Soft Matter Research in Microgravity

Dave Weitz
Peter Lu
Harvard

Bill Meyer
NASA Glenn

- Review of science results to date
- On-going experiments

http://www.weitzlab.seas.harvard.edu/

SSB 11/9/11

NASA support of Soft Matter research

- NASA support established complex fluids research in US
  - Brad Carpenter – early program director
    - Strongly supported complex fluids research

Complex Fluids Research

- Fluids with larger scale structures
- Foams, emulsions, gels, colloids
- Multiple components
- Complex phase behavior
- Materials often have solid-like properties

- Soft Matter Research

Soft Matter Research

- Multiple components with larger length scales
- Complex phase behavior
- In fluids, but not buoyancy matched
- Gravity often plays a critical role
    - Obscures underlying phase behavior
    - Buoyancy matching too constraining

PCS – Physics of Colloids in Space

- NASA support established complex fluids research in US
- Flight experiments were part of program

PCS – Physics of Colloids in Space

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- CGel, BCAT:
  Glove-box experiments on MIR
- PCS:
  Express rack experiment on ISS
- BCAT:
  Ongoing glove-box experiments on ISS

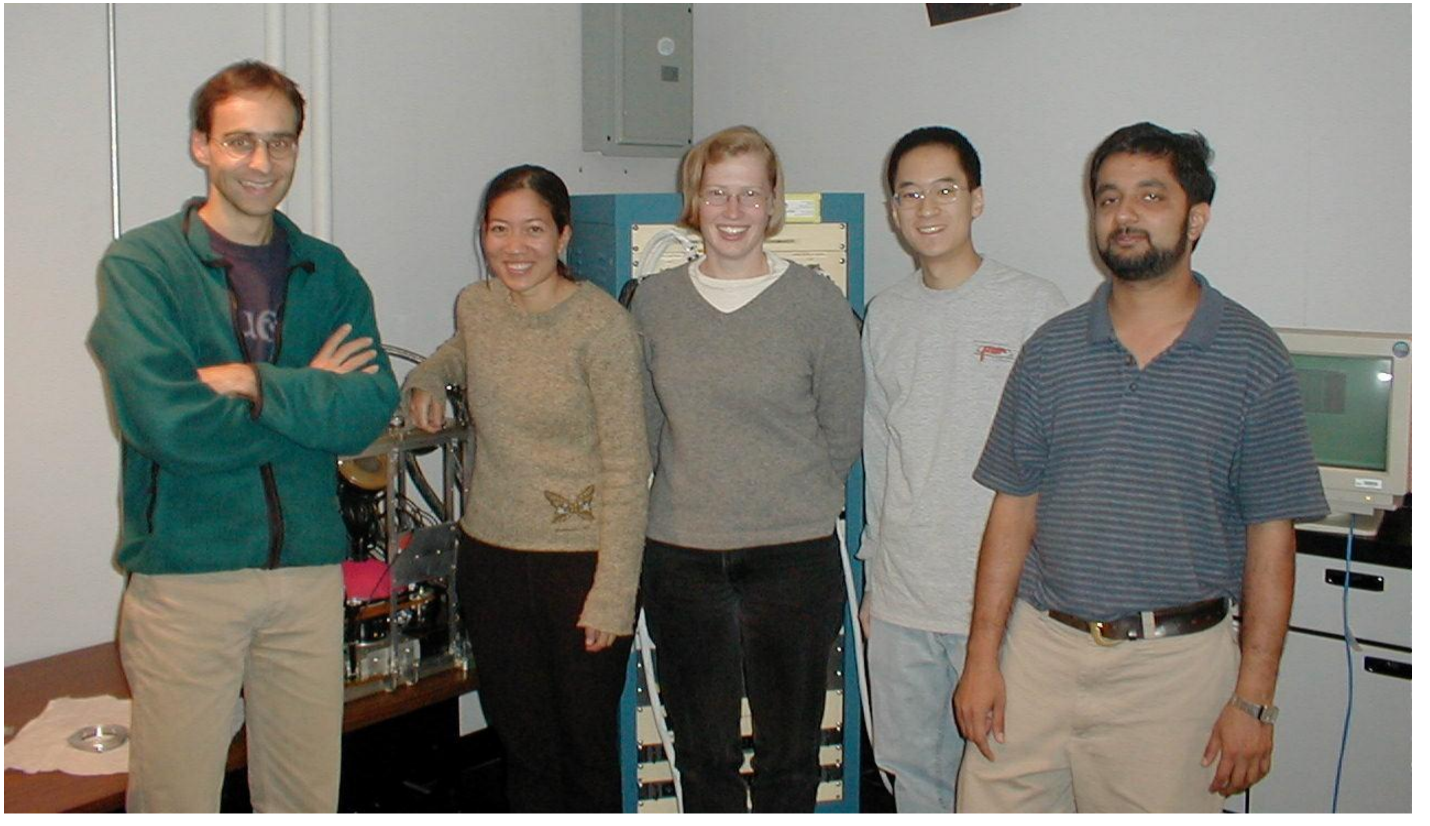
Program Goals

- Develop new discipline of "colloid engineering"
- Fabricate new materials with colloidal precursors
- Study fundamental behavior of colloids
- Extend to earth-based applications
- Train scientific experts in complex fluids
- Enhance economic competitiveness

PCS – Physics of Colloids in Space

- Part of NASA fluids program
- ISS Experiment in Express Rack
- Flew April 2001 – June 2002
- Operated June 2001 – February 2002
- Updated, improved version of PH^{A}SE
- Completely working experiment
- Completely working apparatus

Harvard Science Team – Oct. 2001



Urs Gasser, Suliana Manley, Rebecca Christianson, Peter Lu, Vikram Prasad

SCIENCE TEAM 2002

- **Harvard University**
  - Prof. David A. Weitz — Principle Investigator
  - Art Bailey (SFU) — Science Lead
  - Rebecca Christianson — PDF
  - Suliana Manley (EPFL) — Graduate Student
  - Vikram Prasad (Dow) — Graduate Student
  - Peter Lu — Graduate Student
  - Urs Gasser (Konstanz) — PDF
  - Phil Segre (Atlanta) — PDF
  - Luca Cipelletti (Montpellier) — PDF
- **University of Edinburgh**
  - Prof. Peter N. Pusey — Co-Investigator
  - Andrew Schofield — PDF

NASA TEAM 2001

- **GRC PROJECT MANAGEMENT**
  - Michael Doherty (GRC) — Project Manager
  - Amy Jankovsky (GRC) — Deputy Project Manager

- **HARDWARE AND OPERATIONS TEAM (**Zin Technologies)
  - Tibor Lorik, — Project Manager
  - Bill Shiley, John Bowen, Jeff Eggers — Software
  - Carol Kurta — Safety, Crew Training,
  - Kevin Dendorfer — Mechanical Tech.
  - Jim Greer — Designer

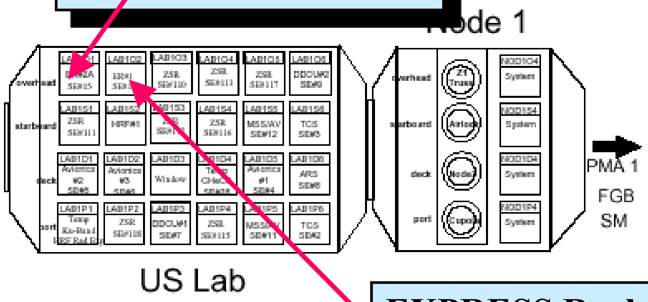
PCS Apparatus

- Integrated Light Scattering apparatus on ISS
- Eight Sample Cells
- Eight different experiments

- Microgravity essential
    - Eliminate sedimentation, convection
    - Eliminate differential sedimentation

