions of Superfluid Helium into Vacuum.

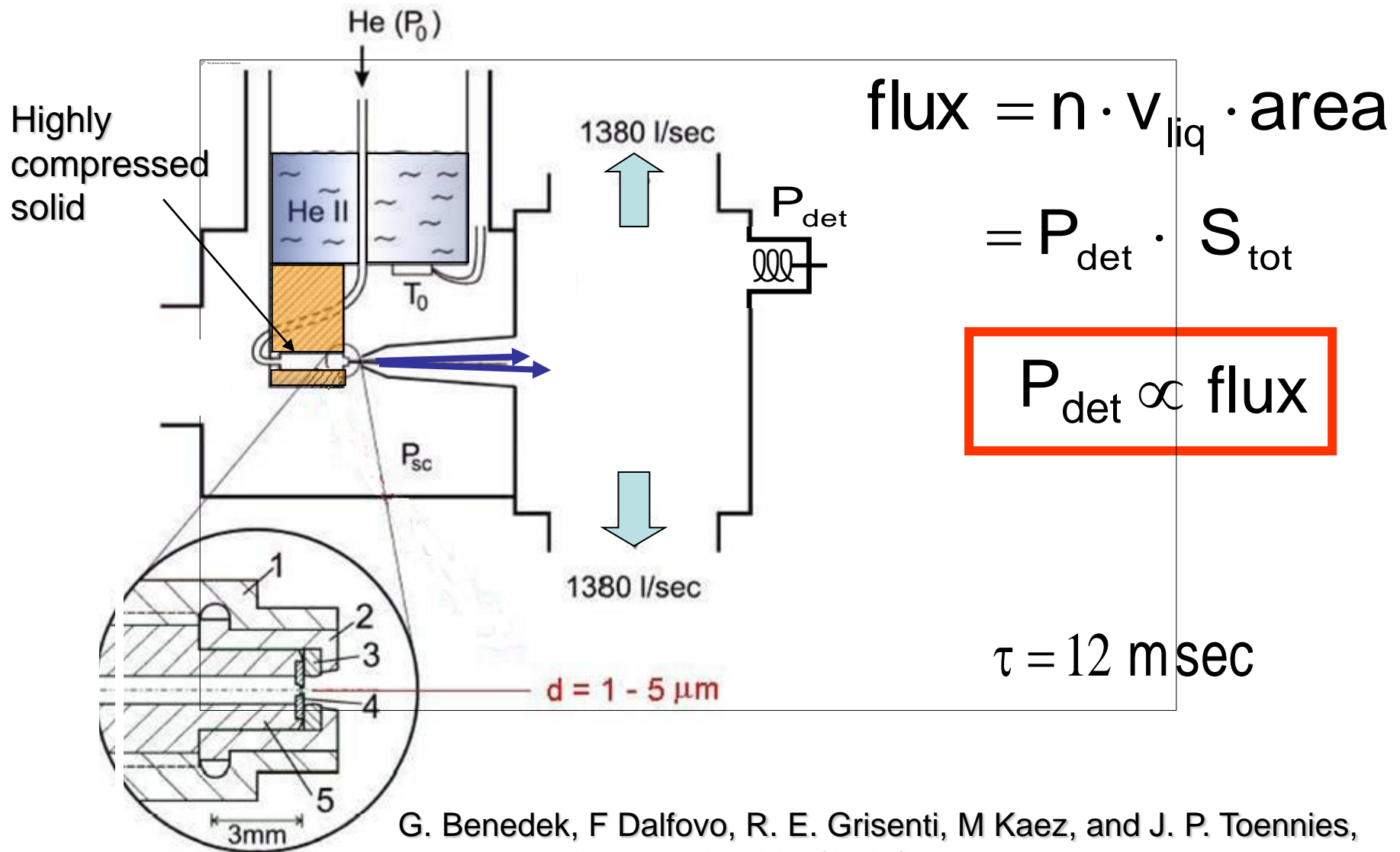


Observation of Liquid Jet



$$v_{\text{liq}} = 200 \text{ m/sec}$$

Apparatus: Expansion of Solid into Vacuum



$$\text{flux} = n \cdot v_{liq} \cdot \text{area}$$

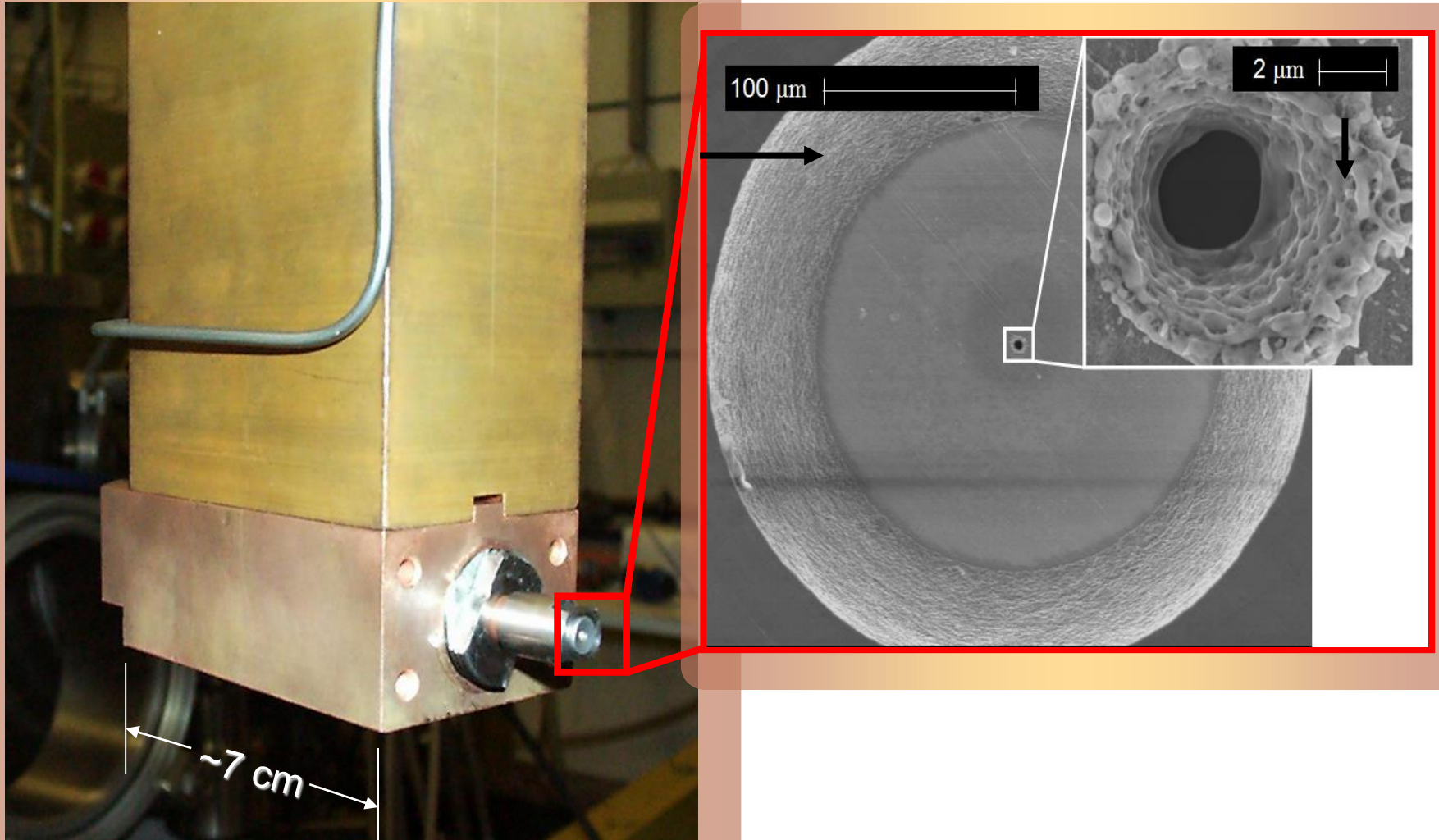
$$= P_{det} \cdot S_{tot}$$

$$P_{det} \propto \text{flux}$$

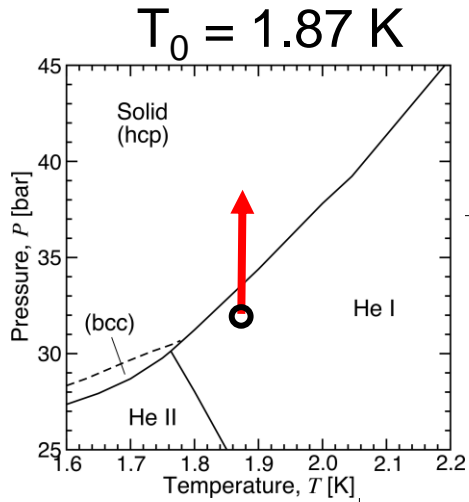
$$\tau = 12 \text{ msec}$$

G. Benedek, F Dalfovo, R. E. Grisenti, M Kaez, and J. P. Toennies,
 Phys. Rev. Lett. 95, 095301 (2005)

Photograph of Source Cell and Aperure Platelet and Orifice



Geyser Oscillations appear at Solidification Pressure

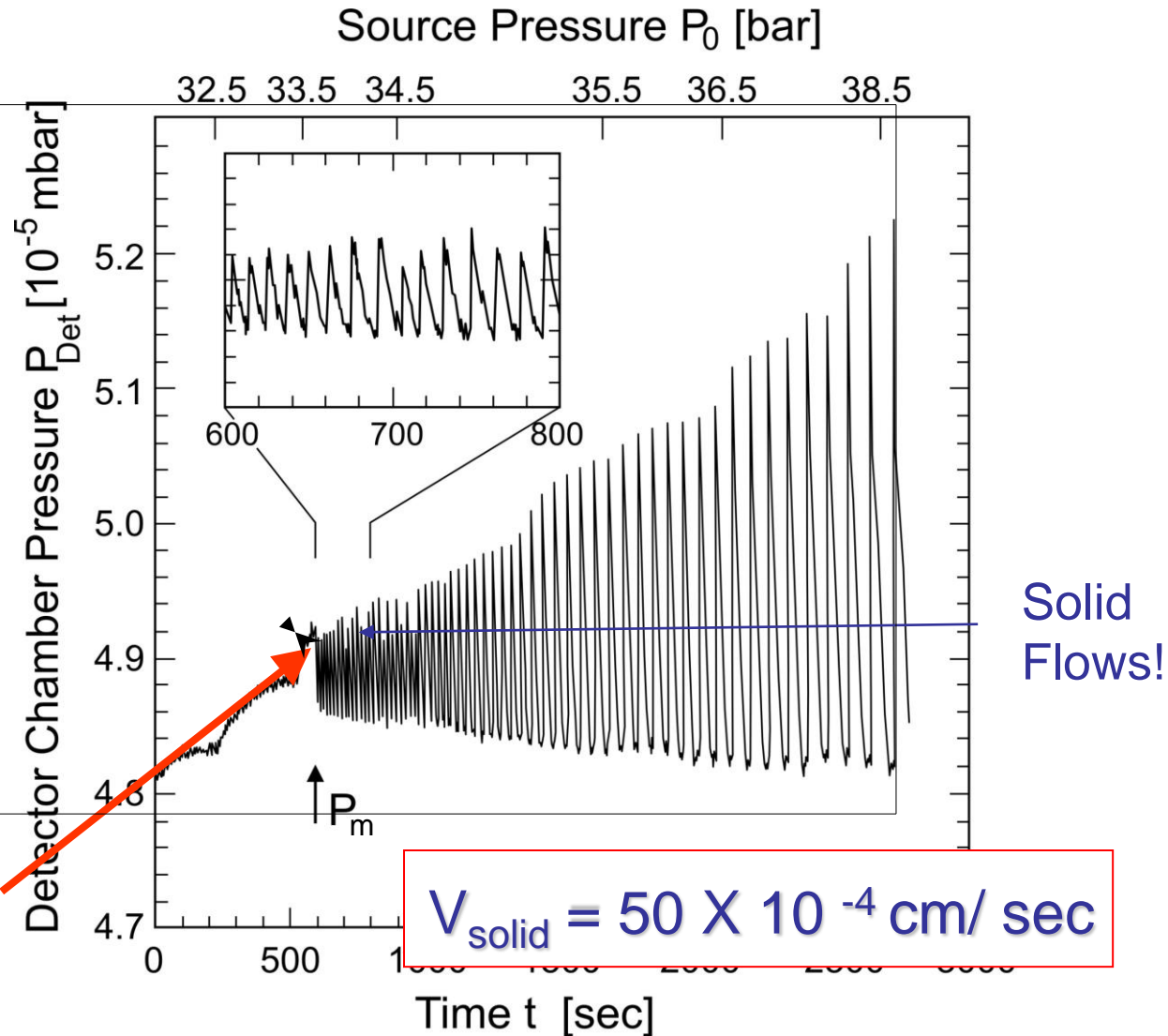


Flux of fluid follows Bernoulli's law

$$\Phi = n \cdot v$$

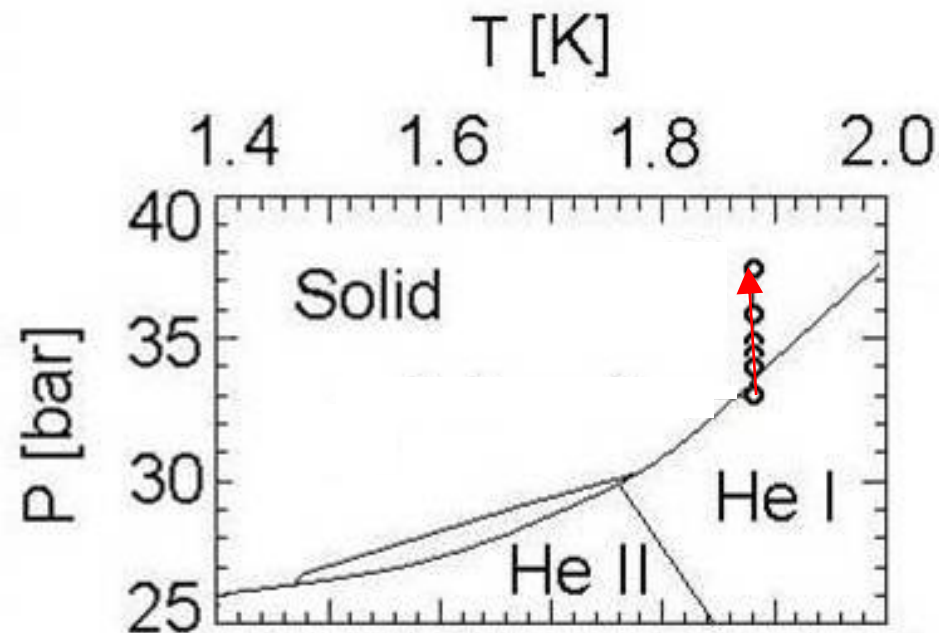
$$v = \sqrt{2P_0 / \rho_0}$$

Reg. behavior

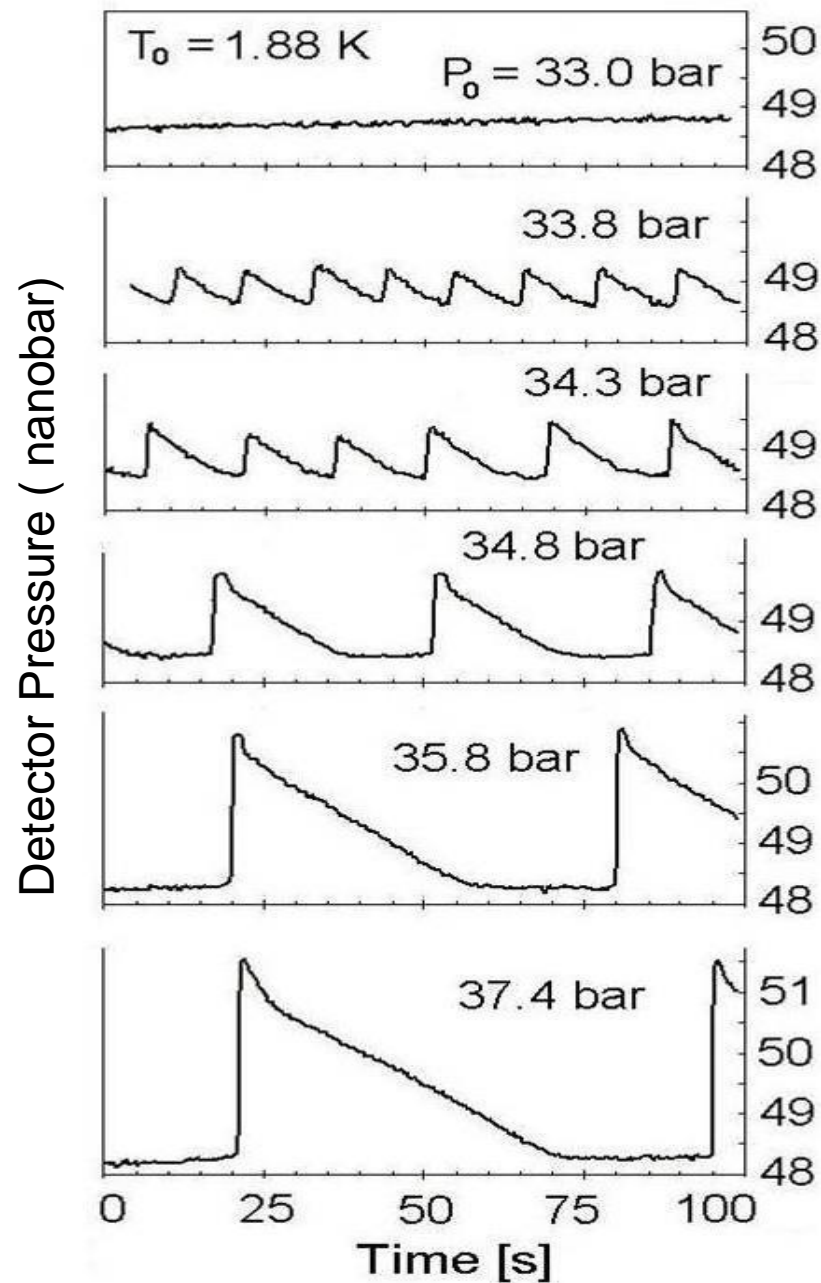


Normal Behaviour

$T_0 = 1.88 \text{ K}$

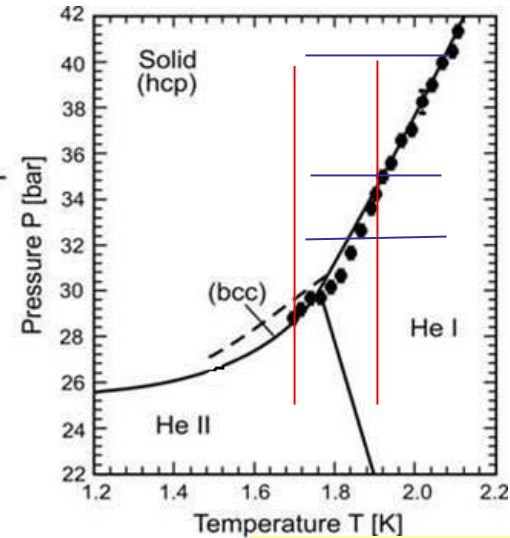
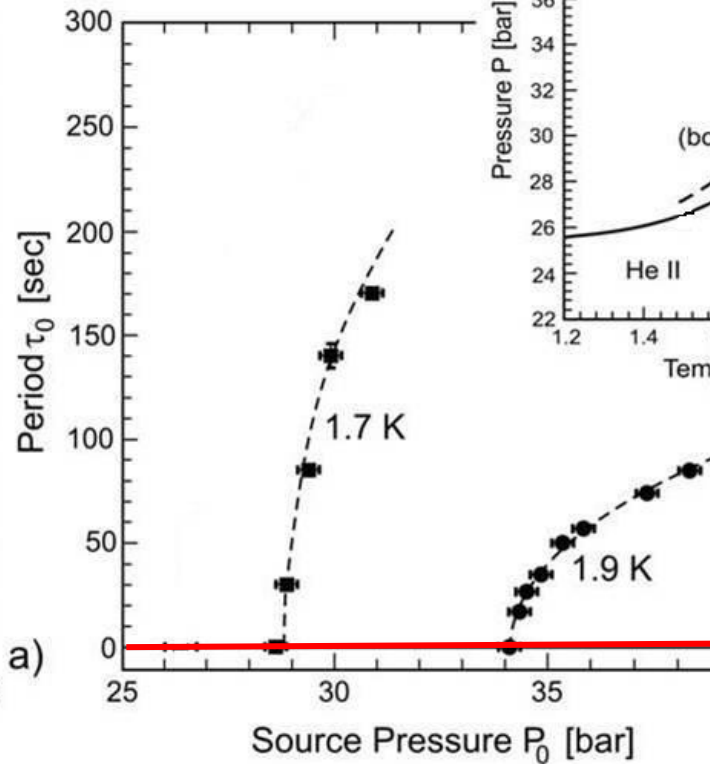
