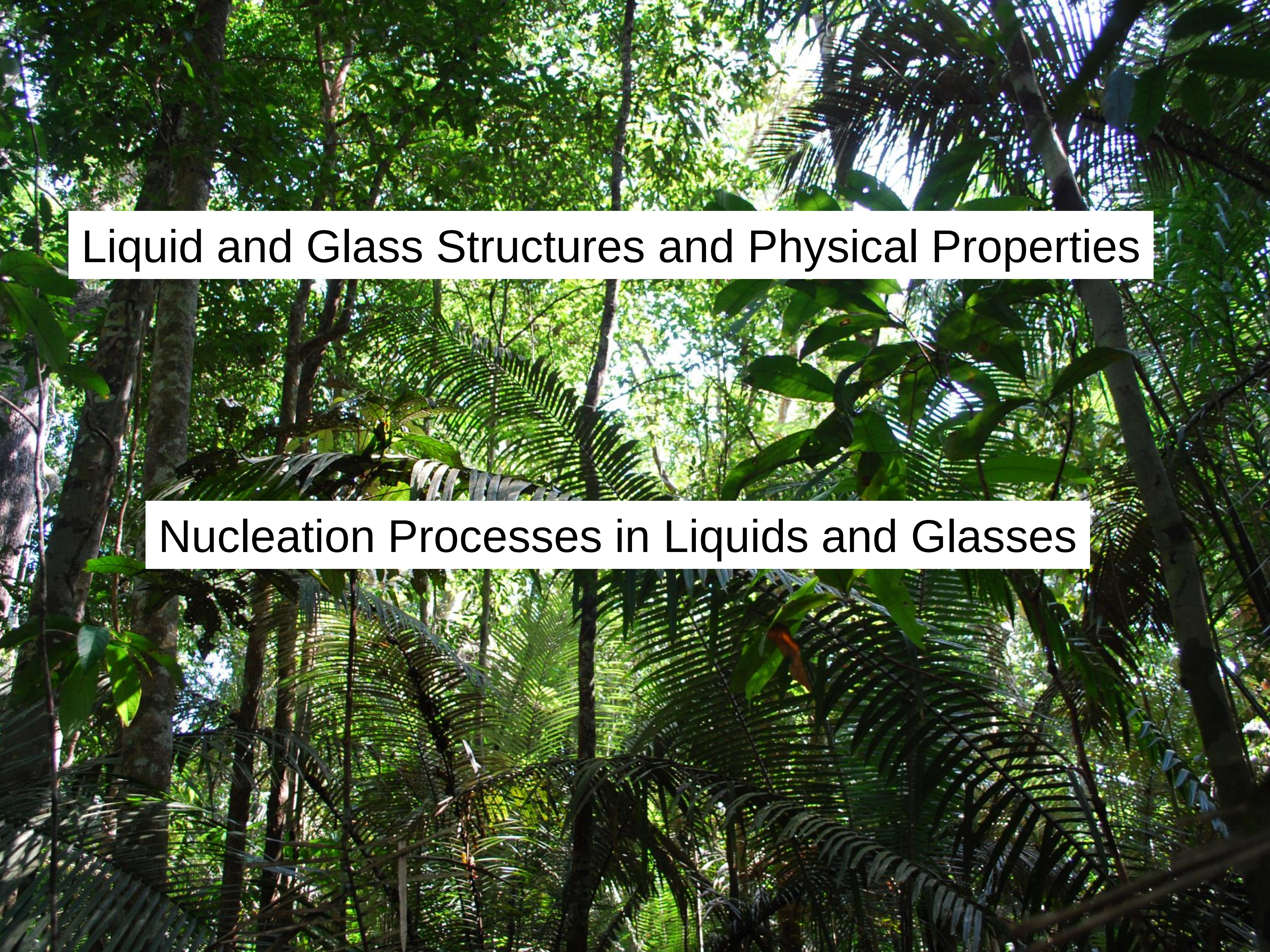
Liquid and Glass Structures and Physical Properties
Nucleation Processes in Liquids and Glasses

Liquid and Glasses
- Structures and Properties -

Ken Kelton

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Center for Materials Innovation
Washington University
St. Louis, MO 63131

Funding

National Science Foundation
WHERE DISCOVERIES BEGIN

NASA

Outline of Talk

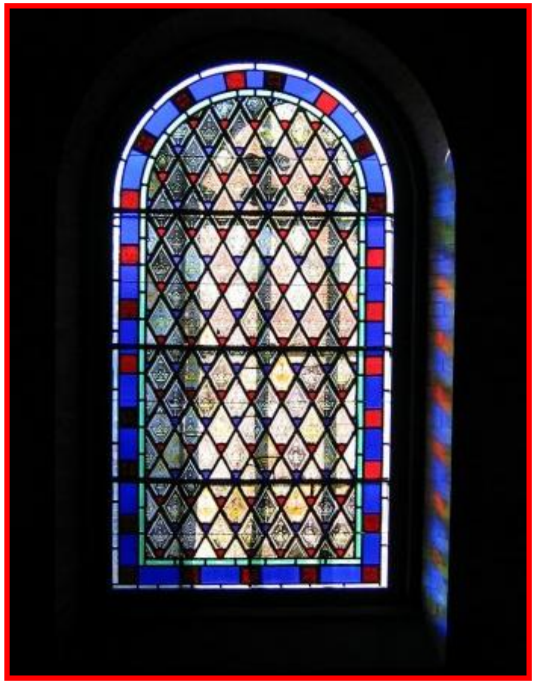
- Introduction

- Containerless processing for liquids
  - Experimental techniques
  - Thermophysical property measurements
  - Diffraction studies

- Selected Case Studies
  - Liquid/liquid phase transition in silicon?
  - Ordering in amorphous metals
    - In glasses
    - In liquids
    - Icosahedral ordering and the glass transition
  - Anomalies in thermophysical properties of transition metal liquids - possible liquid phase transition

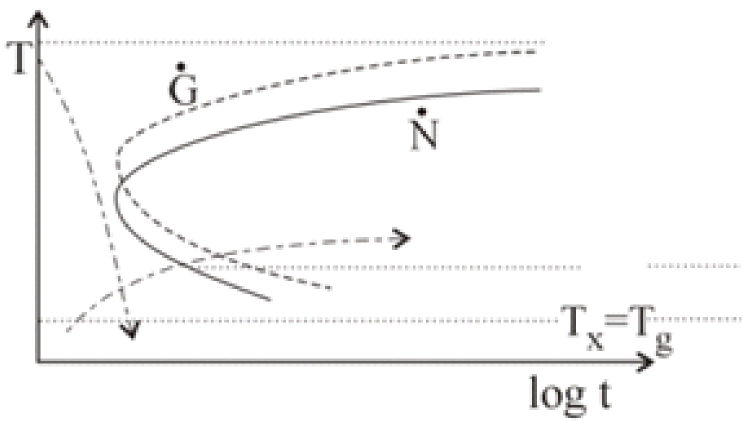
- Conclusions

Examples of Glasses

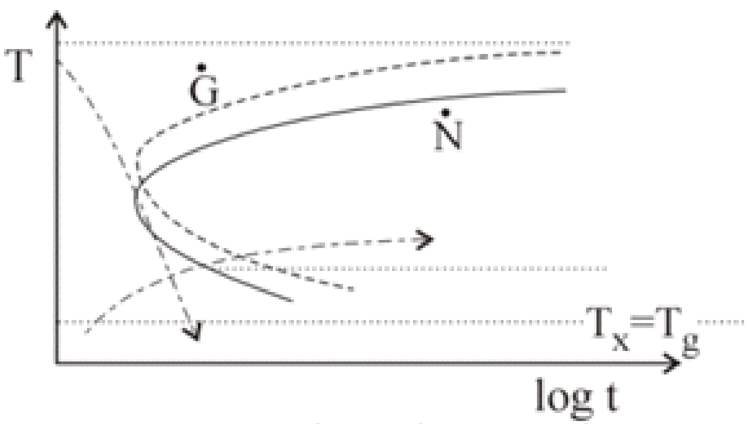


Glass Formation

Nucleation Control:



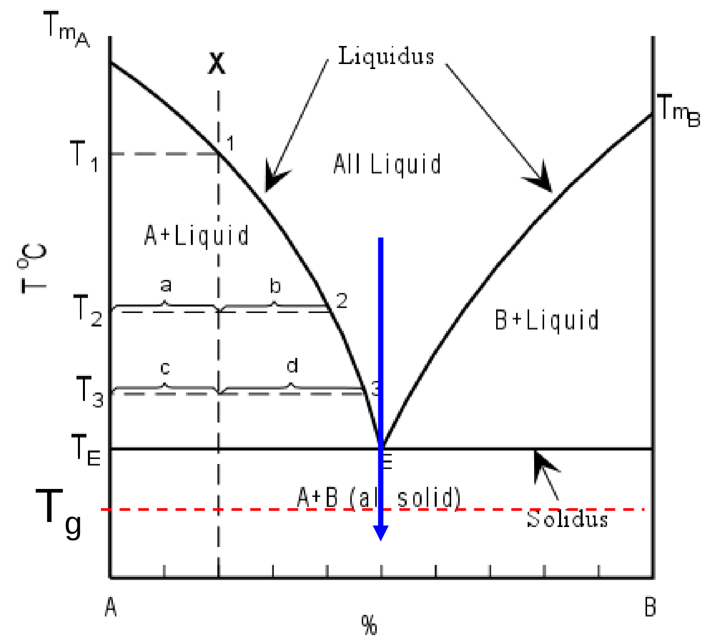
Growth Control:



J. H. Perepezko and R. J. Herbert, JOM, TMS (March, 2002)

Other Criteria - None Perfect
Liquid Structure Important

Deep Eutectic (Turnbull, 1969)



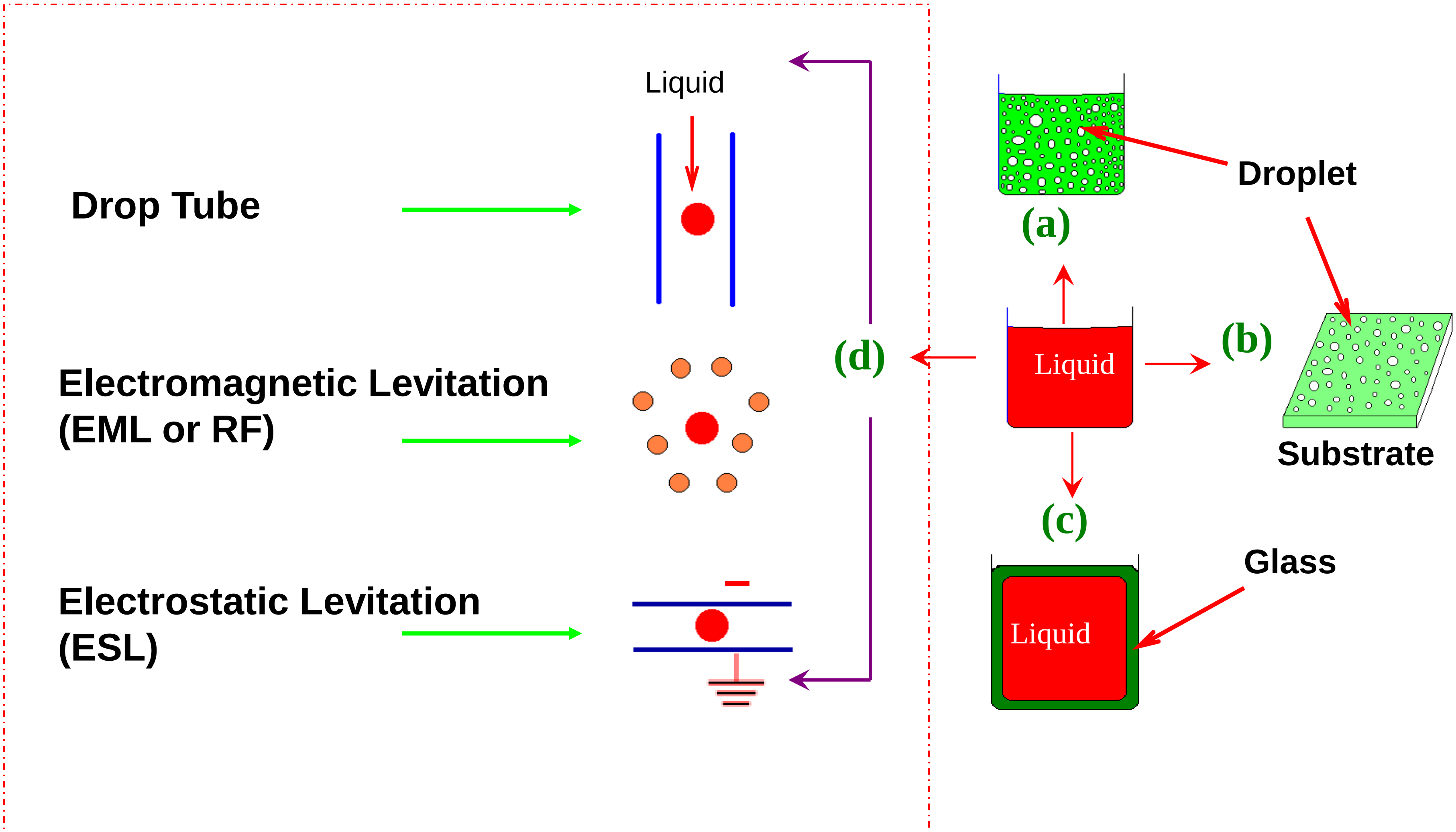
$$I = A^* \exp\left(-\frac{16\pi}{3k_B T}\frac{\sigma^3}{\Delta g^2}\right)$$

- A* is function of atomic mobility, very low below T_g
- Minimize temperature range between T_e and T_g – minimize driving free energy (Δg)

Studies of Liquids
(Mostly Metallic)

- Glasses traditionally formed when liquid is cooled sufficiently fast to avoid significant crystallization
- Studies of liquid structures and physical properties yield information on crystallization and other phase transitions
- Containers tend to limit amount of “supercooling” – heterogeneous nucleation (second lecture)
- Containerless processing for liquids
  - Experimental techniques
  - Thermophysical property measurements
  - Diffraction studies

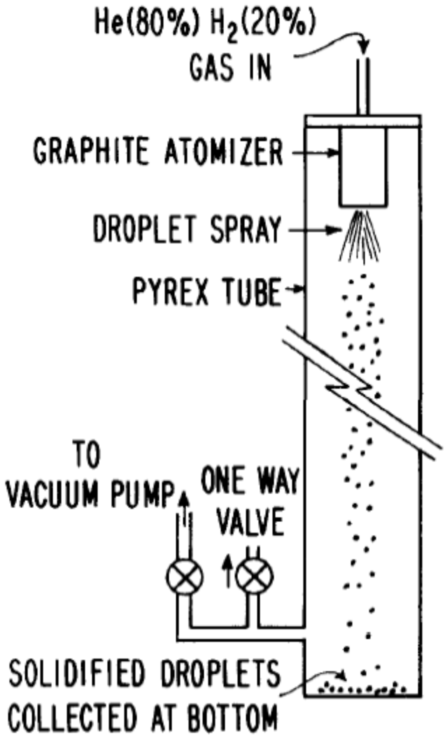
Supercooling Techniques



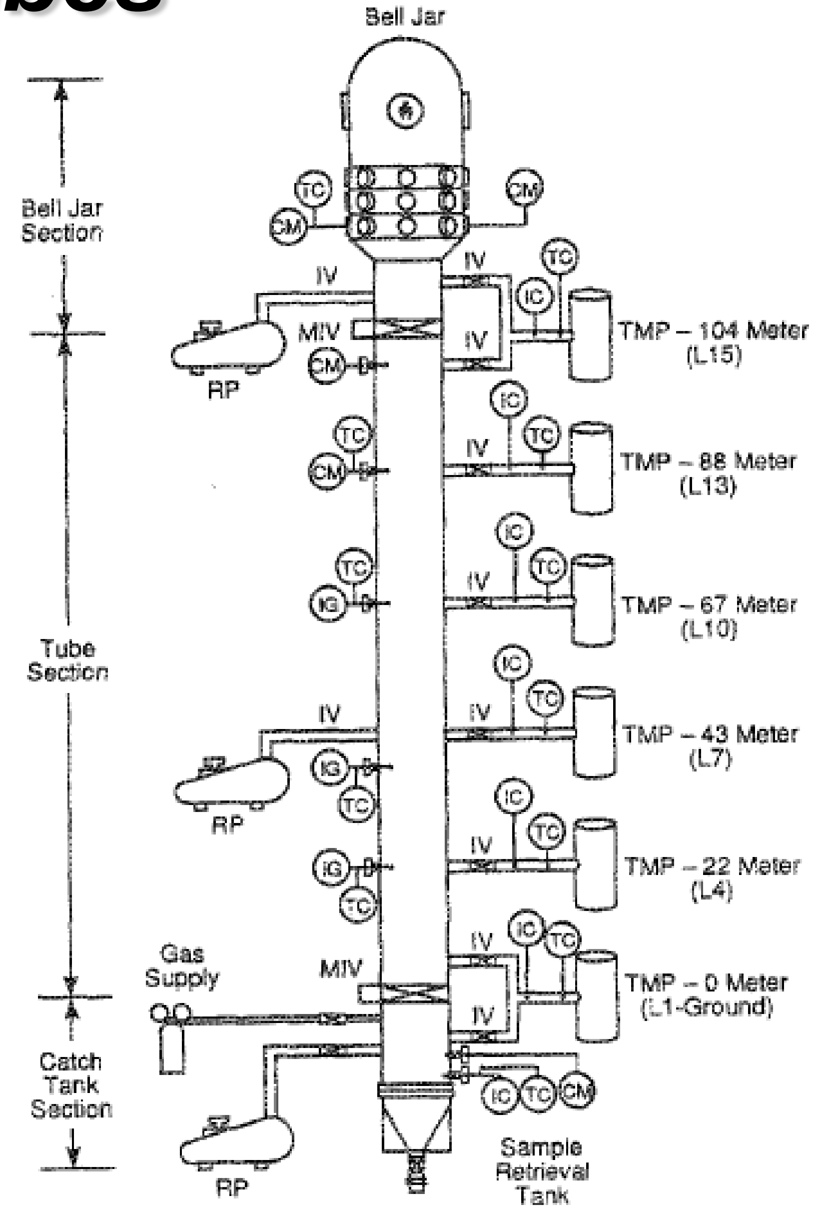
Containerless Solidification

From [1]

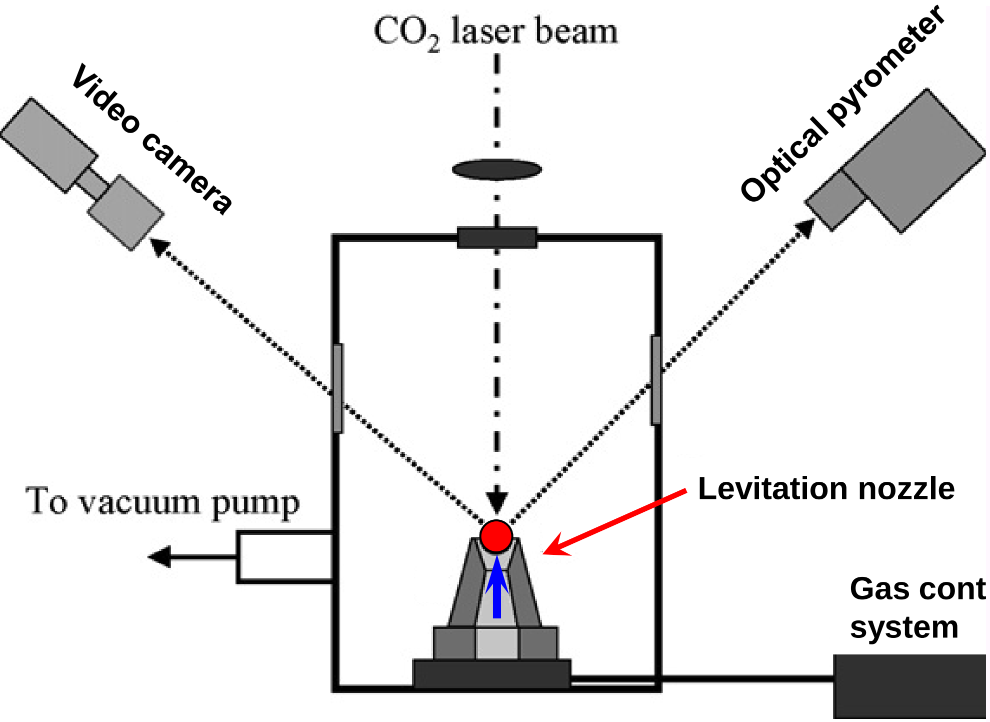
Drop-Tubes



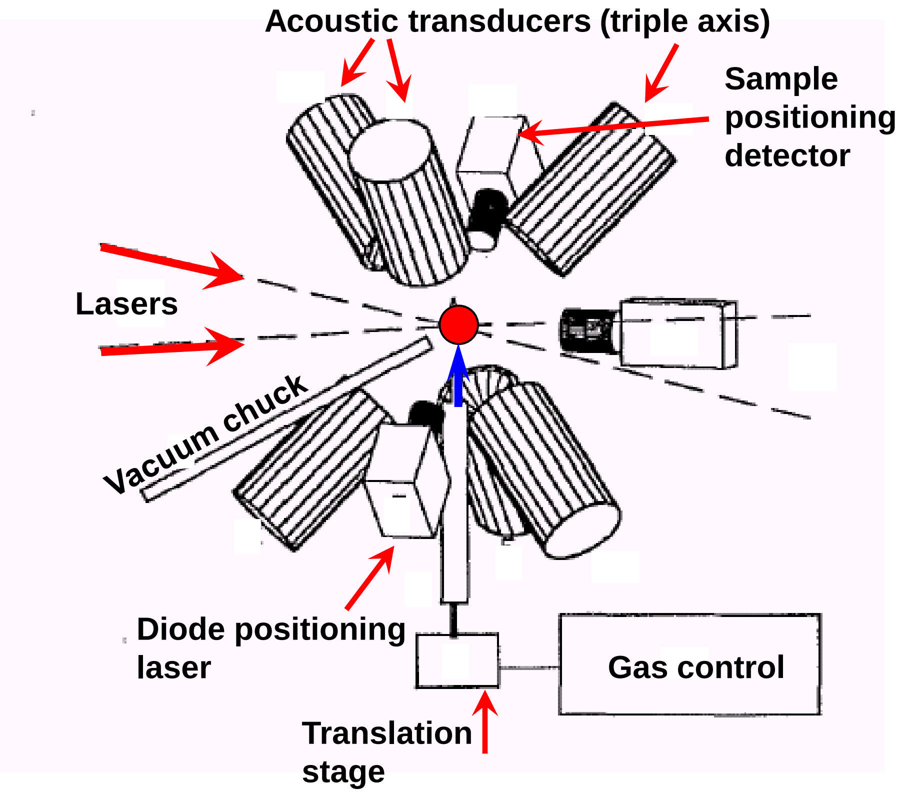
- Samples are melted and allowed to solidify while in free fall in vacuum or inert gas
- Lab-scale – atomized droplet (above, from [2])
- Marshall Space Flight Center (right, from [3])
- Allowed some temperature measurements during free fall



Aerodynamic and Acoustic Levitation



Aerodynamic Levitation (from[4])