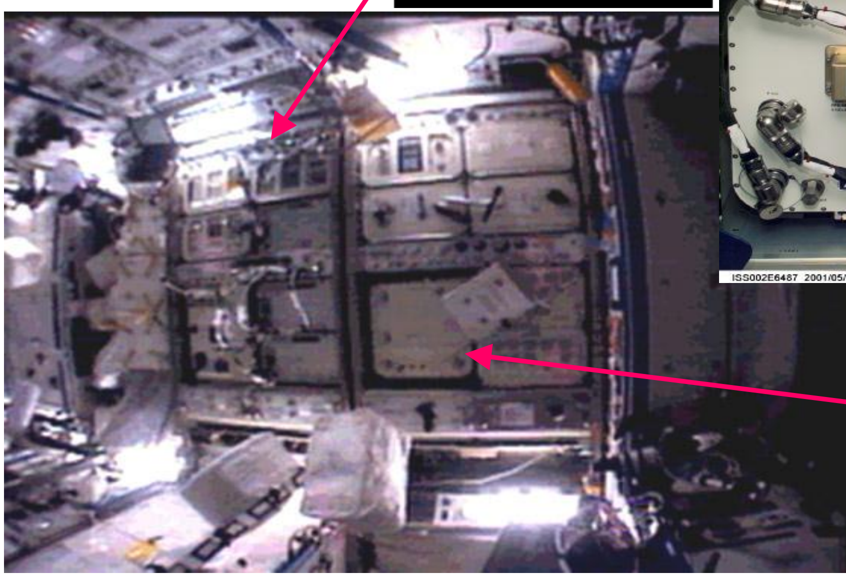
ISS Configuration

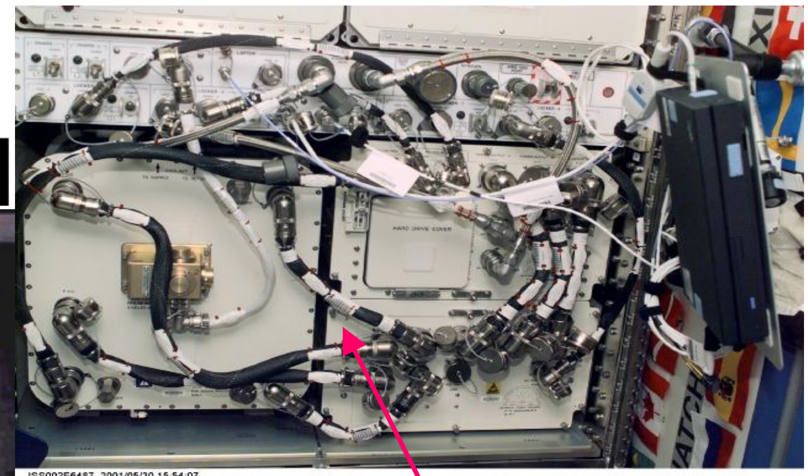
EXPRESS Rack 2



EXPRESS Rack 1

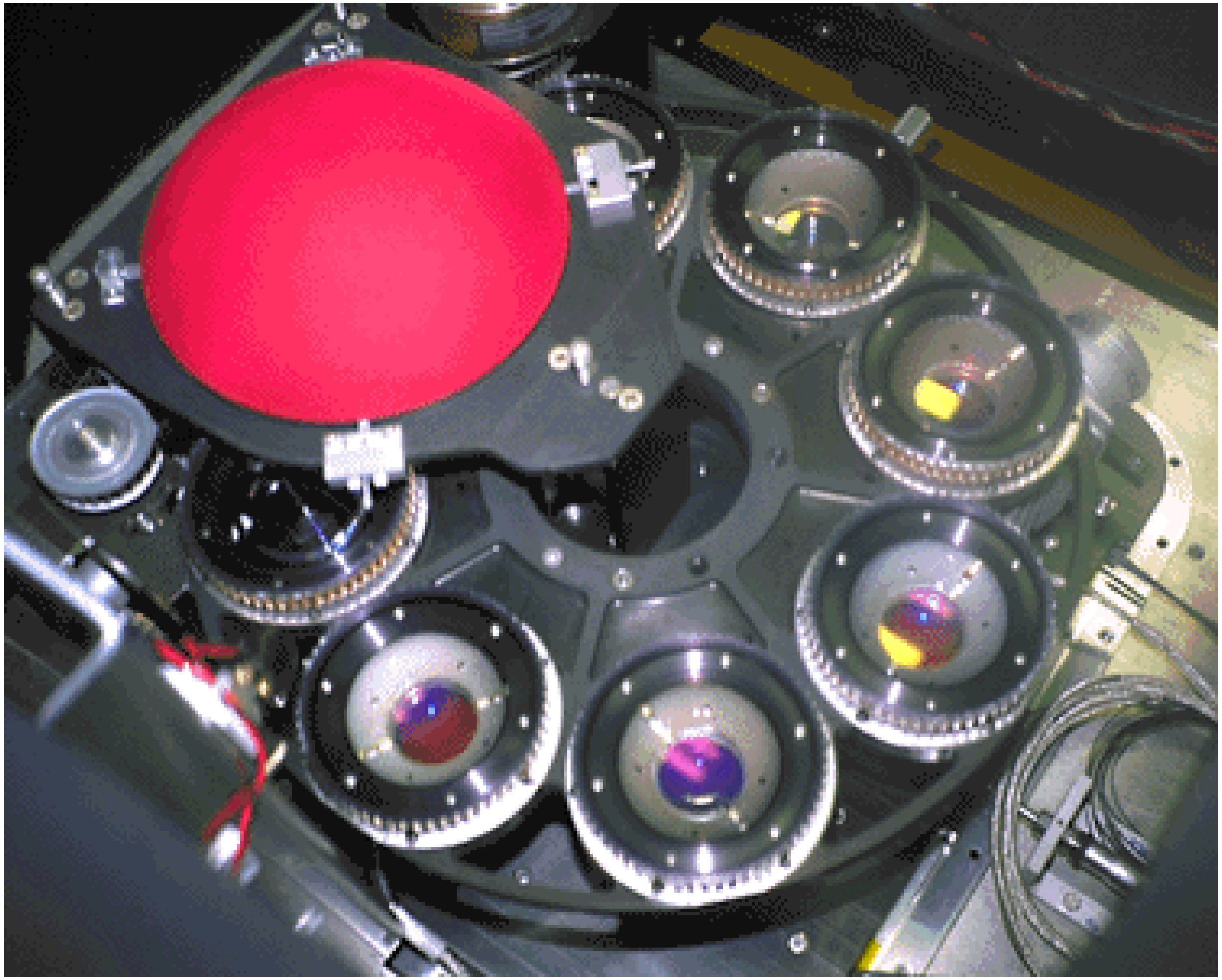
EXPPCS Within Destiny



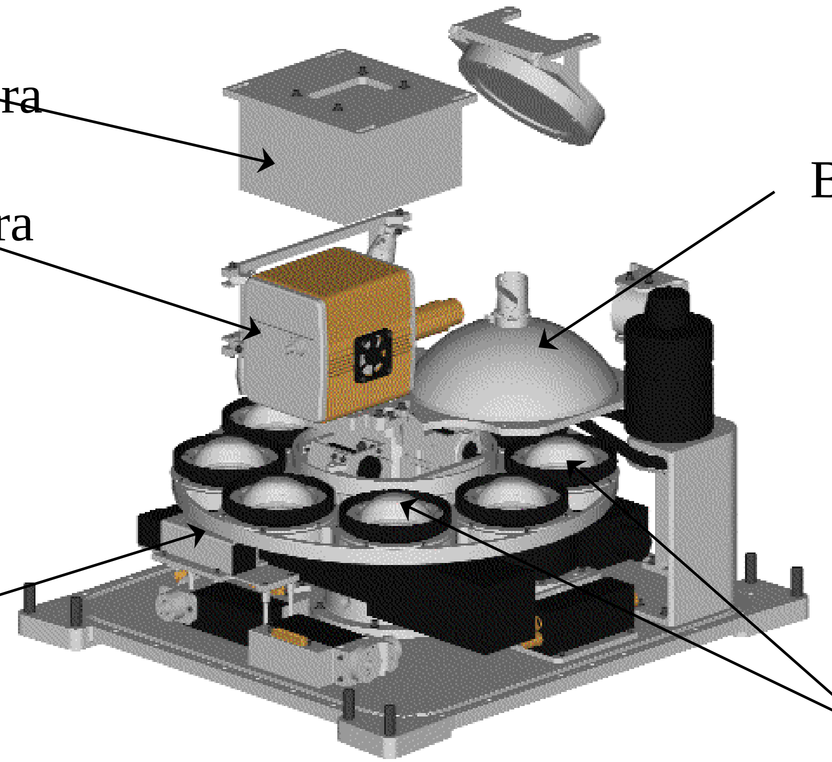


EXPPCS in EXPRESS Rack 2

Sample Cell Carrousel

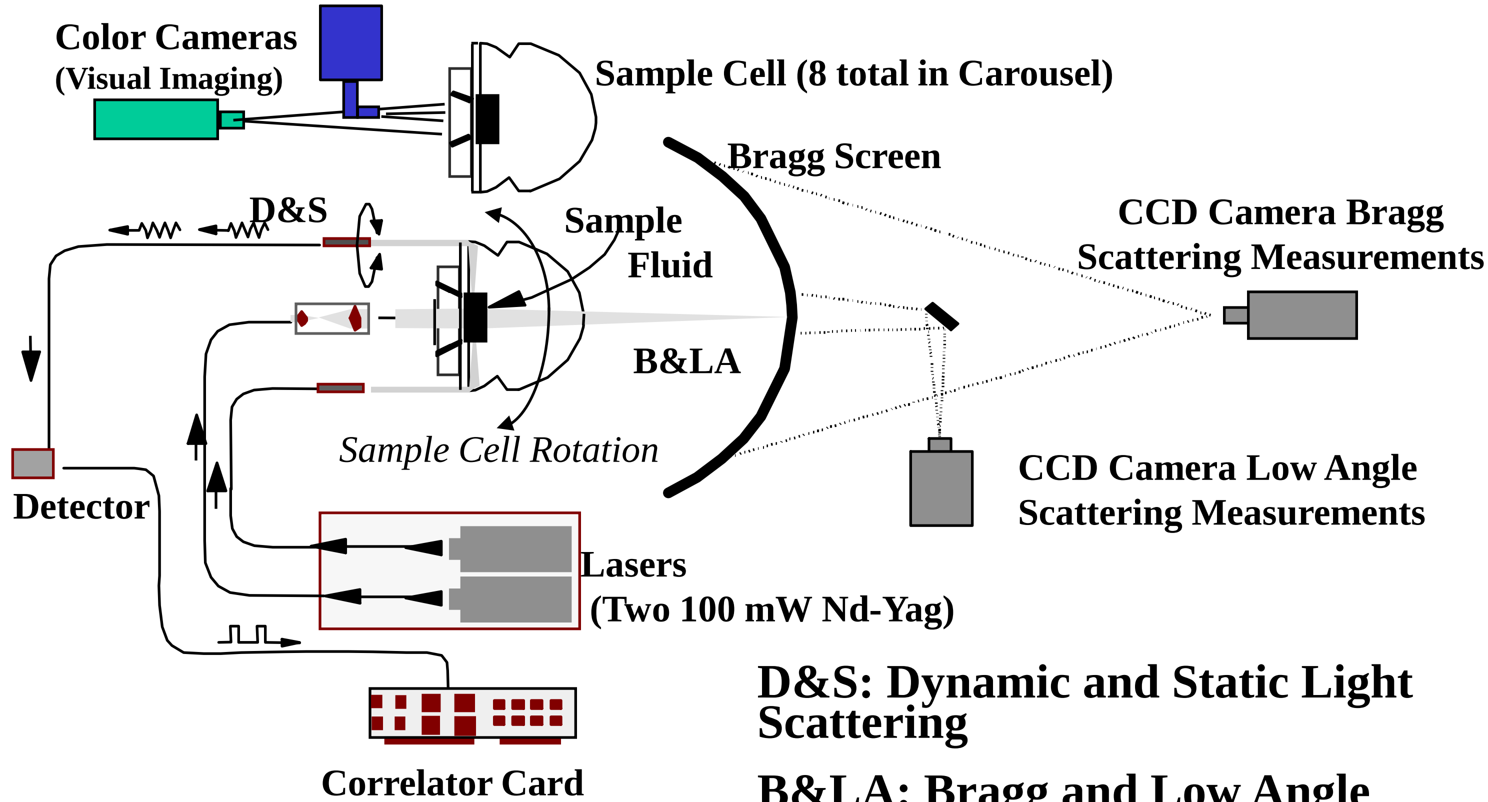


PCS Test Section Internal Features



Note: For reference only, these components are not crew accessible
(Test Section side wall not shown)

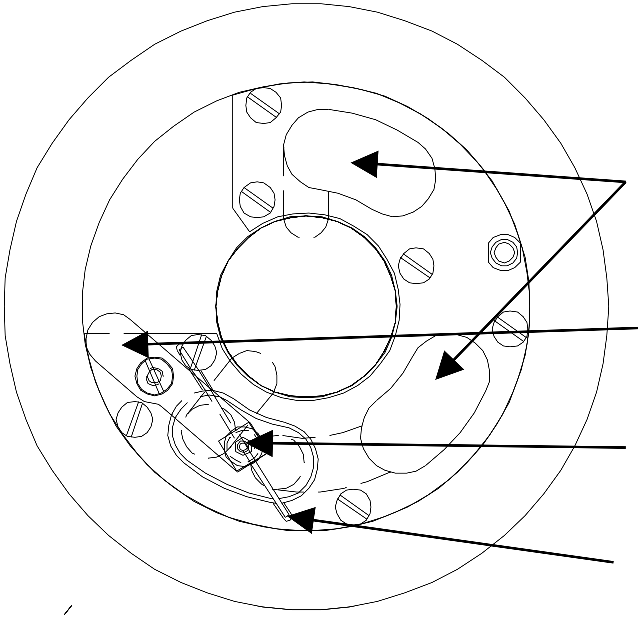
PCS Science Diagnostics



D&S: Dynamic and Static Light Scattering

B&LA: Bragg and Low Angle Scattering