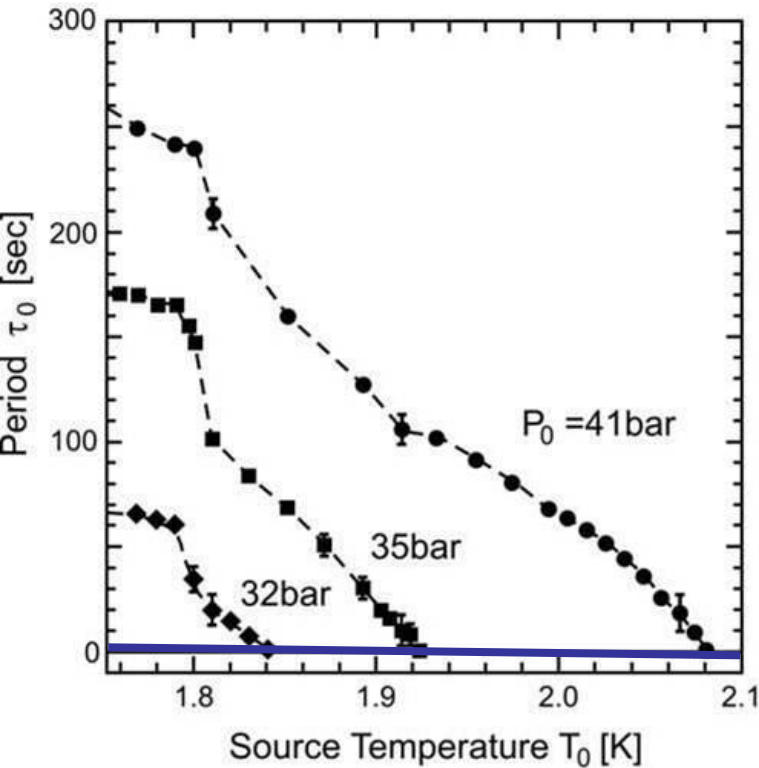


G. Benedek, F Dalfovo, R. E. Grisenti, M Kaez,
and J. P. Toennies,
Phys. Rev. Lett. 95, 095301 (2005)



Temperature and Pressure Dependence of Period

Normal Behavior



$$\tau_0 \propto (P - P_m)^\gamma$$

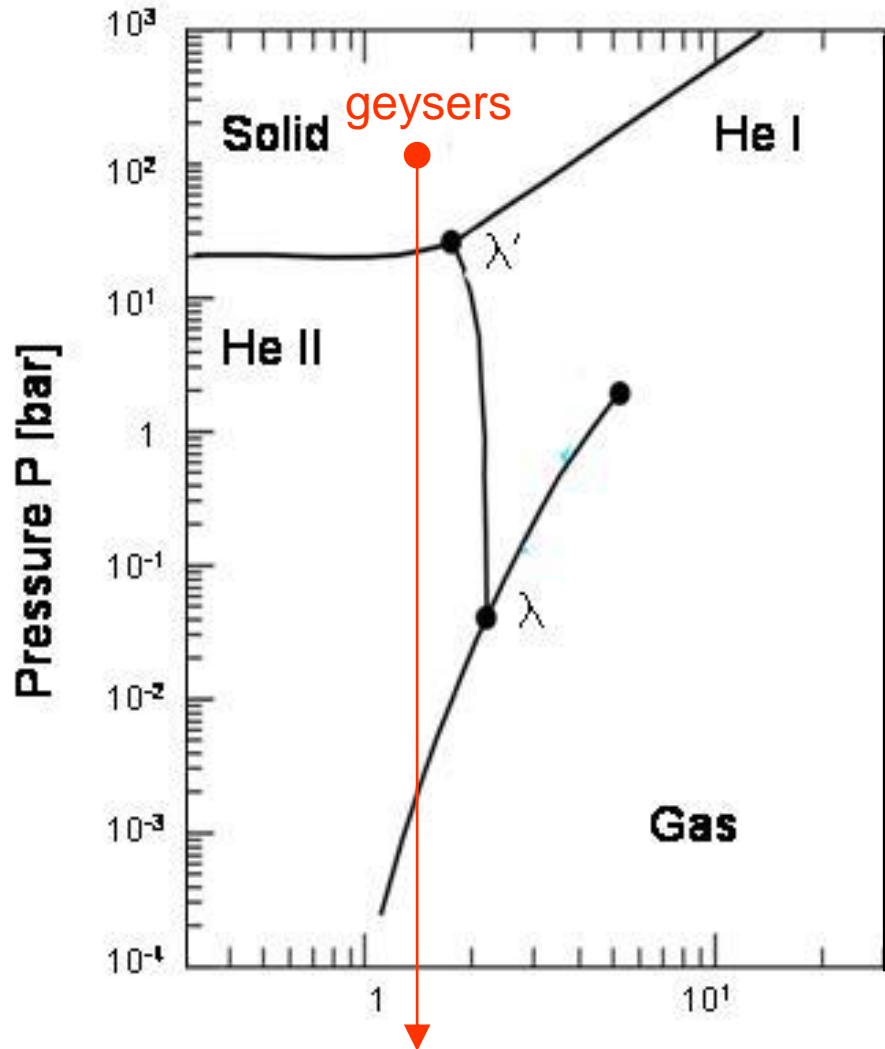
$$\frac{1}{2} \leq \gamma \leq \frac{2}{3}$$

$$\tau_0 \propto T_m - T$$

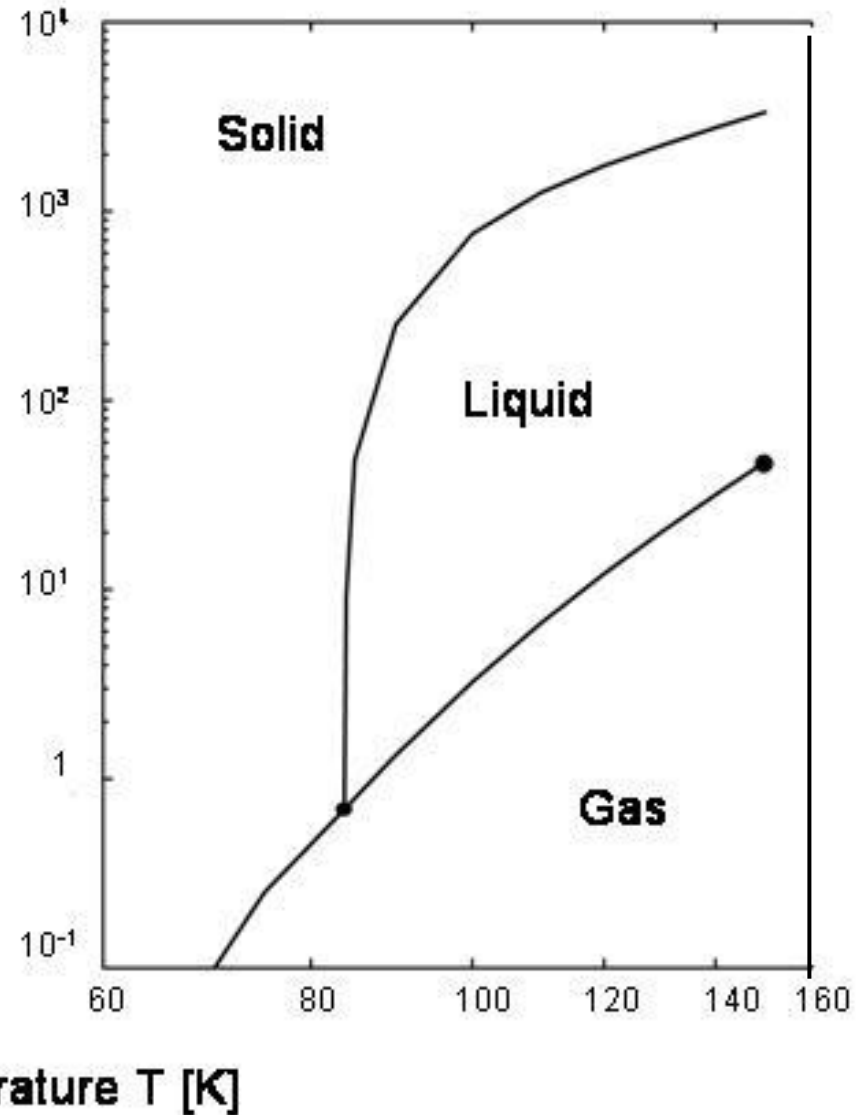
Basic theory

Basic Considerations of a Theory

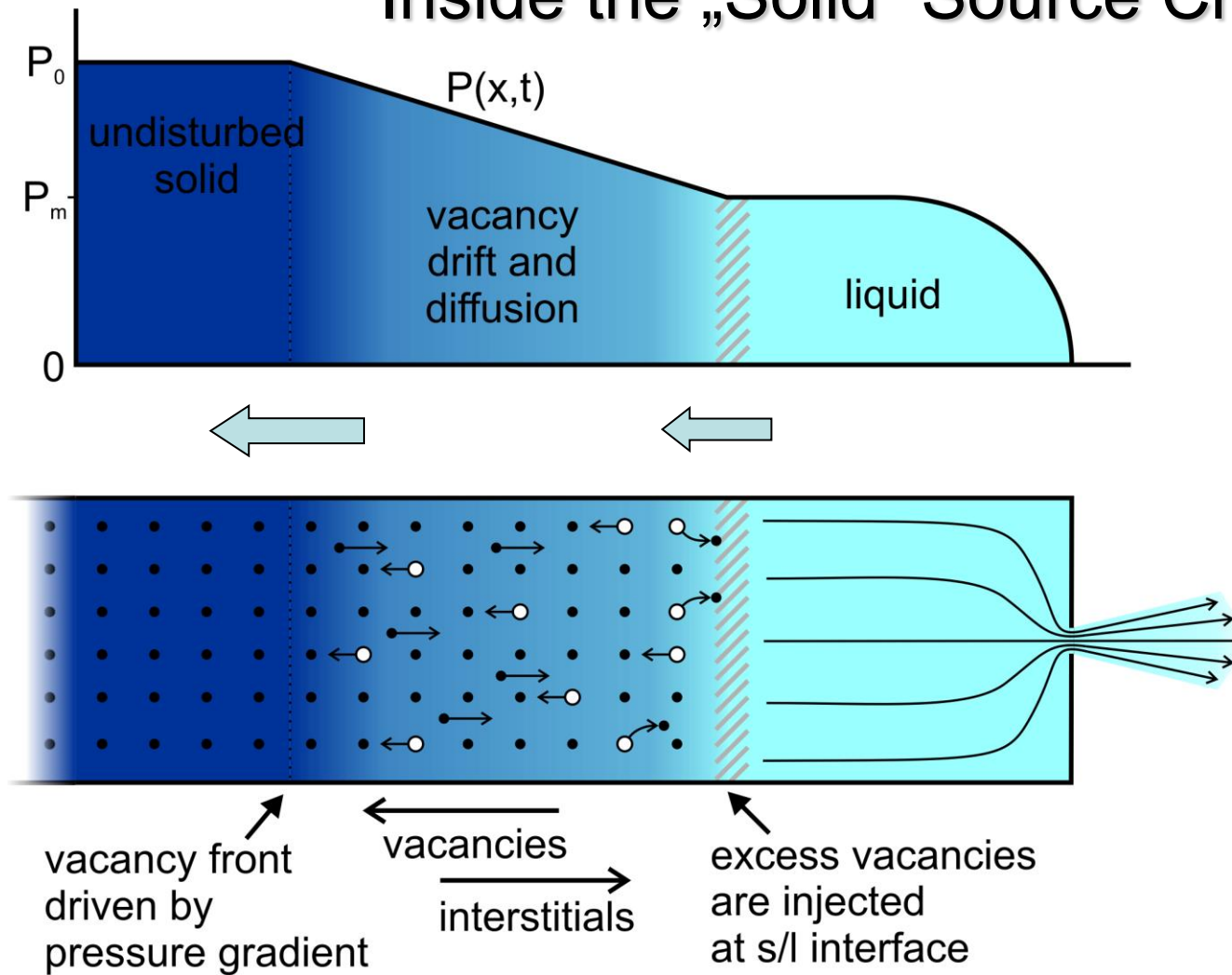
Helium



Argon



Conjectured Scenario of Events Occuring Inside the „Solid“ Source Chamber



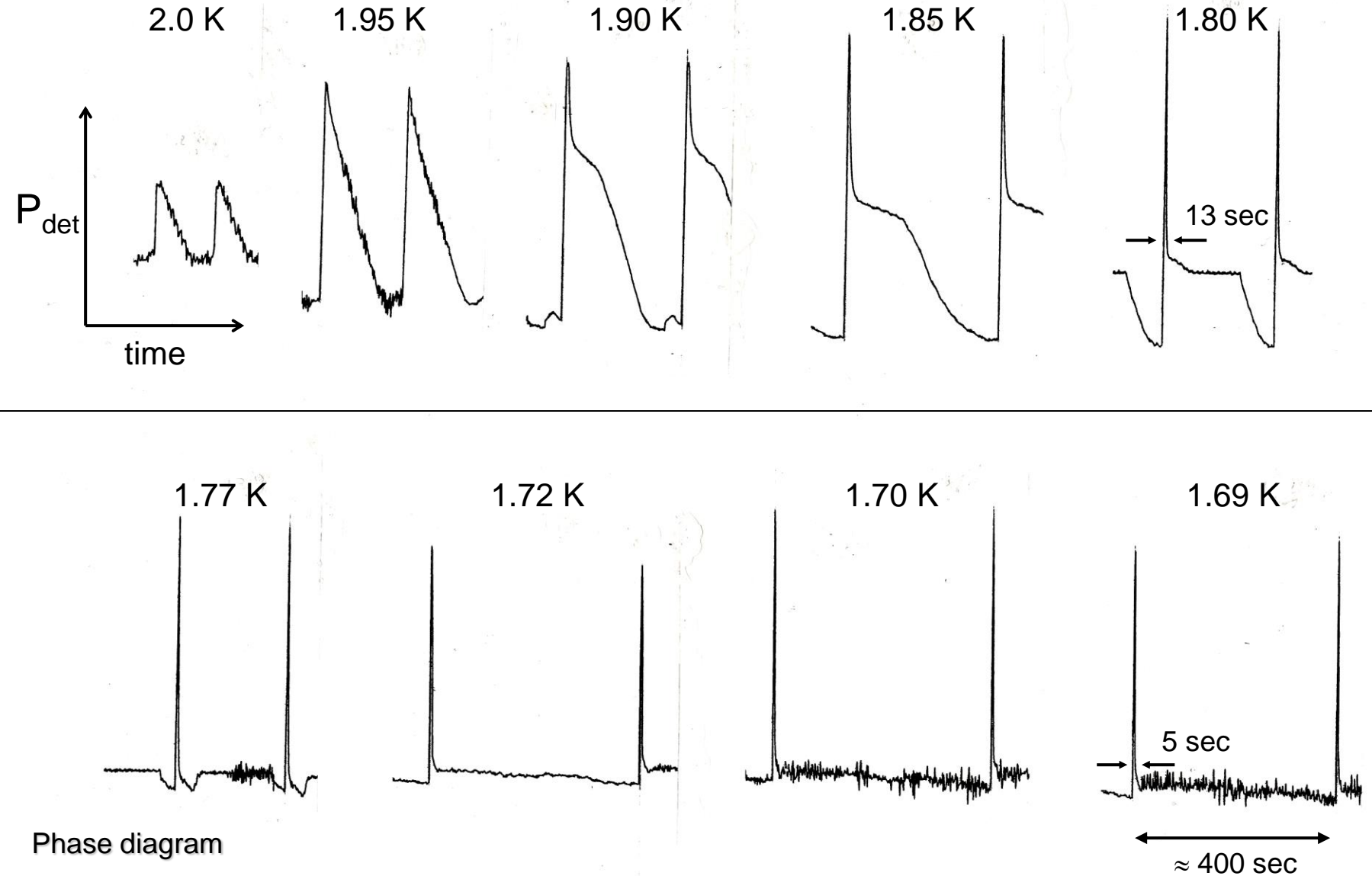
Collapse Occurs at Some Point when Solid can no Longer Support Pressure

Anomalous Behavior

- Below about 1.76 K (upper λ - point)
 - 1) Pulses sharpen at $T \leq 1.76$ K for $P_o \leq 45$ bar
 - 2) Delayed onset of geysers with pressure P_o
- Below about 1.60 K
 - 1) Sharp decrease in τ_o

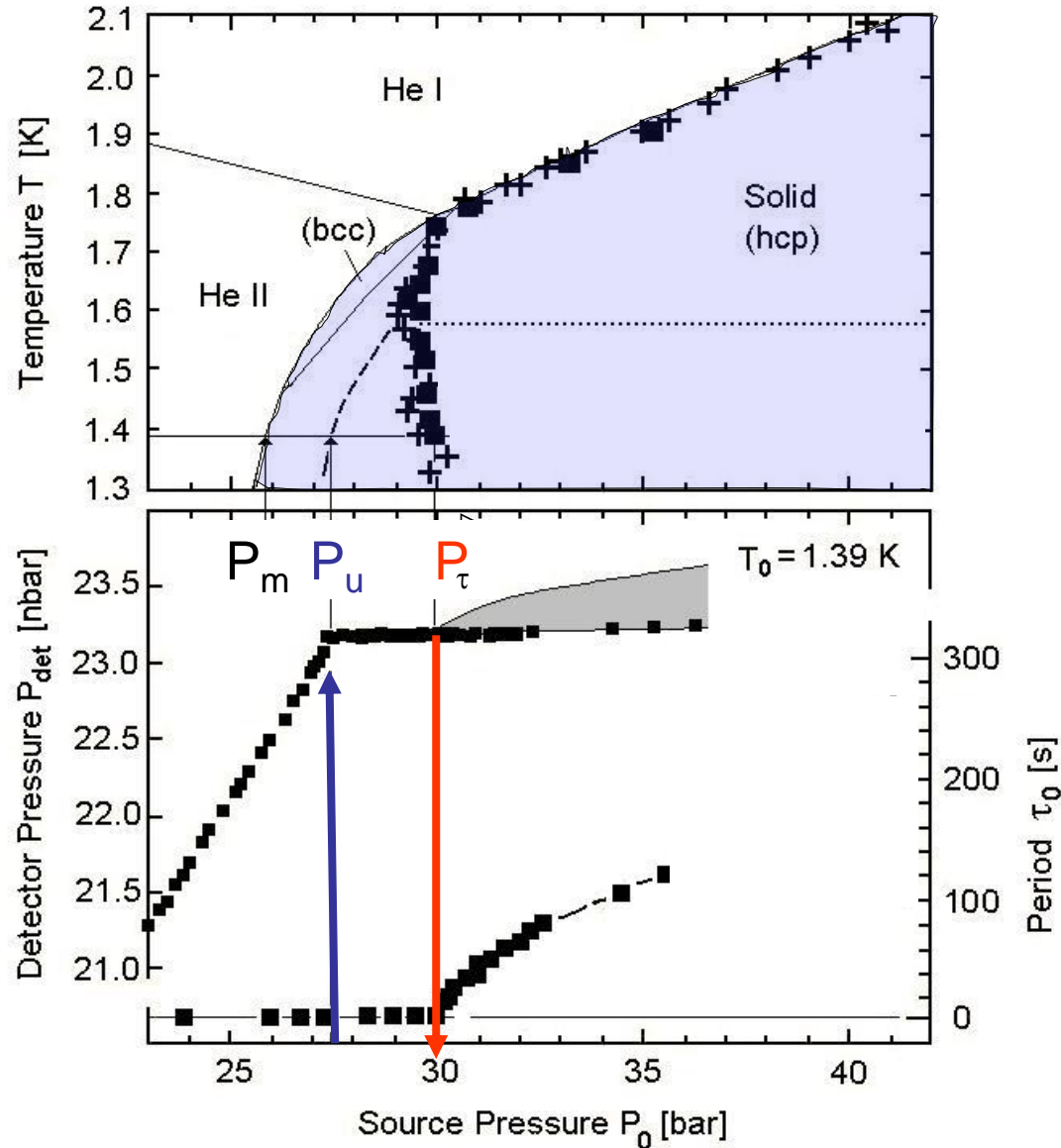
Sharpening of the Pulses with Decreasing Temperature