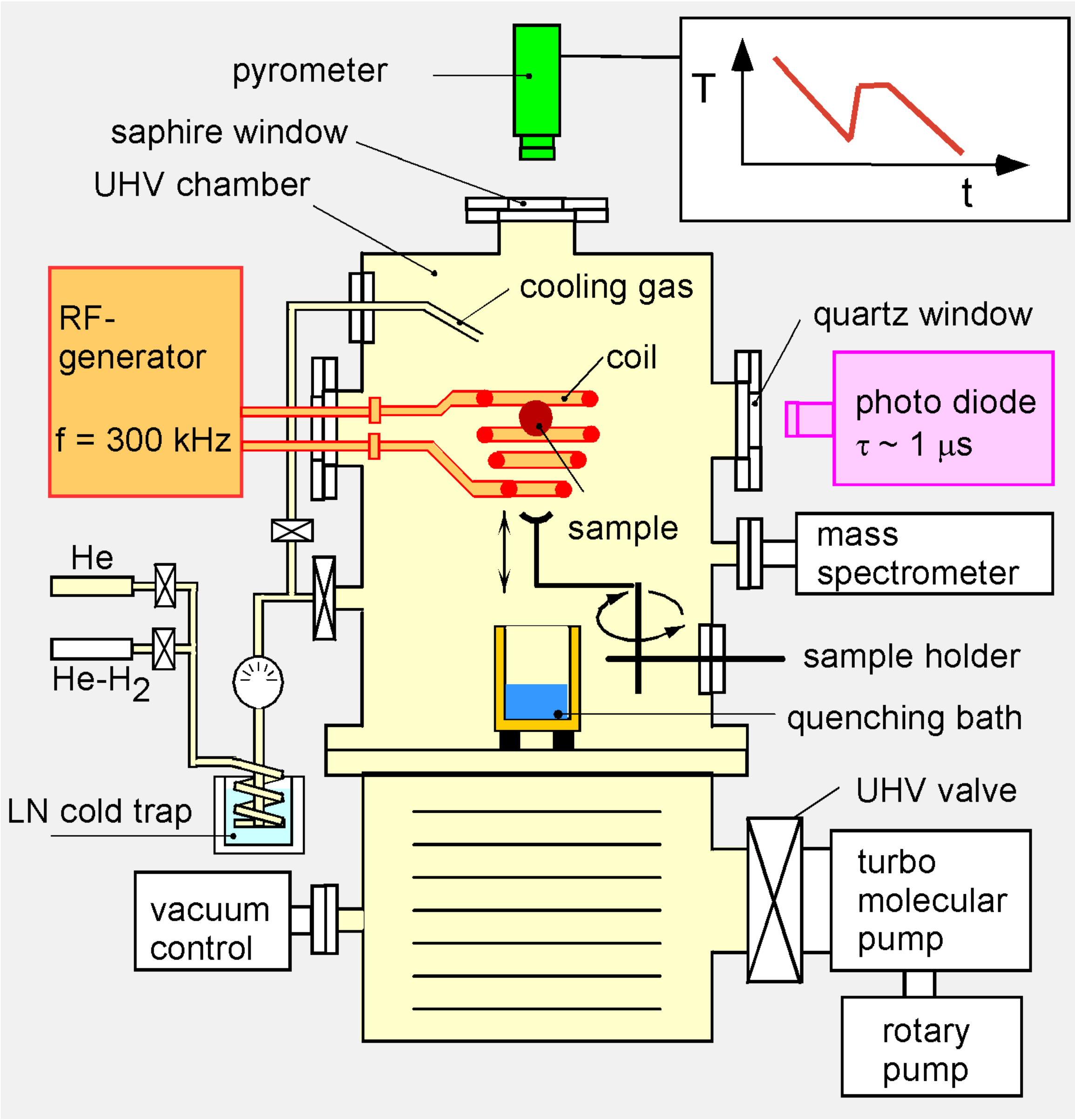


Aeroacoustic Levitation (from[5])

- Liquid oxides and reactive metals
- Levitation in controlled gas flow through nozzles designed for sample size and density
- Samples heated up to 2700K using high-power lasers
- Sample temperature measured with optical pyrometer
- The flowing gas makes temperature and positioning control difficult & gas impurities may limit supercooling

- Combines aerodynamic and acoustic forces
- Additional positioning control (diode laser and detector)
- Gas flow provides sable quiescent boundary layer around sample – suprersses oscillation from acoustic forces
- Sample positioning and containment better than aerodynamic levitation alone

Advanced EML (TEMPUS)



From [6]

- More stable control than aerodynamic levitation
- Can be used to measure a variety of thermophysical and electrical properties and liquid structures

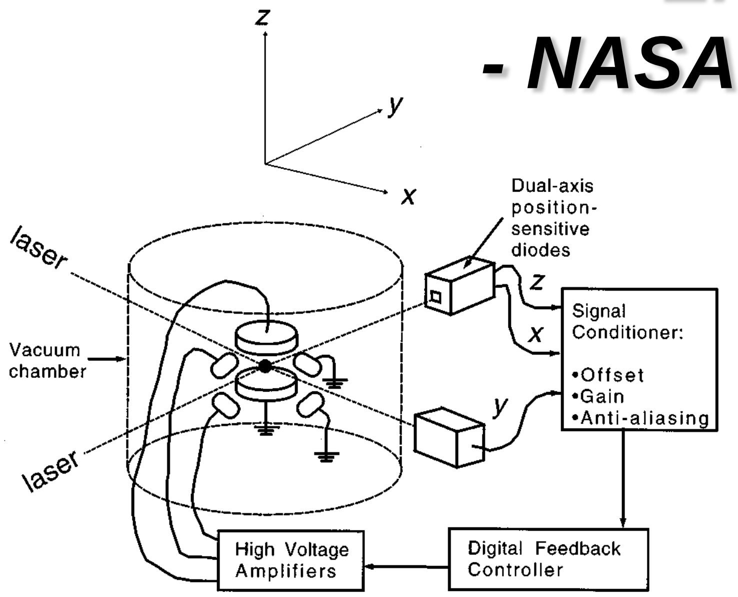
BUT

- Requires conducting sample
- Dense samples with low melting temperatures require cooling gas for undercooling studies

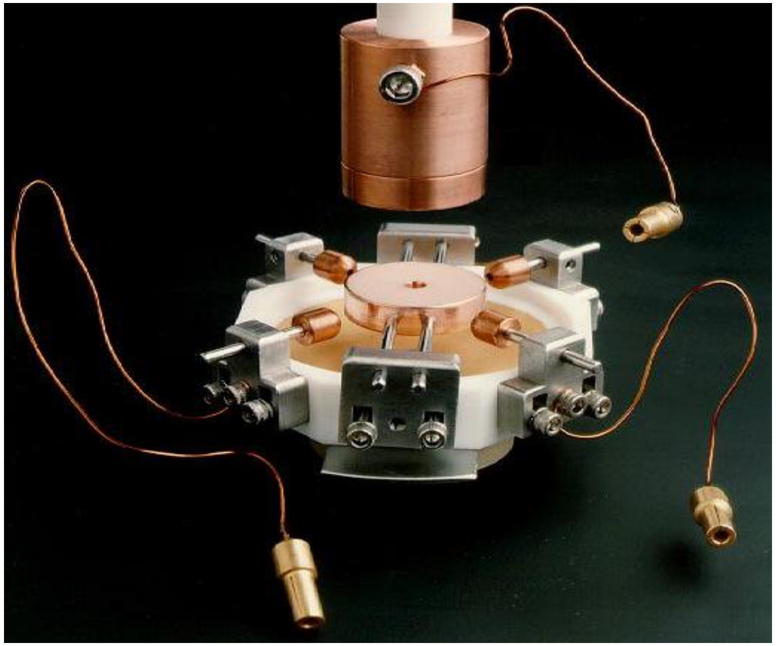
TEMPUS – Microgravity experiments on space shuttle (MSL-1)

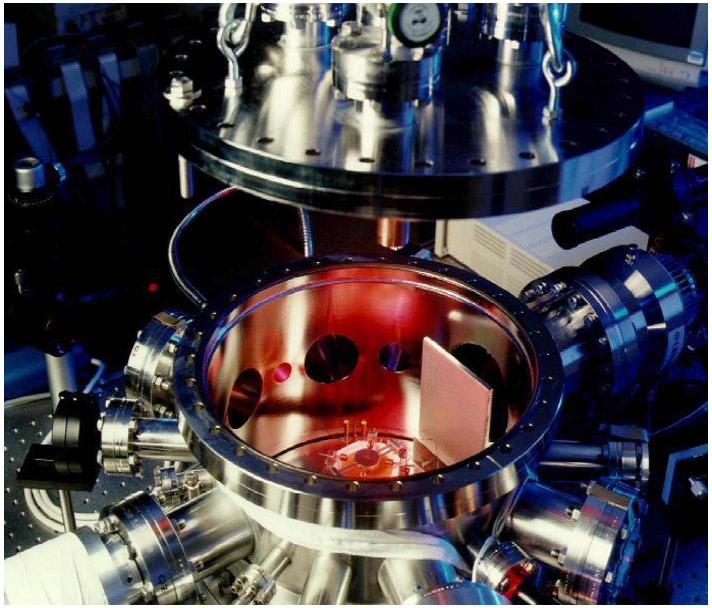
ISS – MSL-EML facility under construction; planned to be flown in 2011

Electrostatic levitation (ESL)
- NASA Marshall Space Flight Center -

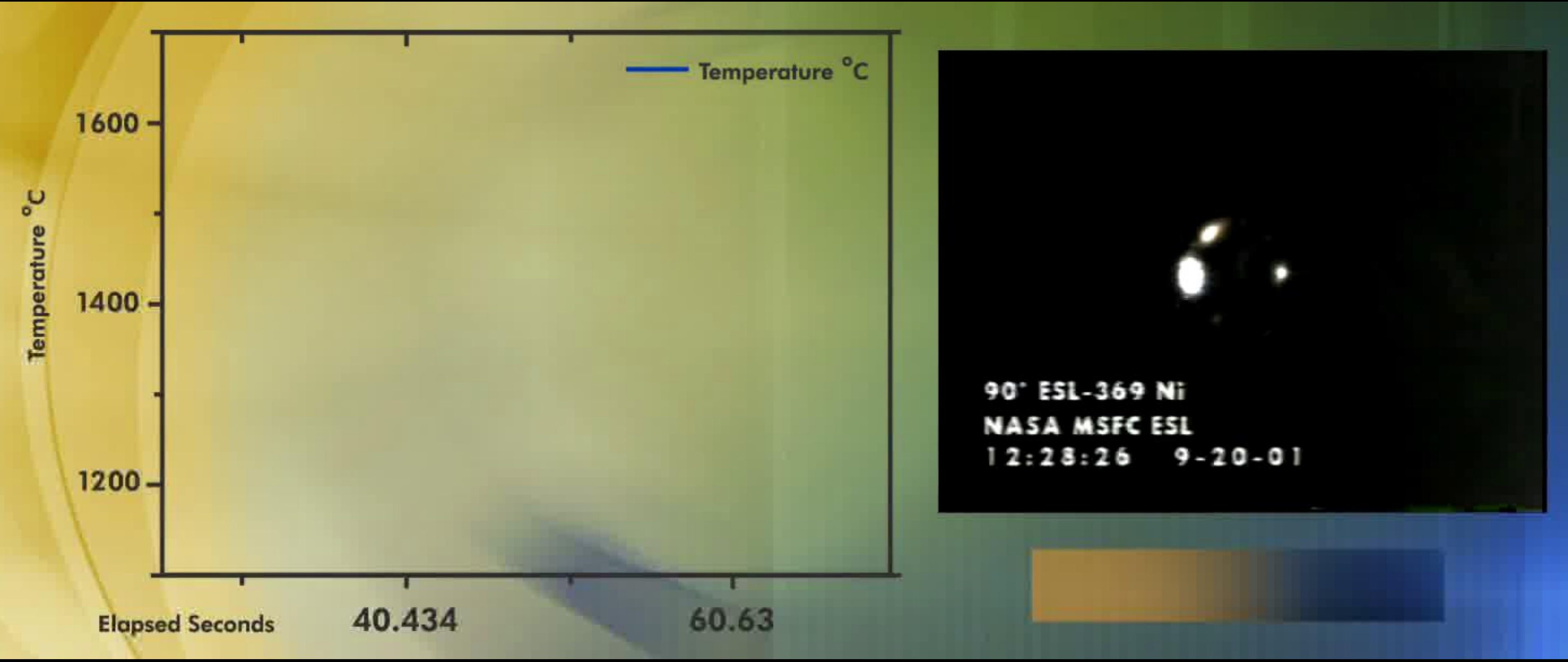


From [7]



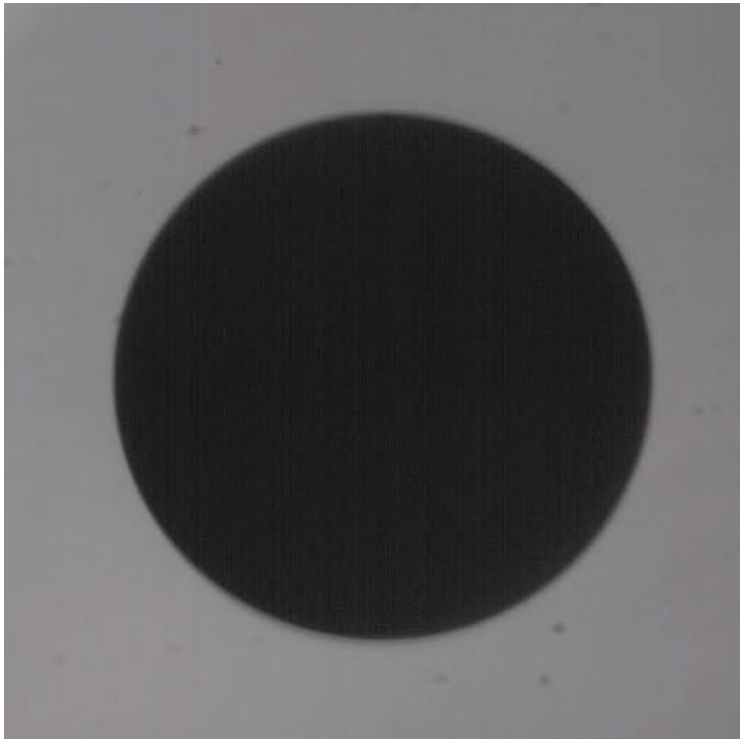


- Sample levitated in high vacuum ($\approx 10^{-7}$ -10^{-8} torr)
- Add surface charge on sample by induction
- Maintain surface charge with ultraviolet lamp
- Apply large dc-field to generate sufficient force to counter gravity
- Fast feed-back mechanism to stabilize sample position (three independent sets of electrodes for x, y, and z positioning)
- Position stability to better than 50 micrometers
- Lasers used to heat the sample



J. R. Rogers, NASA

Oscillating Droplet Measurements

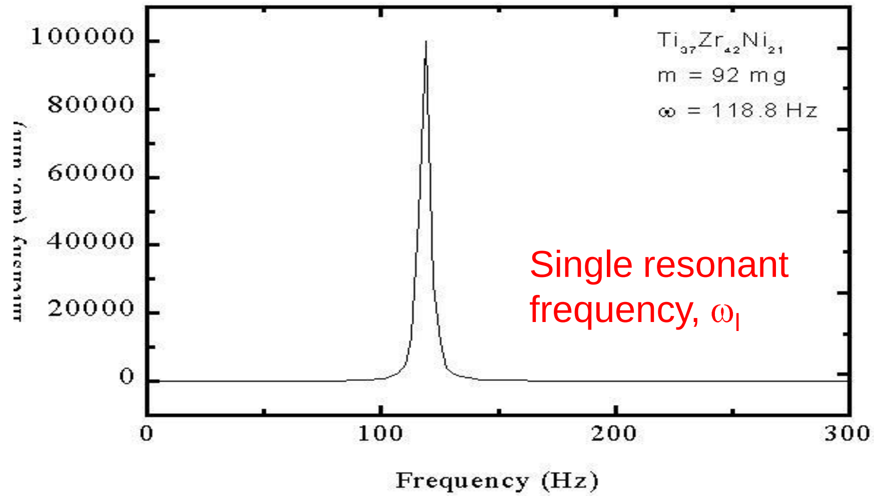


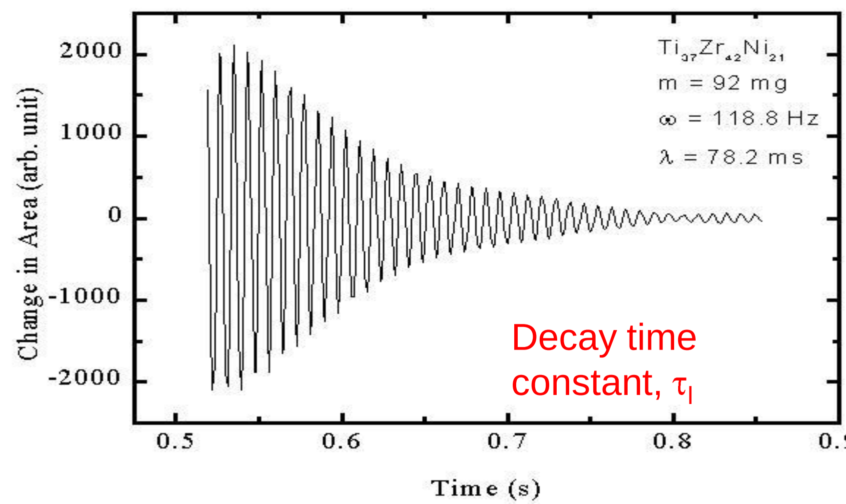
$$R = R_0 (1 + \delta \cos(\omega t) e^{-\lambda t})$$

$$\omega_l = \sqrt{\frac{l(l-1)(l+2)\sigma}{\rho R_o^3}}$$ Rayleigh (1879)

$$\tau_l = \frac{\rho R_o^2}{(l-1)(2l+1)\eta}$$ Lamb (1881)

- Modulate ESL field near sample resonant frequency
- Damped Oscillations $Ti_{37}Zr_{42}Ni_{21}$ at 1048 K
- Recorded at 1000 Hz, played at 10 Hz





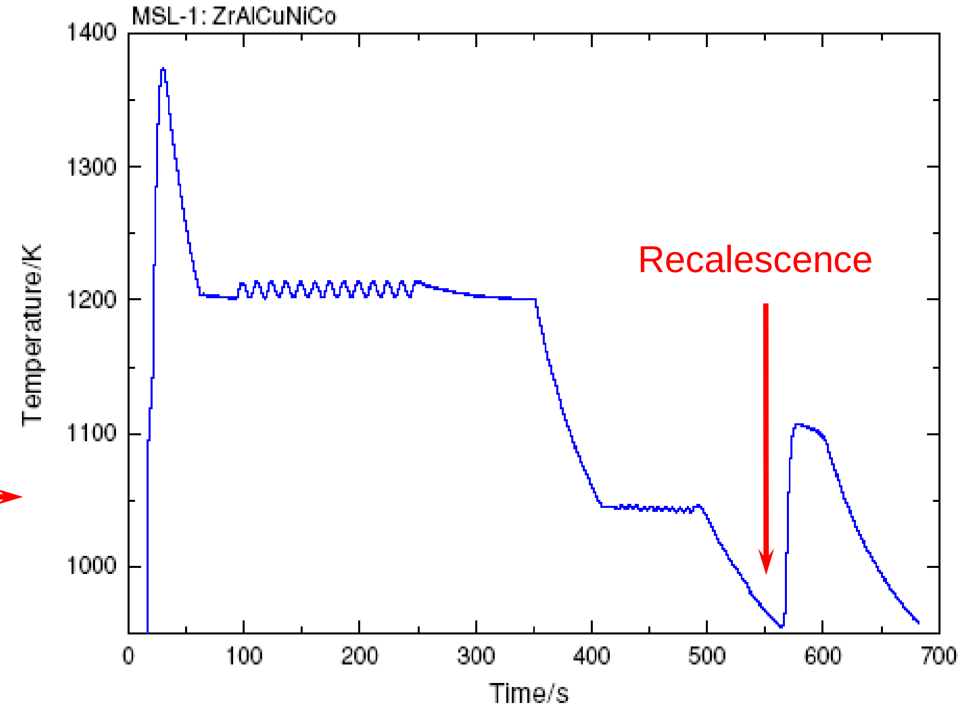
Other Property Measurements

Specific Heat (C_p/ε)

- Radiation Cooling $$mC_p(T)\frac{dT}{dt} = \sigma_B A \varepsilon_T (T^4 - T_r^4)$$

- Modulation Calorimetry
  - Modulate power
  - Measure response in sample temperature

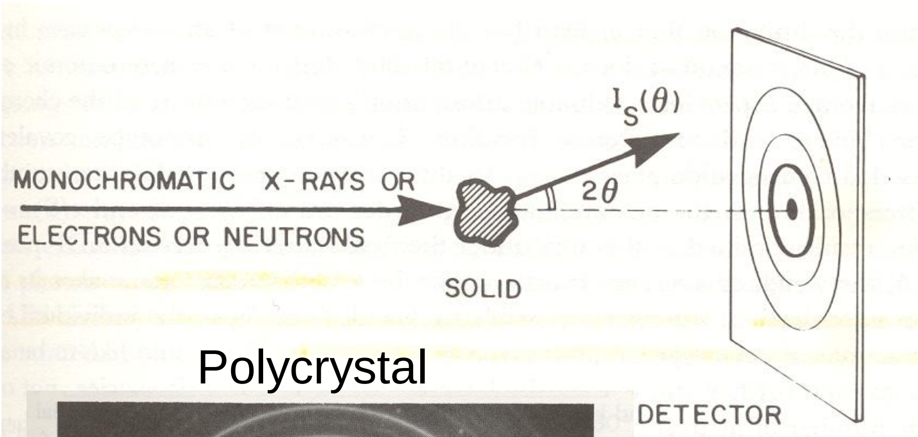
MSL-1 Spacelab mission. Experimental study of $Zr_{60}Al_{10}Cu_{18}Ni_9Co_3$ liquid using modulation calorimetry



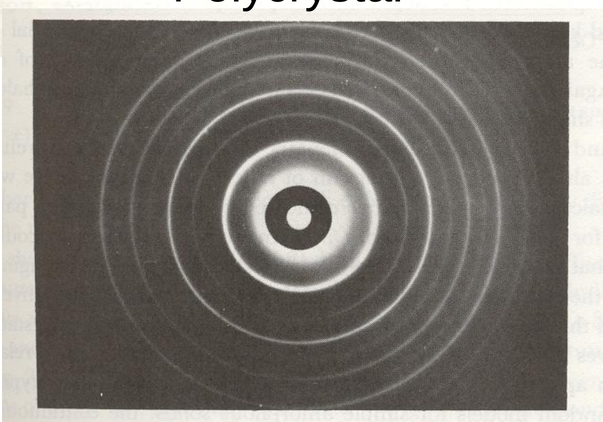
Density

High resolution image of sample (perpendicular to axis)
Sub-pixel resolution edge fitting