Sample Preparation



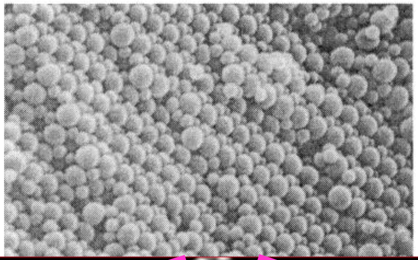
- 11 nm diameter colloidal spheres
- Screen charges with salt
  - van der Waals attraction

Polystyrene: $\phi = 8x10^{-6}$
Silica: $\phi = 2x10^{-4}$

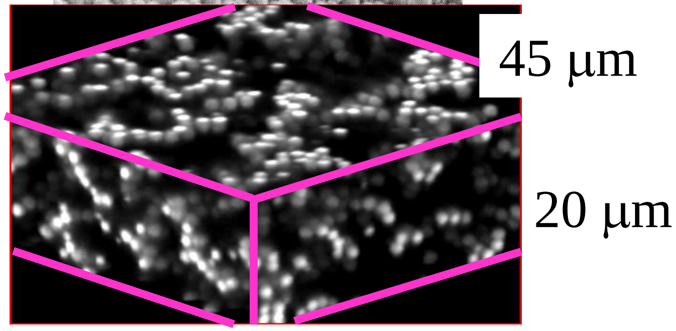
- On Board Mixer
- FCD cell

Colloid Samples

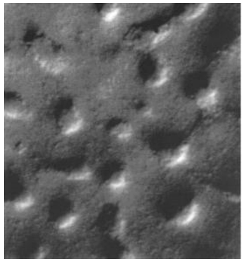
Binary Colloid Alloy Crystals
2 AB_6
AB_{13}



Fractal Aggregates
Colloid-polymer mixture
3 Polystyrene
Silica



Colloid-polymer mixtures
2 Critical point
Crystal



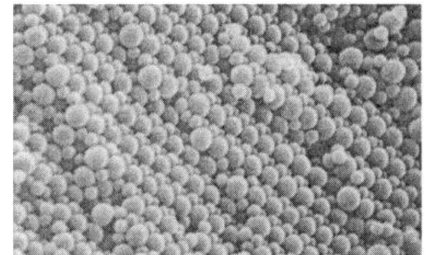
1 Colloidal Glass (Chaikin-Russel)