$P_0 = 34$ bar



In the Anomalous Region:

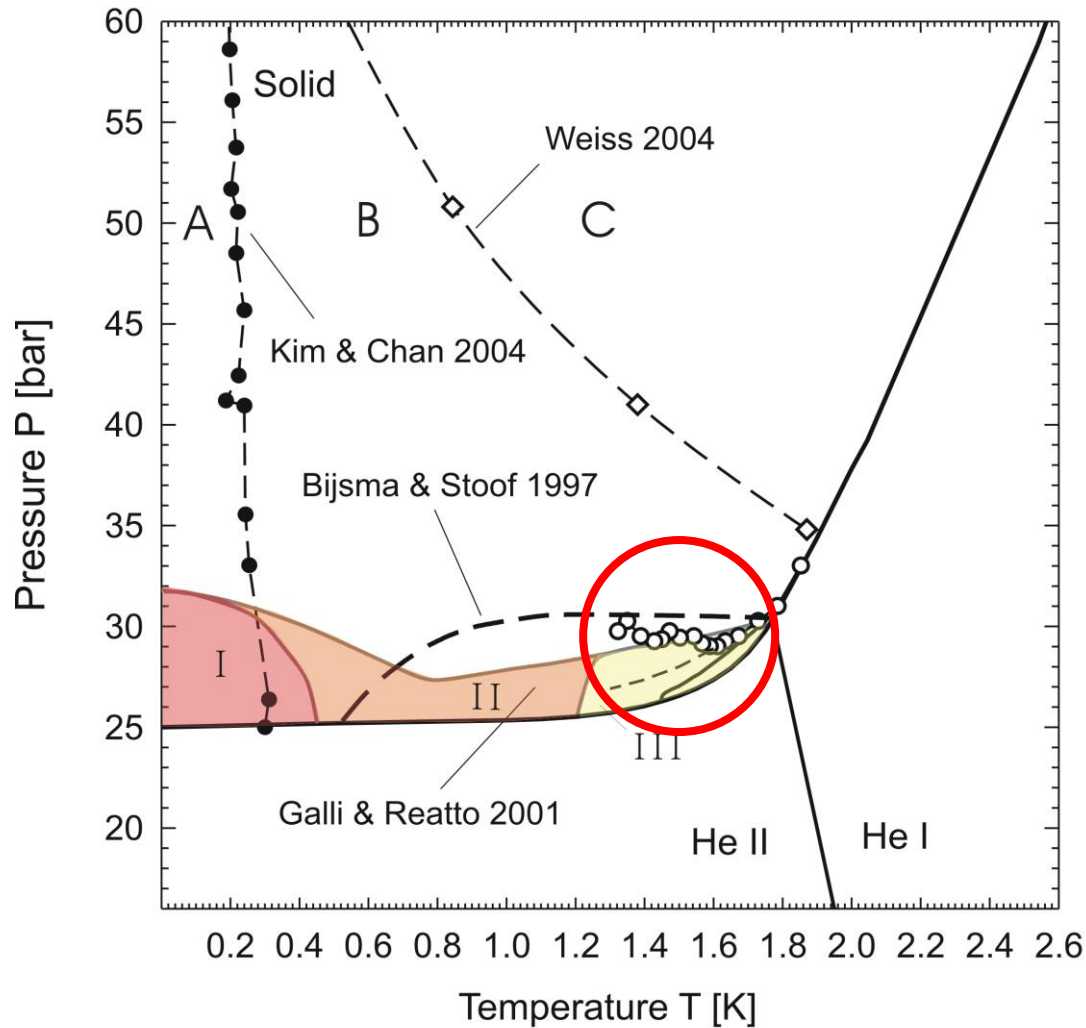
Bernoulli up to $P_u > P_m$ and Gysers set in at $P_\tau > P_u$



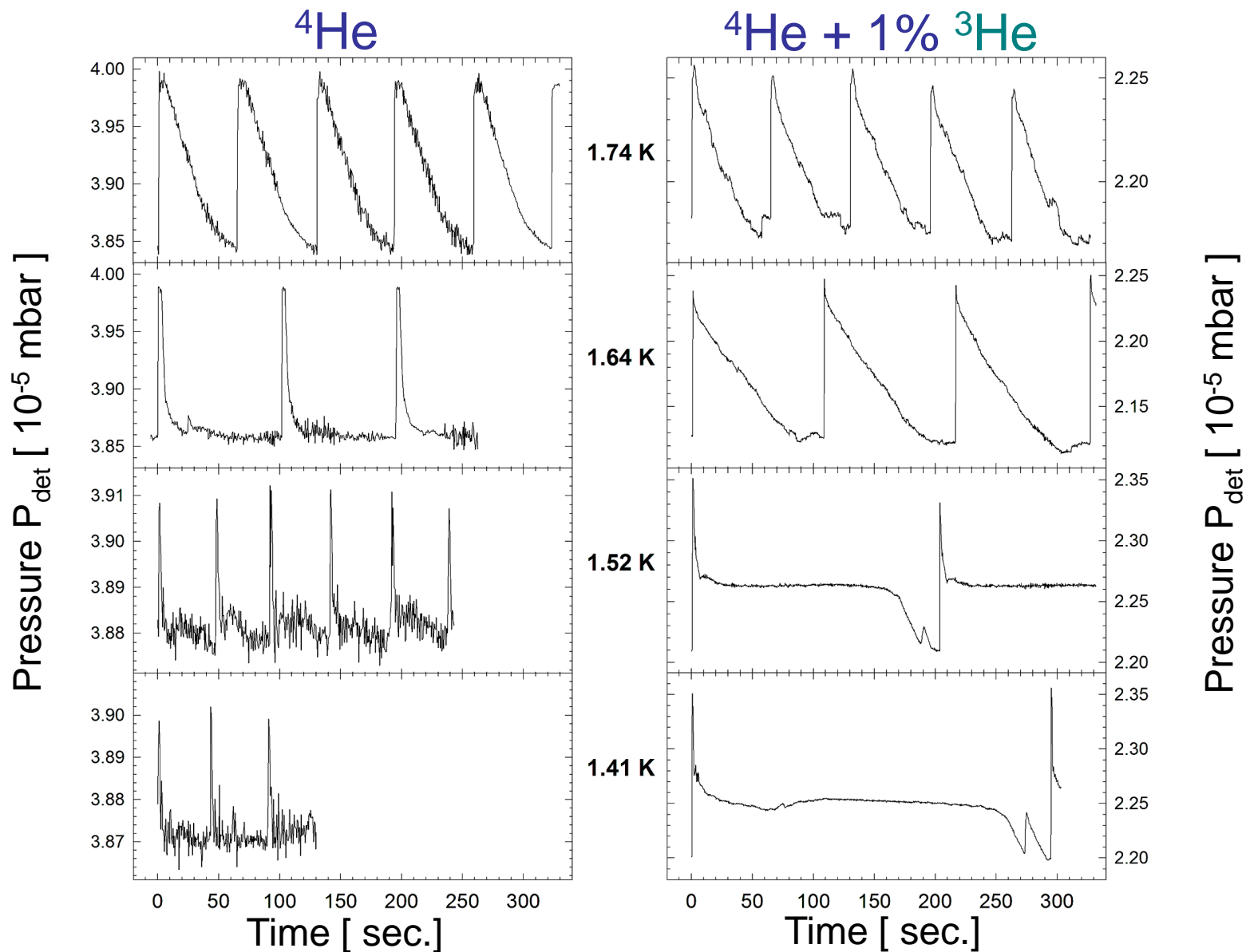
Galli and Reatto

G. Benedek et al. Phys. Rev. Lett. 95, 095301 (2005)

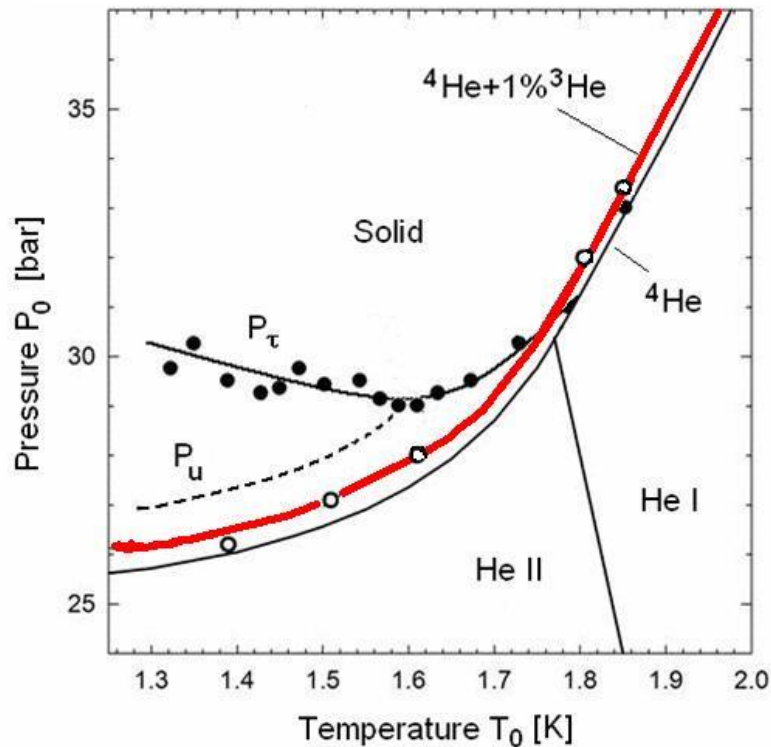
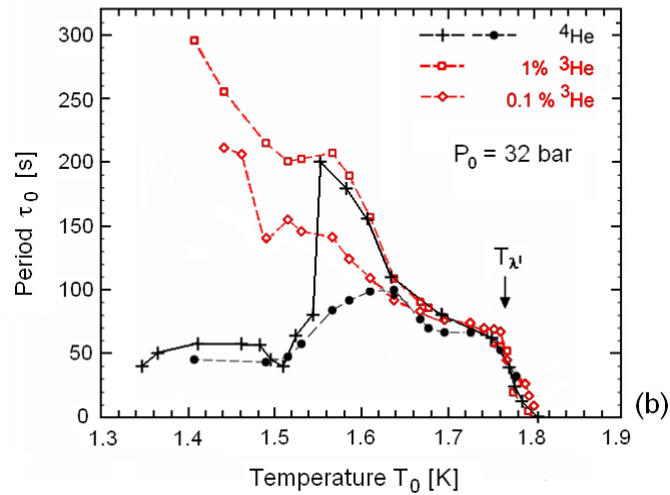
The Anomalous Region is in Agreement with Galli and Reatto's Scenario III for a Defect-Induced Supersolid.



A Small Amount of ^3He Effects Both the Shapes and Periods

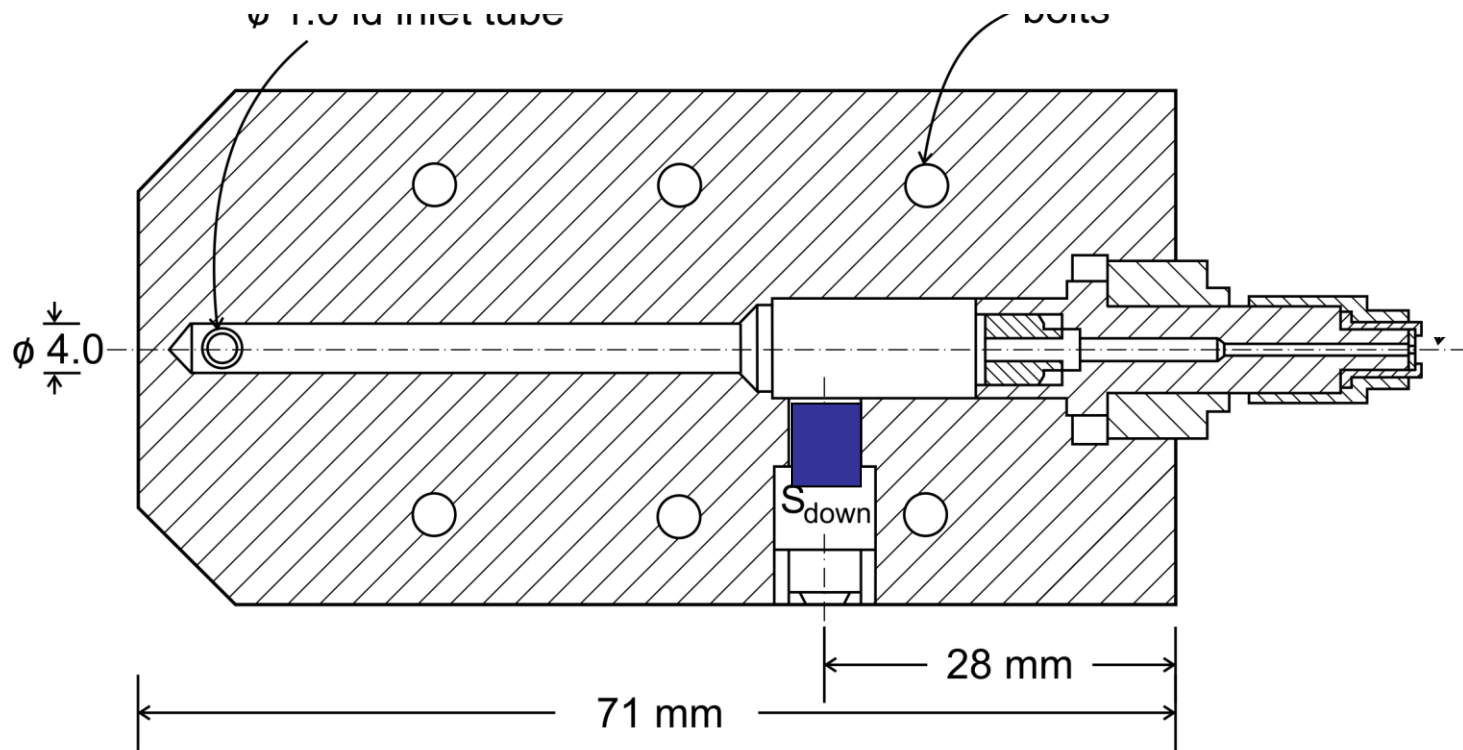


^3He Removes Anomalous Behavior



New Experiments I

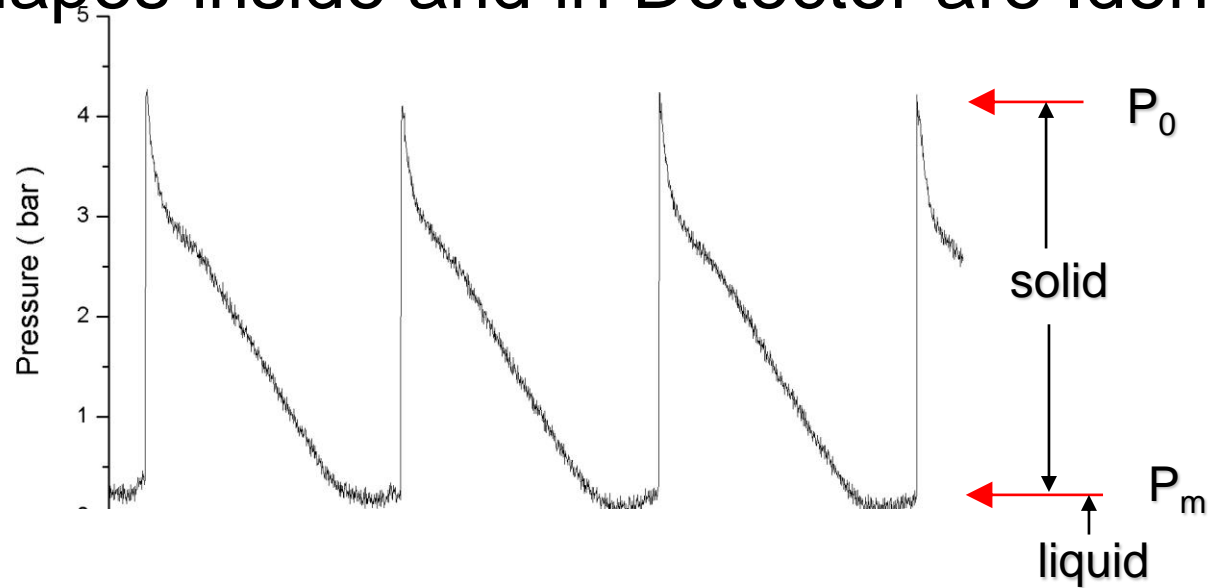
Top View of Cell With One Pressure Sensor



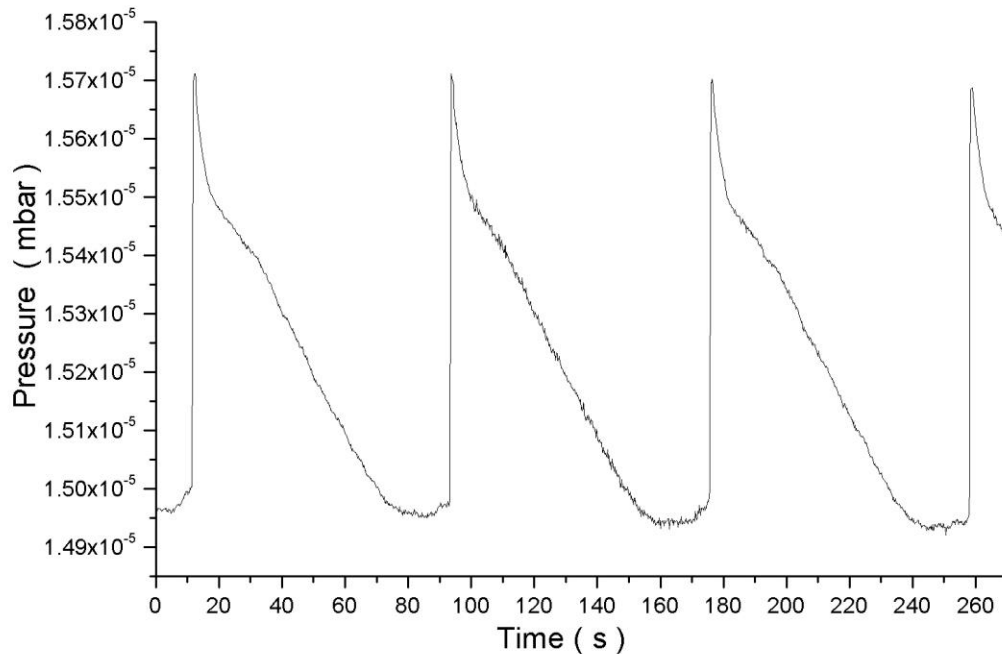
Pulse Shapes inside and in Detector are Identical