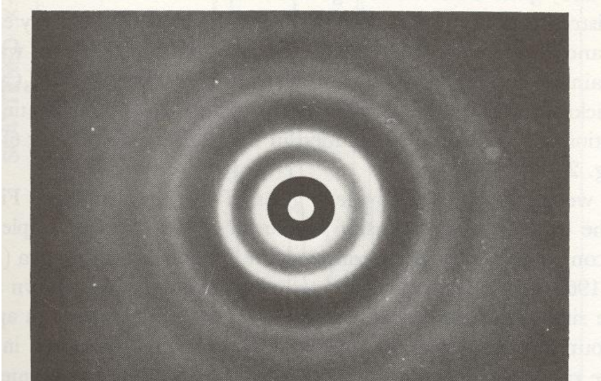
Amorphous Phase Structure



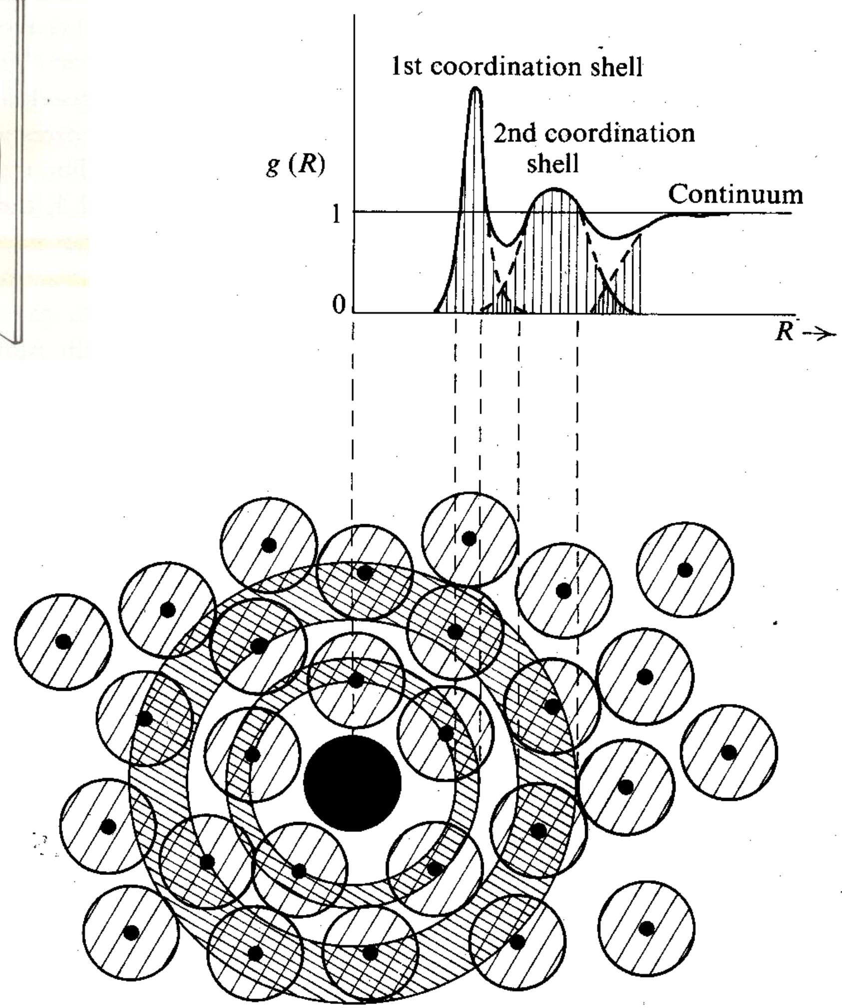
Polycrystal



Glass



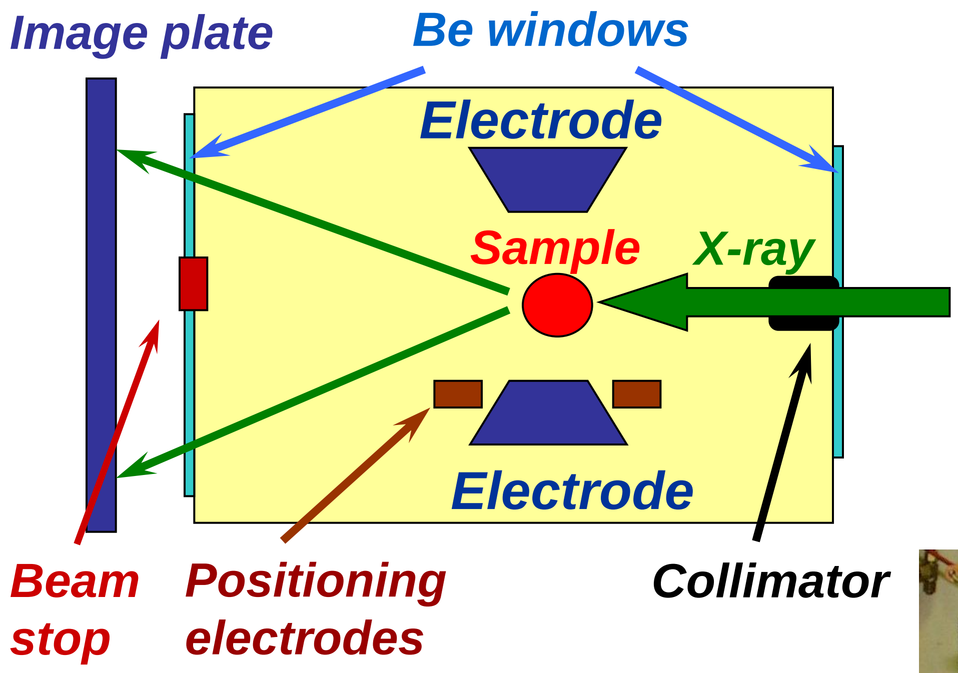
Radial Distribution Function



Glasses (and liquids*) have significant nearest-neighbor order

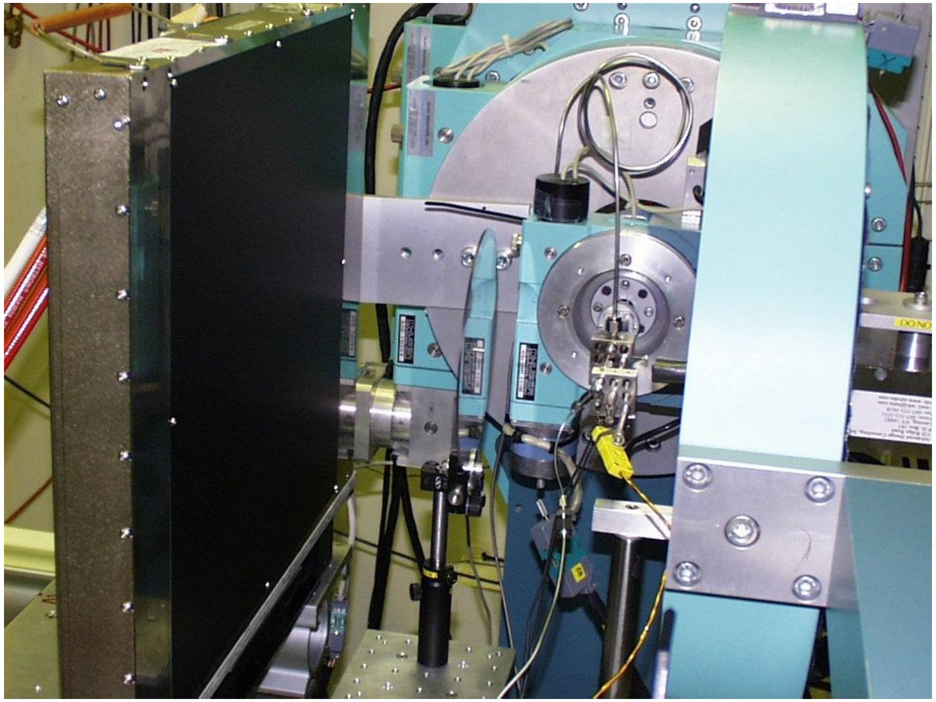
(See, for example, papers by Y. Waseda et al.)

Beamline ESL (BESL)

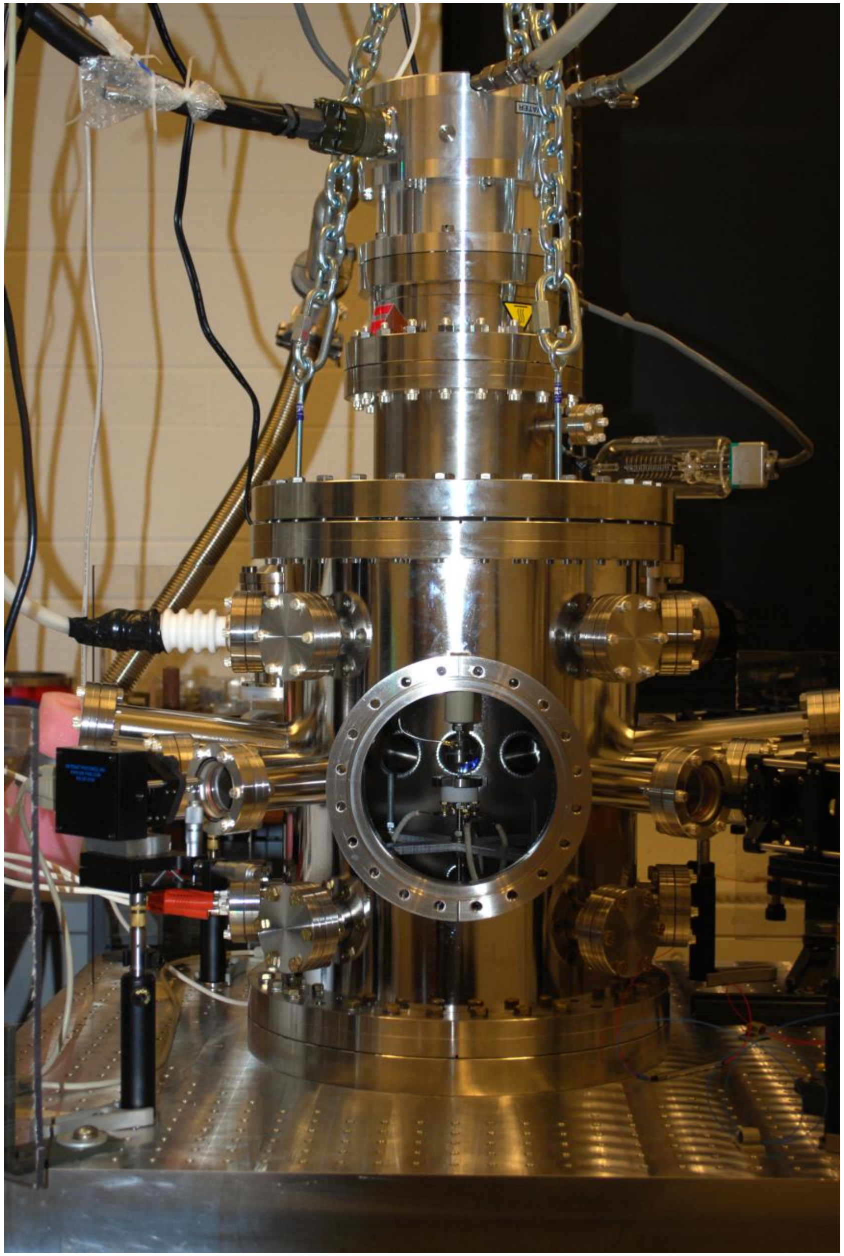


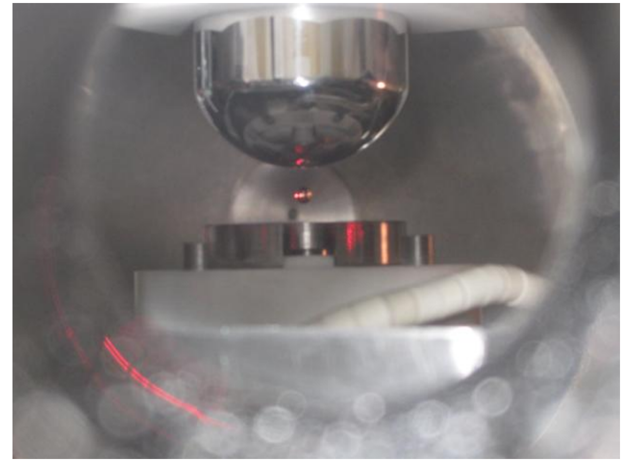
- First measurements made using ESL at Marshall Space Flight Center
- Washington University, Marshall Space Flight Center, Iowa State University
- Ref. [8,9]
- First experimental confirmation of Frank's hypothesis (second lecture – Nucleation)

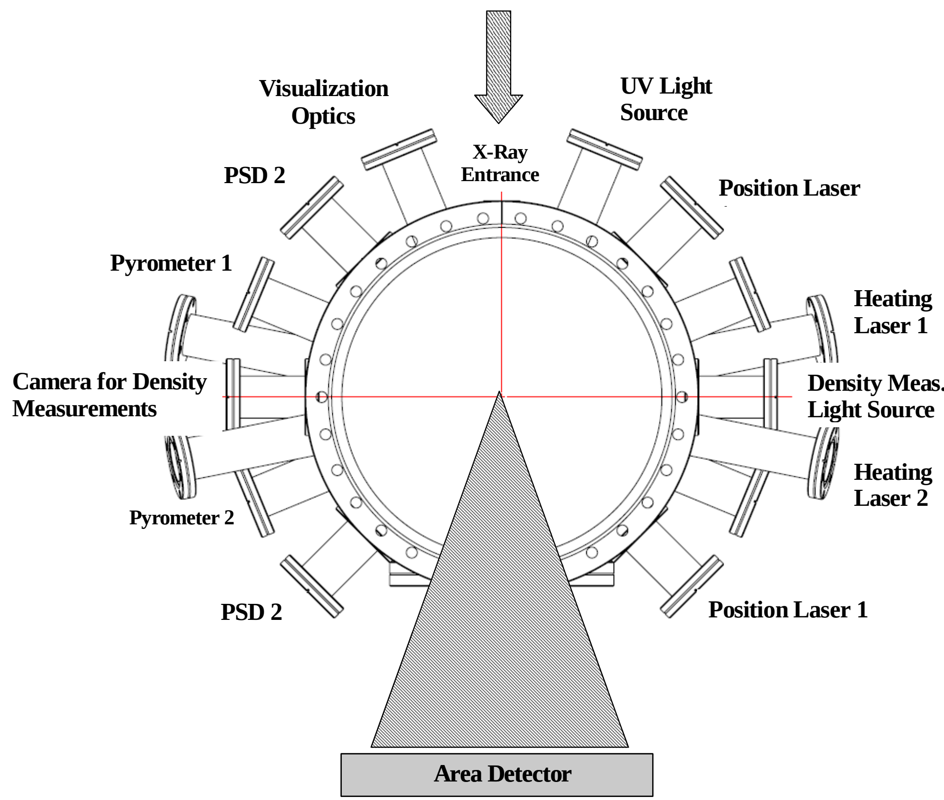
GE - Image Plate Detector



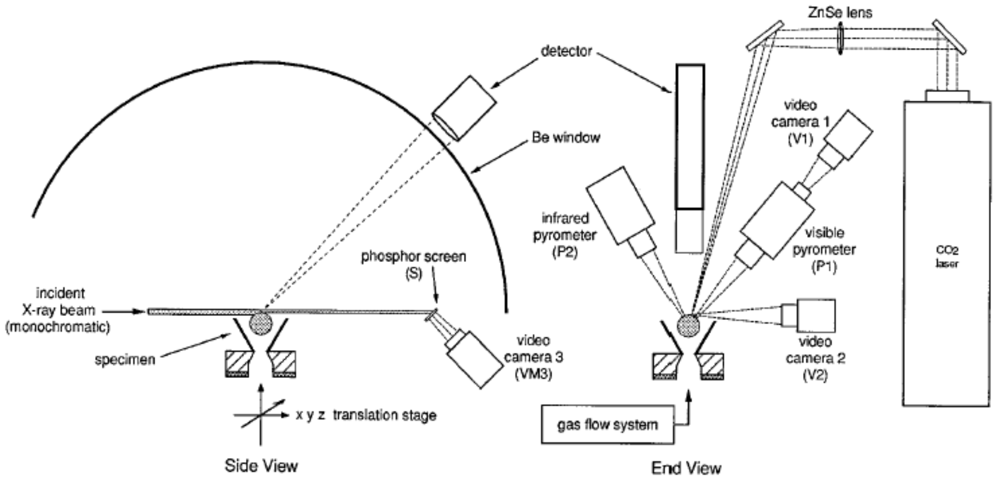
WU-BESL (Washington University Beamline ESL)

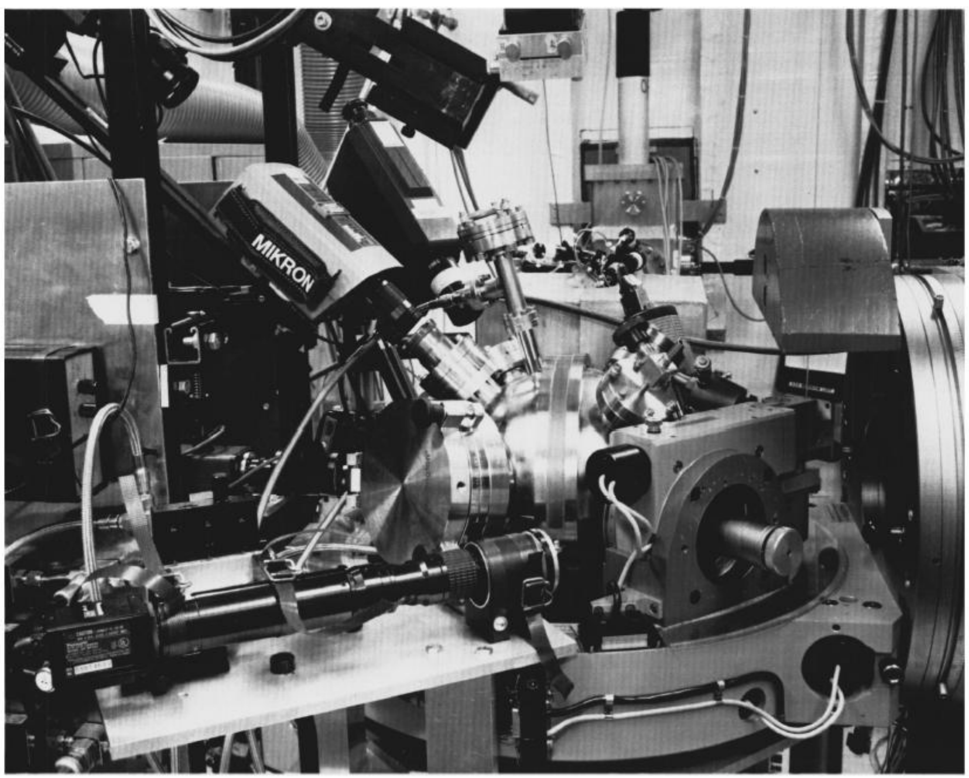






Aerodynamic Levitation Diffraction Apparatus





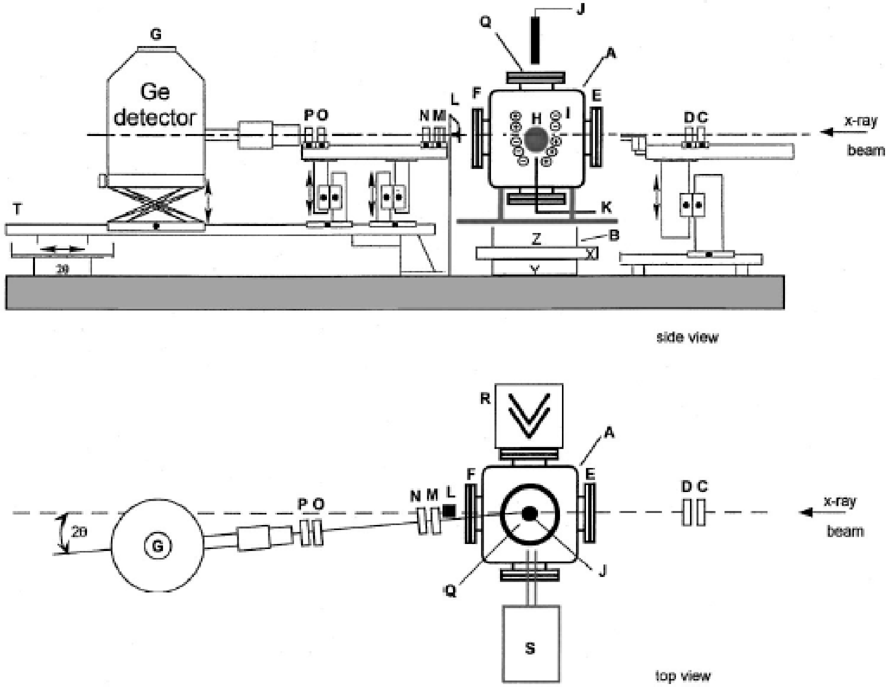
- Based on θ-2 θ geometry
- Heating with one or two CO_2 lasers
- Capable of studying very high temperature liquids

But

- Sample stability not as good as EML or ESL
- Large temperature gradients in poorly conducting samples
- Diffraction geometry not suited for studies of phase transitions or structure evolution in deeply undercooled liquids

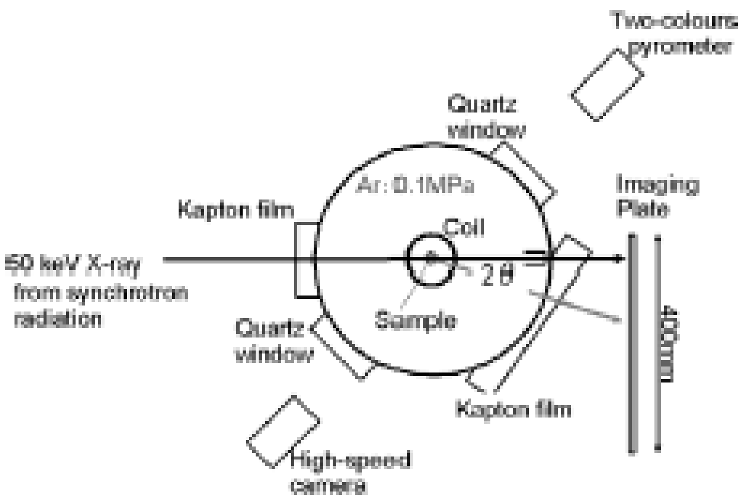
From [10]

Other Levitation Diffraction Approaches



EML levitation chamber (Germany)

- Energy dispersive x-ray diffraction using white beam synchrotron radiation
- Diffracted beam is by energy dispersive germanium detector at a constant angle 2θ. From [11]



ESL levitation chamber (Japan)

- Fixed energy (50 kV) x-rays
- Imaging plate detection
  From [12]
- **Laboratory-based x-ray diffraction**
  From [13]

References for Levitation Apparatus

1. *Nucleation in Condensed Matter – Applications in Materials and Biology,* K. F. Kelton and A. L. Greer, Elsevier (to be published, Spring, 2010).
2. A. J. Drehman and D. Turnbull, "Solidification behavior of undercooled Pd83Si17 and Pd82Si18 liquid droplets," *Scripta Metall*, **15** (1981) 543.
3. T. J. Rathz, M. B. Robinson, W. M. Hofmeister and R. J. Bayuzick, "The Marshall Space Flight Center drop tube facility," *Rev. Sci. Instrum.* **61** (1990) 3846.
4. J. J. Wall, R. Weber, J. Kim, P. K. Liaw, H. Choo, "Aerodynamic levitation processing of a Zr-based bulk metallic glass," *Mat. Sci. Eng.,* **A445-446** (2007) 219.
5. J. R. Weber, D. S. Hampton, D. R. Merkley, C. A. Rey, M. M. Zatarski, P. C. Nordine, "Aero-acoustic levitation: a method for containerless liquid-phase processing at high temperatures," *Rev. Sci. Instrum.* **65** (1994) 456.
6. D. M. Herlach, R. F. Cochrane, I. Egry, H. J. Fecht, A. L. Greer, "Containerless processing in the study of metallic melts and their solidification," *Int. Mater. Rev.***,** **38** (1993) 273.
7. A. J. Rulison, J. L. Watkins, B. Zambrano, "Electrostatic containerless processing system," *Rev. Sci. Instrum.* **68** (1997) 2856.
8. K. F. Kelton, G. W. Lee, A. K. Gangopadhyay, R. W. Hyers, T. J. Rathz, J. R. Rogers, M. B. Robinson, D. S. Robinson," First X-ray scattering studies on electrostatically-levitated metallic liquids – demonstrated influence of local icosahedral order on the nucleation barrier," Phys. Rev. Lett., **90** (2003) 195504.
9. A. K. Gangopadhyay, G. W. Lee, K. F. Kelton, J. R. Rogers, A. I. Goldman, D. S. Robinson, T. J. Rathz, R. W. Hyers, "Beamline electrostatic levitator for in situ high energy x-ray diffraction studies of levitated solids and liquids," *Rev. Sci. Instrum.* **76**(2005) 073901.
10. S. Krishnan, J. J. Felton, J. E. Rix, J. K. R. Weber, P. C. NOrdine, M. A. Beno, S. Ansell and D. L. Price, "Levitation apparatus for structural studies of high temperature liquids using synchrotron radiation," *Rev. Sci. Instrum*., **68** (1997) 3512.
11. C. Notthof, H. Franz, M. Hanfland, D. M. Herlach, D. Holland-Moritz, W. Petry, "Electromagnetic levitation apparatus for investigations of the phase selection in undercooled melts by energy-dispersive x-ray diffraction" Rev. Sci. Instrum. **71** (2000) 3791.
12. K. Higuchi, K. Kimura, A. Mizuno, M. Watanabe, Y. Katayana and K. Kuribayashi, Meas. Sci. Technol., **16** (2005) 381.
13. T. Masaki, T. Ishikawa, P.-F. Paradis, S. Yoda, "Compact electrostatic levitator for diffraction measurements with a two axis diffractometer and a laboratory x-ray source," *Rev. Sci. Instrum., **78** (2007) 026102.*

A Few Selected Case Studies

- Liquid/liquid phase transition in silicon?
- Possible chemical ordering in liquid Cu-Zr
- Ordering in amorphous metals
  - In glasses
  - In liquids
  - Icosahedral ordering and the glass transition
  - Alloying and glass formation
- Anomalies in thermophysical properties of transition metal liquids - possible phase transitions associated with ordering?

Liquid-Liquid Phase Transition in Supercooled Silicon?