Colloid Samples

Binary Colloid Alloy Crystals

2 AB_6

AB_{13}

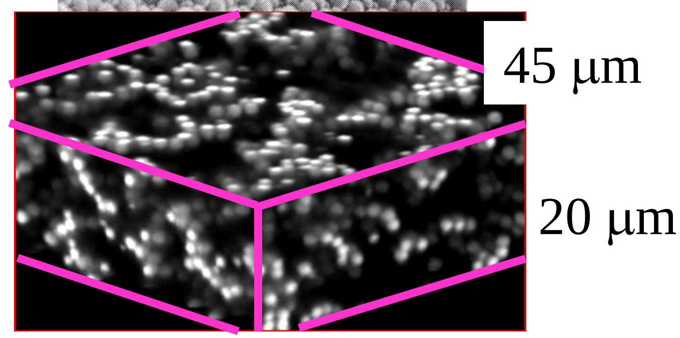


Fractal Aggregates

Colloid-polymer mixture

3 Polystyrene

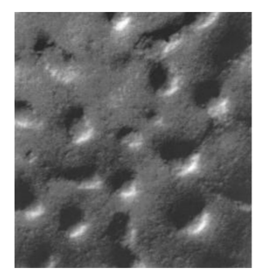
Silica



Colloid-polymer mixtures

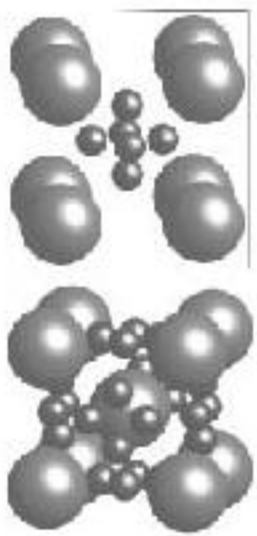
2 Critical point

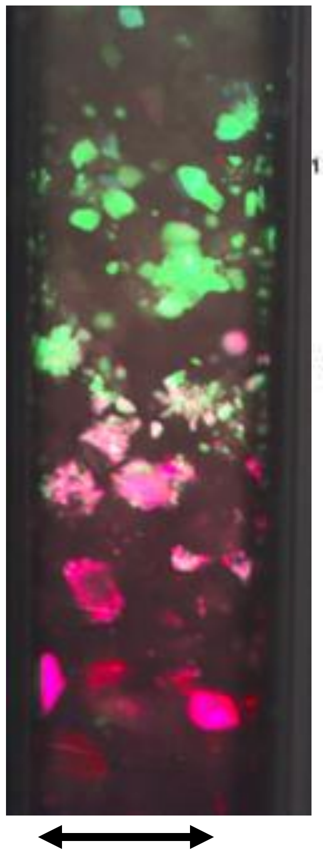
Crystal



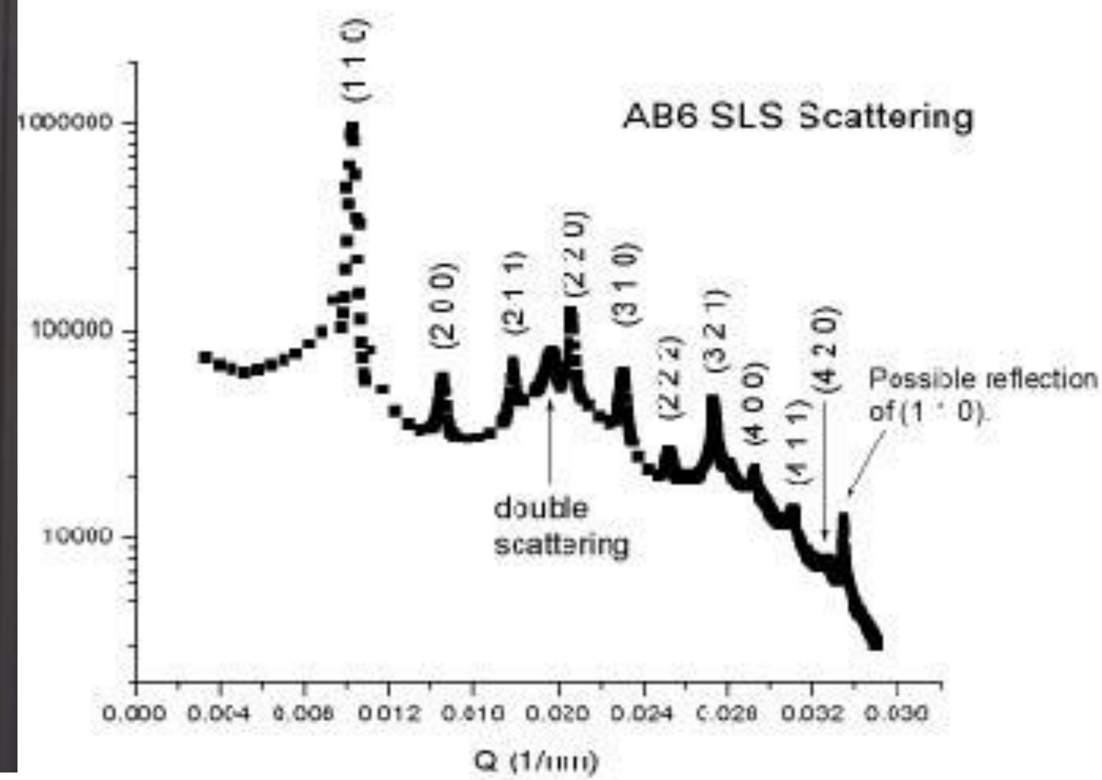
1 Colloidal Glass (Chaikin-Russel)

AB_6 Binary Alloy Crystal - BCC



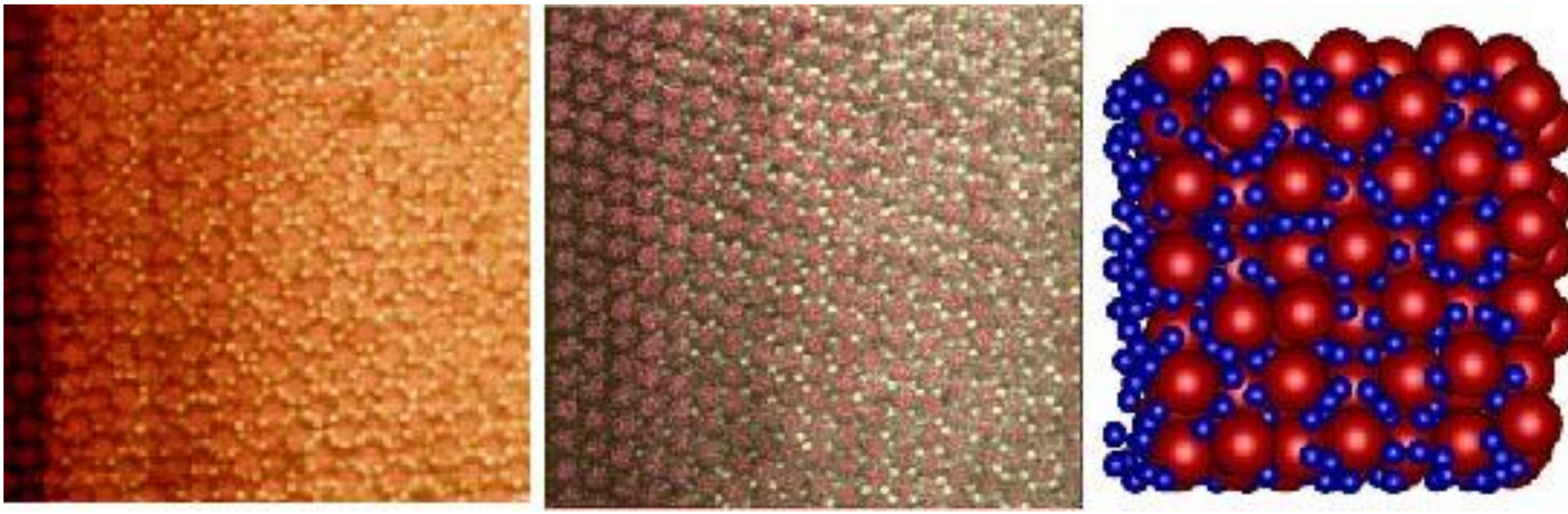


1 cm



- Very intense Bragg scattering
- Very large crystals

AB_6 Binary Alloy Crystal



- Very well ordered FCC structure
- Small particles induce effective long-range intereaction
    - Creates highly ordered large particle lattice

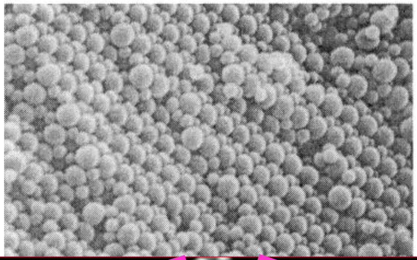
Major Results

Binary Alloys:

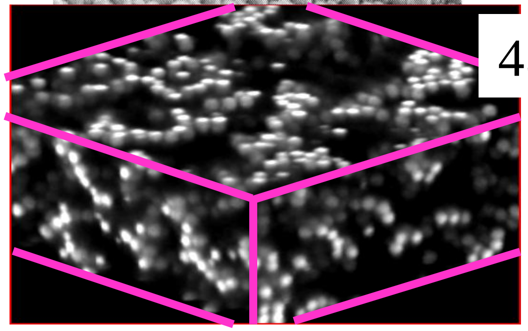
New, low density crystal structures

Colloid Samples

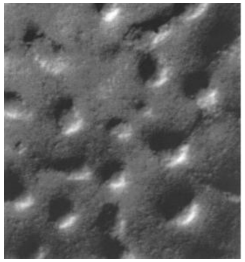
Binary Colloid Alloy Crystals
2 AB_6
AB_{13}