$P_0=35$ bar
 $T_0=1.88$ K

Pulse in Cell



Pulse at External Flux detector

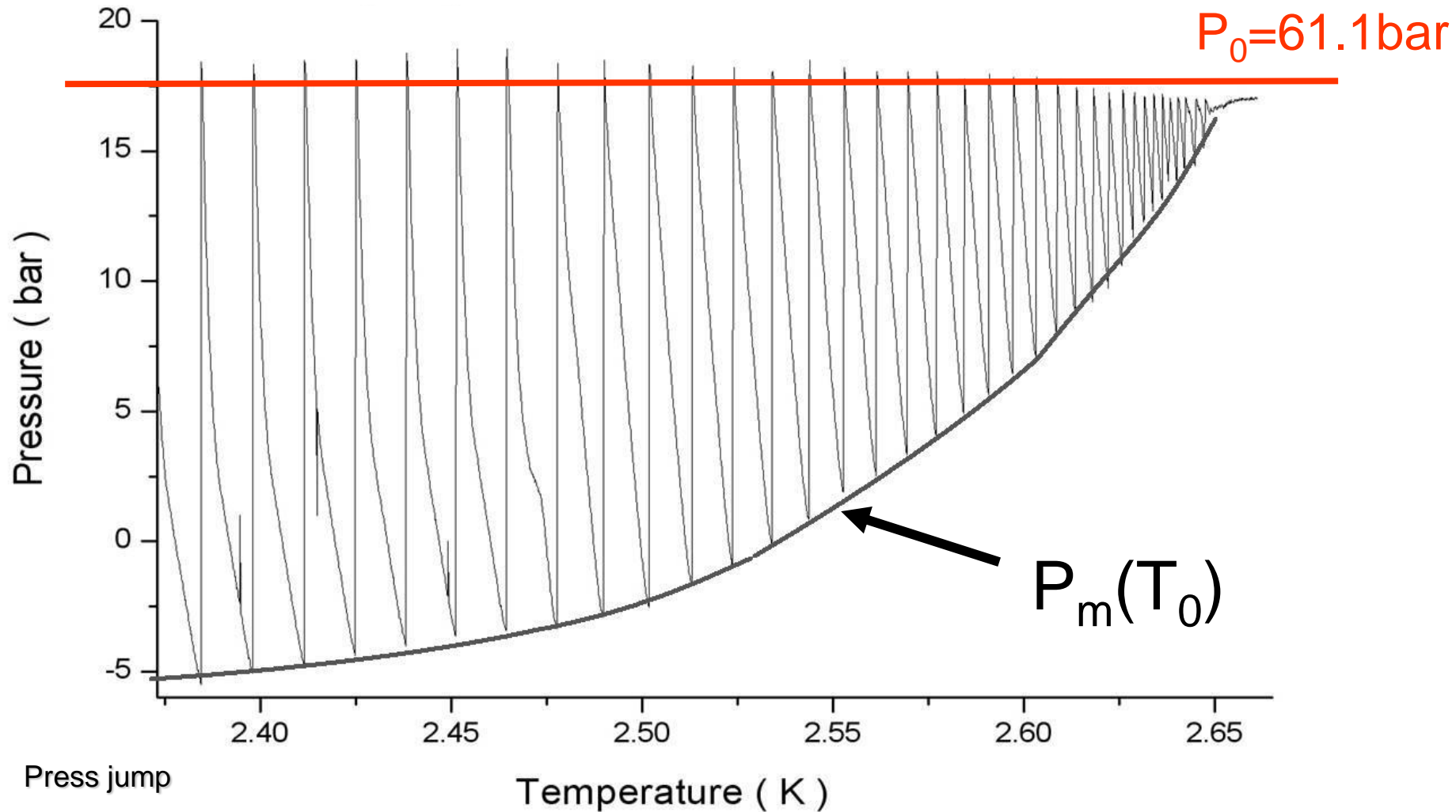


➔ Solid flows faster than the liquid
($\tau \approx 10^3$ sec.)

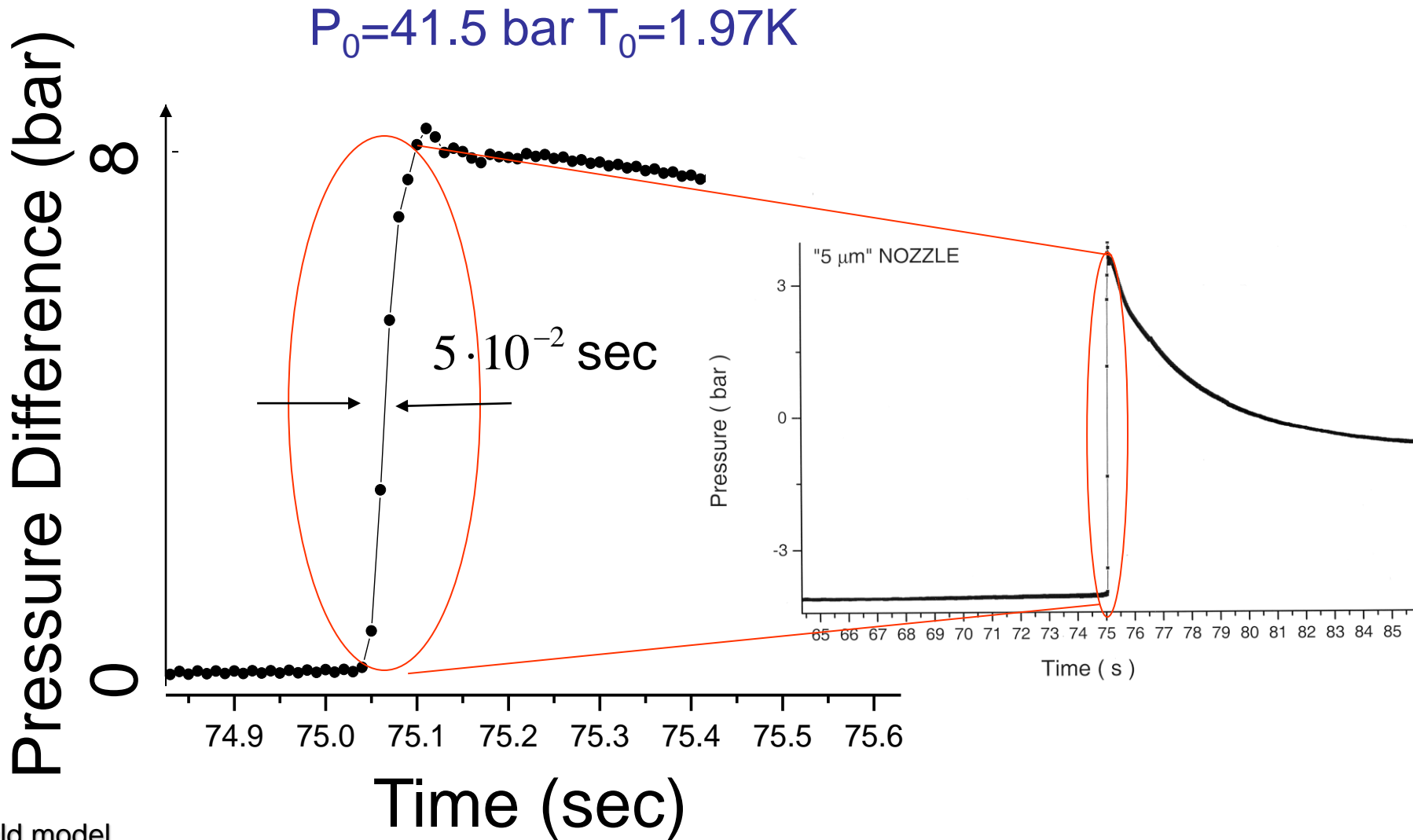
Delta p as fct T

Sensor Pressure Pulses = $P_0 - P_m$

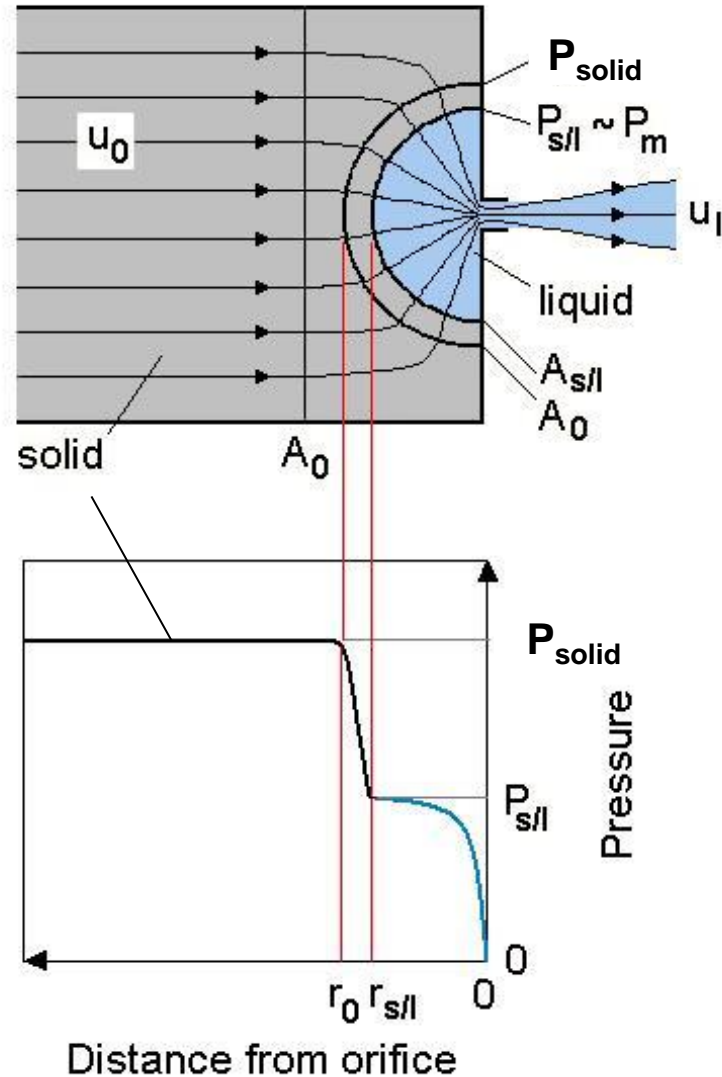
Note: Sensor sees only pressure differences



Sensor Pressure Rises at 200 bar/sec!



Large Pressure Jumps throughout the Entire Cell are at Variance with Earlier Model:

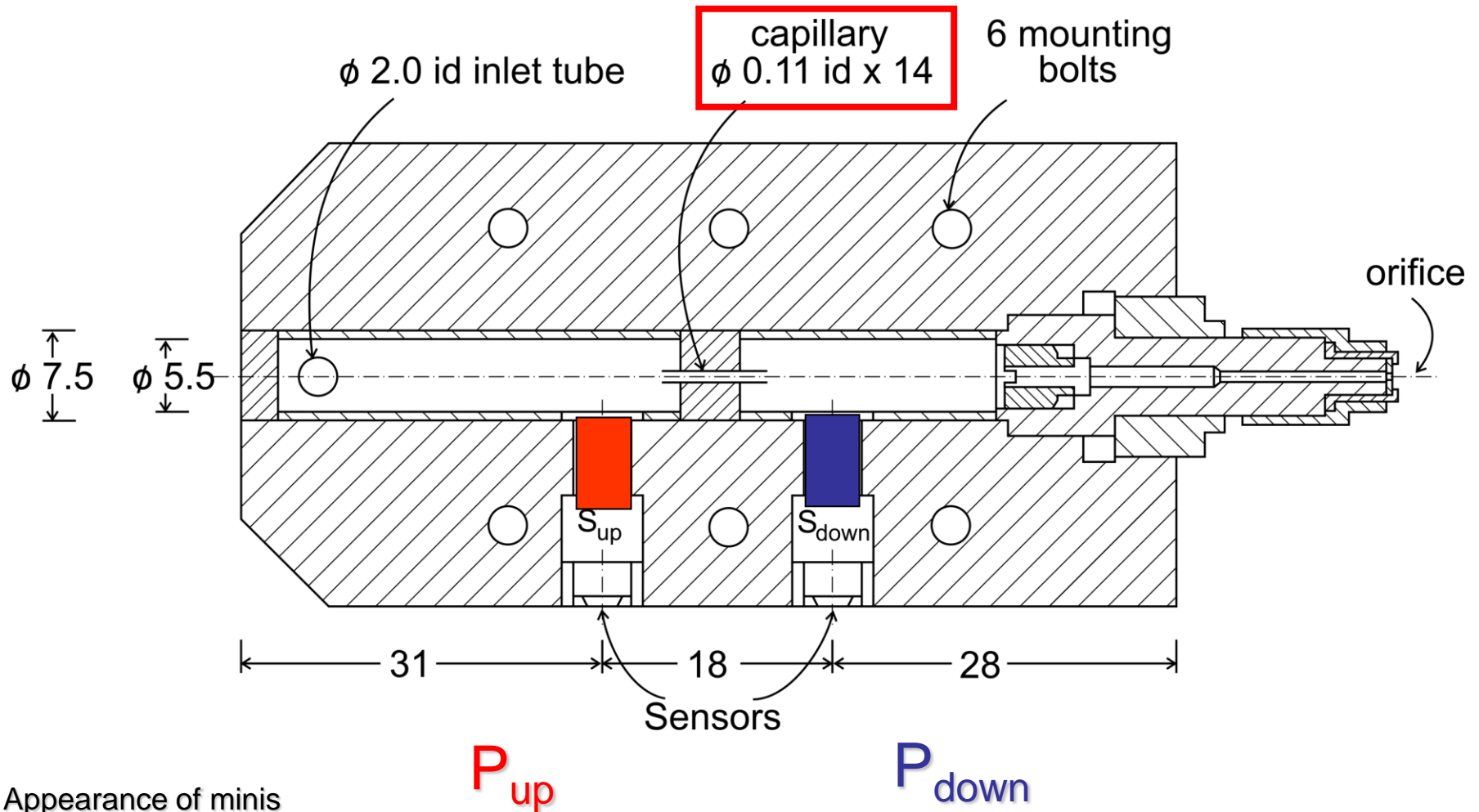


New expts 2

Benedek et al Phys. Rev. Lett 95,095301 (2005)

New Experiments II

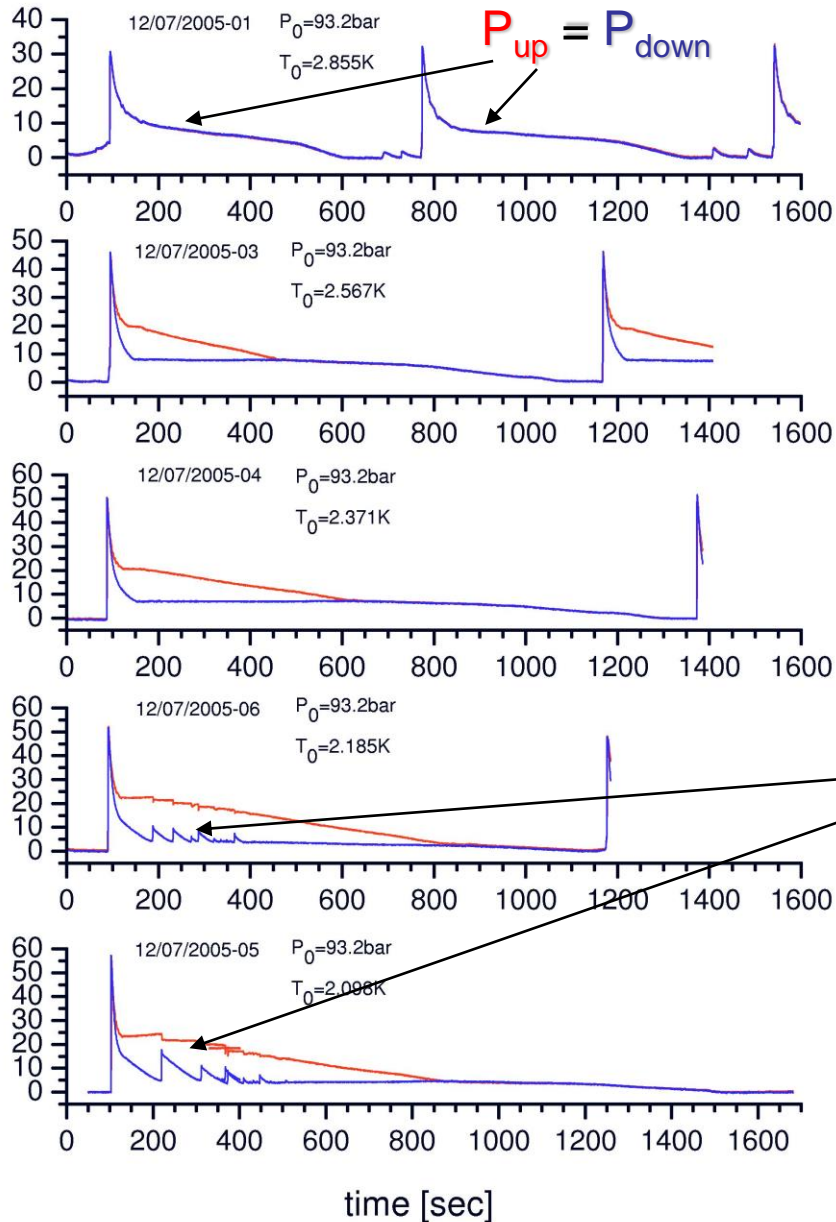
Top View of New Two Pressure Sensor Cell