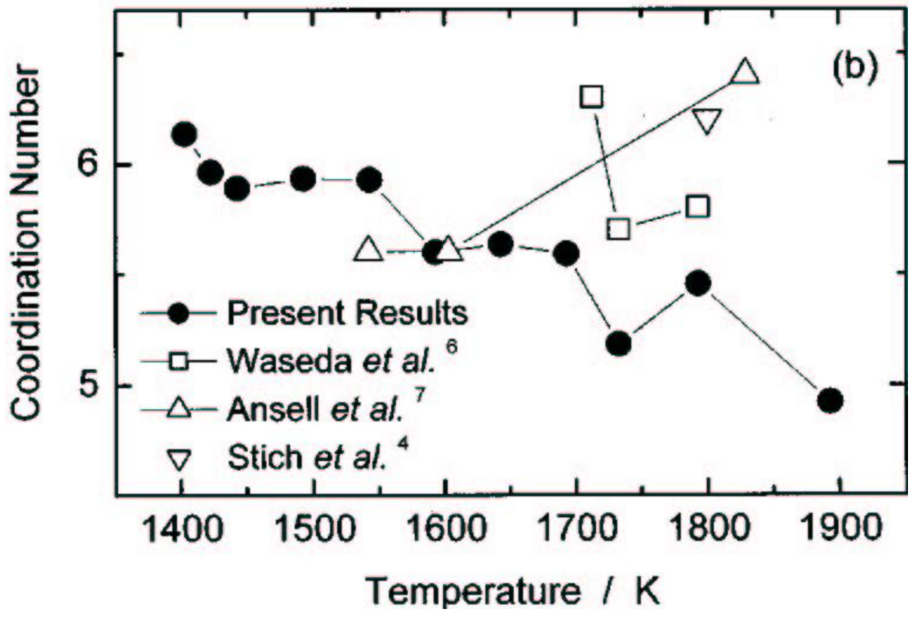
Predicted high-density – low-density liquid phase

- L. I. Aptekar, Sov. Phys. Dokl. **24**, 993 (1979).
- P. H. Poole et al., Science, 275, 322 (1997)
- S. Sastry and C. A. Angell, Nature Materials **2**, 739 (2003)
- C. R. Miranda and A. Antonelli, J. Chem. Phys. **120**, 11672 (2004).

Coordination Number Change ?

Electromagnetic Levitation

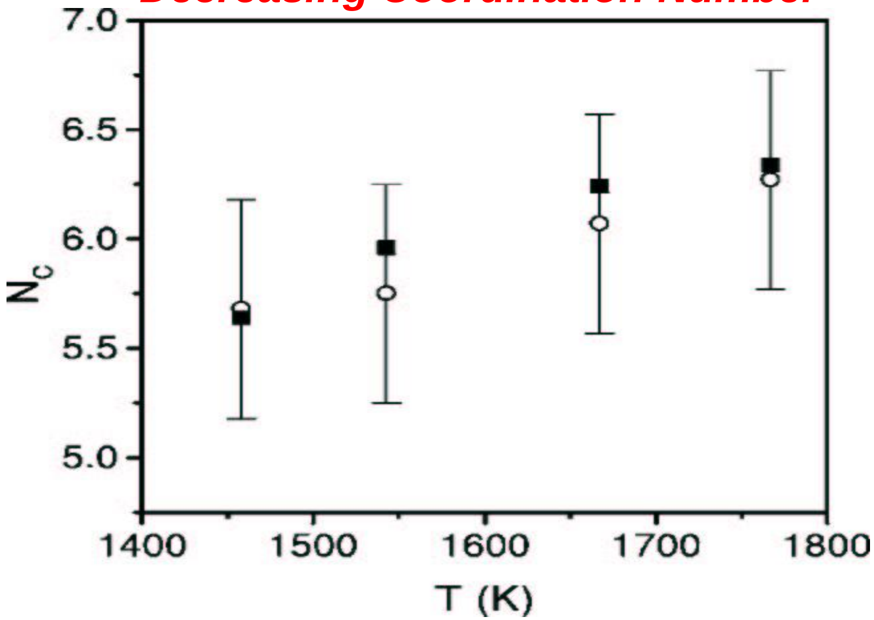
Increasing Coordination Number



H. Kimura, M. Watanabe, K. Izumi, et al., App. Phys. Lett. **78**, 604 (2001).

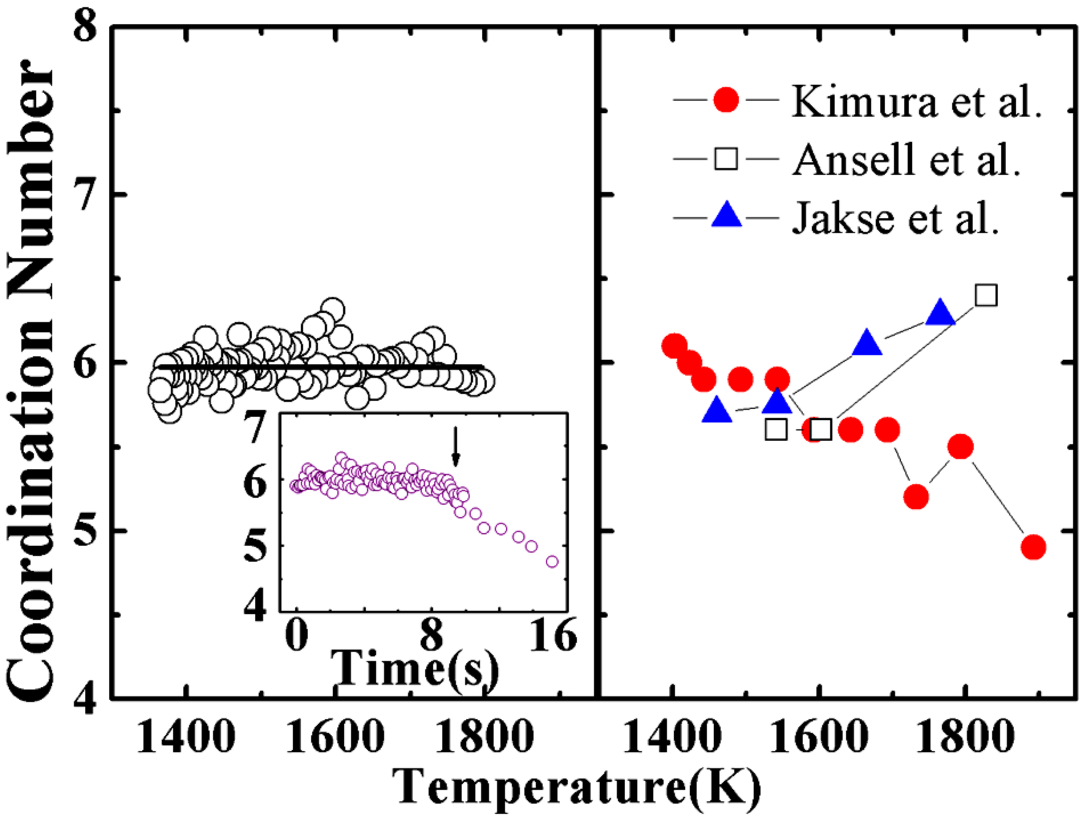
Aerodynamic Levitation

Decreasing Coordination Number



N. Jakse, L. Hennet, D. L. Price, *et al.*, App. Phys. Lett. **83**, 4734 (2003)

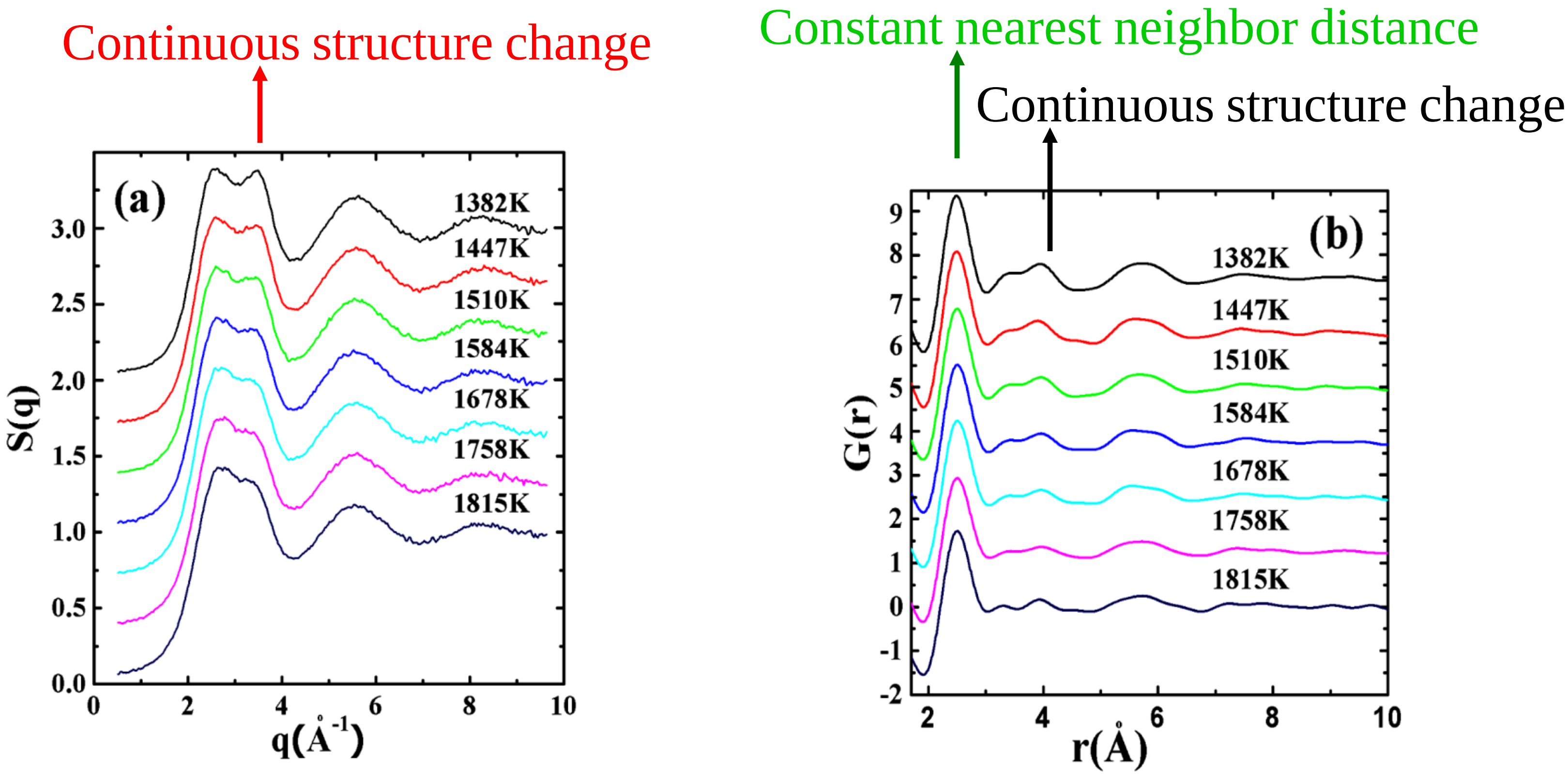
Constant Coordination Number of supercooled liquid Si (10 Hz)



- **Constant CN of 6.0±0.5 over the entire temperature range**
- In conflict with previous experimental reports (right figure).
- No signal of a LL phase transition in CN down to 1382K

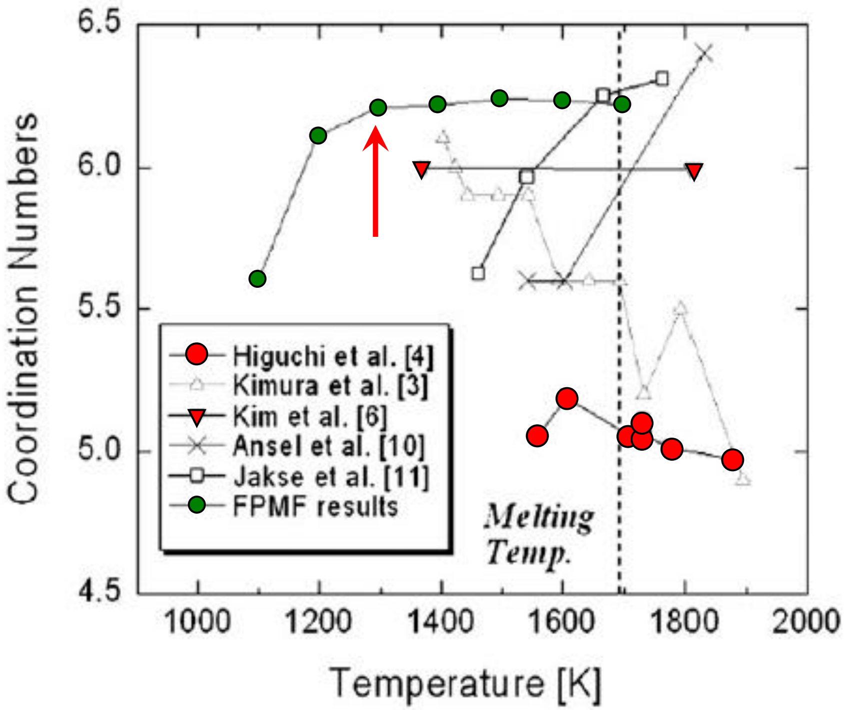
T. H. Kim, G. W. Lee, B. Sieve, A. K. Gangopadhyay, R. W. Hyers, T. J. Rathz, J. R. Rogers, D. S. Robinson, K. F. Kelton and A. I. Goldman, Phys. Rev. Lett., **95**, 085501 (2005).

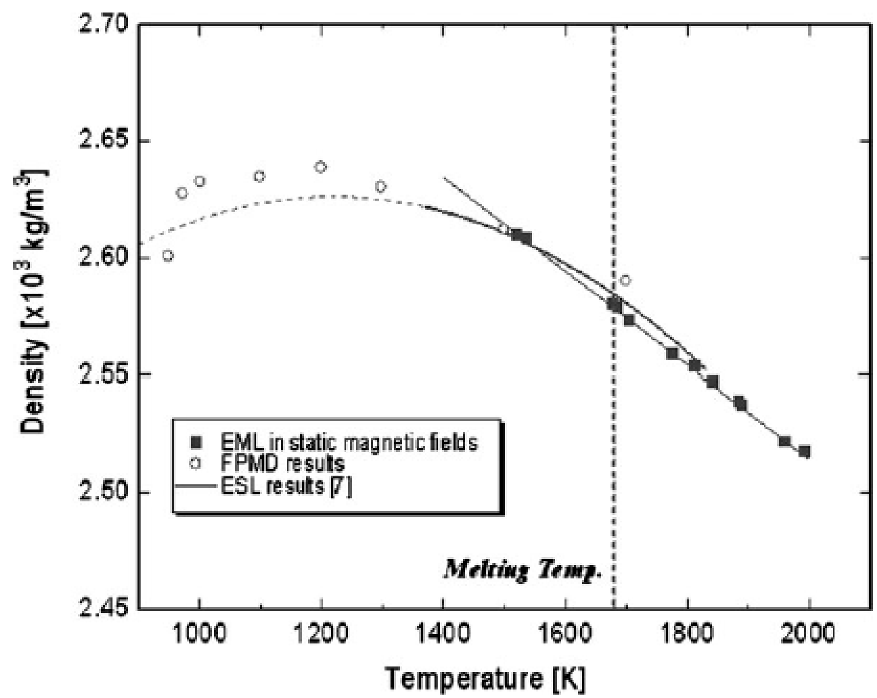
Structure factor S(q) & reduced pair correlation function G(r) of supercooled liquid Silicon (1 Hz data)



- A primary peak in S(q) is observed at approximately 2.6 (/Å) with a shoulder on the high-q side that becomes better resolved as temperature is lowered.
- The second peak in G(r) is composed of two sub-peaks increasing in intensity, signaling a change in the medium-range order of the liquid upon cooling.

More Recent Studies





- **First Principles Molecular Dynamics (FPMD)**
- **Predicts constant coordination number from melting temperature to approximately 1300K** (consistent with data from T. H. Kim et al., Phys. Rev. Lett., **95**, 085501 (2005)).
- **Predicted decrease below 1200K correlates with predicted density maximum**
- **See no change in short-range order above 1200K** (agrees with analysis of T. H. Kim et al. Phil. Mag., **88,** 171-179 (2008))

M. Watanabe et. al., Faraday Discuss., **136**, 279 (2007)

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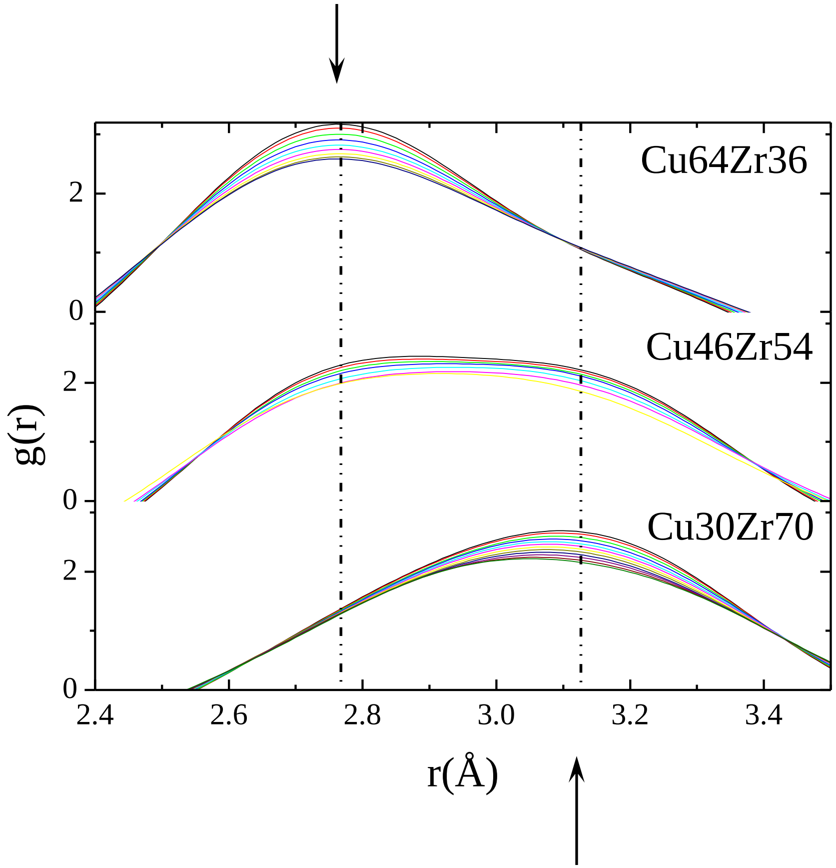
First peak in Pair Correlation for Cu-Zr

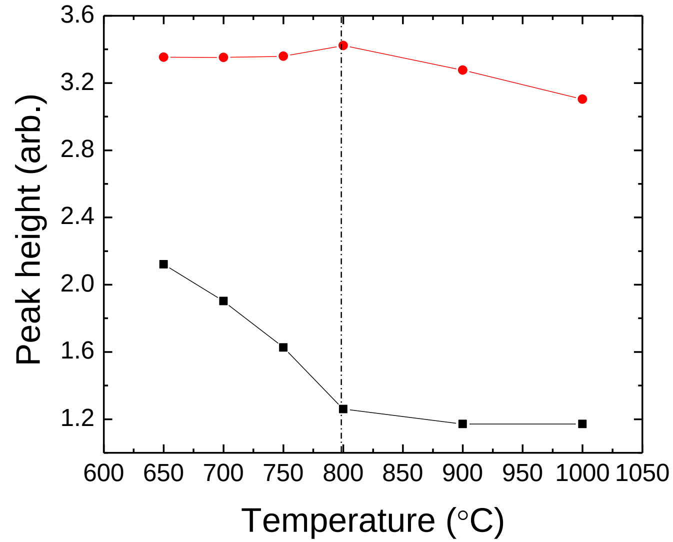
Cu-Cu and Cu-Zr separation distance

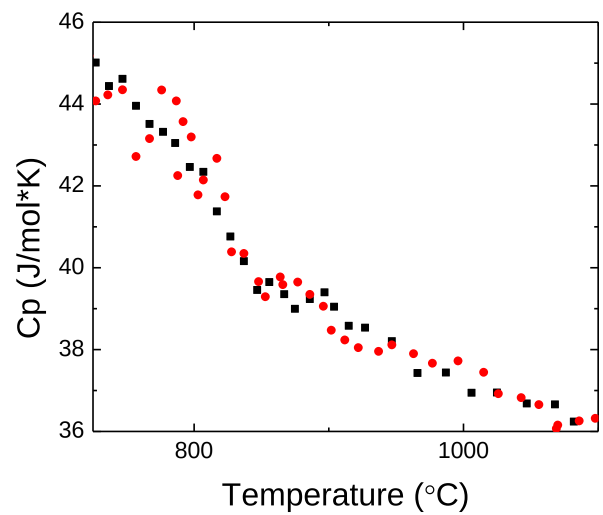


Zr-Zr separation distance

A. Sadoc et Al. J. Non-Cryst. Solids,
B. 1984. **65**(1): p. 109-129

$Cu_{46}Zr_{54}$





Chemical Ordering in the Liquid

A Few Selected Case Studies

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- Anomalies in thermophysical properties of transition metal liquids - possible phase transitions associated with ordering?

Packing Models for Glasses

Dense Random Packing

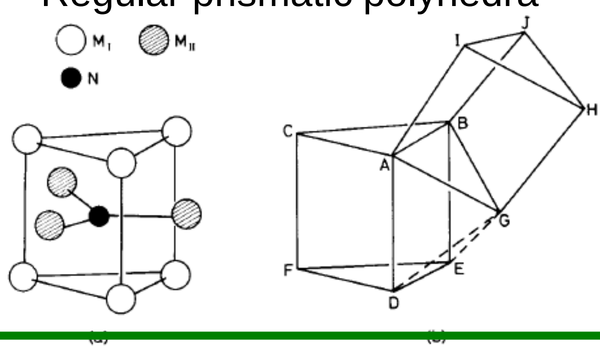
J. D. Bernal, Nature, **185**, 68 (1960)

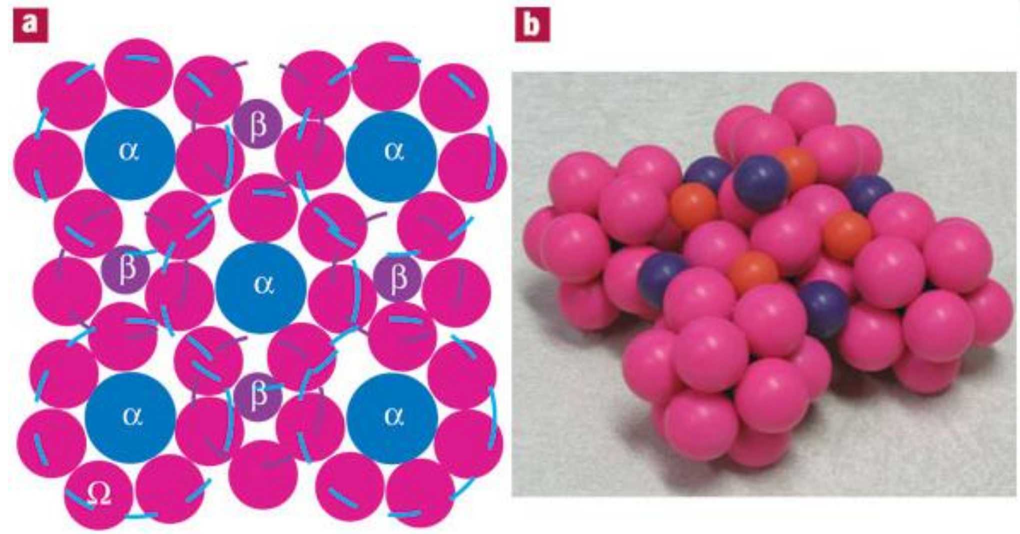
- Dominant polyhedra
- Reasonable model for
  - monatomic systems
  - alloys with atoms of similar size, no chemical short-range order

Stereochemical Model

P. H. Gaskell, Nature, **276**, 484 (1978)

- Metal/metalloid glasses
- Local units have same structures as in crystal counterparts
- Regular prismatic polyhedra





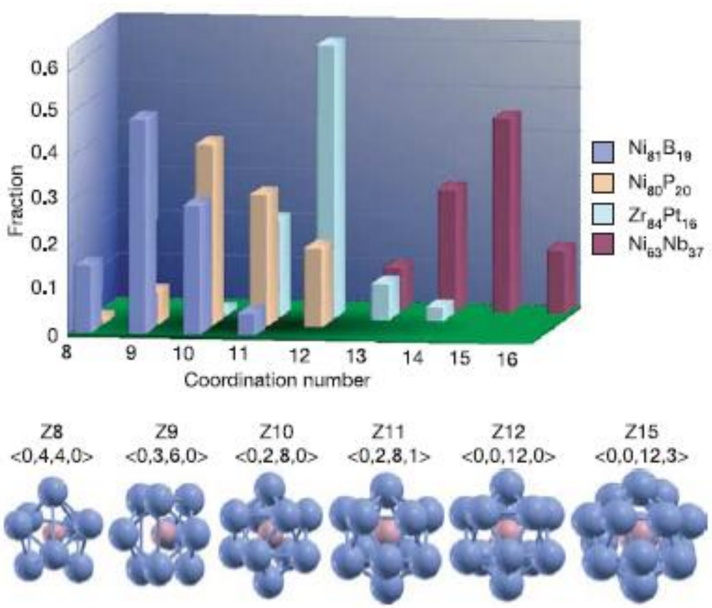
D. B. Miracle, Nature Materials, **3**, 697 (2004)