Fractal Aggregates
Colloid-polymer mixture
3 Polystyrene
Silica

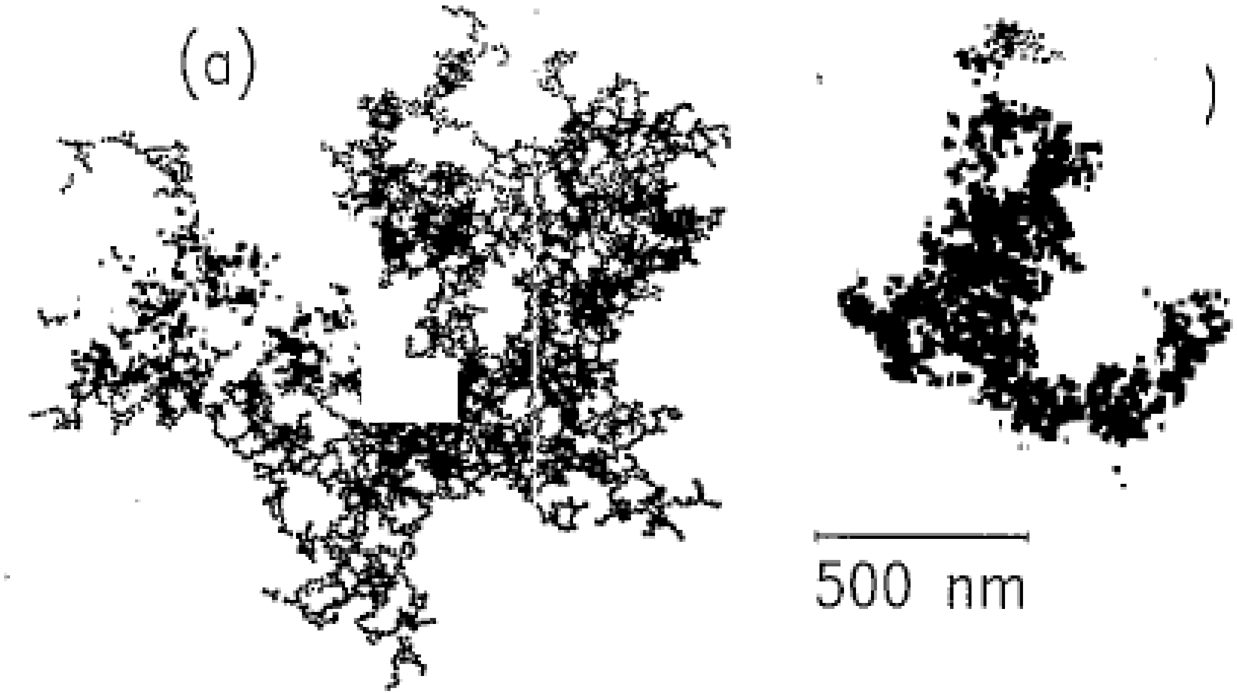


Colloid-polymer mixtures
2 Critical point
Crystal



1 Colloidal Glass (Chaikin-Russel)

Colloidal Fractal Gels

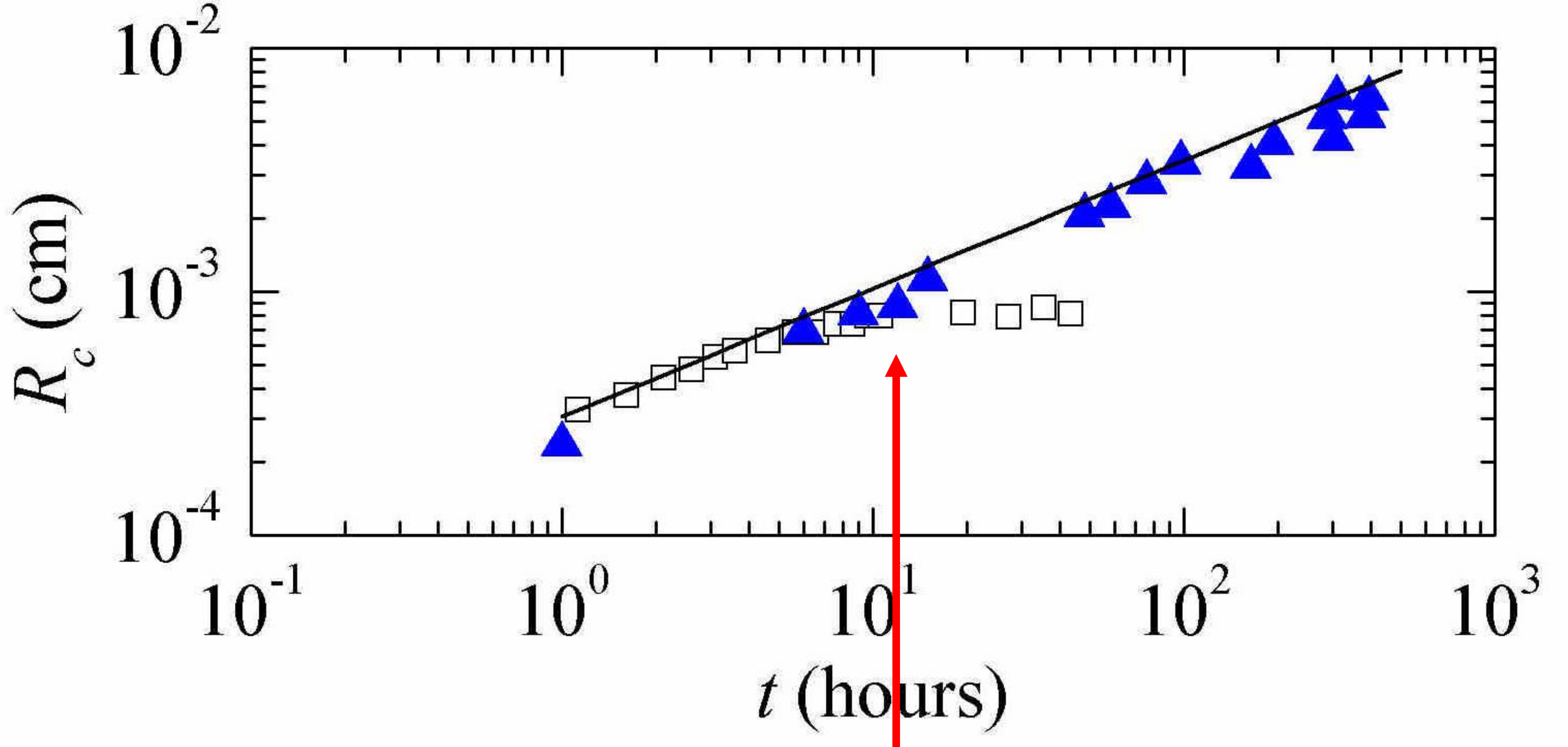


Network is fractal: $M \sim R^{df}$

Tenuous structures, must density match

- What are properties of very low ϕ gels?
- What is intrinsic limitation of gelation?
- How do gels age?

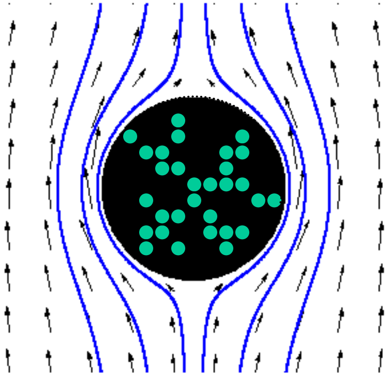
Polystyrene – Gravity disrupts growth



Limitation of size
due to gravity

Limits: Mechanical strength

Gravitational stress exceeds yield stress:



hydrodynamic drag balances weight

internal stress

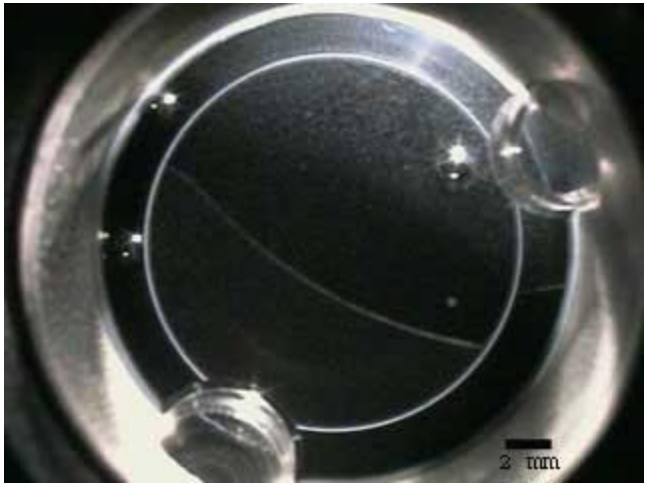
$$\rightarrow \quad \gamma_g = Mg / \kappa_c R_c$$

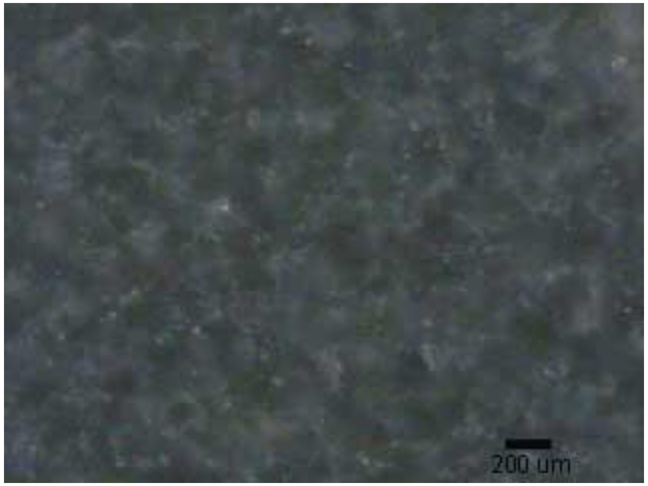
$\gamma \sim 1$, clusters can break or deform

Assuming $\Delta\rho \sim 10^{-3}$, limit to cluster size: 10 μm

$$\longrightarrow \quad \phi_L = \left(\frac{R_c}{a} \right)^{\frac{1}{d_f - 3}} = 10^{-4}$$

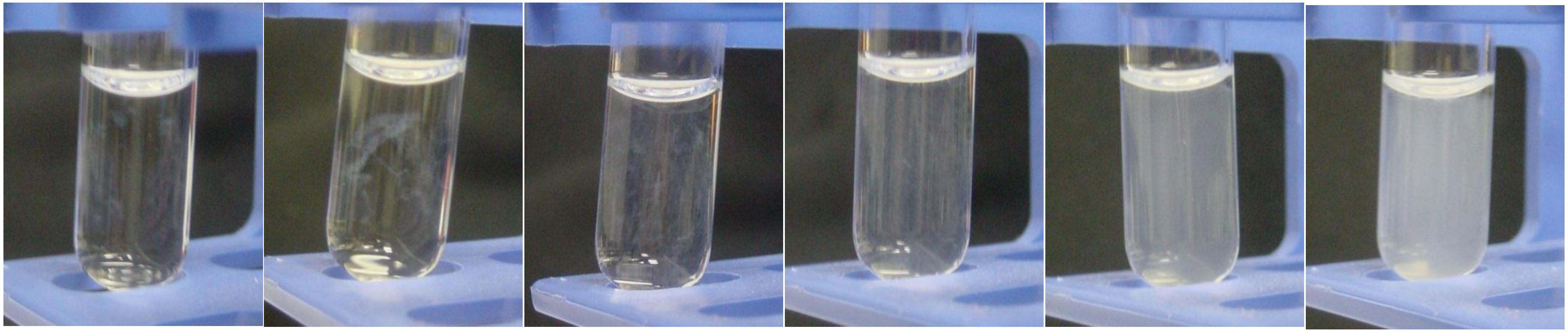
Thermal Limitation to gel formation?