Appearance of minis

Onset of Minigeysers on Lowering the Temperature

2.098 K ← 2.855 K
K



$P_0=93.2\text{ bar}$

Call these
„minigeysers“

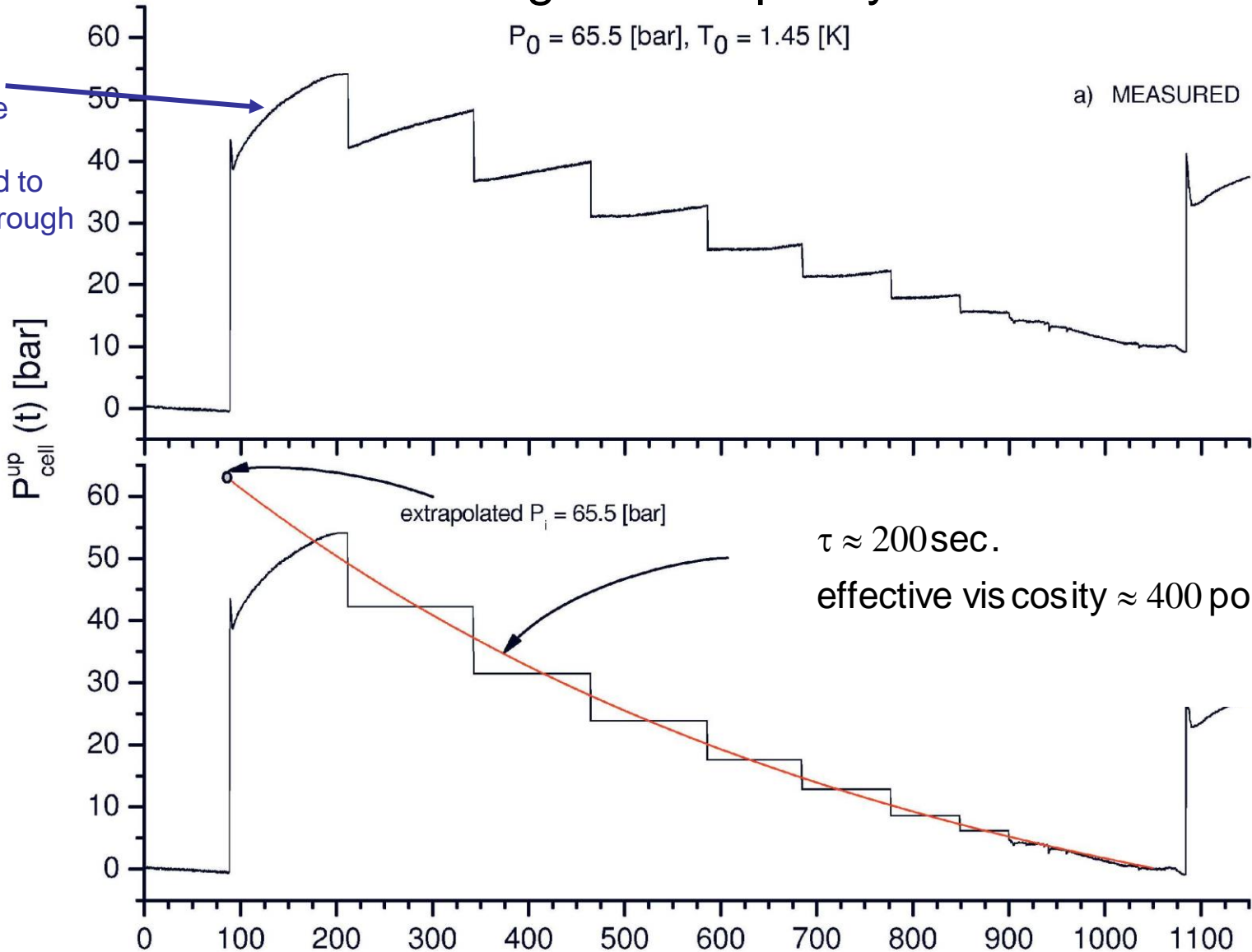
Exp fall off

If We Correct for „Leak“ from Upstream get Expt. Fall-Off for Flow Through the Capillary

$P_0 = 65.5$ [bar], $T_0 = 1.45$ [K]

a) MEASURED

Rise in Pressure Initially, Attributed to „leak“ through plug

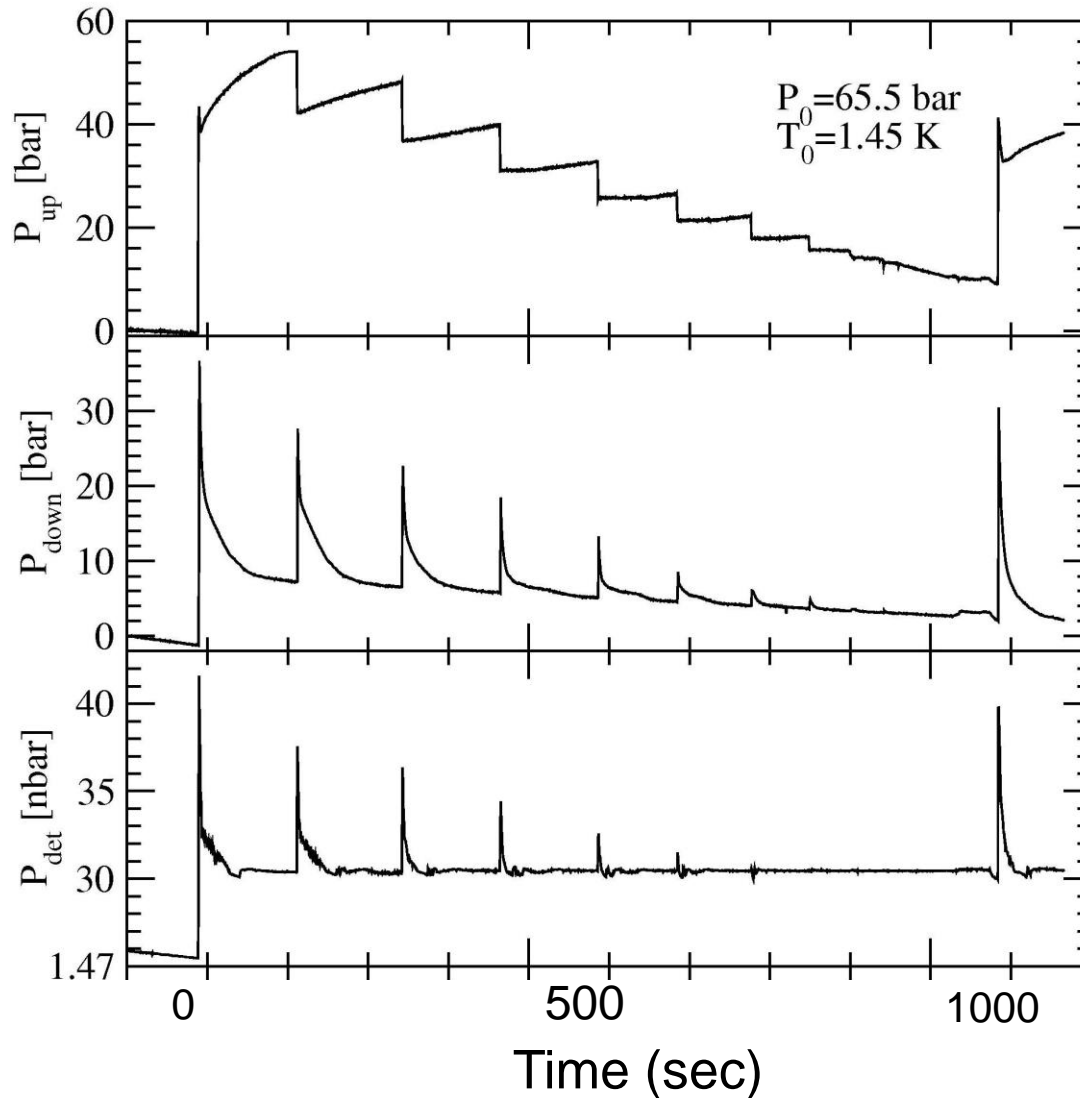


Pdet vs Pupand Pdown

time [sec]

15/09/05-09

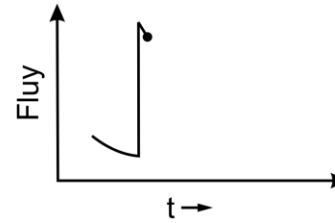
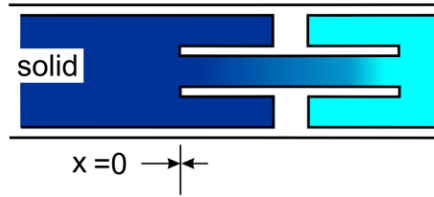
Sharp Minigeysers at Low Temperature in the Anomalous Region



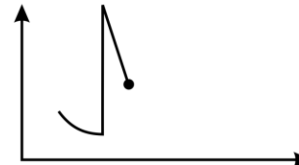
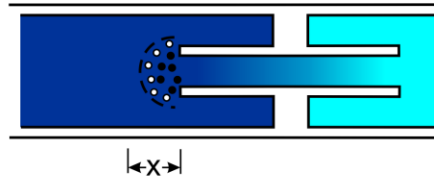
➔ Solid flows
faster than the
liquid

Schematic Diagram of the Minigeysler Effect

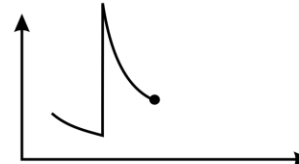
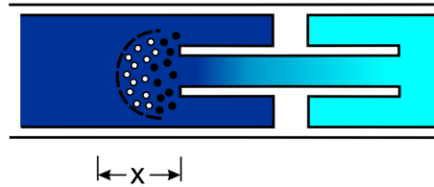
Collapse



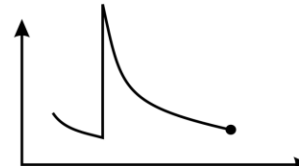
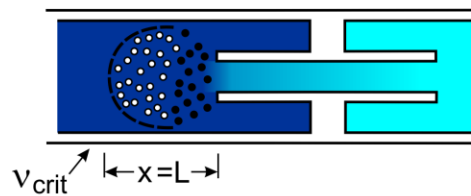
Diffusion of interstitials



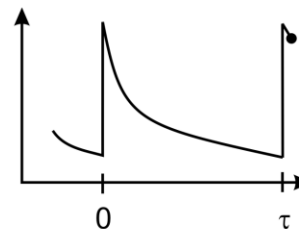
Diffusion of both



Diffusion of vacancies



Collapse



Summary

- The recent experiments of Kim and Chan are controversial. At present there is still no conclusive evidence for the supersolid state of helium !
- The new geyser effect is very robust. Now seen in two different constrictions. Very reproducible.
- We find that the regularity of the behavior is indeed remarkable! Must be related to vacancy diffusion. A theory is in progress.
- Region of anomalous behavior corresponds to vacancy induced supersolidity predicted by Galli and Reatto

Supersolid Helium

Andreev and Lifshitz back in 1969
had a great idea far better than any of mine.
They knew that solidity is an imperfect state
and helium crystals might be incommensurate,
then the helium vacancies could proliferate
and probably form a Bose condensate.
and the solid, like the liquid, might be super!
Now wouldn't that indeed be superduper?

Since then many have tried the experiment, but, alas, the effect defied every measurement. Until in 2004 Kim and Chan used their best pendular oscillator to put theory to a test. When they thought they had a fit theoreticians said „this wasn't it!“

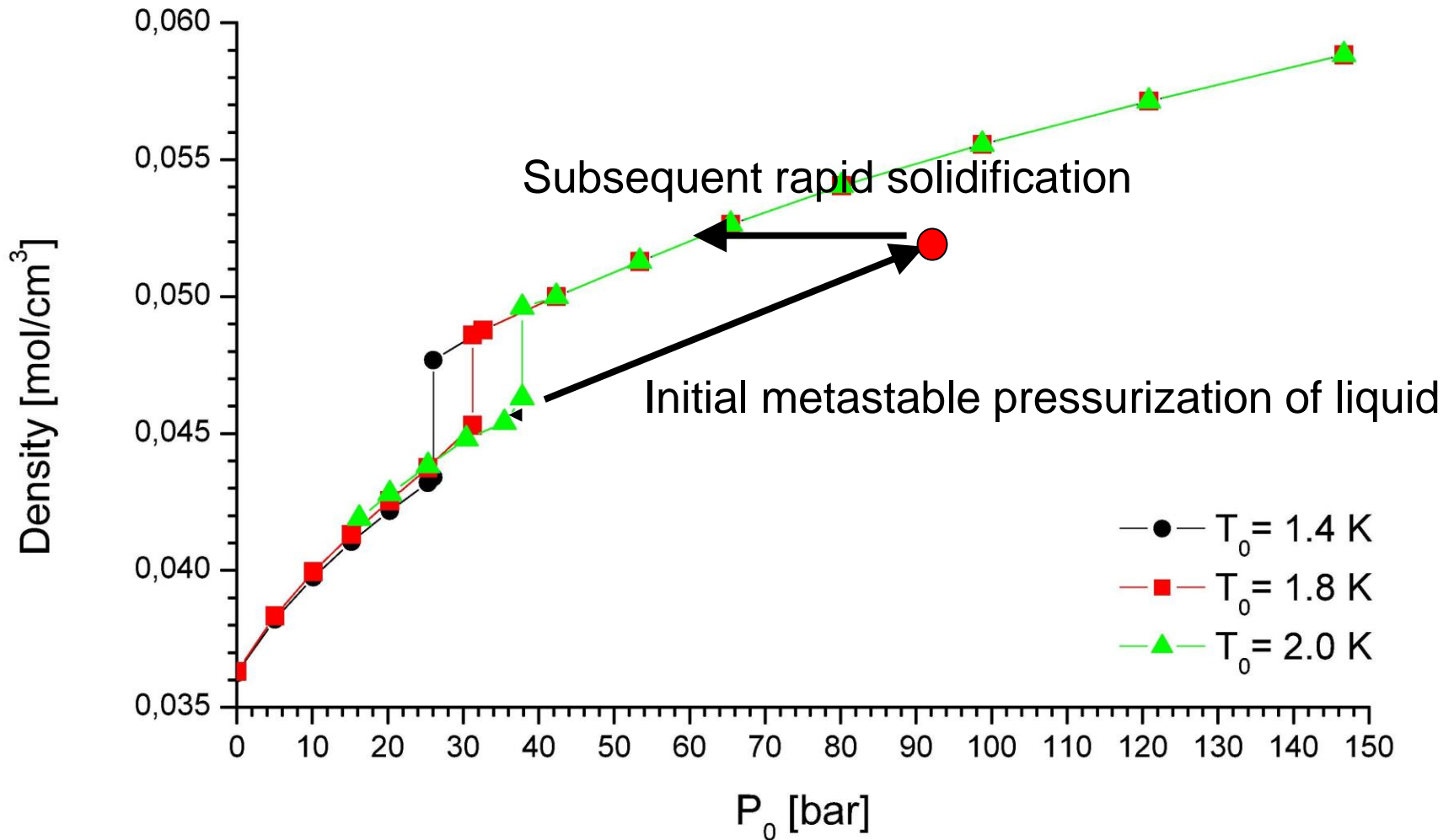
Now strange geysers may provide the answer, equally mysterious, but much fancier

So even today this little atom helium still is the cause of great delirium!

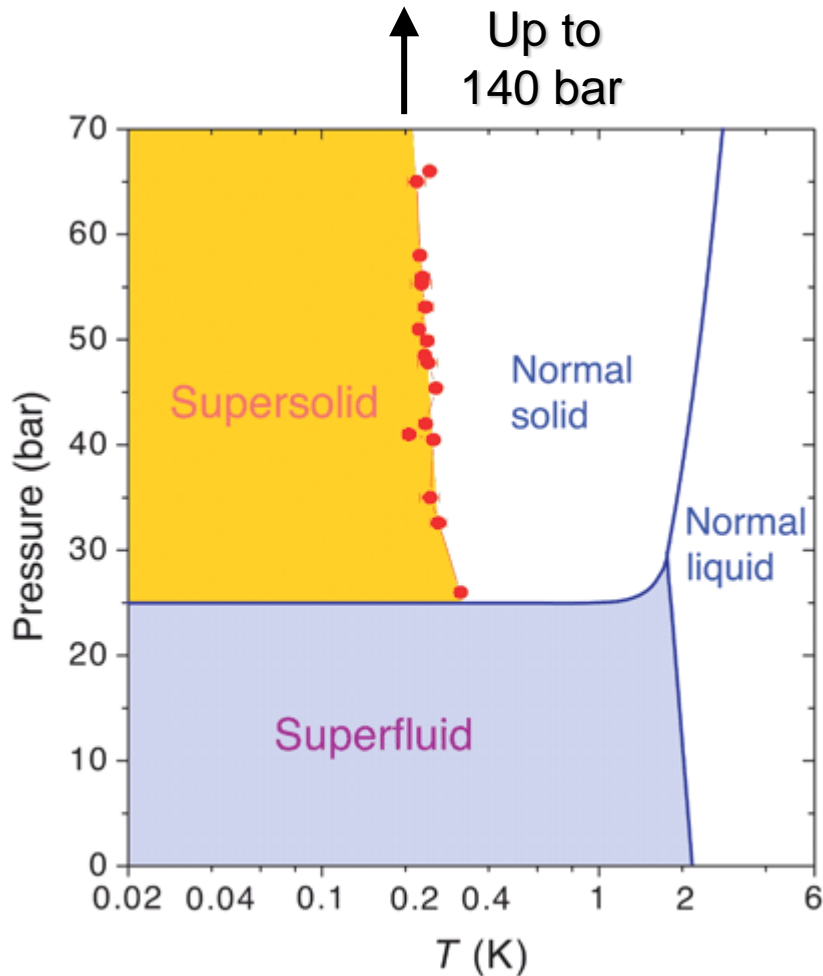
Thank You

Please ask questions

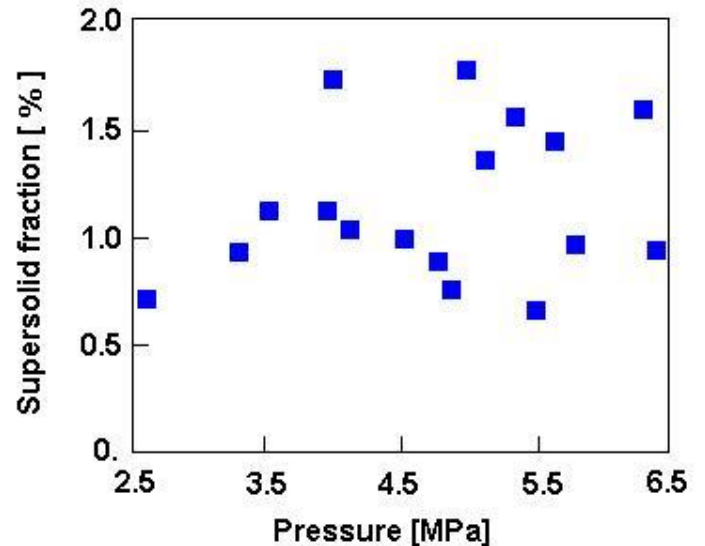
Speculative Explanation for Sharp Drop-Off