- Interpenetrating Clusters
- Ω - solvent atoms
- Solutes (in order of size)
  - α - primary cluster-forming solute
  - β - secondary solute (cluster-octahedral sites)
  - γ - secondary solute (cluster-tetrahedral sites)
- Preferred sizes of α relative to Ω give efficient packing in solute-centered clusters (Rα =Dα/DΩ)
- Solute sizes for β and γ enable efficient packing in the first coordination shell
- Clusters packed into fcc/hcp packing – short coherence length due to strain effects

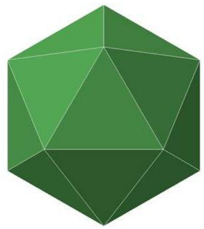
Determining the Structure – Rather than Assuming One

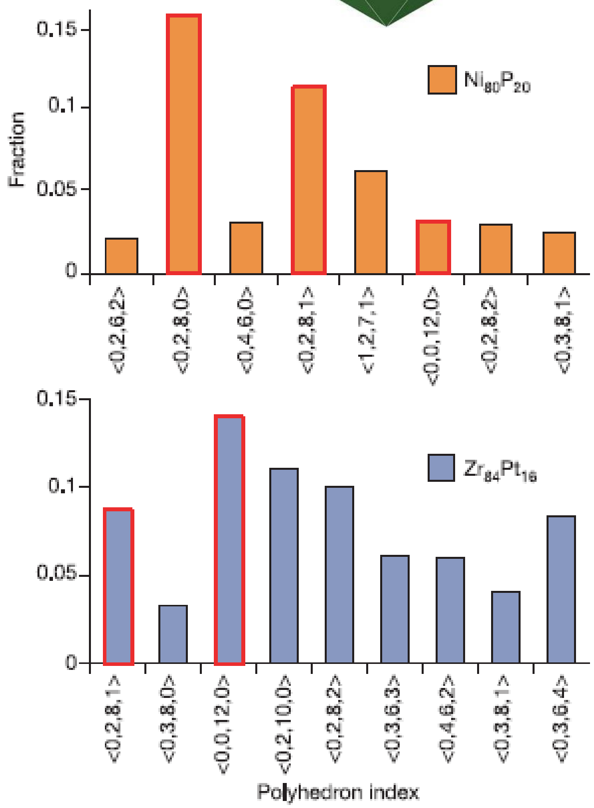
H. W. Shen *et al.*, Nature, **439**, 419 (2006)

- Experimental Studies
  - X-ray and EXAFS
  - Reverse Monte Carlo Analysis
  - Voronoi tessellation
- Computational Studies - ab-initio MD
- Found distinct polyhedron types
- Solute centered (chemical SRO)
- Supports cluster packing



- Significant icosahedral order in some glasses



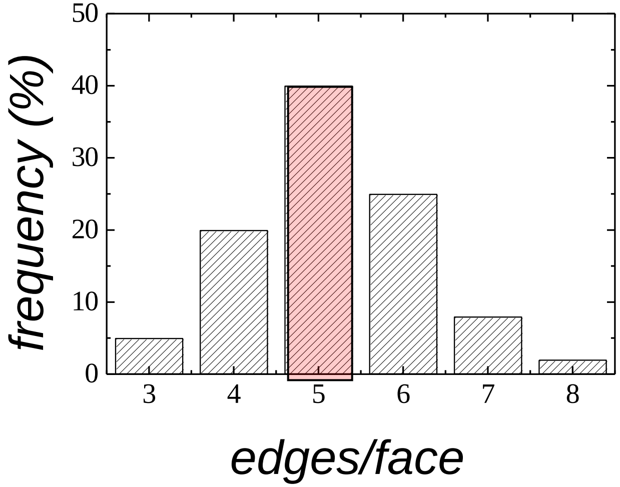


- Solute-centered icosahedral connected to form strings

Evidence for Icosahedral Order in Liquids and Glases

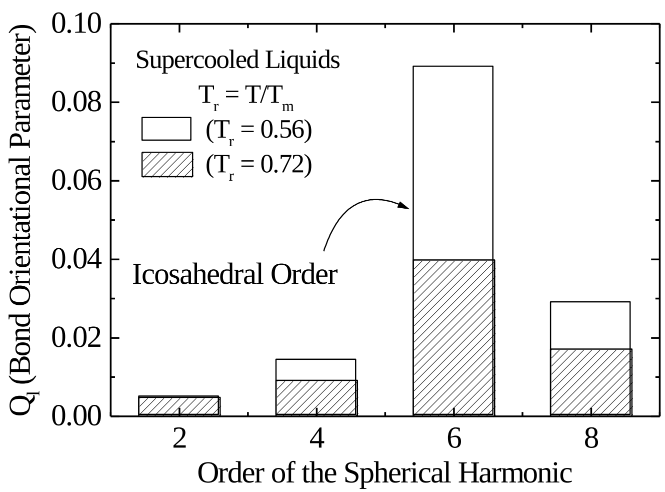
Computer Calculations of DRP

Bernal and Finey



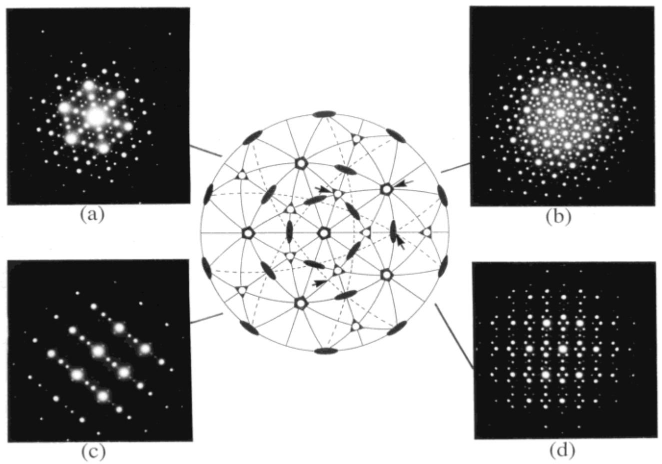
Molecular Dynamics (Lennard-Jones Potential)

Steinhardt, Nelson, Ronchetti (1981, 1983)



Icosahedral Quasicrystal

(D. Shechtman etl al, PRL, 1984)

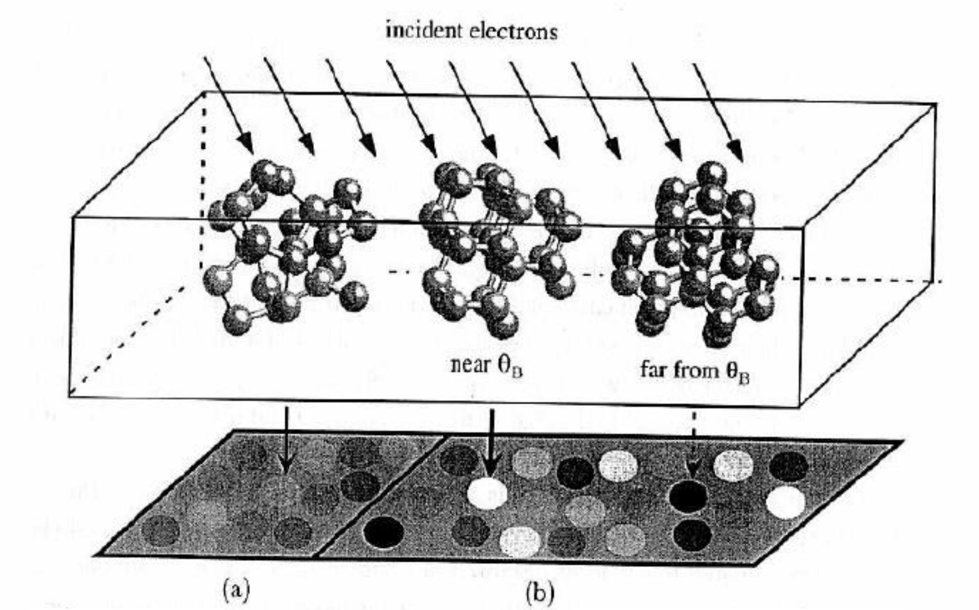


i(HoMgZn) - I. R. Fisher and P. C. Canfield

Metallic glass diffraction peaks related to those from quasicrystal (S. Sachdev and D.R. Nelson, PRL (1984))

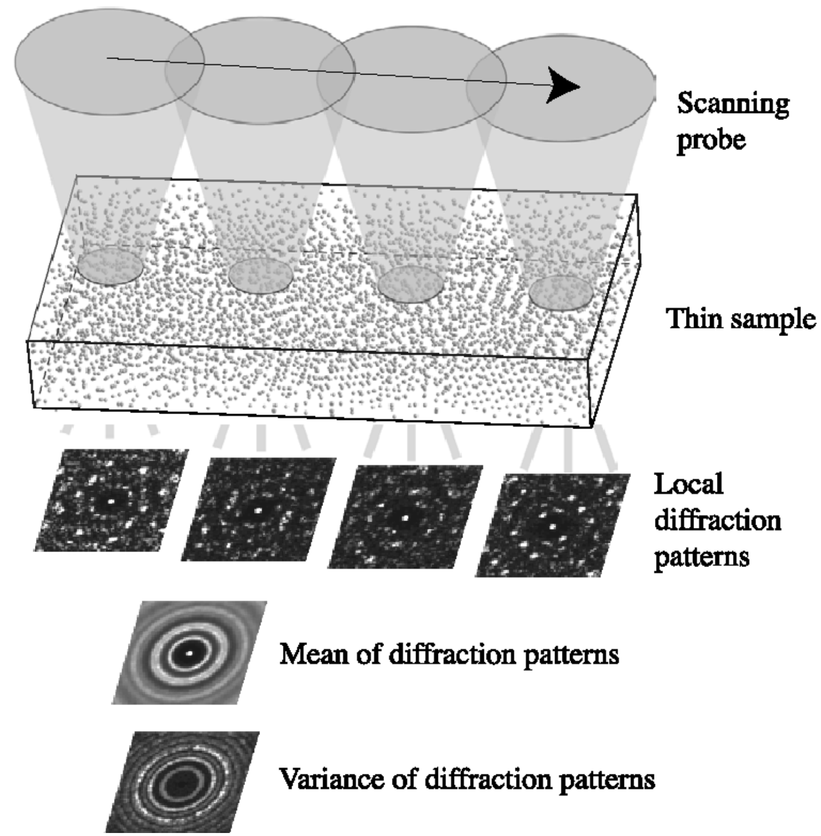
Fluctuation Transmission Electron Microscopy

M. Gibson, M. Treacy, P. Voyles



Local diffraction from
(a) Random Structure
(b) Oriented Clusters

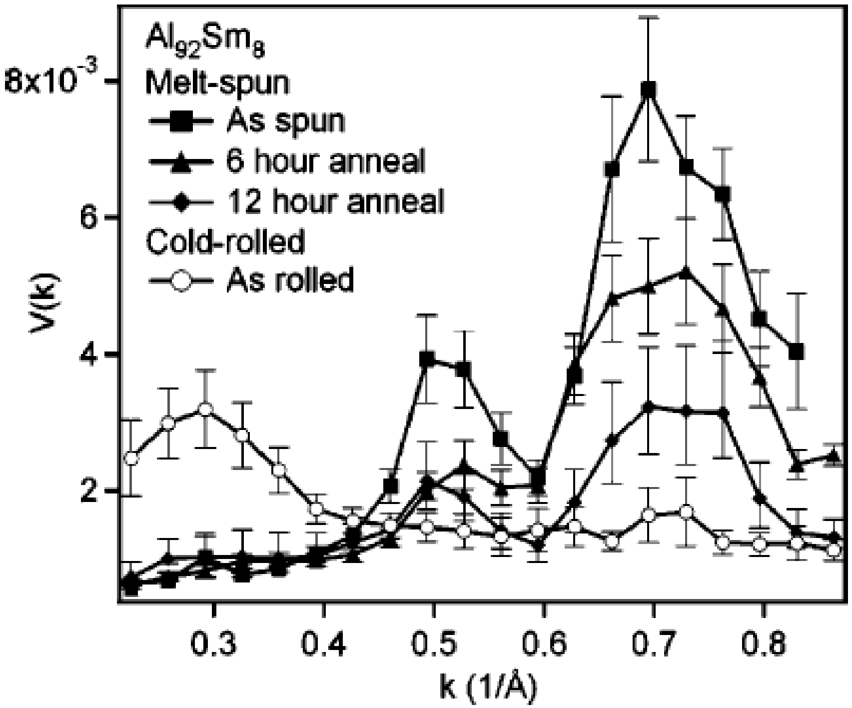
Rastered Nanoprobe diffraction

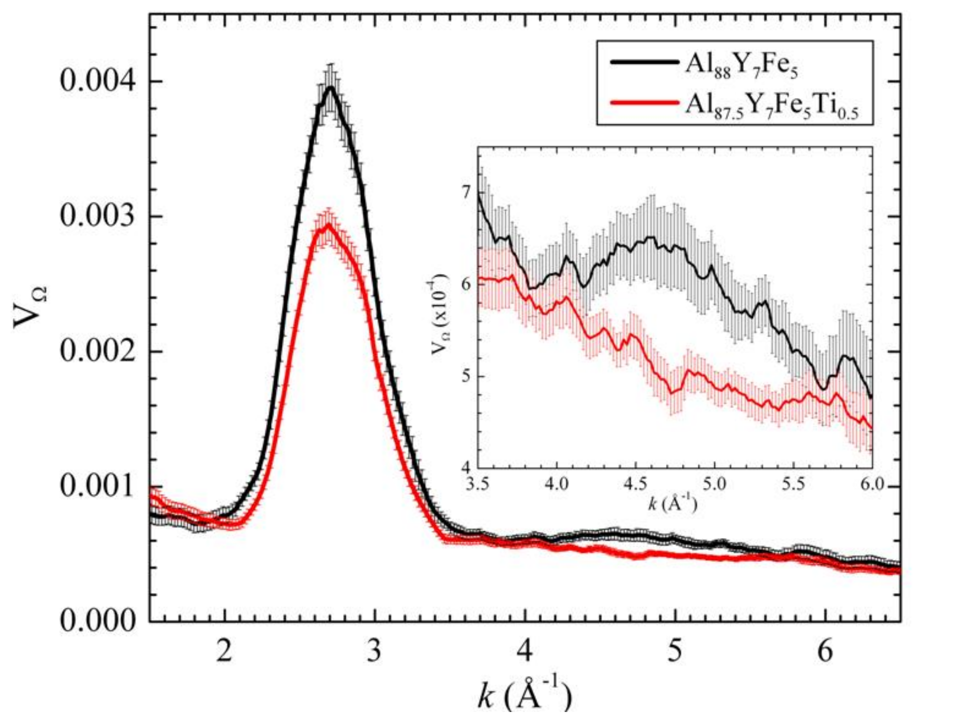


- **Determination of Speckle in Image**
- **Measure dark-field image as function of k**
- **Calculate the variance, V as a function of k**

FEM provides information on medium-range order
- and 3 and 4 body correlation functions -

Sample FEM Results





- Nanoscale (of order 1 nm diameter) Al-like ordering in melt-spun glass ribbons
- Suggests quenched-in clusters of order
- W. G. Stratton et al., APL, **86**, 141910 (2005)

- Microaddition of Ti changes medium range order
- AlYFeTi more ordered on range of probe size (1.5 nm)
- Increased medium range Al order
- Consistent with Ti-induced suppression of nanoscale phase separation (3D atom probe tomography)

A Few Selected Case Studies

- Liquid/liqud phase transition in silicon?
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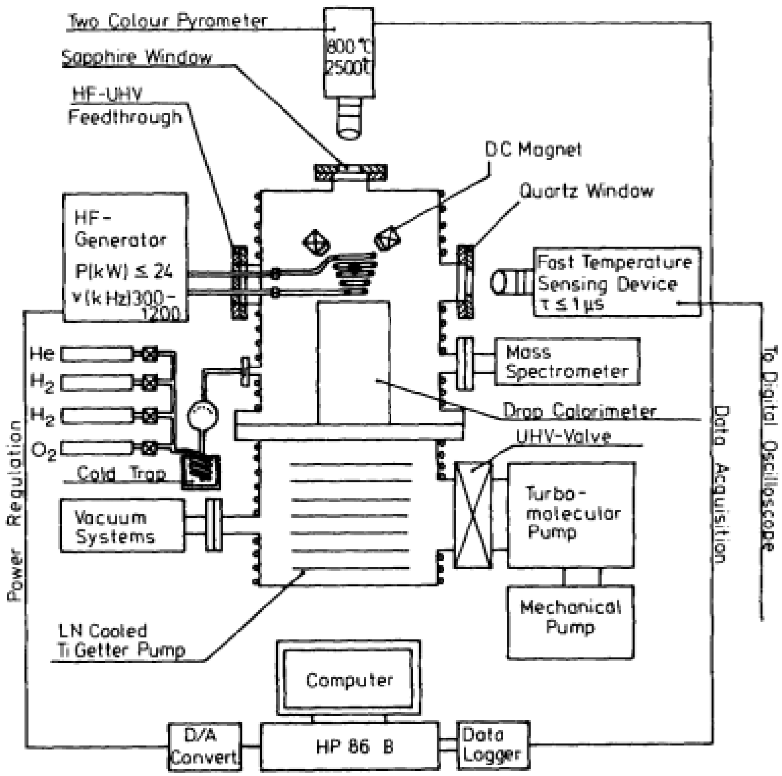
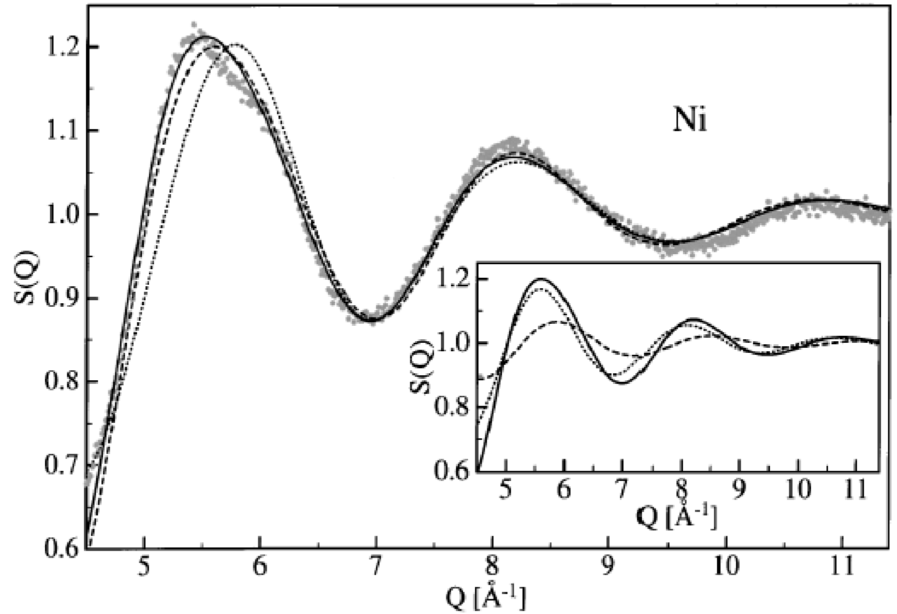
  - In liquids
  - Icosahedral ordering and the glass transition
  - Alloying and glass formation
- Anomalies in thermophysical properties of transition metal liquids - possible phase transitions associated with ordering?

Experimental Scattering Evidence for Icosahedral Order

Electromagnetic Levitation



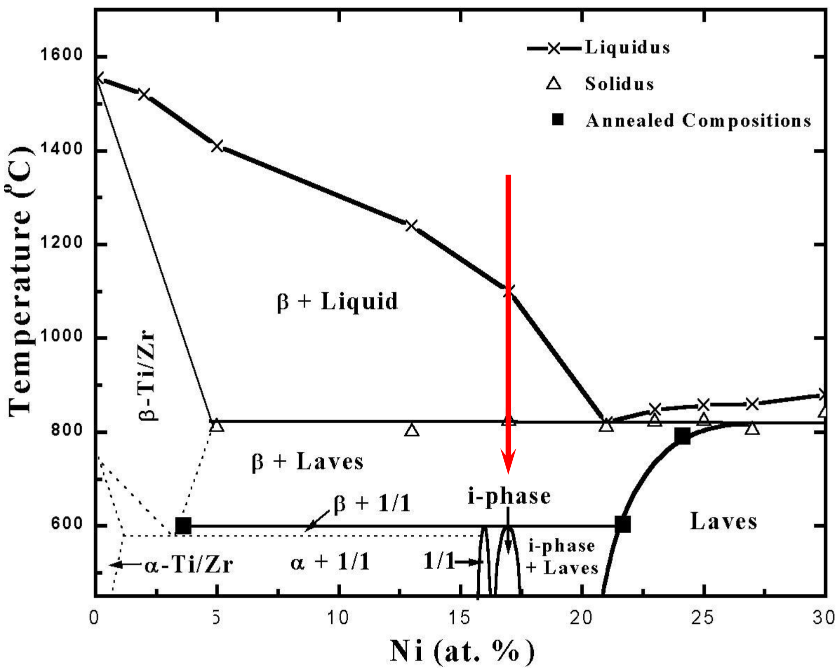


- Neutron diffraction
- Fits to single shell icosahedra
- Icosahedral cluster (dashed line); dodecahedra, (solid line); fcc (dotted line)

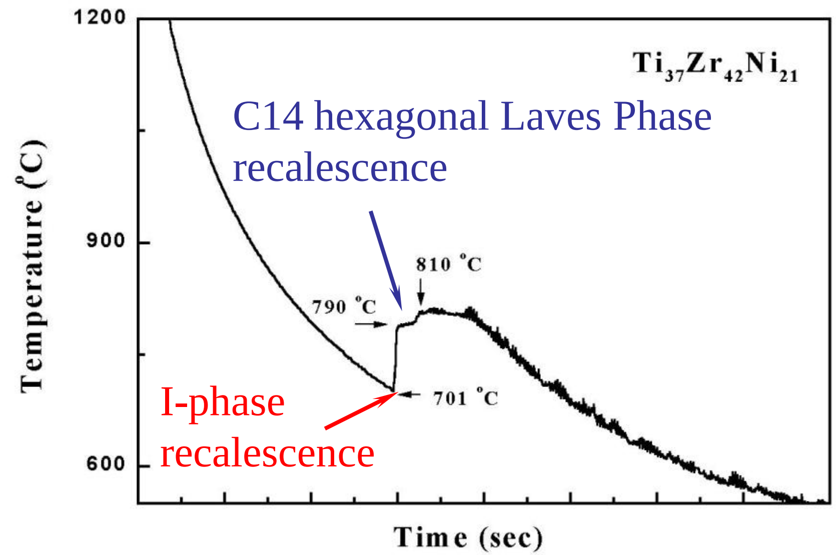
T. Schenk, D. Holland-Moritz, V. Simonet, R. Bellissent, and D. M. Herlach, Phys. Rev. Lett., 89, 075507 (2002)

Nucleation of Metastable Ti-Zr-Ni Quasicrystals

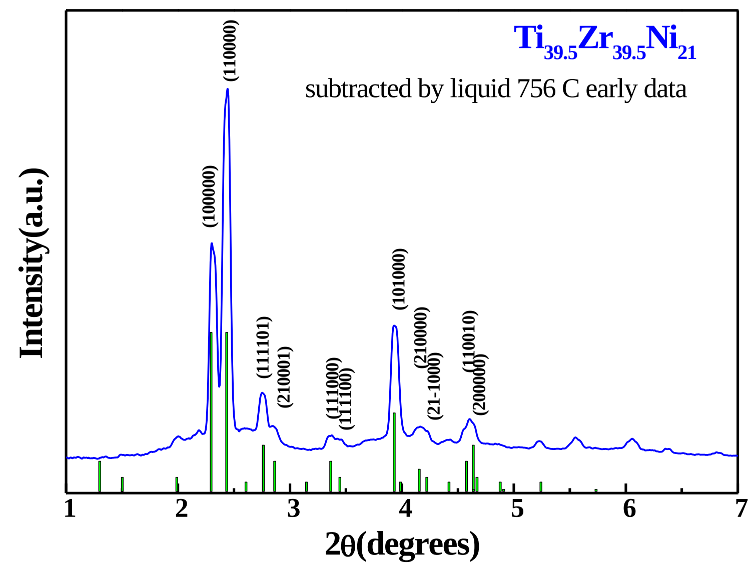
Pseudo-binary Phase Diagram for [Ti]/[Zr] = 1