PCS photos
17 days

Buoyancy matched (6:4 D_2O:H_2O)



$\phi = 8x10^{-6}$ $\phi = 2x10^{-5}$ $\phi = 4x10^{-5}$ $\phi = 8x10^{-5}$ $\phi = 2x10^{-4}$ $\phi = 4x10^{-4}$

Ground photos courtesy of Darren Link

Major Results

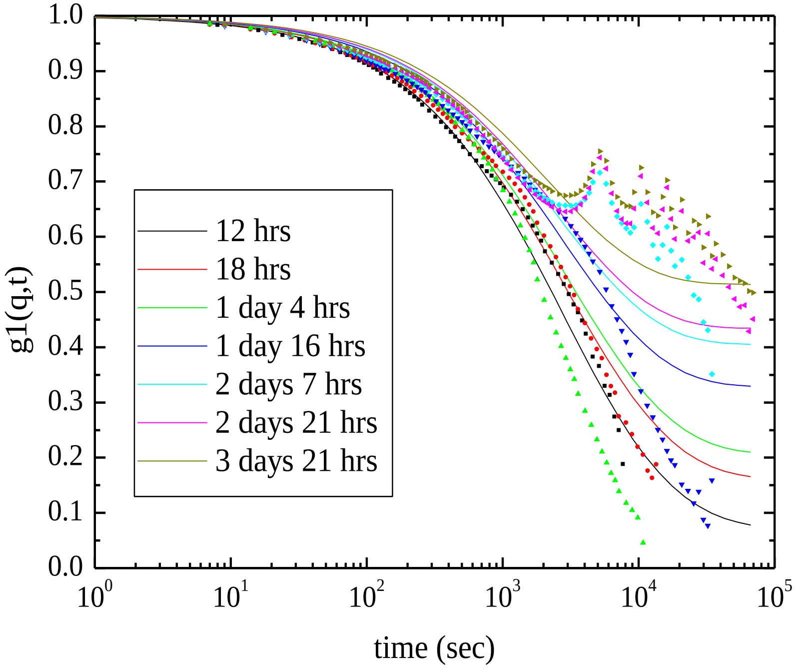
Binary Alloys:

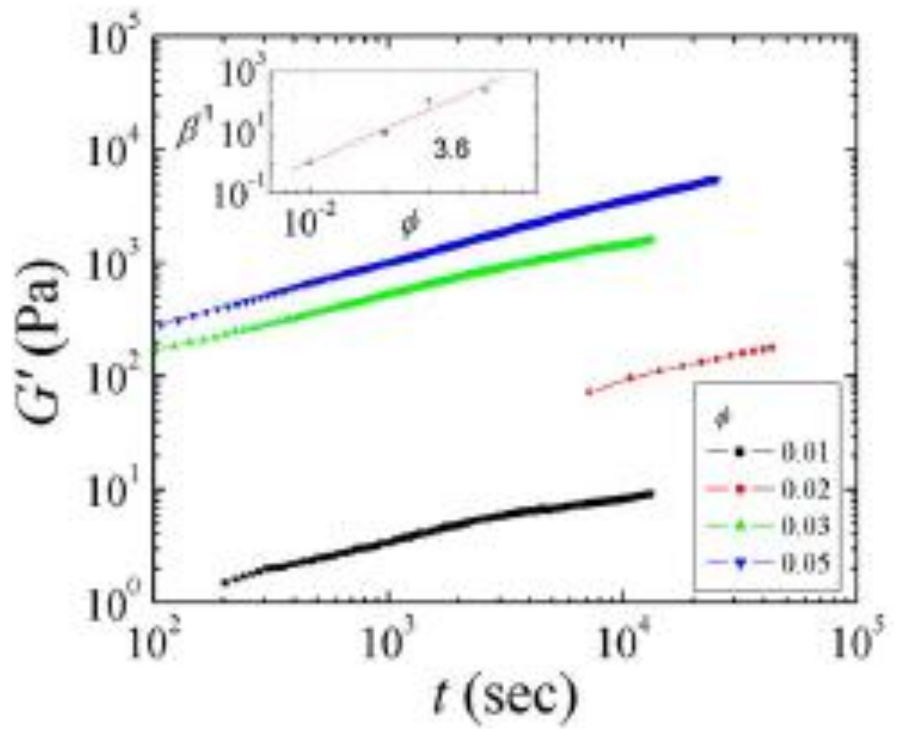
- New, low density crystal structures

Fractal Aggregates:

- Lowest density structure possible
- Fundamental origin of instability

Aging behavior: silica

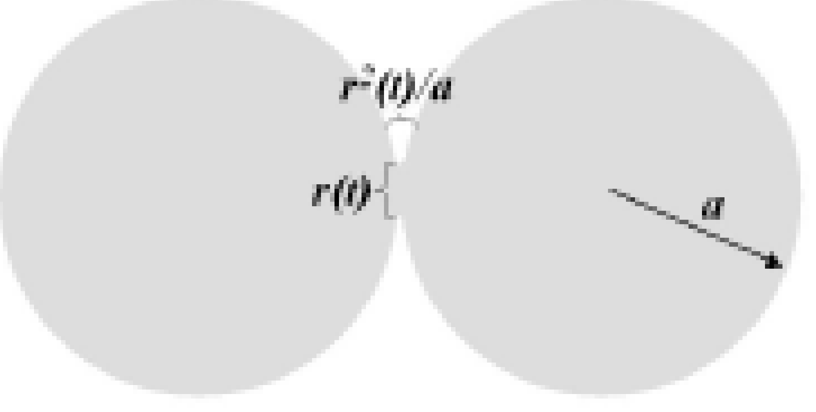




Aging results in stiffening – increase in κ_0.

Silica Gels

- Aging of silica gels
- Sintering of bonds
- Same effect on earth, but can’t probe it



Major Results

Binary Alloys:

New, low density crystal structures

Fractal Aggregates:

Lowest density structure possible

Fundamental origin of instability

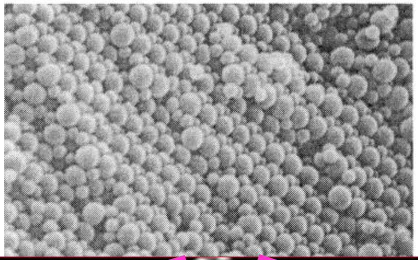
Fundamental coarsening of silica aggregates