Phase Diagram: Pressure Dependence

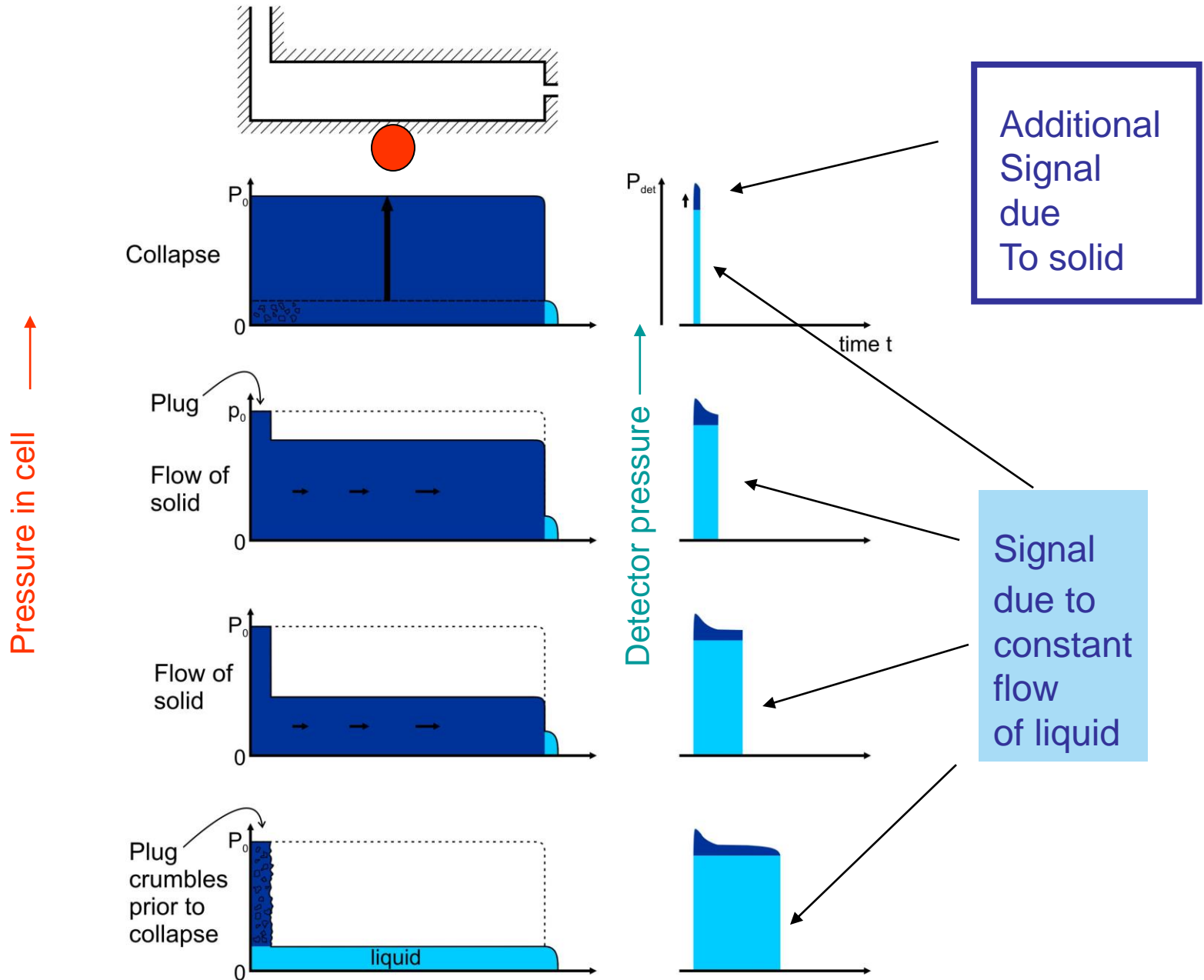


Low Temp. Superfluid Fraction Shows scatter with Pressure

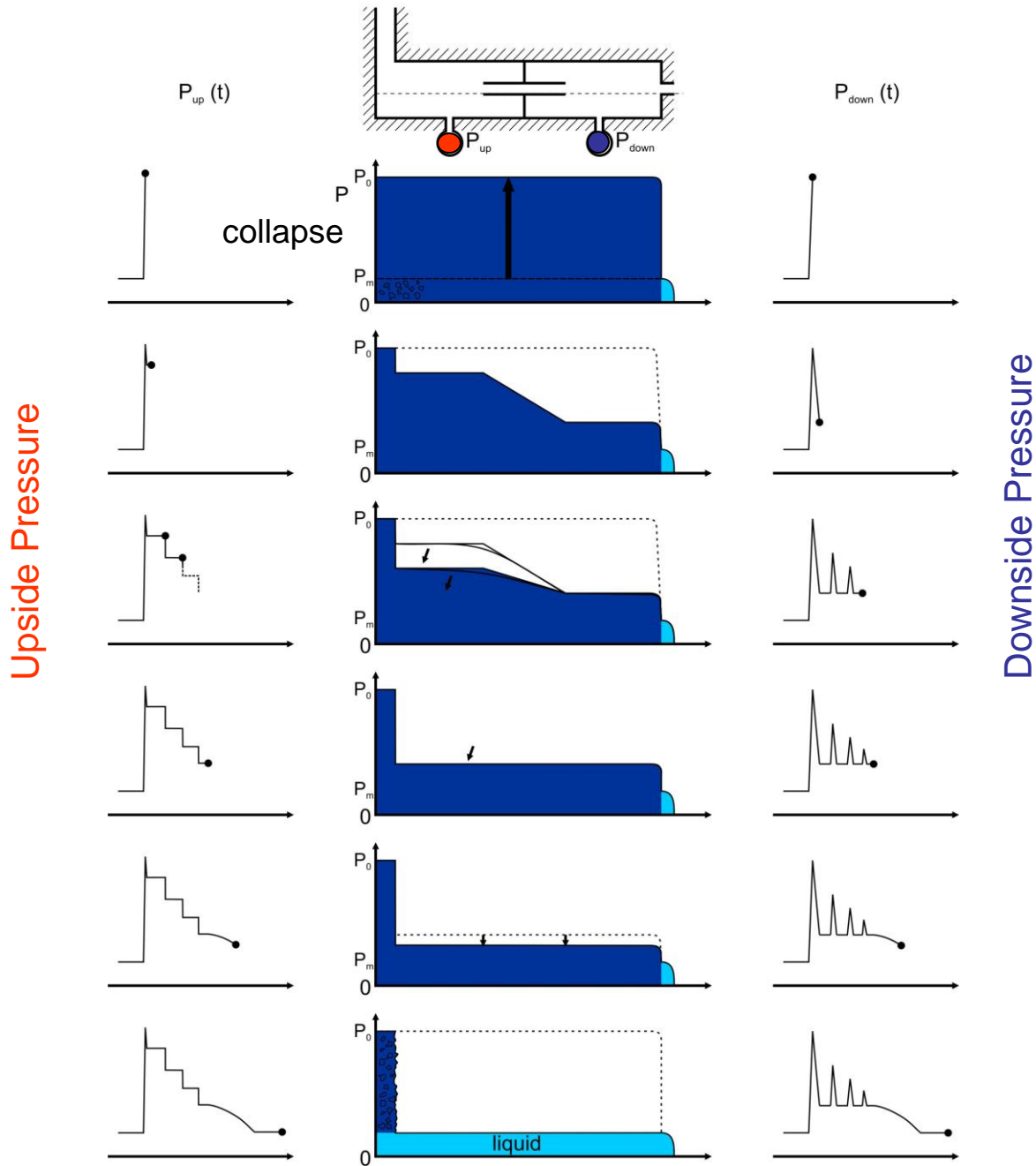


E. Kim and M. H. W. Chan, Nature 427, 225 (2004); Science 305, 1941 (2004)

New Model for the Geyser Effect



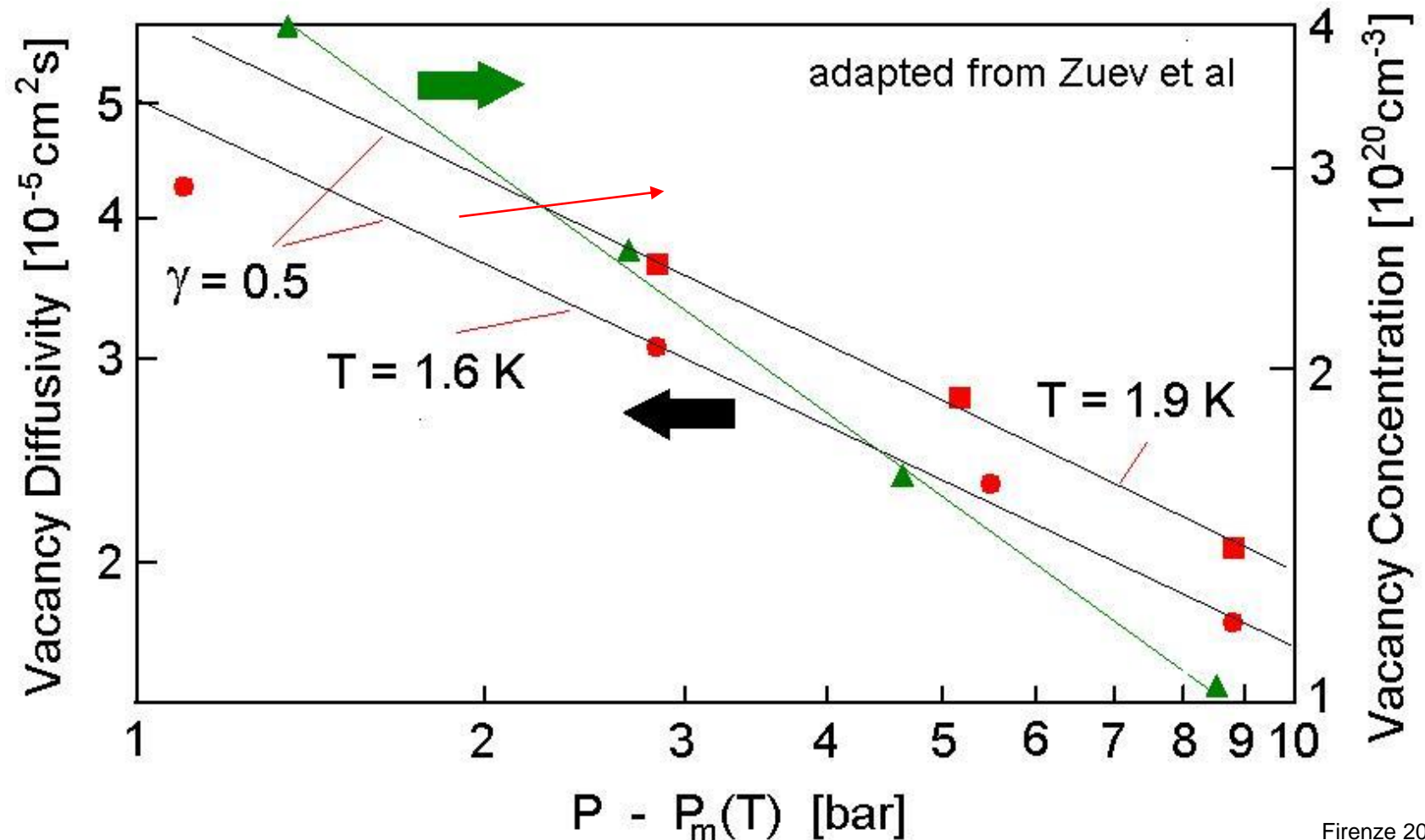
Model for Minigeysers



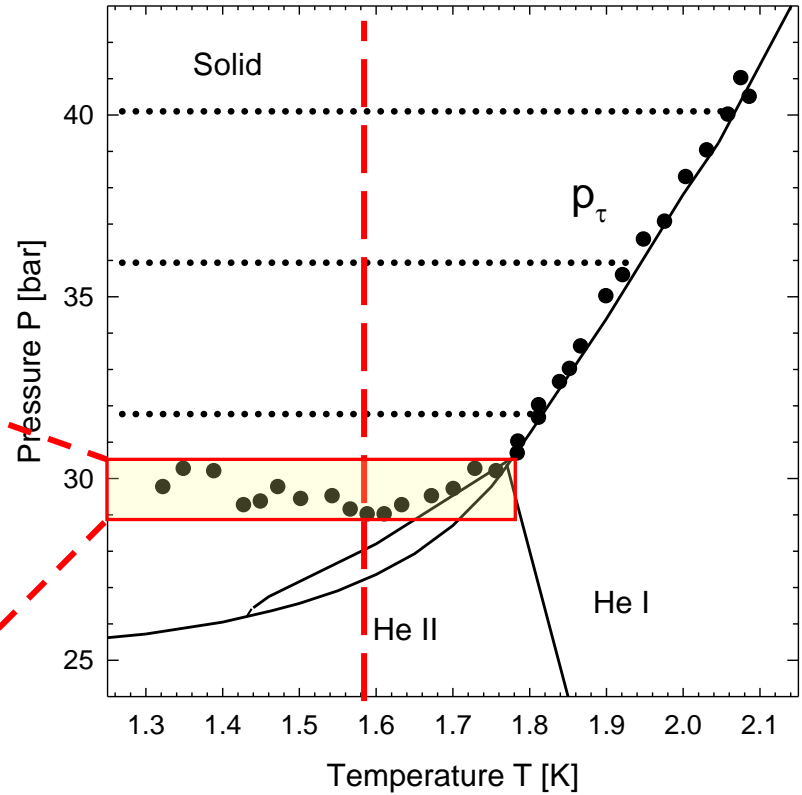
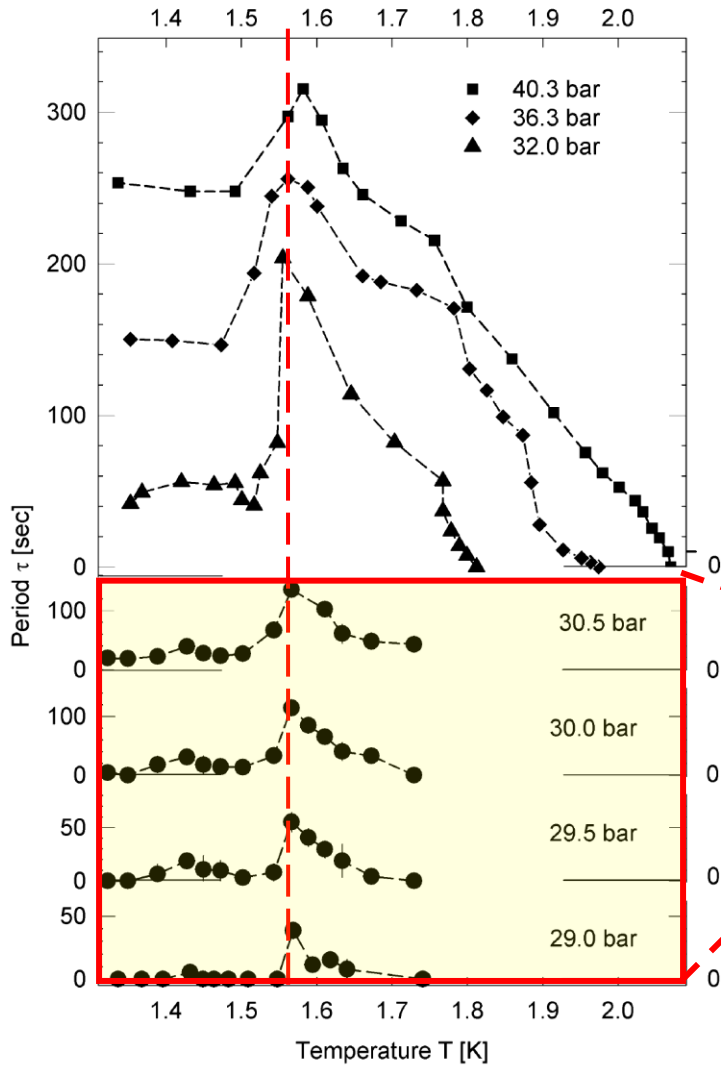
Geysers can not be due to Stick-slip Mechanism

Stick-slip: Period would decrease with pressure

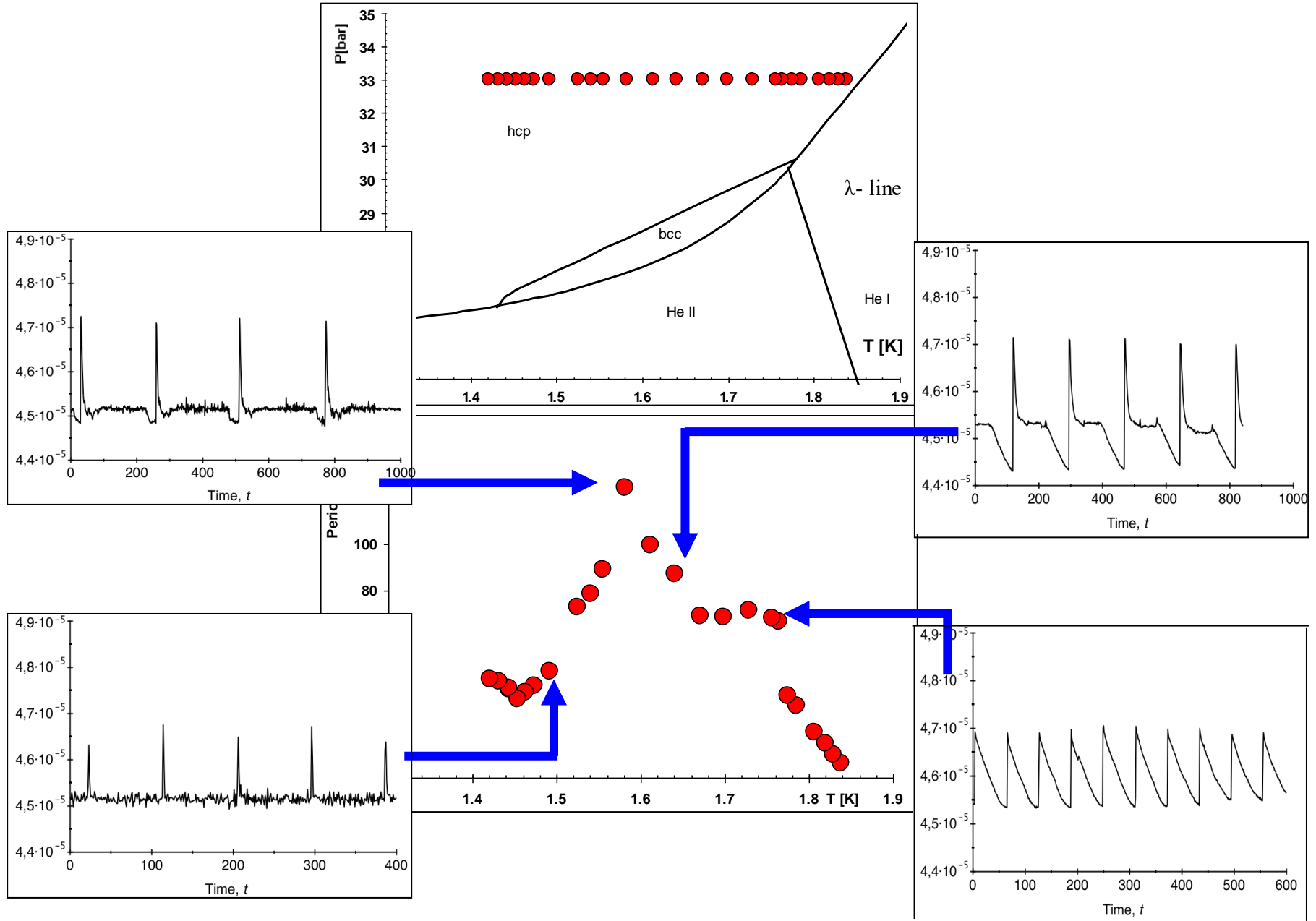
Geysers: Period increases with pressure! Consistent with decreasing vacancy diffusivity