- I-phase forms reversibly from β (Ti/Zr) and C14 Laves phase over 600°C below the liquidus
- Quasicrystal is possible ground-state

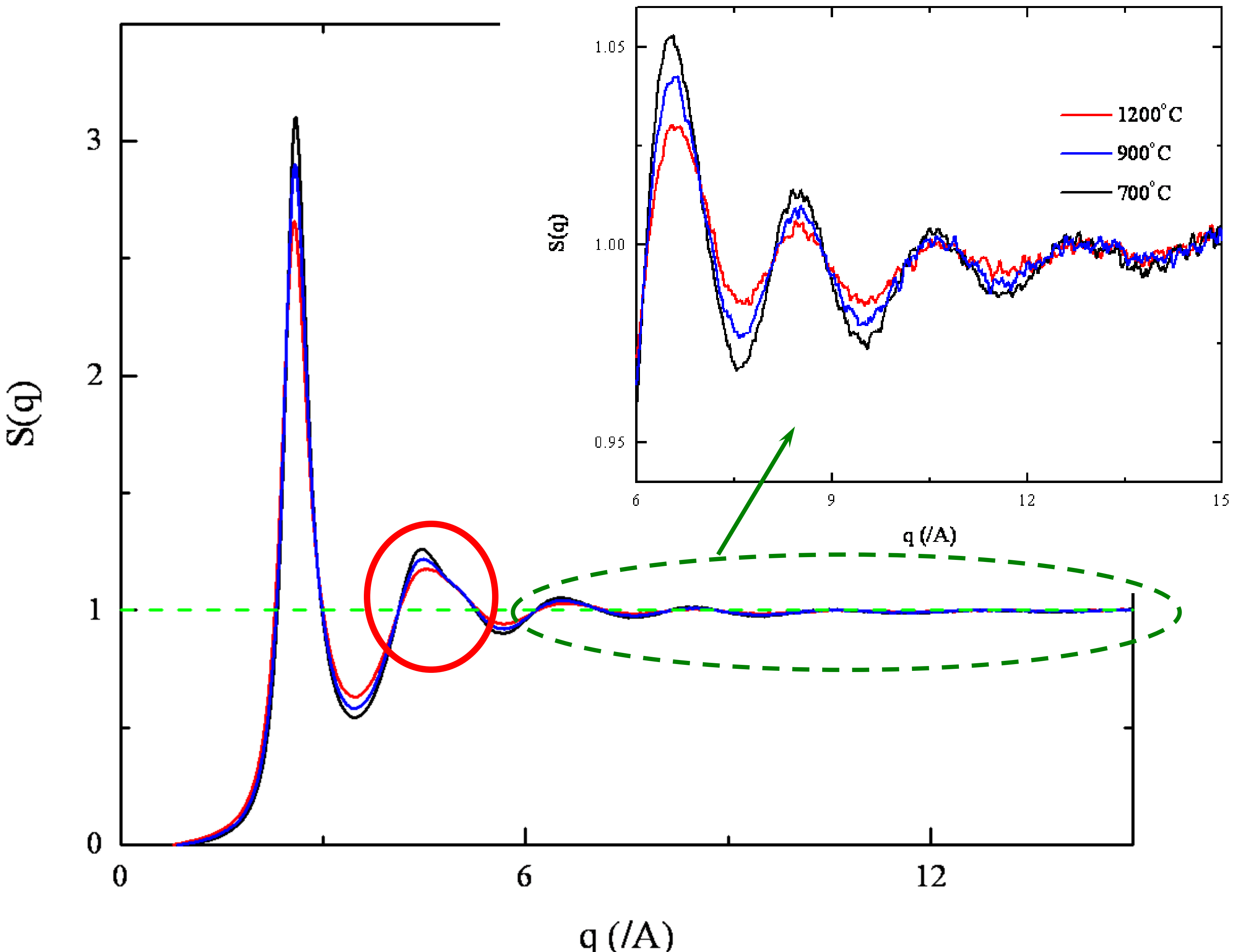


ESL of Liquid During Recalescence



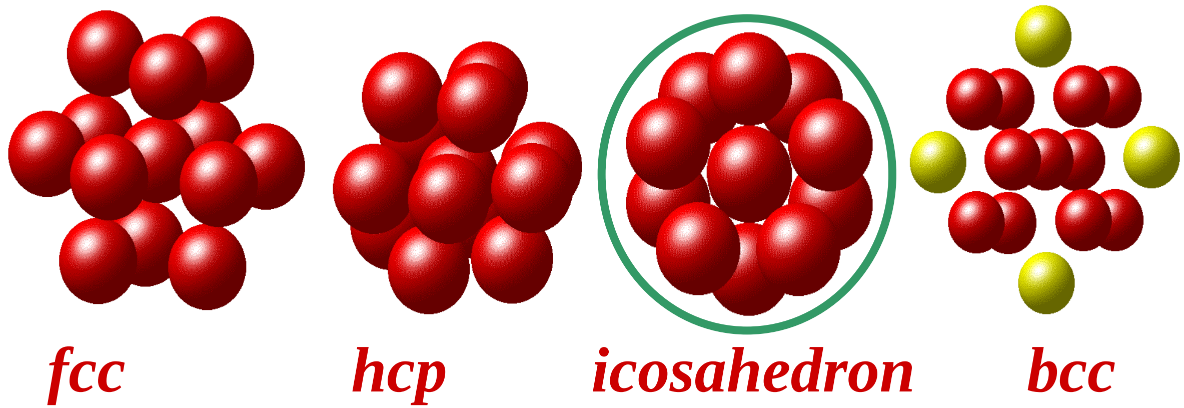
From K. F.Kelton et. al., *Phys. Rev. Lett*, **90**, 195504 (2003).

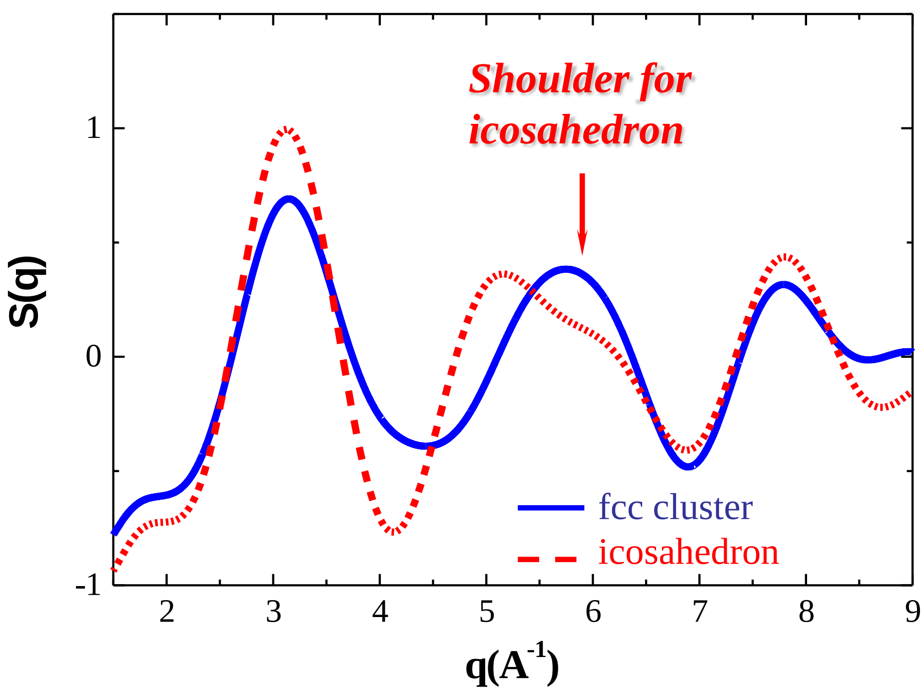
ESL Diffraction Measure



K. F.Kelton, A. K. Gangopadhyay, G. W. Lee, R. W. Hyers, R. J. Rathz, J. Rogers, M. B. Robinson, D. Robinson, *Phys. Rev. Lett*, **90**, 195504 (2003).

Assuming a Dominant Cluster ⇒ Icosahedral Ordering in the Liquid





Ratios of S(q) peak positions:

q(2nd)/q(1st) = 1.74 ± 0.01

q(shoulder)/q(1st) =1.95 ±0.01

Perfect icosahedron:*

*(*S. Sachdev and D. R. Nelson, PRL **53** , 1947 (1984).)*

q(2nd)/q(1st) = 1.71

q(shoulder)/q(1st) =2.04

Going Beyond the Single Cluster Model

Reverse Monte Carlo (McGreevy)

- Iteratively refines 3-d structural model of system from structural measurements
- Can combine results from x-ray and neutron diffraction, EXAFS, NMR, etc.

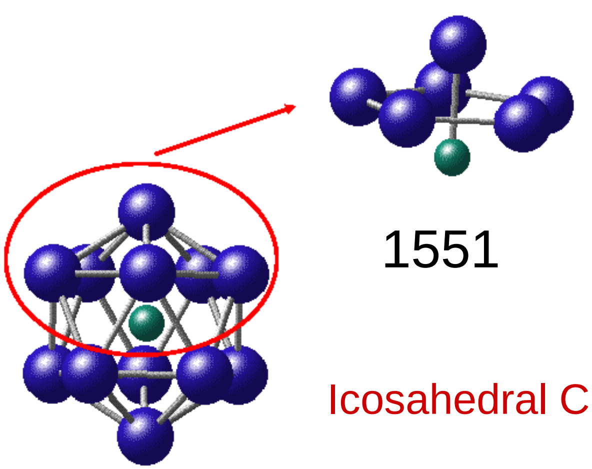
Bond Orienational Order Parameter Analysis (Steinhardt *et al.*)

- Calculate bond angles (θ and φ) between atom at center of cluster and vertex atoms
- Express as average order parameter in terms of spherical harmonics

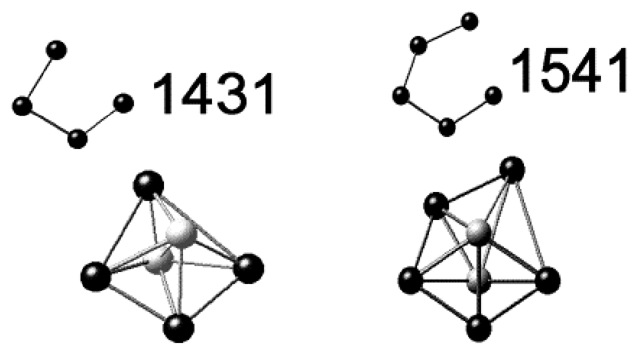
$$Q_l = \left[\frac{4\pi}{2l+1} \sum_{m=-l}^{l} \left| \overline{Q_{lm}} \right|^2 \right]^{1/2} \quad where \quad \overline{Q_{lm}} = \frac{1}{N_b} \sum_{bonds} Y_{lm}\left(\theta(\vec{r}), \varphi(\vec{r}) \right)$$

- Icosahedral order – Q_6

Honeycutt Andersen Indices (local topology in terms of 4 indices)

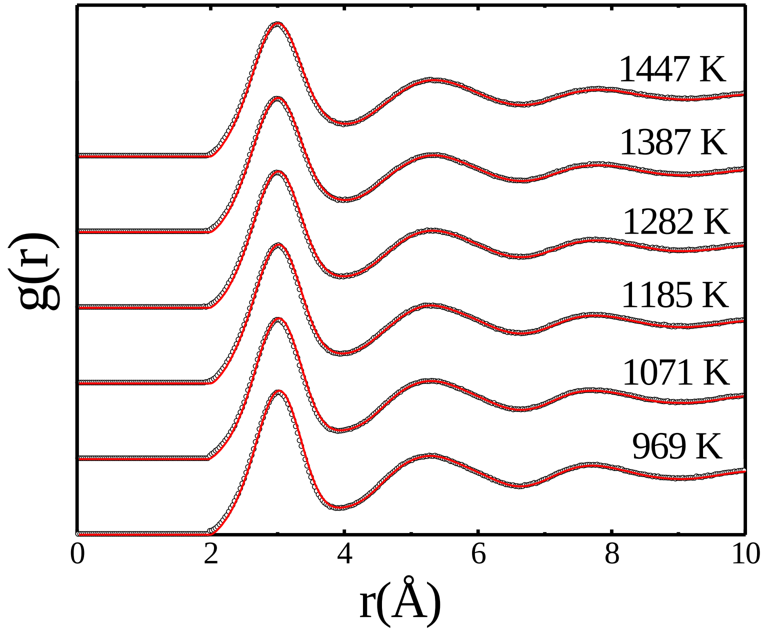


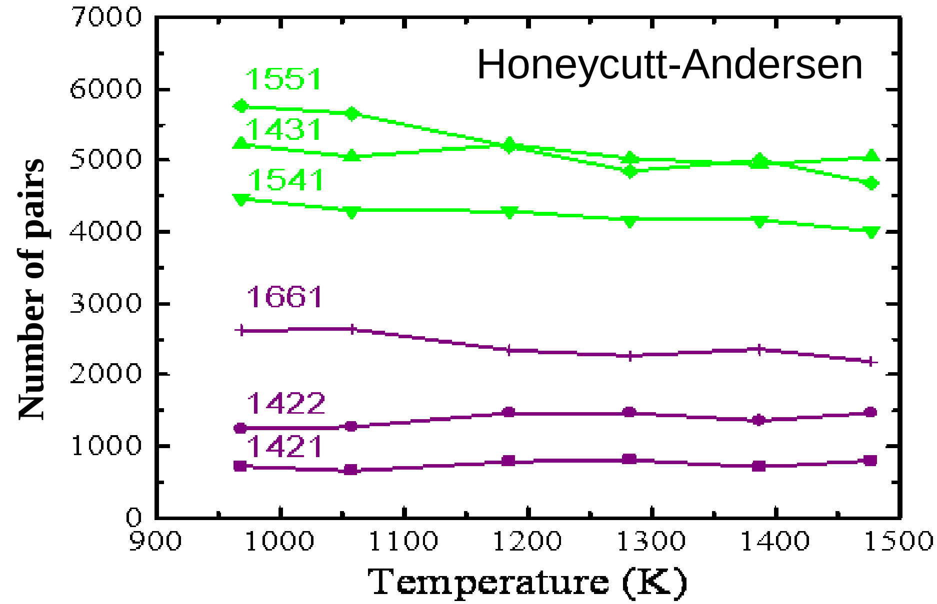
Icosahedral Cluster

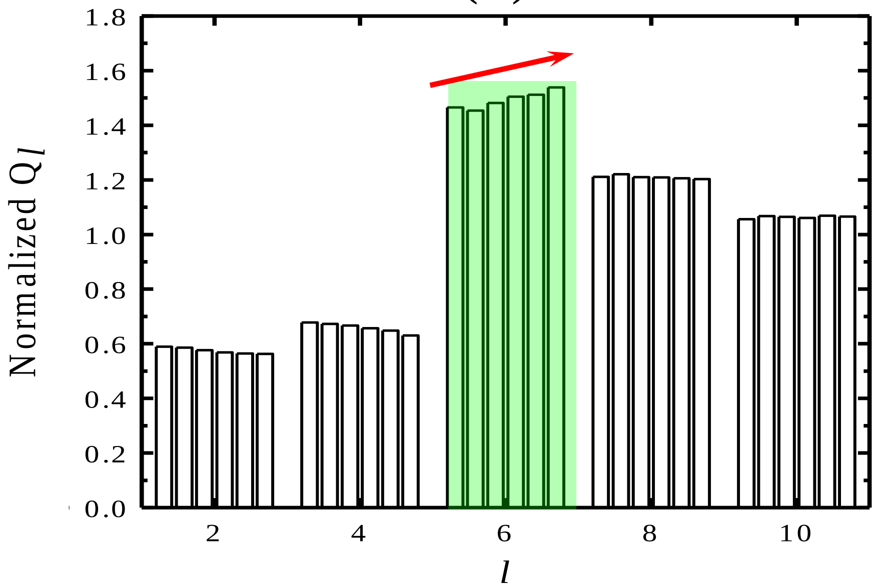


Distorted Icosahedral Cluster

Results from RMC Fits





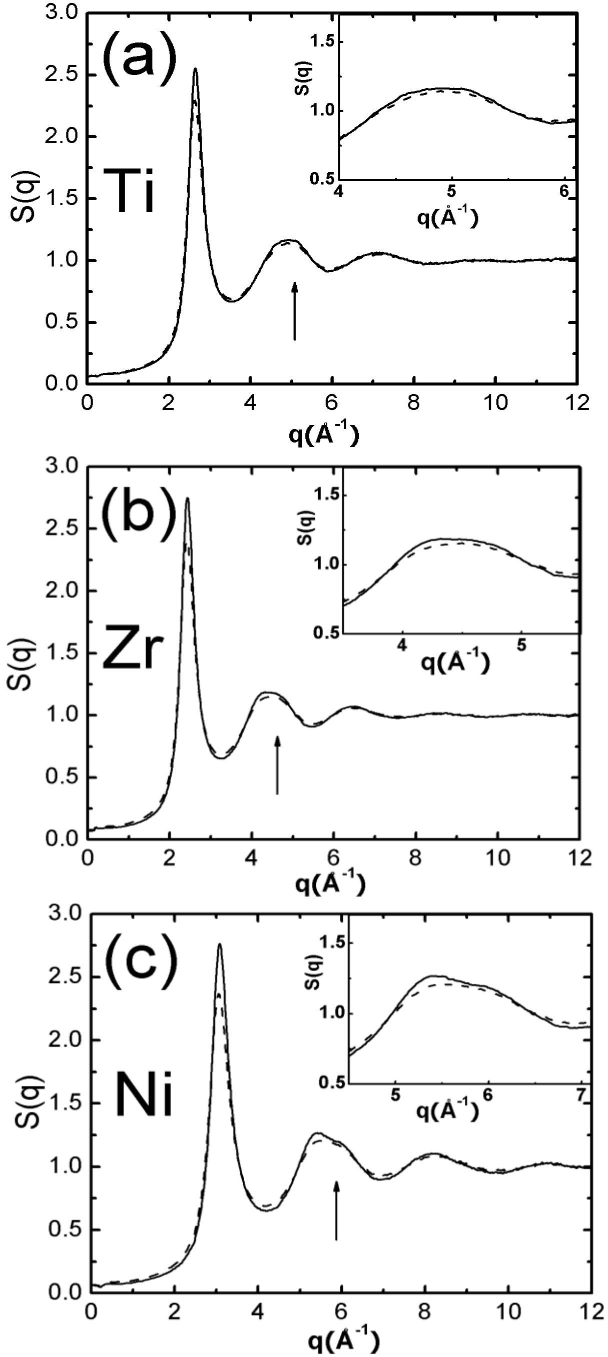


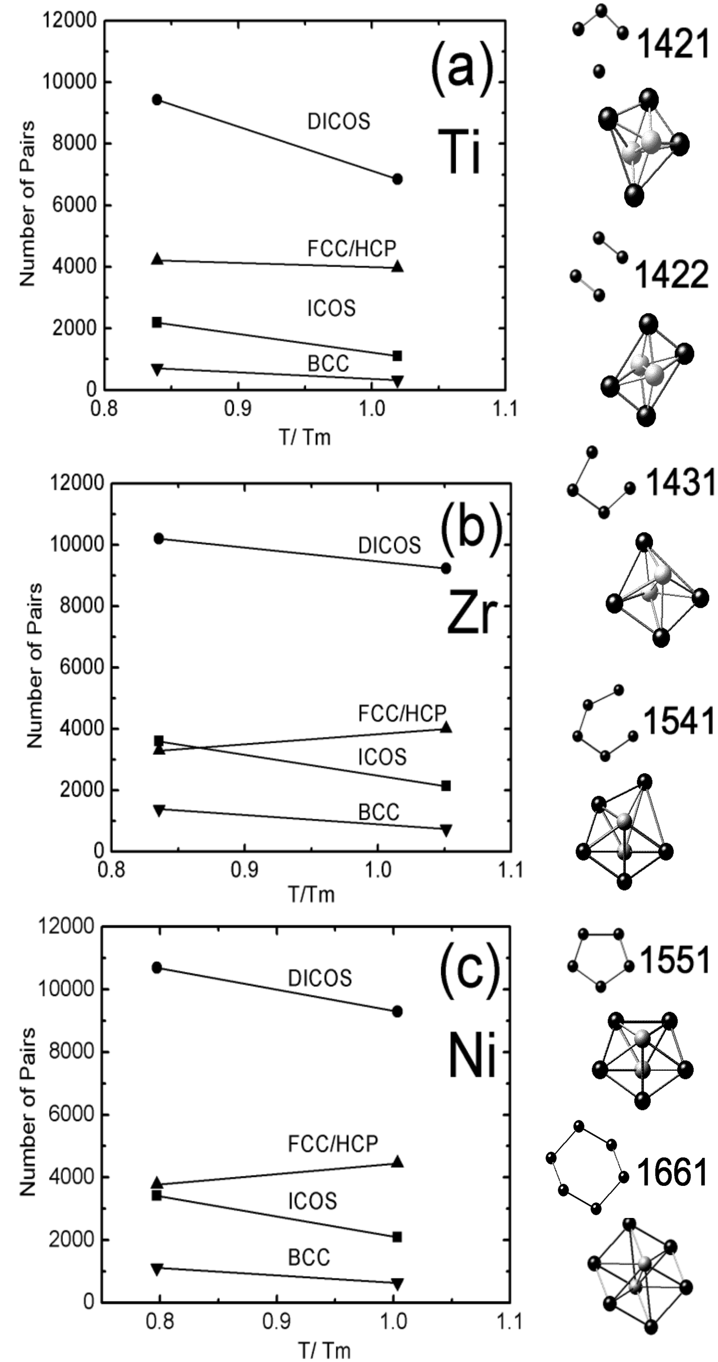
Honeycutt Andersen Indices

- Icosahedral order is greatest
  - 1551 (pure)
  - 1431 and 1541 (distorted)
- Icosahedral order increases with supercooling
- Significant fraction of crystal order (bcc)

Bond Orientational Order

- Q6 – measure of icoshaedral order
- Q6 increases with supercooling
- All others decrease

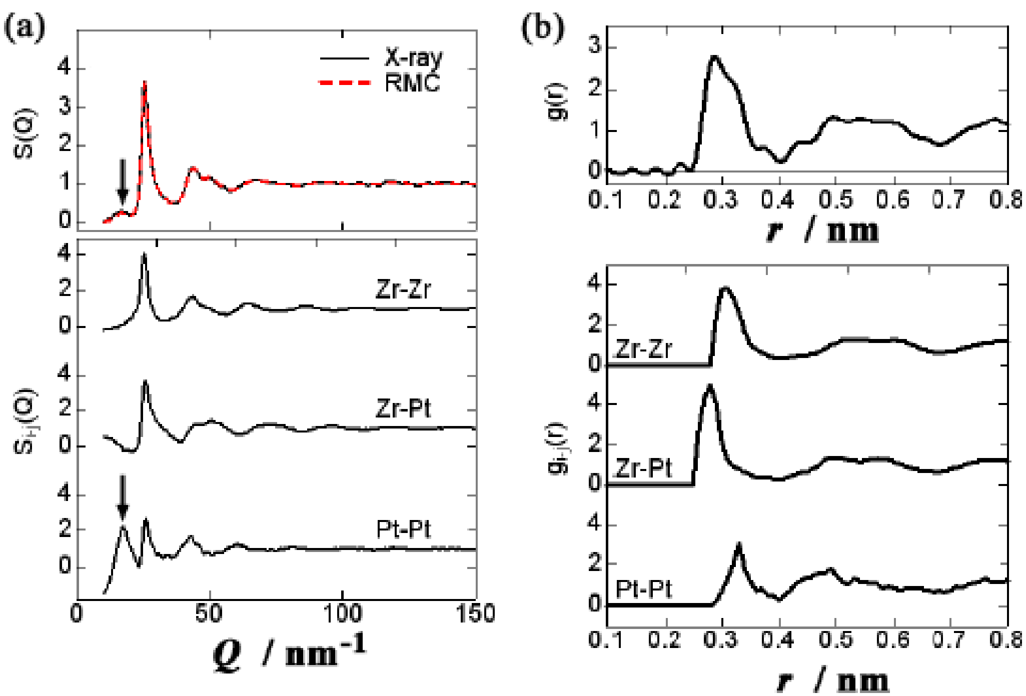




T. H. Kim and K. F. Kelton, J. Chem. Phys. 126, 54513 (2007)

Prepeak in S(q) –Medium-Range Order

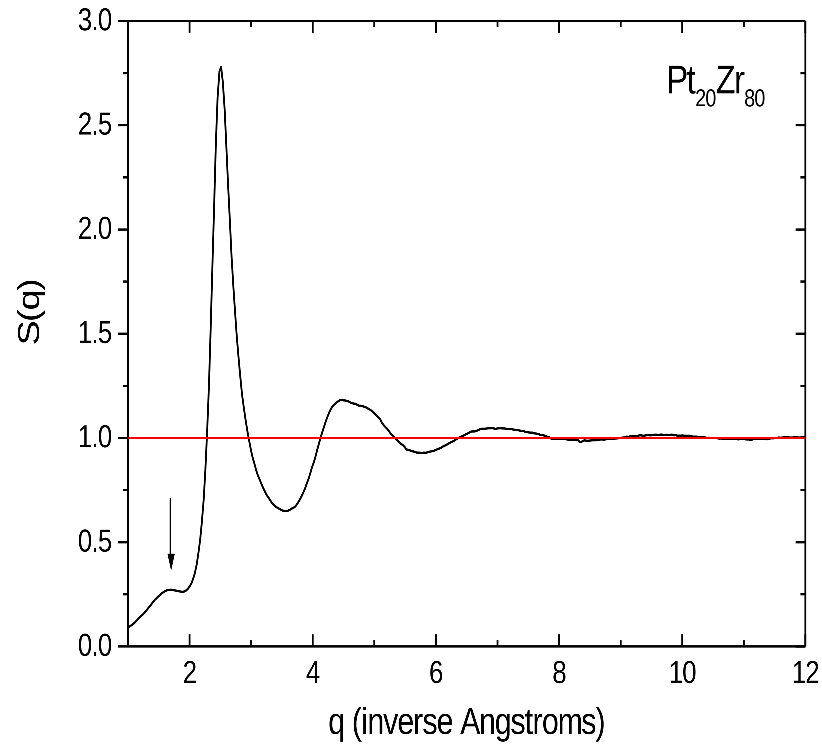
$Zr_{80}Pt_{20}$ Metallic Glass



- Prepeak at 17 nm^{-1} - medium-range ordering
- Pt-Pt Ordering
- Icosahedral Ordering (Voronoi polyhedron analysis)