Colloid Samples

Binary Colloid Alloy Crystals

2 AB_6

AB_{13}

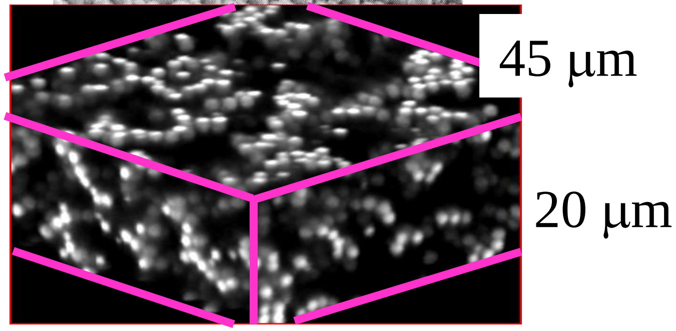


Fractal Aggregates

Colloid-polymer mixture

3 Polystyrene

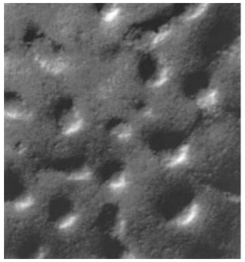
Silica



Colloid-polymer mixtures

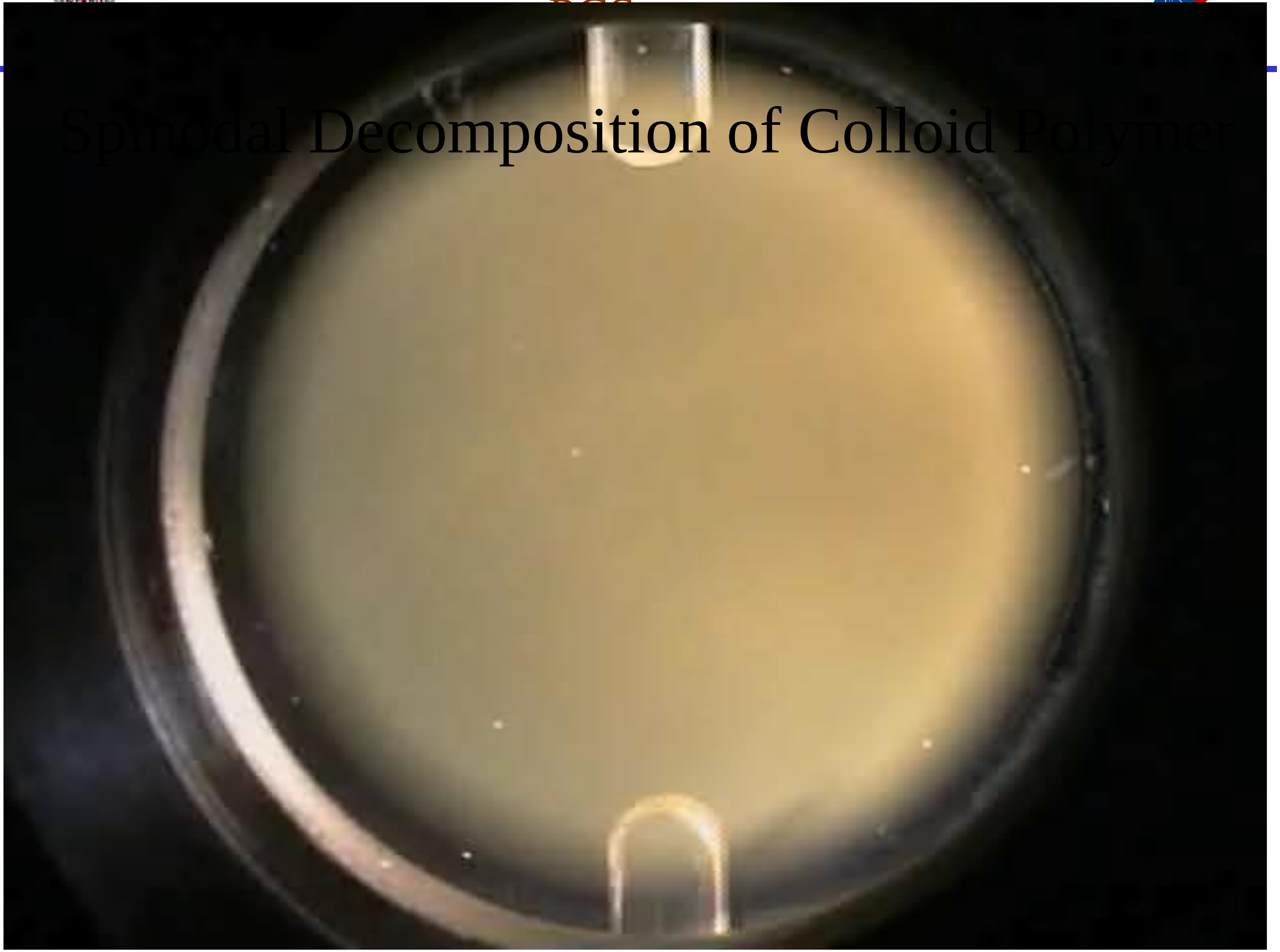
2 Critical point

Crystal



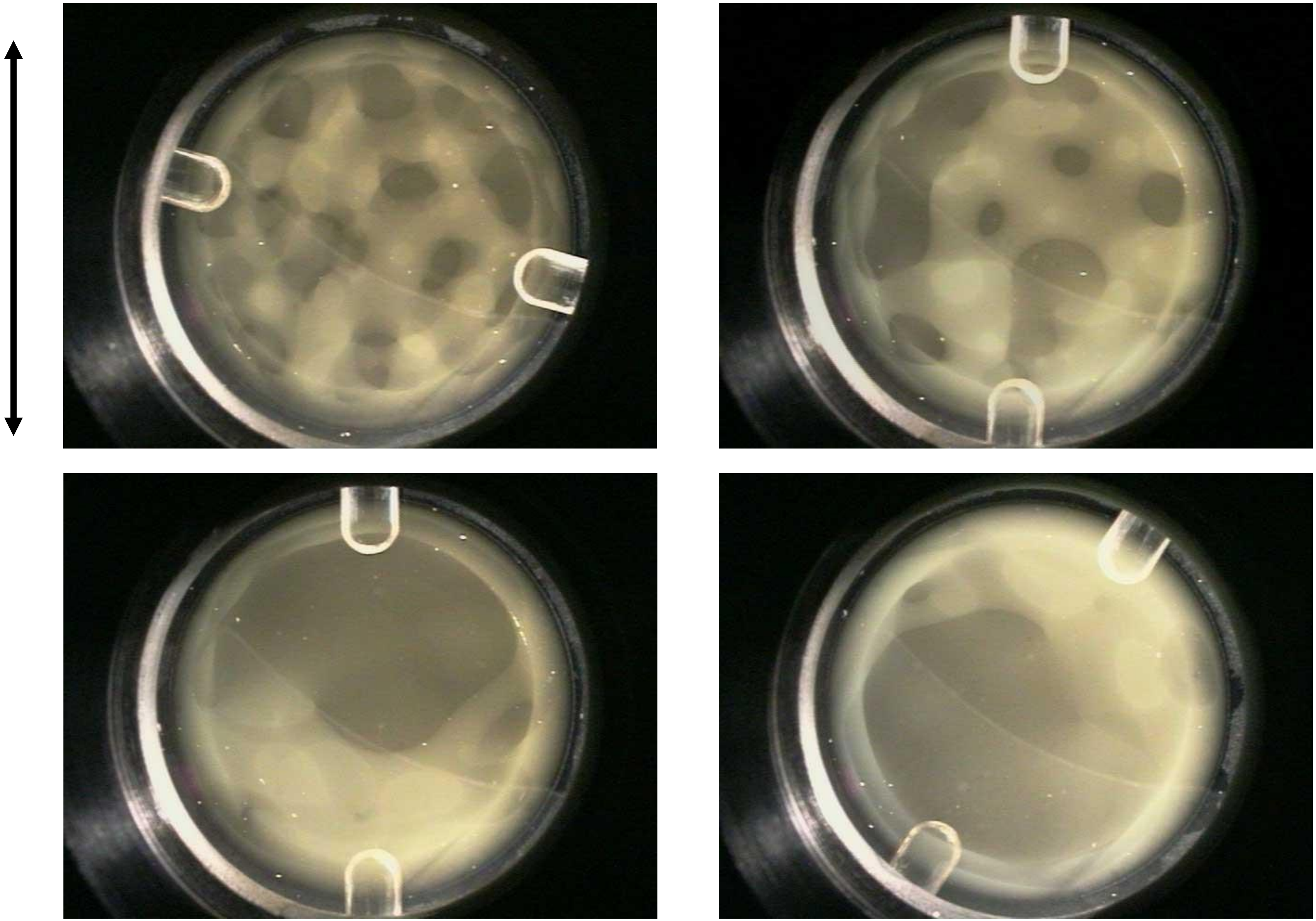
1 Colloidal Glass (Chaikin-Russel)