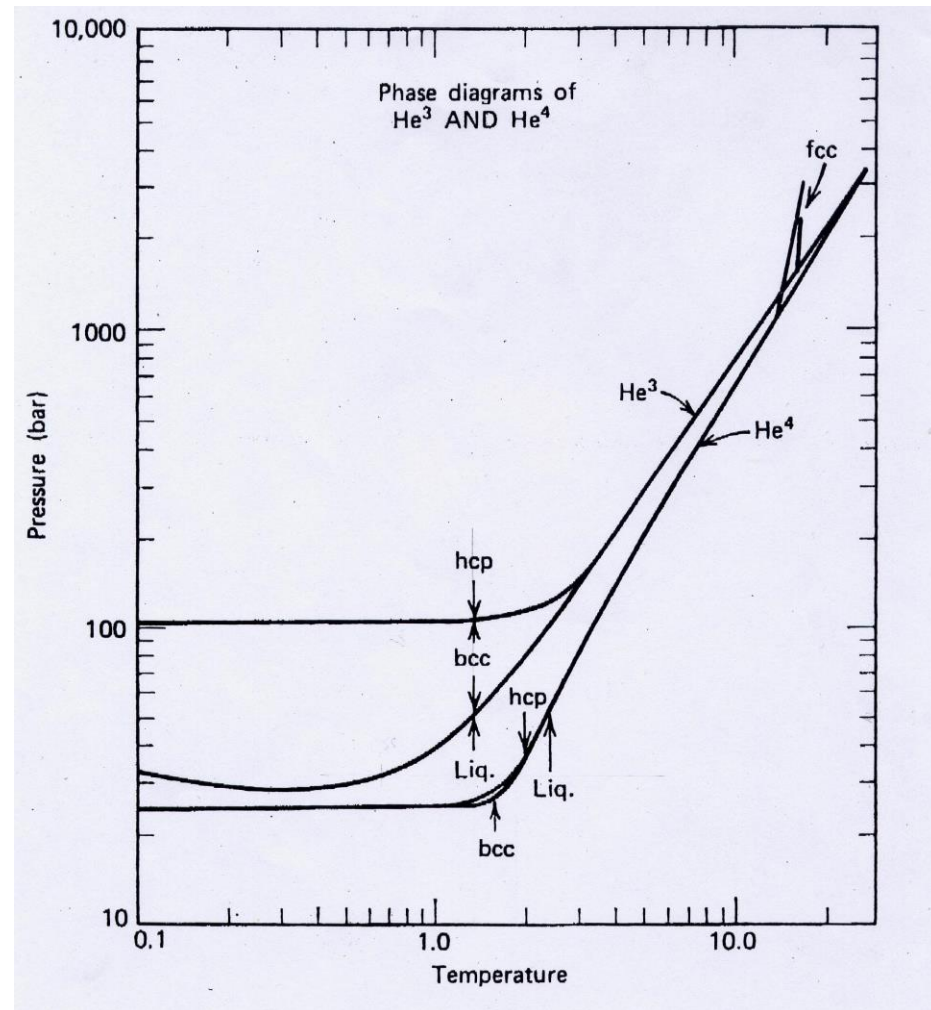
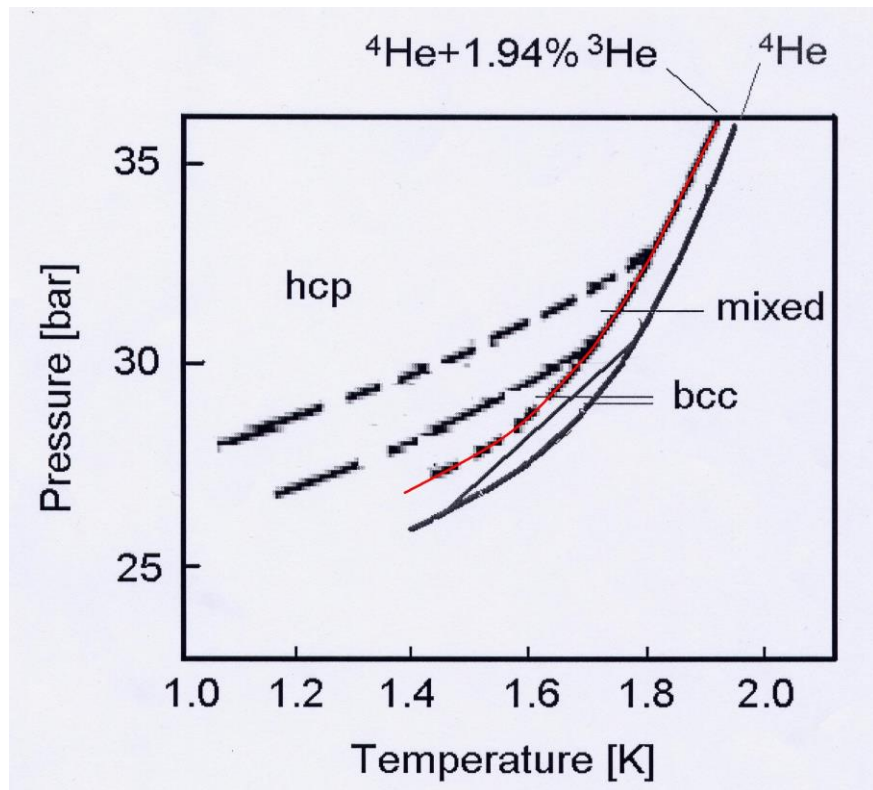
Drop in Period Below 1.58 K



Drop in Period and Pulse Sharpening Go Together



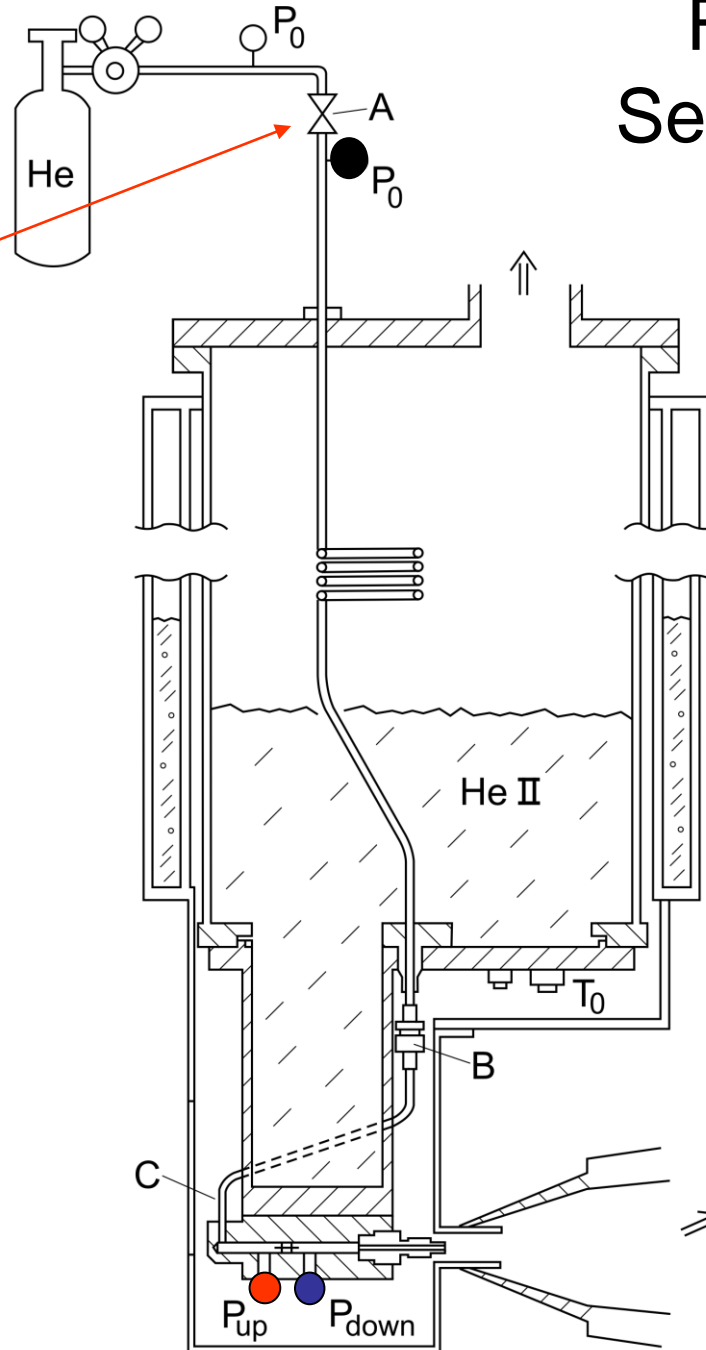
Effect of ^3He on Melting Line



from R. Richardson et al

Four Pressure Sensor Apparatus

Valve to
shut off
gas supply

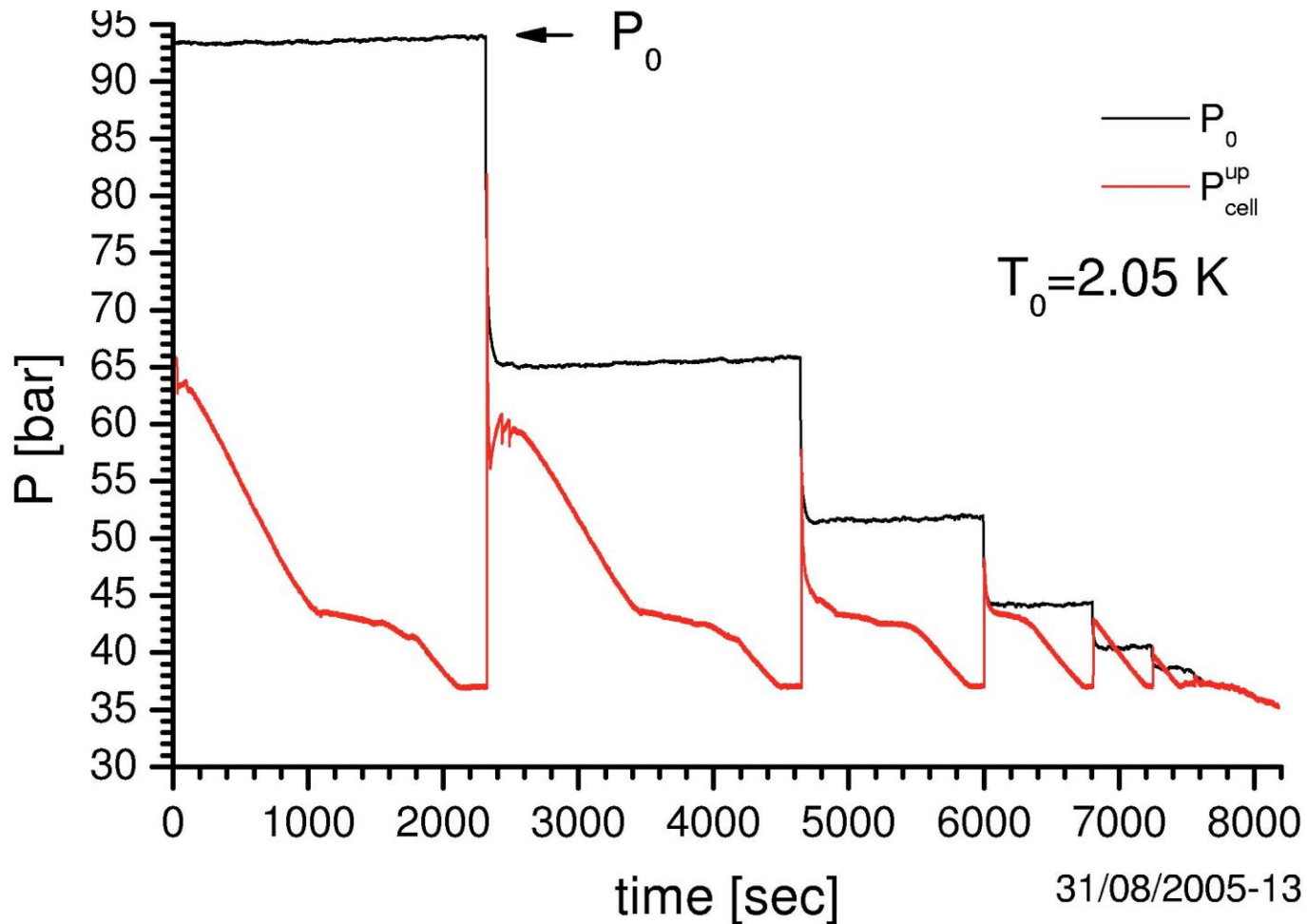


to Pitot
tube det.

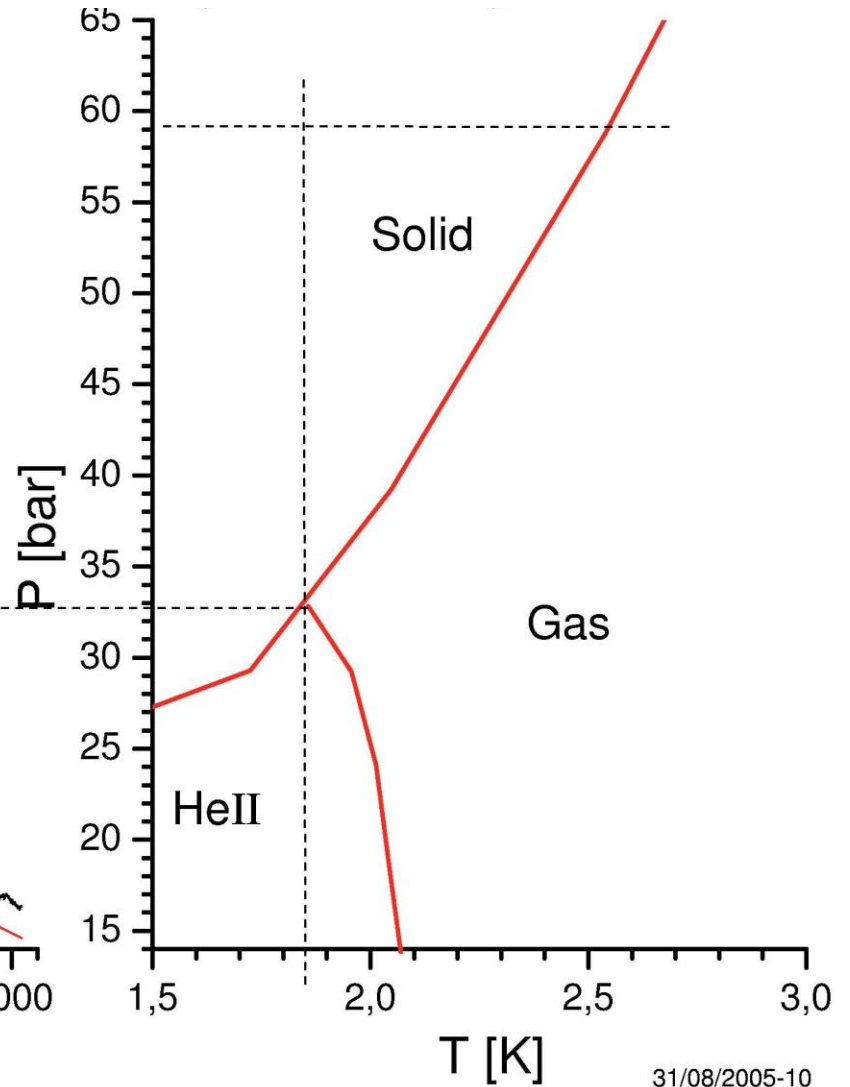
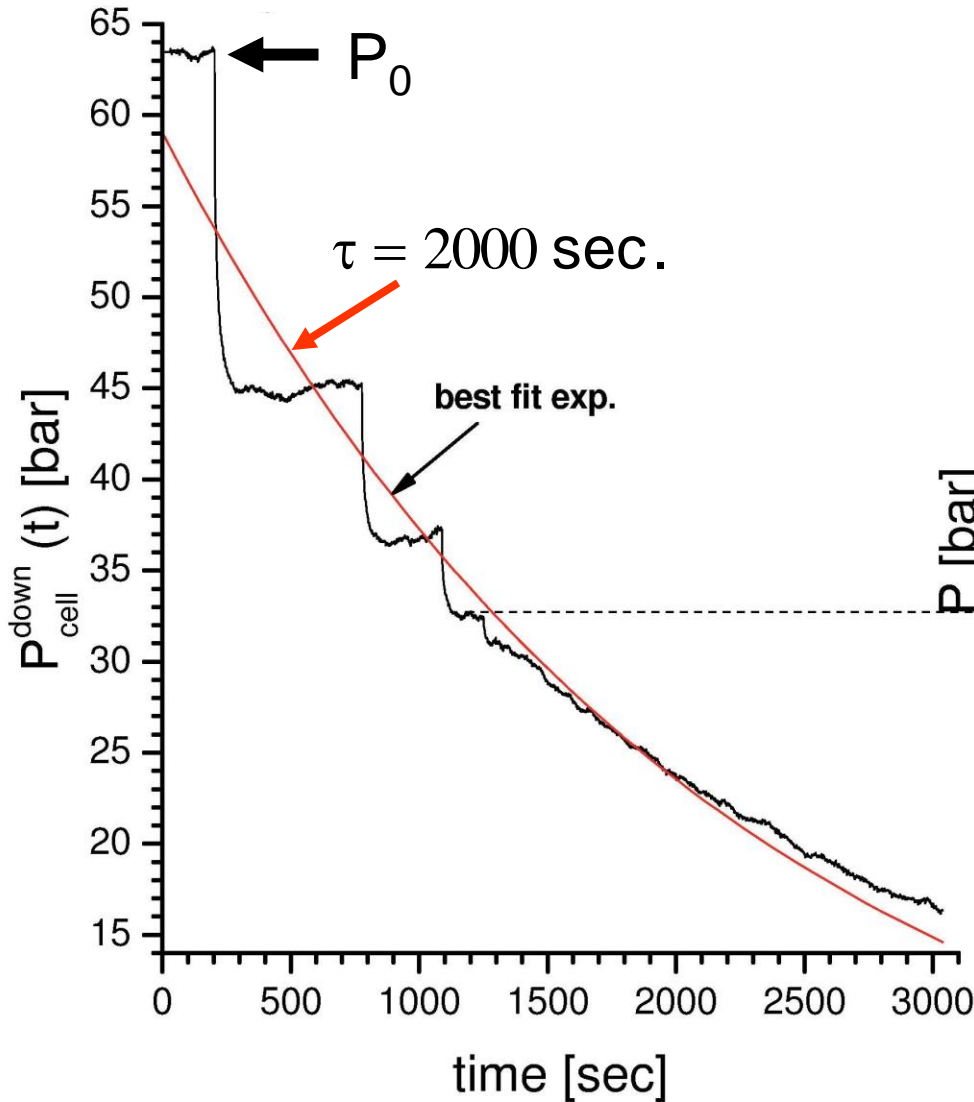
P_{det} ●

Geysers Measured with Valve Shut Off and Without Capillary

At Every Geyser Pulse in the Cell the Upstream Gas Pressure Drops Sharply

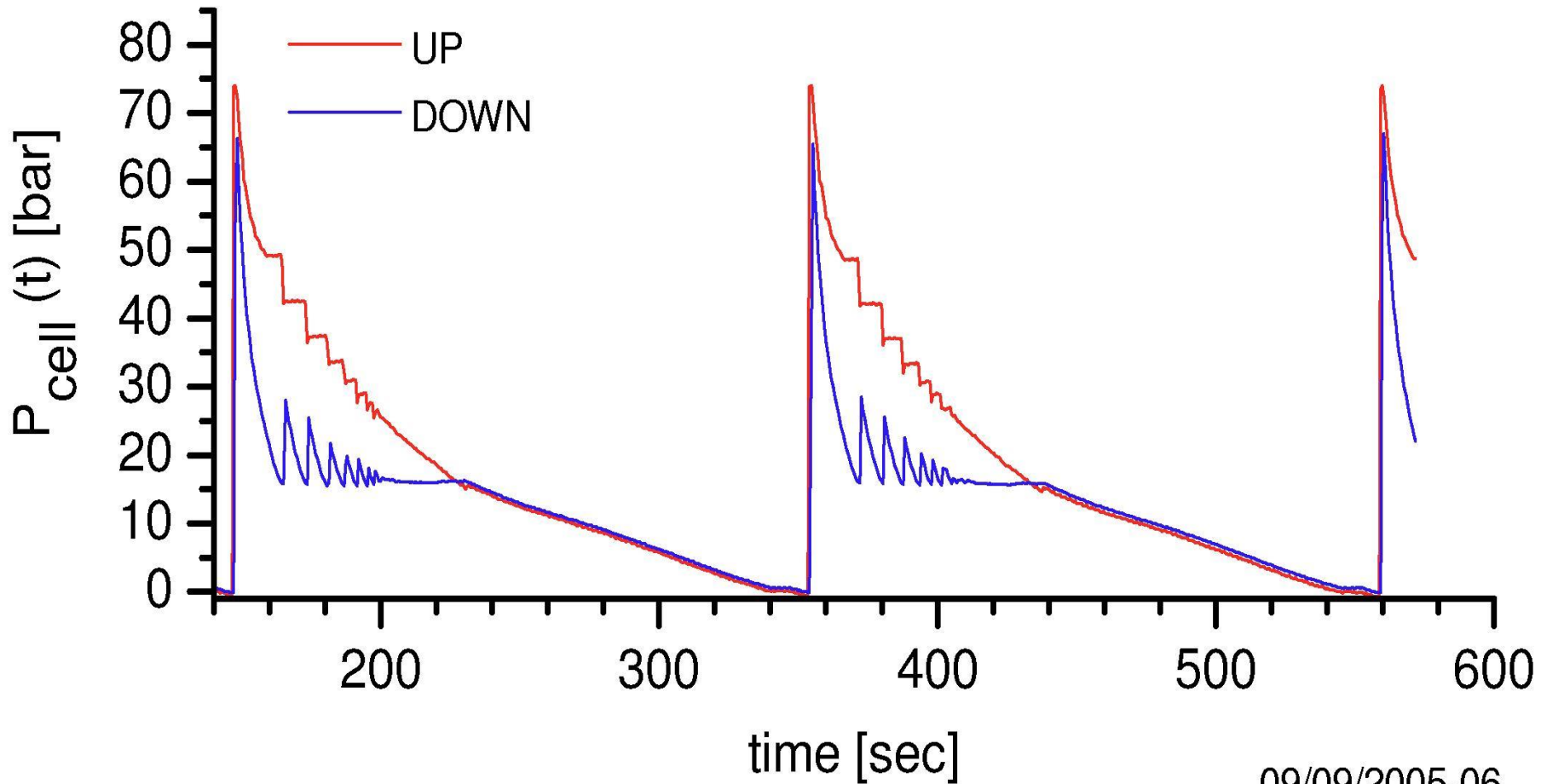


Upstream Gas Pressure „Drop-offs“ Cease at Melting Pt.