J. Saida, et. Al., J. Phys. Condens. Matter., **21,** 375104 (2009).

$Zr_{80}Pt_{20}$ Liquid



- Same prepeak in liquid
- RMC analysis also indicates Pt-Pt ordering and HA analysis indicates icosahedral ordering
- Due to very strong negative heat of mixing between Zr and Pt

N. Mauro and K. F. Kelton private comm.

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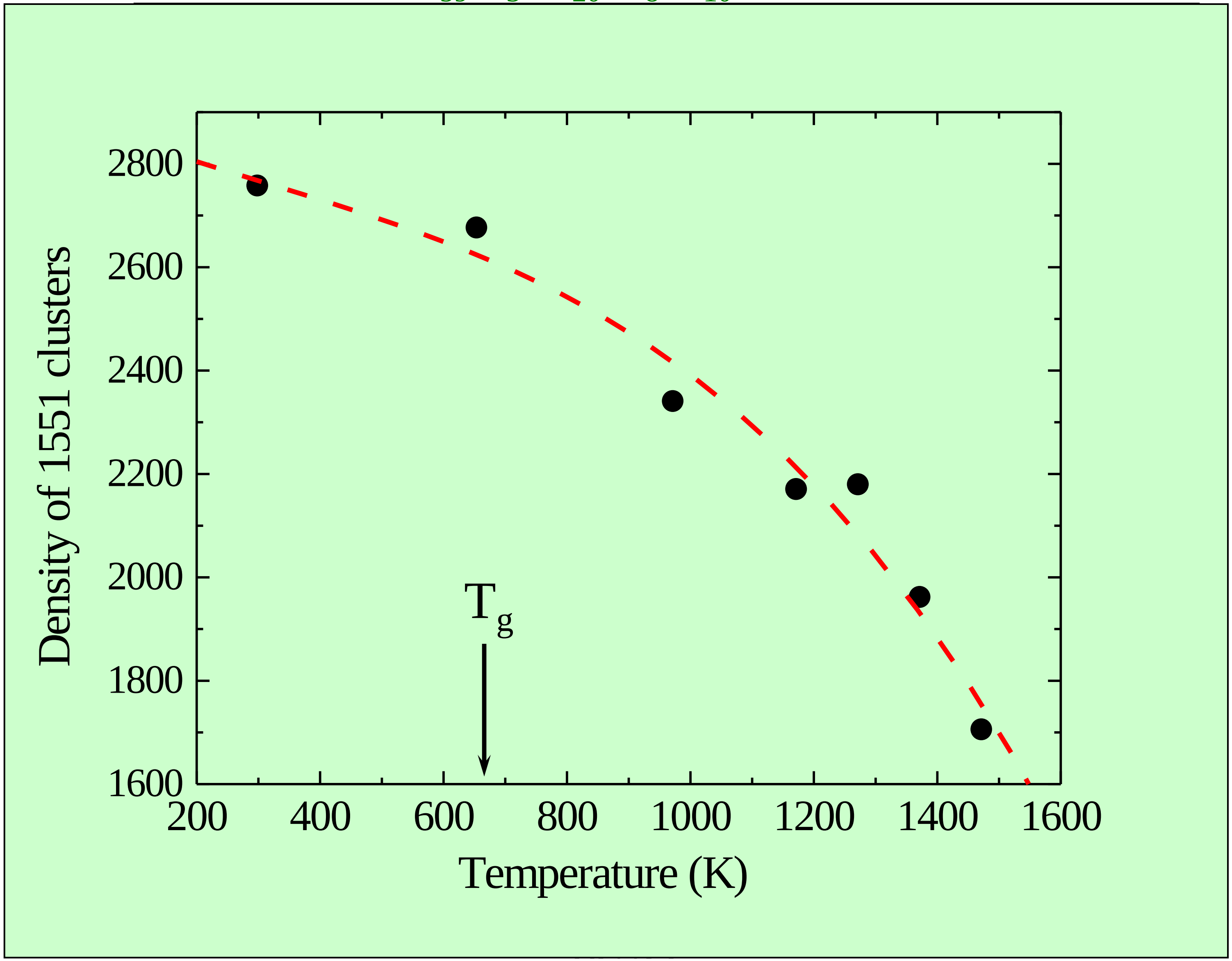
Synchrotron High Energy X-Ray Diffraction Studies

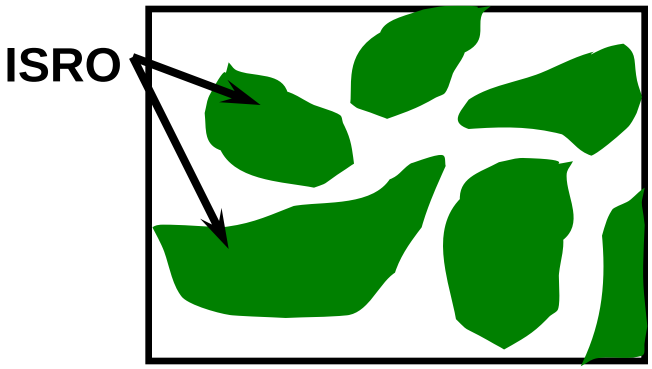
$Zr_{59}Ti_3Cu_{20}Ni_8Al_{10}$



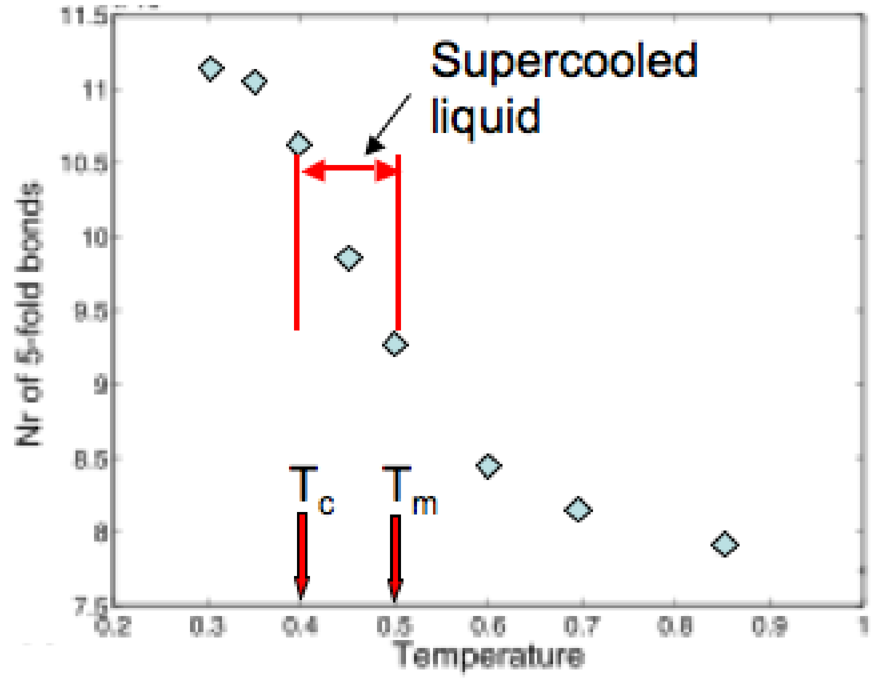
Y. Shen, T. H. Kim, K. F. Kelton, *Phys. Rev. Lett.*, 102 (2009) 057801

The Glass Transition

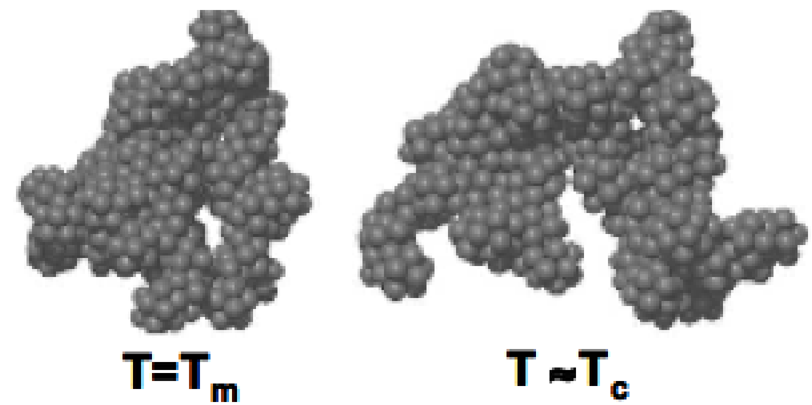
- Geometrical fustration



- ISRO - geometrical fluctuation



- MD Calculations - LJ potential
- Cluster extent > container as T → T_c
- Resembles percolating bond network



Zetterling et al, JNCS, **293-295**, 39 (2001)

A Few Selected Case Studies

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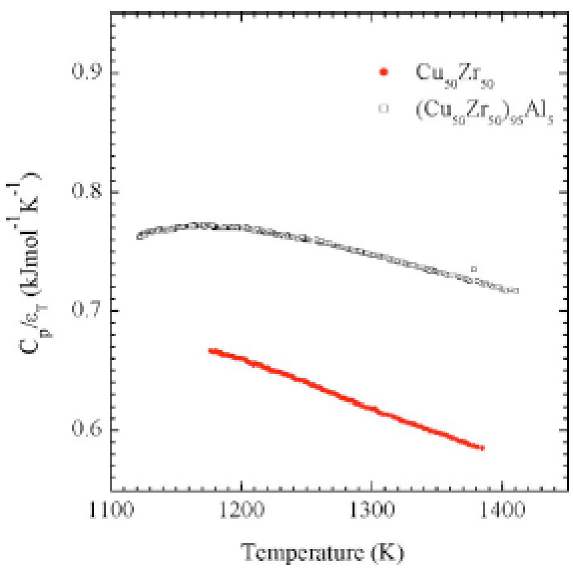
Addition of Al to Cu-Zr

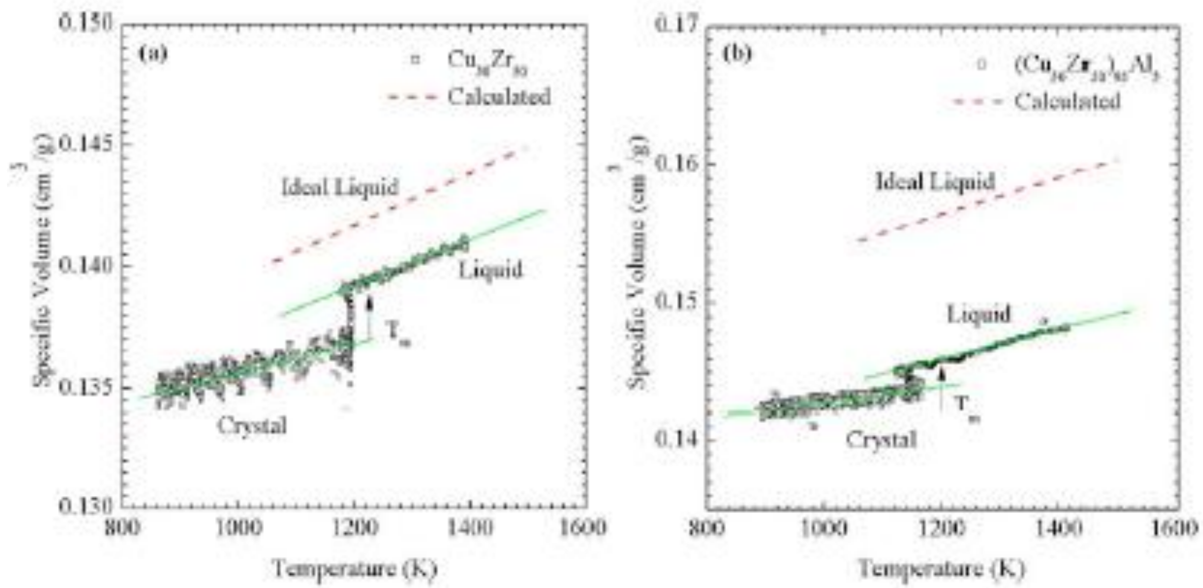
Fan et al, APL, **89**, 241917 (2006)

- **Addition of 5 at.% Al for Cu/Zr improves glass formation**

Increases C_p/ε



Decreases volume from rule of mixtures AND difference between crystal and liquid phases



- **And increases viscosity**

Addition of Al causes structural modifications in the liquid – stabilizing the liquid and improving glass formability

A Few Selected Case Studies

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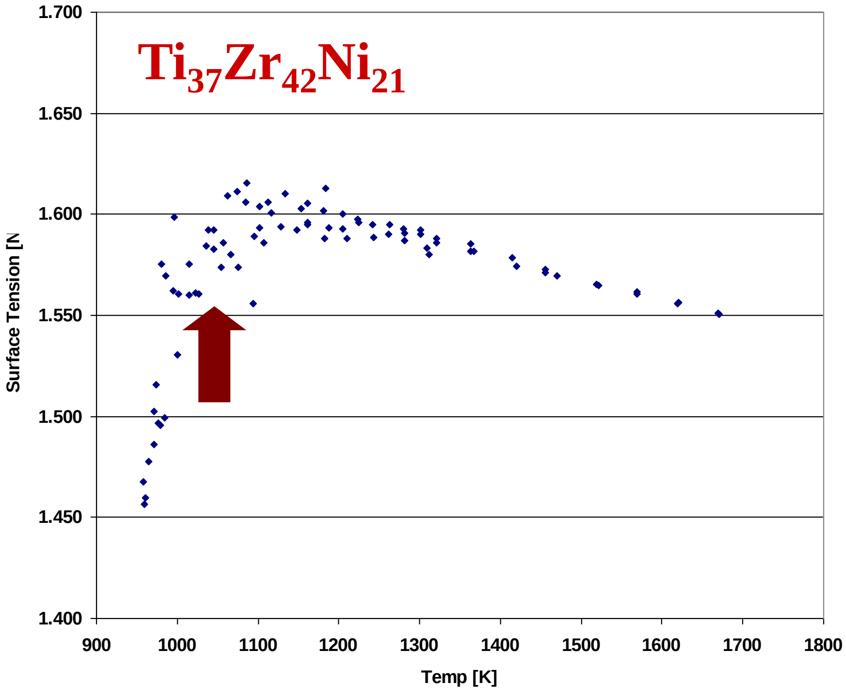
  - In liquids
  - Icosahedral ordering and the glass transition
  - Structure and Glass Formation
- Anomalies in thermophysical properties of transition metal liquids - possible phase transitions associated with ordering?

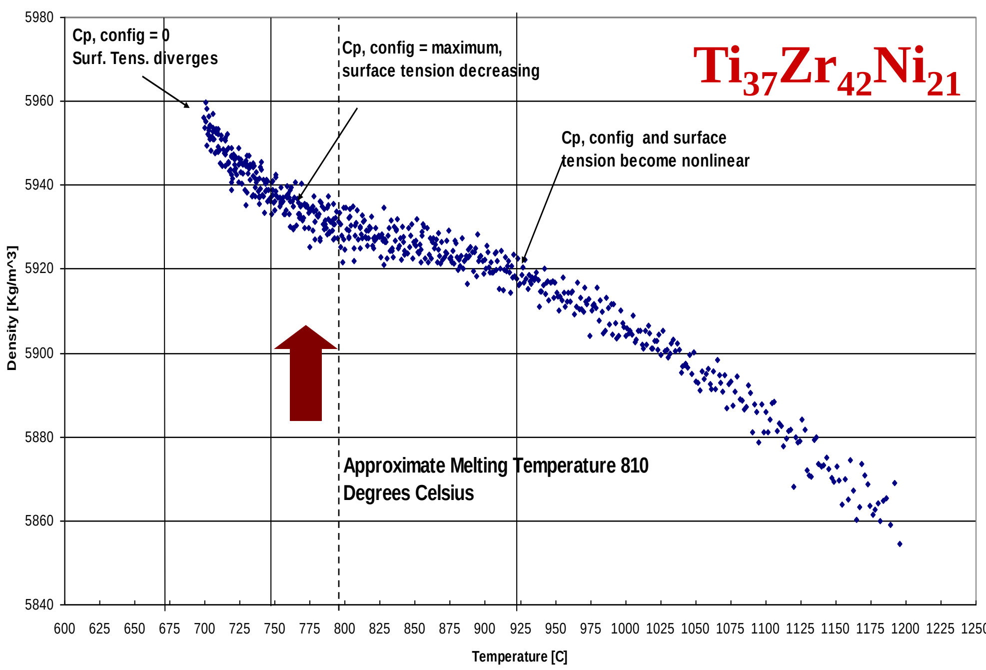
Thermo- physical Properties of Supercooled Liquid



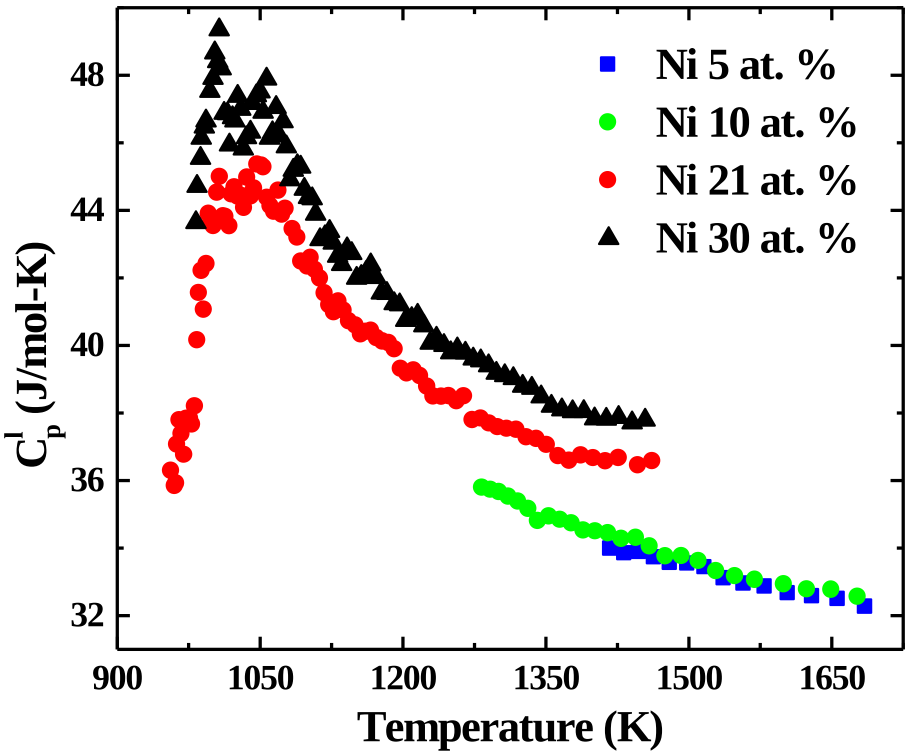
R. W. Hyers, R. Bradshaw, U. Mass

Dramatic decrease in surface tension – indicates chemical surface segregation

Density Inflection



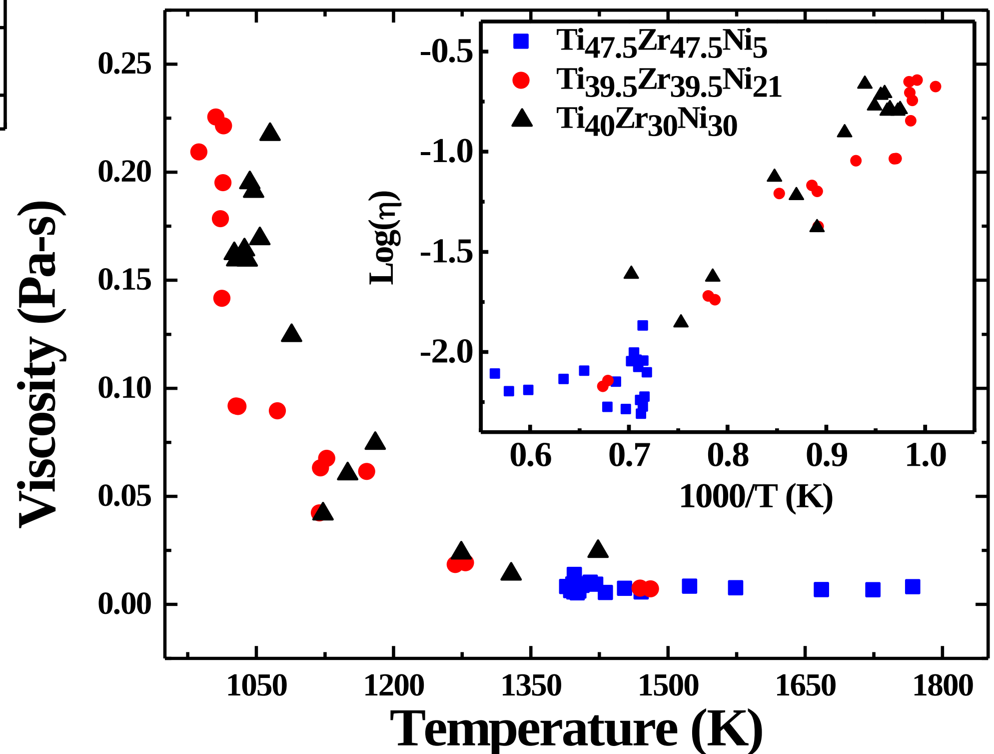
Thermo- physical Properties of Supercooled Liquid



Specific heat maximum

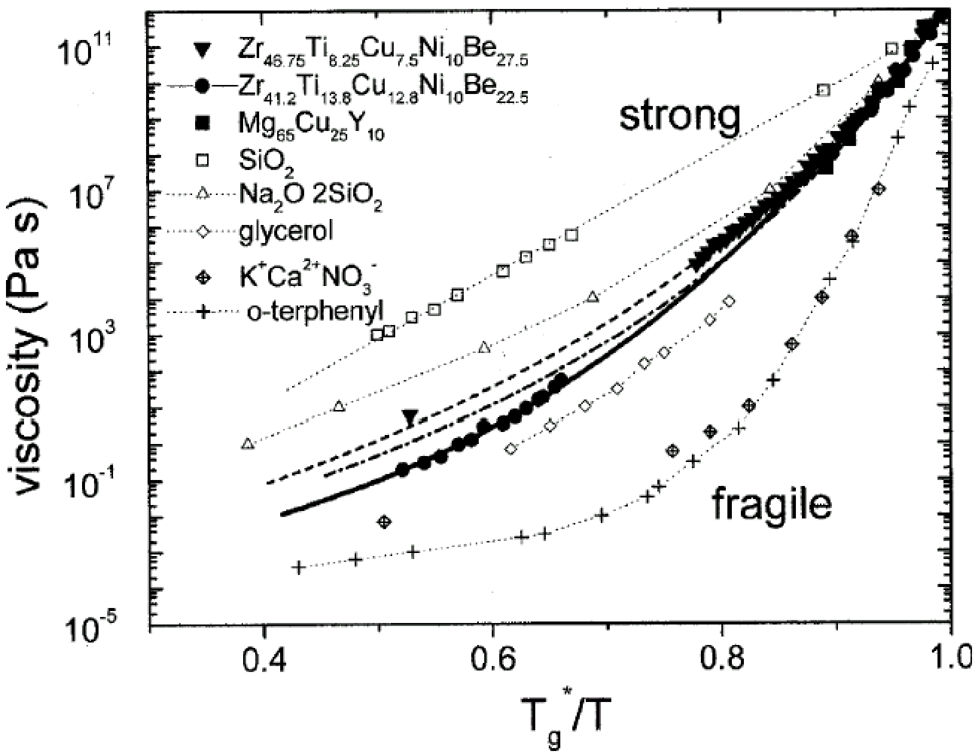
Issues with noise, emissivity - under investigation …

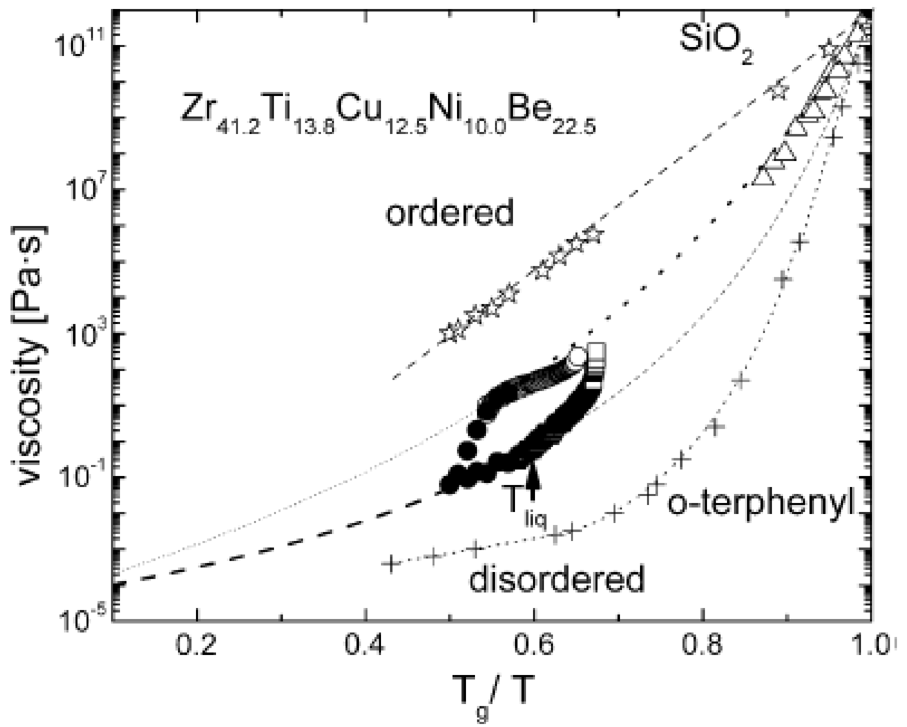
Rise in viscosity



R. W. Hyers, R. Bradshaw, G. W. Lee, A. Gangopadhyay, J. Rogers, K. F. Kelton.

Strong - Fragile Transition in Vit106a

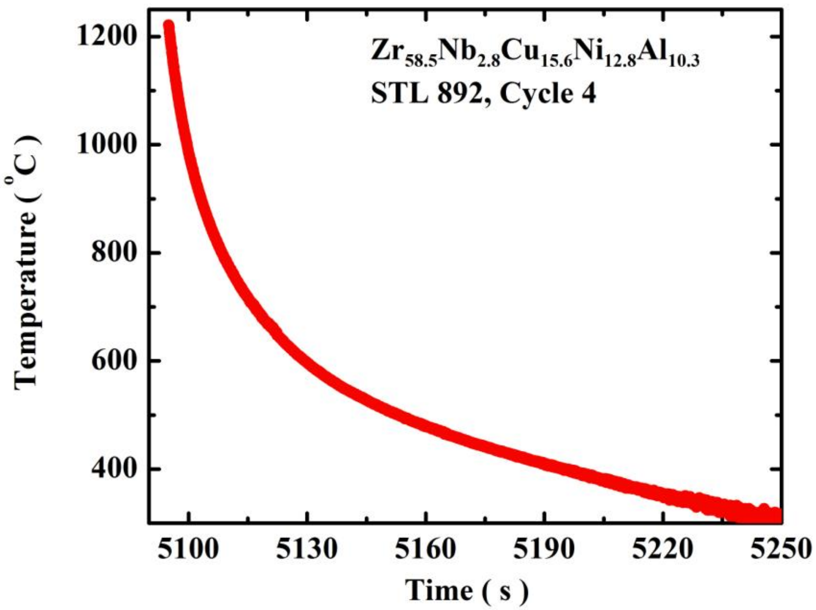


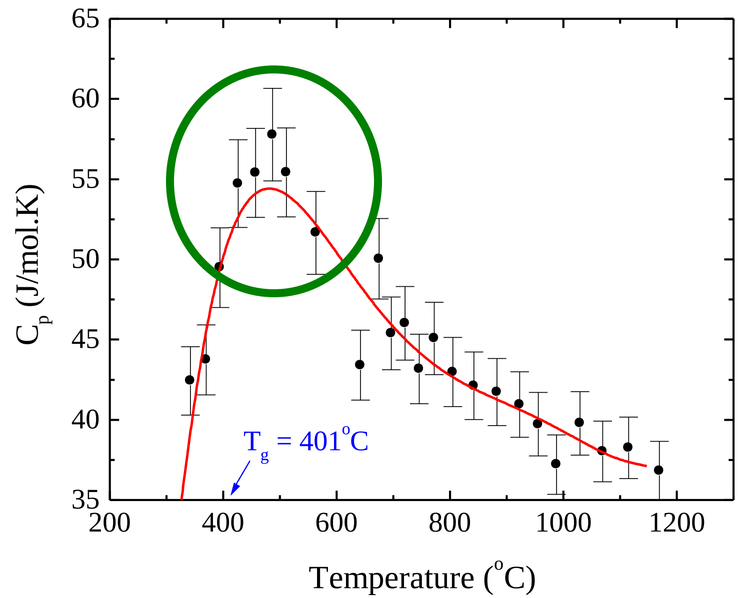


- Fragility proposed by Angell (C. A. Angell, “Relaxation in Complex Systems” US Dept of Commerce, Springfield (1985)).
- Viscosity
  - strong glasses - Arrhenius behavior
  - fragile glasses – non-Arrhenius more collective process
- Metallic glasses fall in between

- In Vit106a observe hysteresis
- Strong behavior on initial heating from glassy state
- Transforms to more fragile state on further heating (completed above 1225K)
- Speculated that strong to fragile transition due to destruction of local order

Thermo- physical Properties of Supercooled Vit 106a

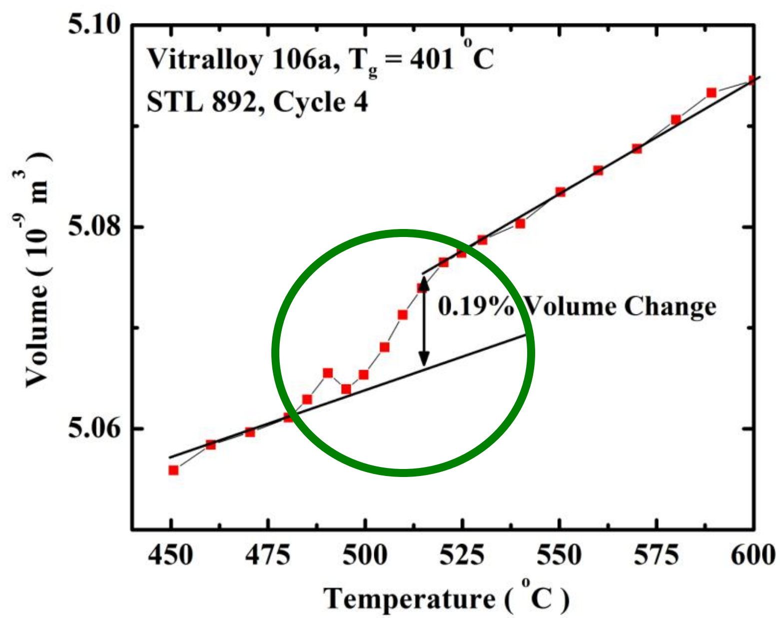




- **No evidence for recalescence in time-temperature plot (formed glass)**
- **Broad specific heat maximum -**

  $$mC_p(dT/dt) = 4\pi r^2\sigma\varepsilon(T^4-T_o^4)$$

- **Volume/density anomaly near specific heat maximum**

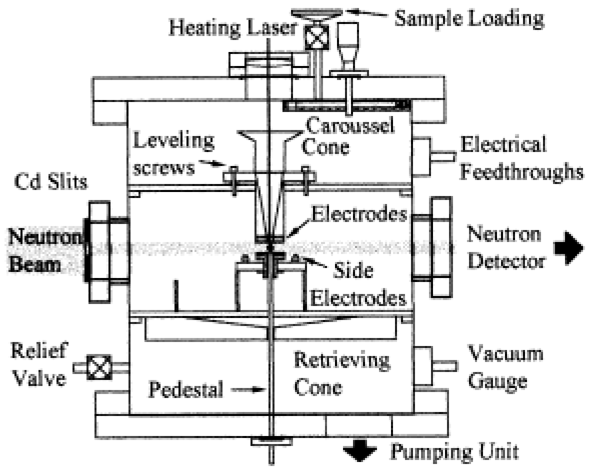


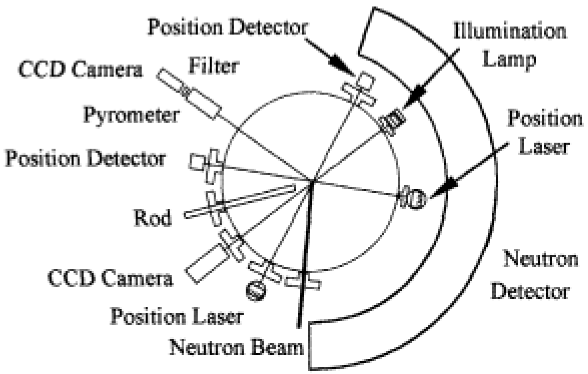
A. Gangopadhyay, R. W. Hyers, K. F. Kelton

Summary and Conclusions

- New experimental techniques are allowing deeper investigations of amorphous structures
- Both liquids and glasses show distinct short-range order and in some cases even medium ranger order
- Evidence for novel liquid/liquid phase transitions
- Neutron studies of liquids - an emerging area

Coming - Neutron Diffraction Studies of Liquids

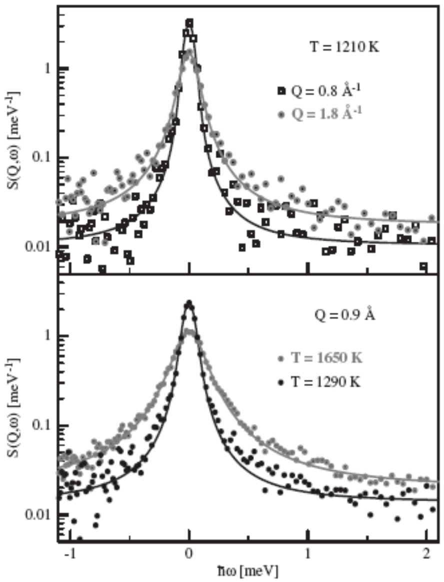


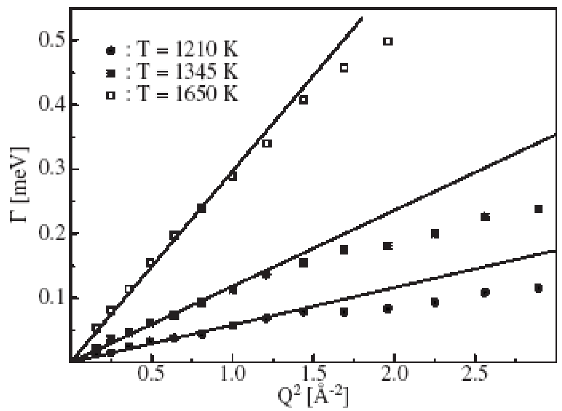


P.-F. Paradis et al., J. Non-Cryst. Solids, **312-314,** 309-313 (2002)

Example*

- Obtain partial structure factors (isotopic substitution
- Quasielastic and inelastic scattering studies (information on dynamical effects and diffusion)





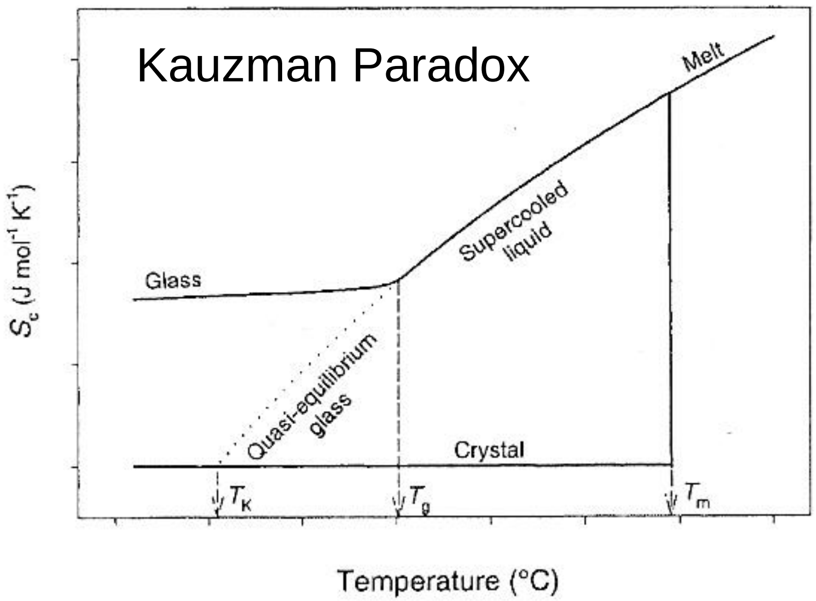
Small momentum transfer –

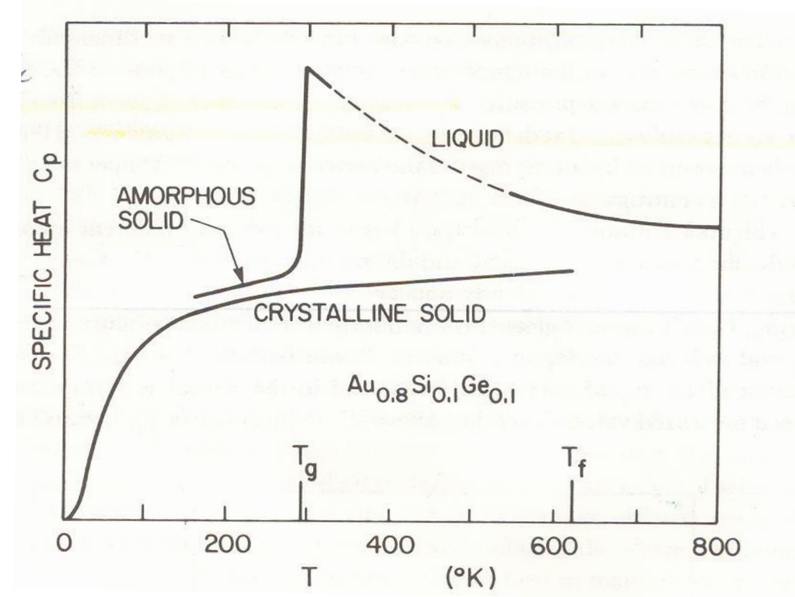
$$\Gamma = 2\hbar D_{Ni} Q^2$$

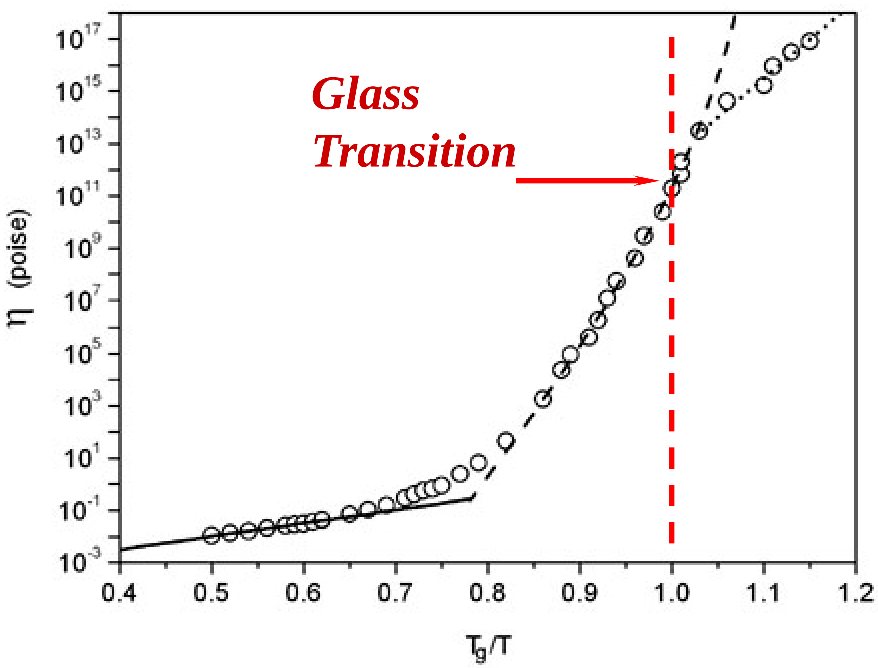
- $D \propto (T - T_c)^{\gamma}$ - agrees with prediction from mode coupling
- Large activation energy for Ni diffusion reflects chemical short range ordering (not icosahedral)

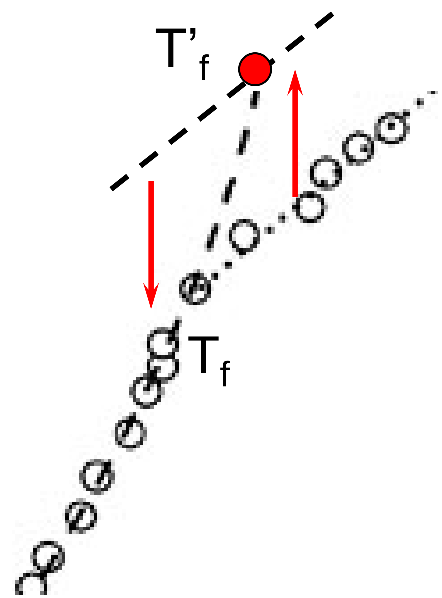
*D. Holland-Moritz, Phys. Rev. B., **79**, 064204 (2009)

The Glass Transition

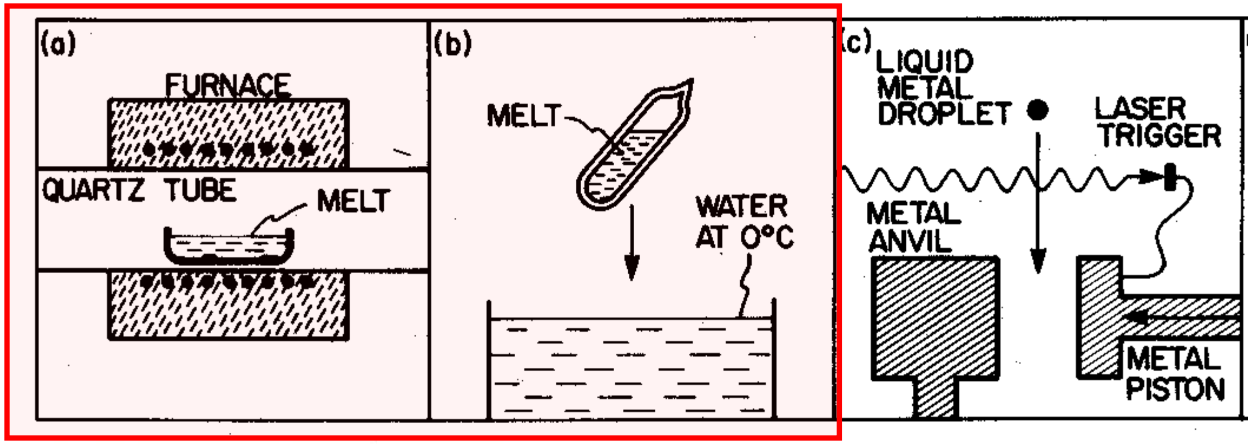


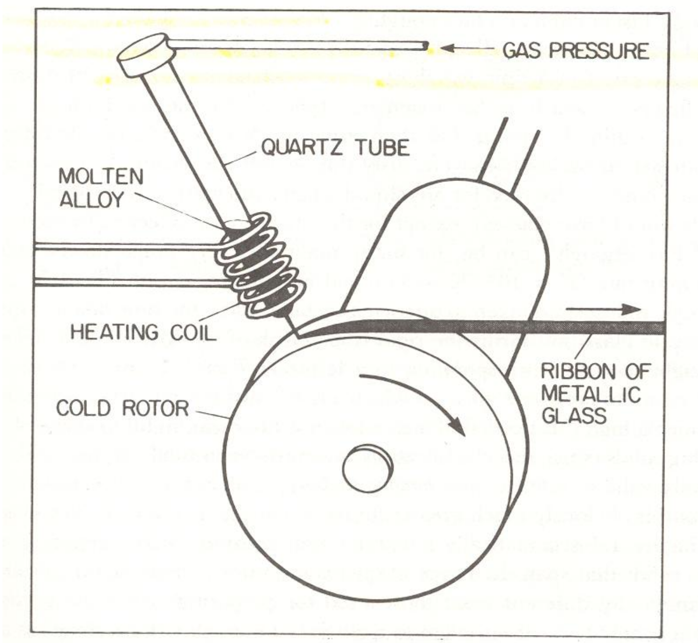






Glass Formation - Cool the Liquid Quickly





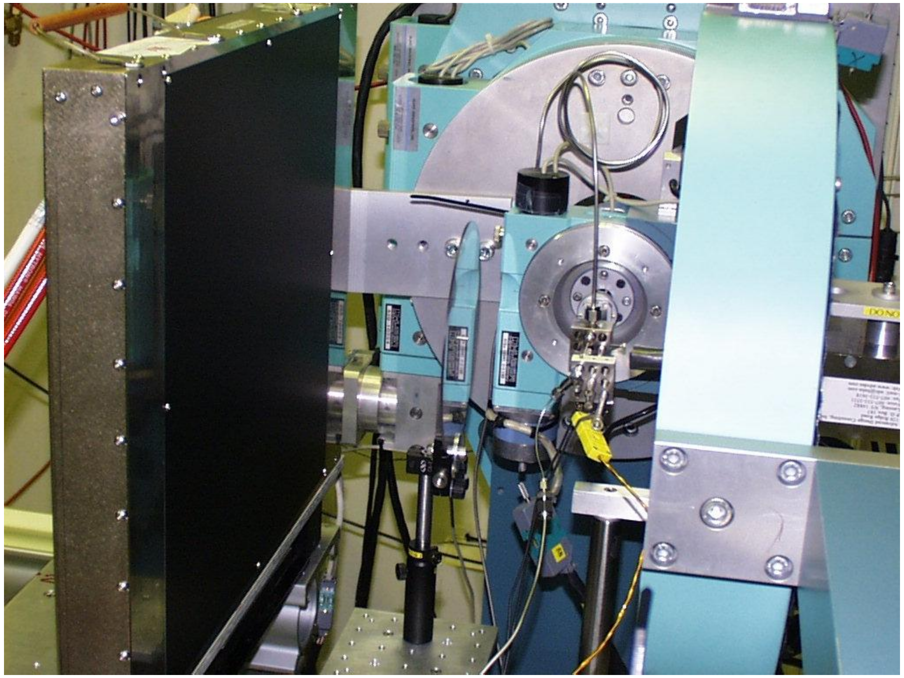
Melt Spinning – Most common for formation of early metallic glasses

Now Bulk Metallic Glasses (BMG)– cooling rates like traditional silicate glasses

Area Detectors

- Image Plate (IP) allows rapid acquisition of diffraction patterns
- Example - MAR3450

General Electric Medical Systems Radiography Detector



- Faster than IP – up to 30 patterns per second
- Smaller dynamic range than IP
- Higher background (dark current) than IP.