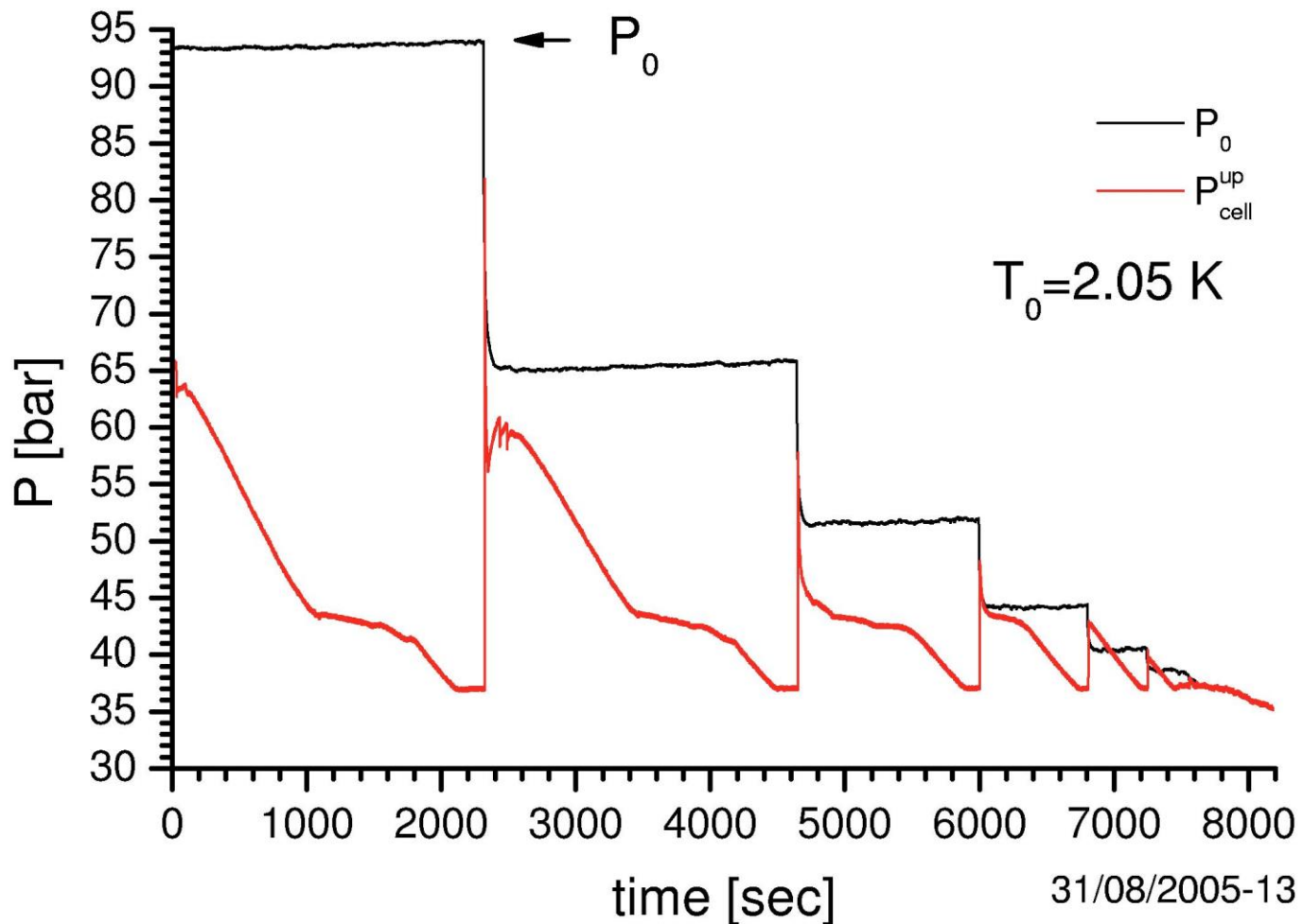
The Minigeysers Fall Off Much Faster than the Drain Time

$P_0 = 102 \text{ bar}$ $T_0 = 1.67 \text{ K}$

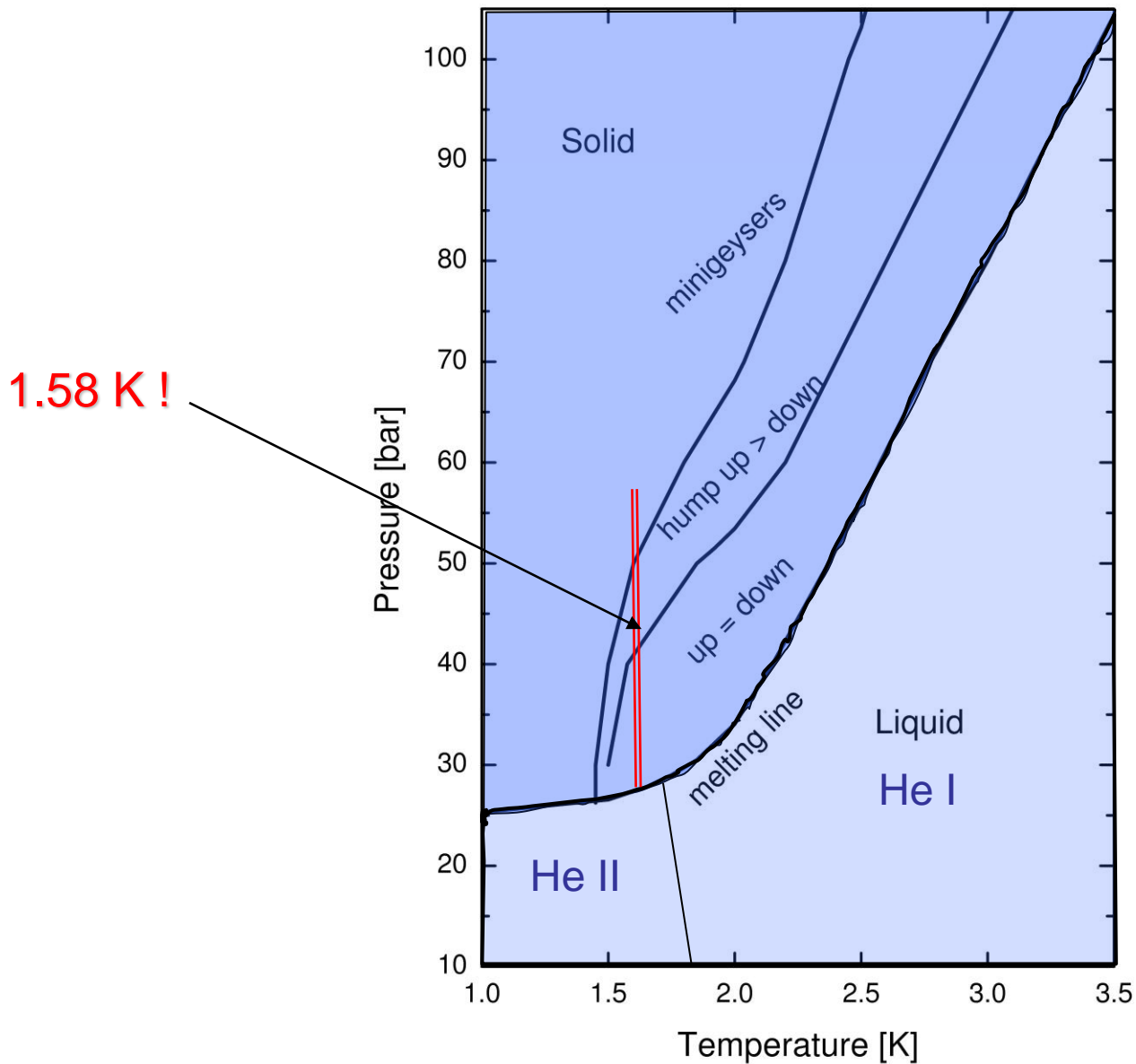


09/09/2005-06

Note the Remarkable Similarity to the Main Geysers:

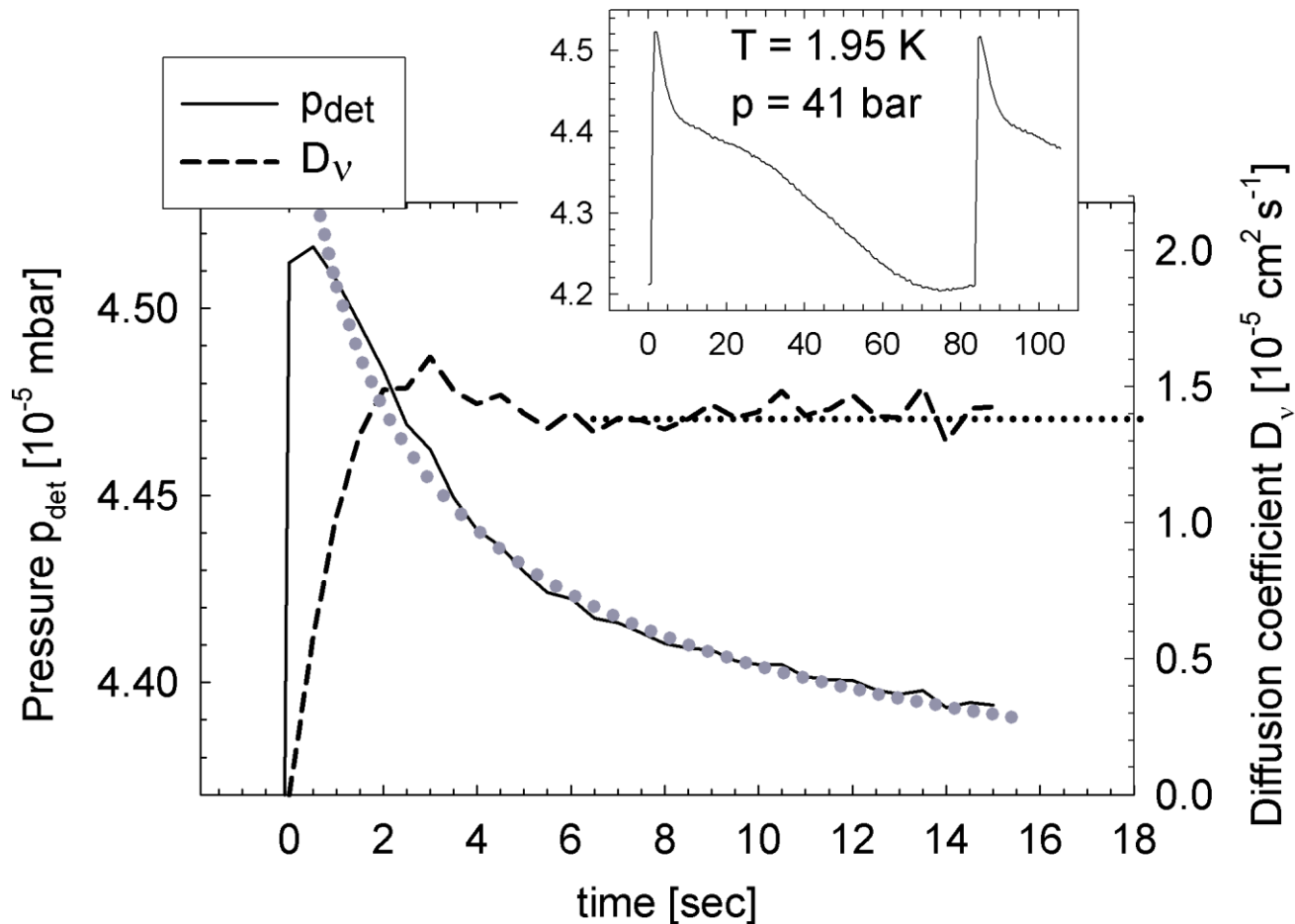


„Phase Diagram“ for Minigeysers



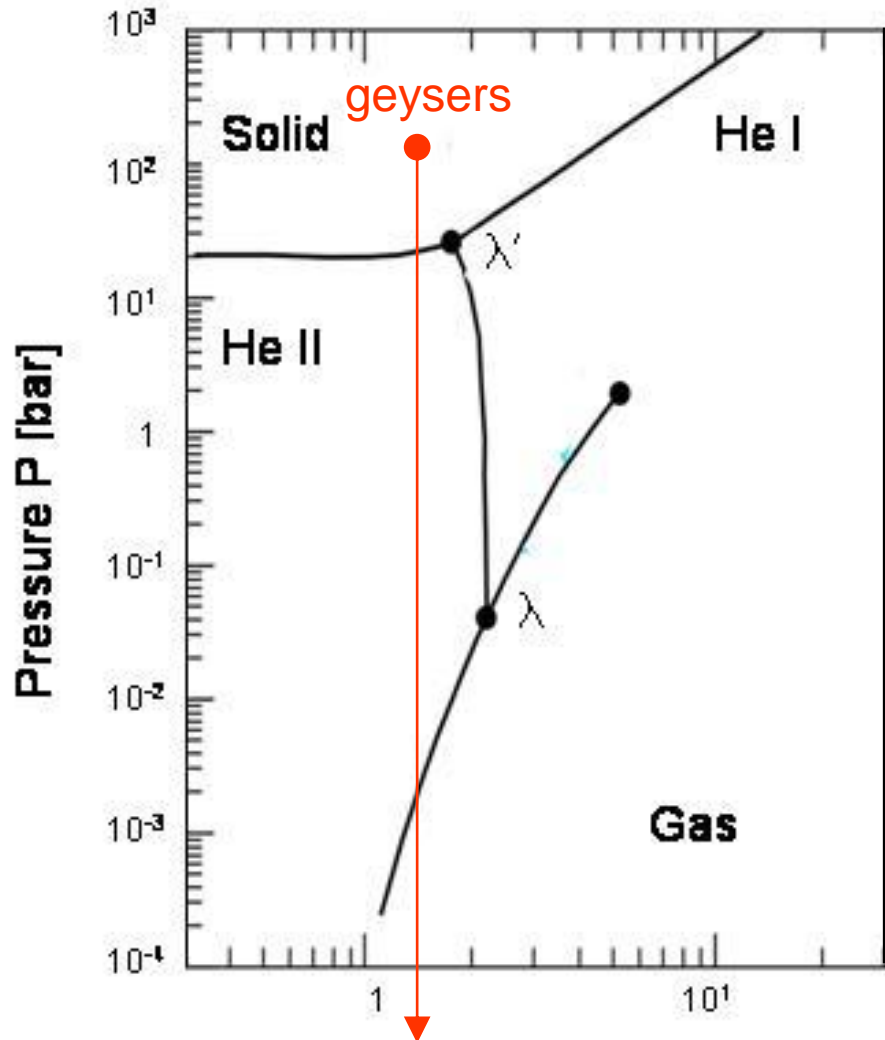
At Short Times (sec.) Initial Drop-off Depends on Vacancy Diffusion. Constant

$$\Phi \propto v(t) = \sqrt{\frac{4D_v}{\pi t}} \left(\frac{A_{\text{tube}}}{A_0}\right)^2, \quad t \ll \tau_v, \tau_{\text{rec}}$$

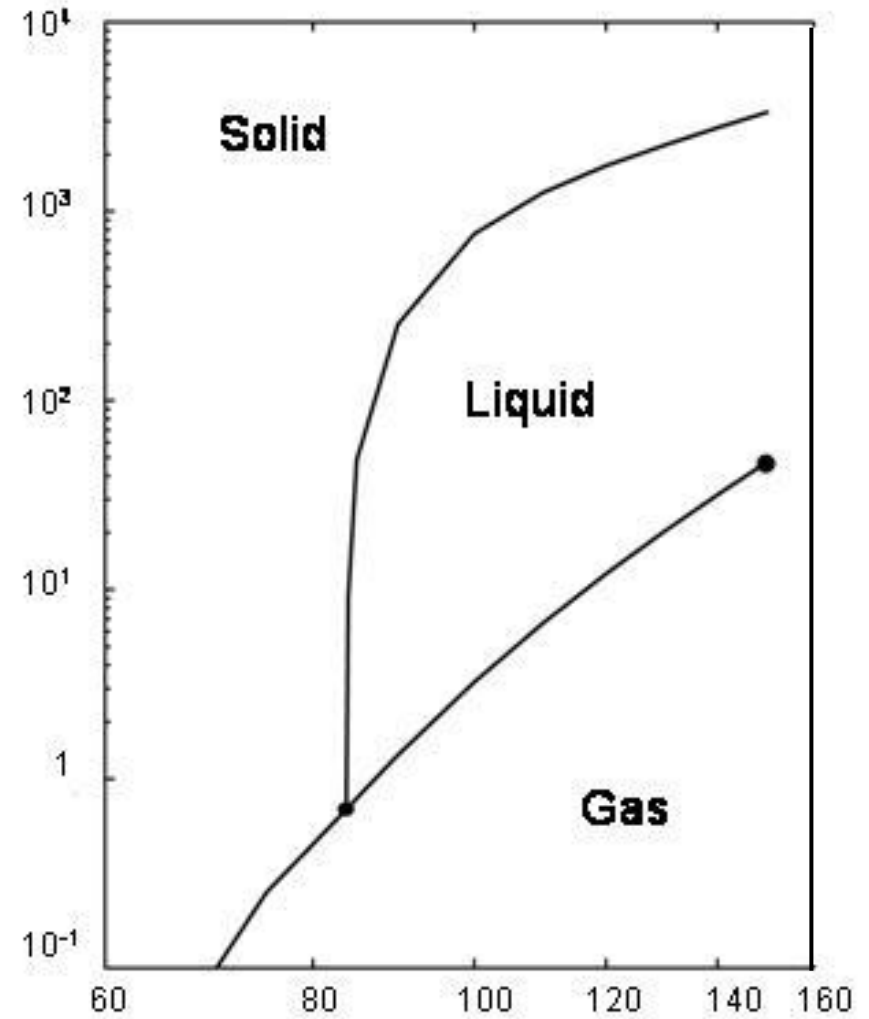


Helium has a Unique Phase Diagram

Helium



Argon



Temperature T [K]

Major Riddle

The sharp fall-offs in the anomalous region are orders of magnitude faster than the pumpdown times in both main and minigeysers chambers.

Either

1) the high vacancy concentration resulting from the violent pressurizing (200 bar/sec.) endows material with vanishing viscosity (SUPERGLASS?) .

or

2) In the initial rapid compression the material remains initially liquid and the sharp fall-off is due to the pressure drop accompanying solidification.