Spinodal Decomposition of Colloid Polymer

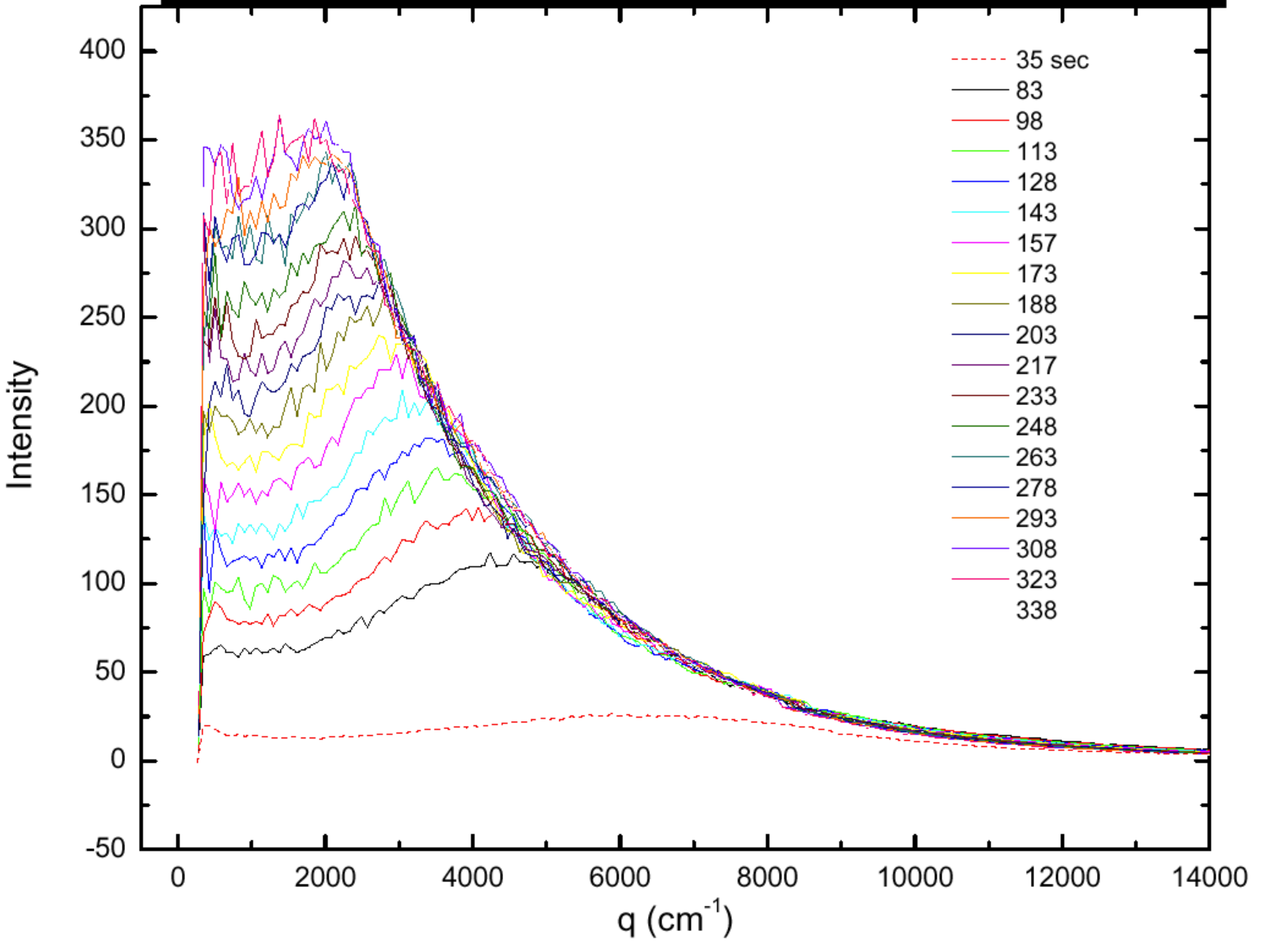


Time Evolution of Phase Separation

~3 cm



Col-Pol Critical Point: Sample Evolution

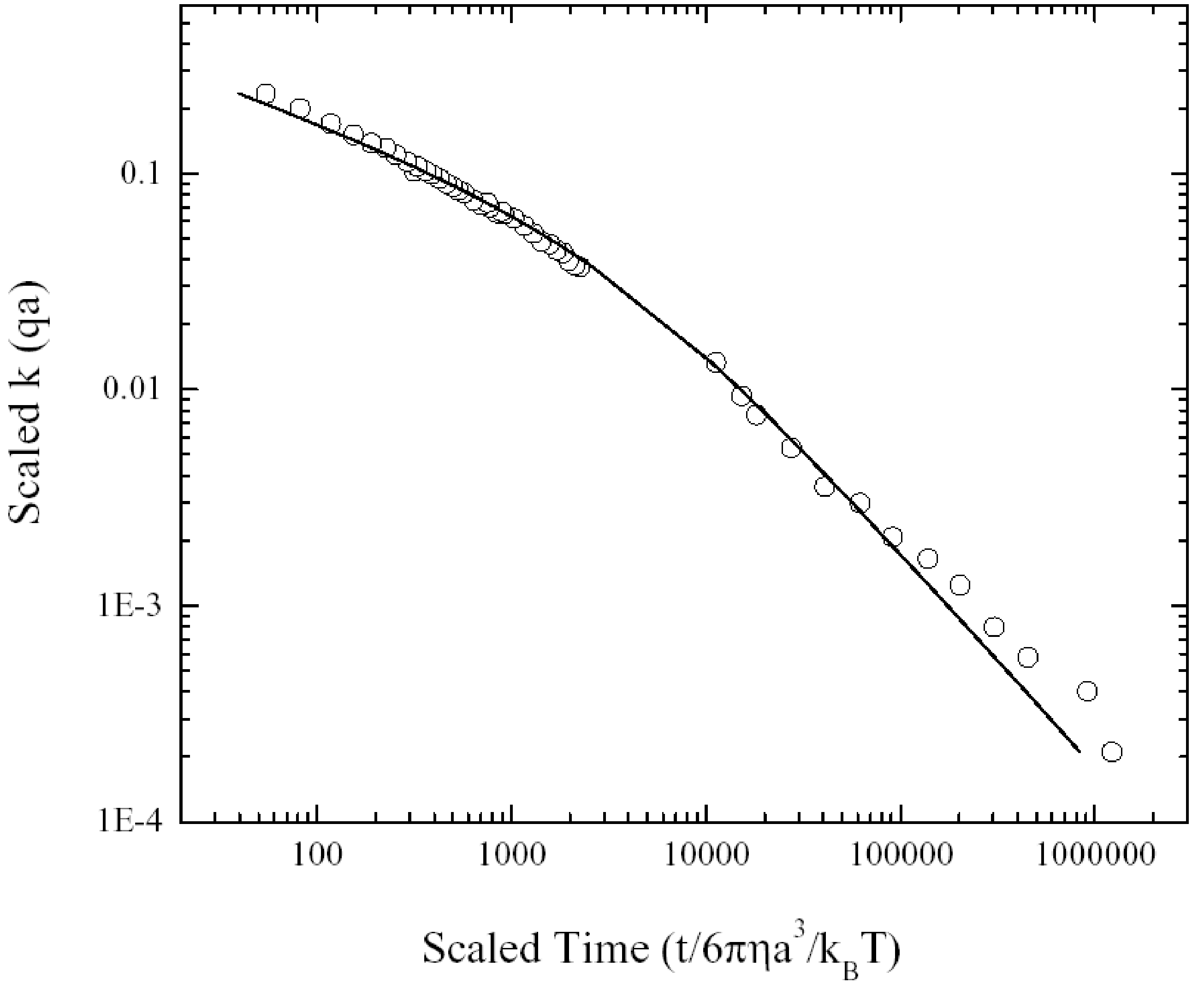


Motion of Interface between two drops

•Measure of surface tension?

•Measure of kinetics

Comparison with Furukawa Theory



Long-time evolution of spinodal decomposition

Spinodal Decomposition of Attractive Colloids

- Large range of length scales
- 1 μm to 3 cm
- Hydrodynamics of late stages of spinodal decomposition
- Surface tension of colloidal particle mixtures
- Wide range of phase separation behavior possible

Major Results

Binary Alloys:

New, low density crystal structures

Fractal Aggregates:

Lowest density structure possible

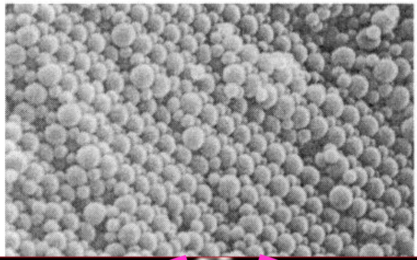
Fundamental origin of instability

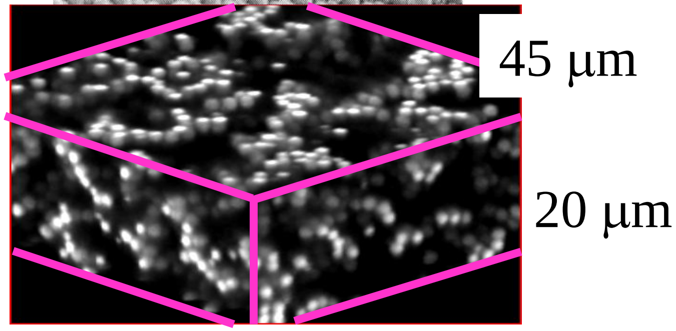
Fundamental coarsening of silica aggregates

Colloid-polymer phase behavior

Fundamentals of spinodal decomposition

Colloid Samples

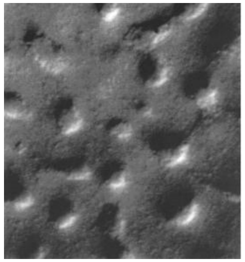




2 Binary Colloid Alloy Crystals
- AB_6
- AB_{13}

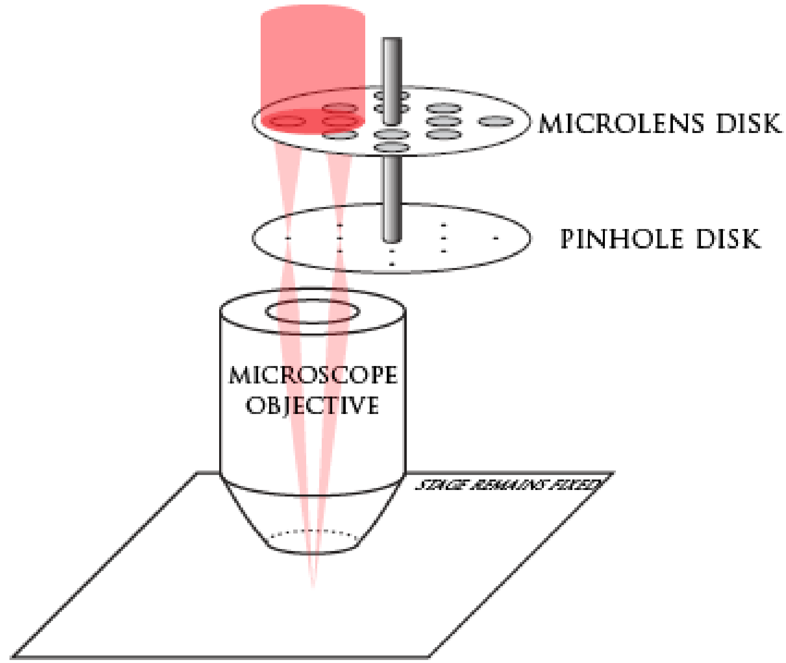
3 Fractal Aggregates
- Colloid-polymer mixture
- Polystyrene
- Silica

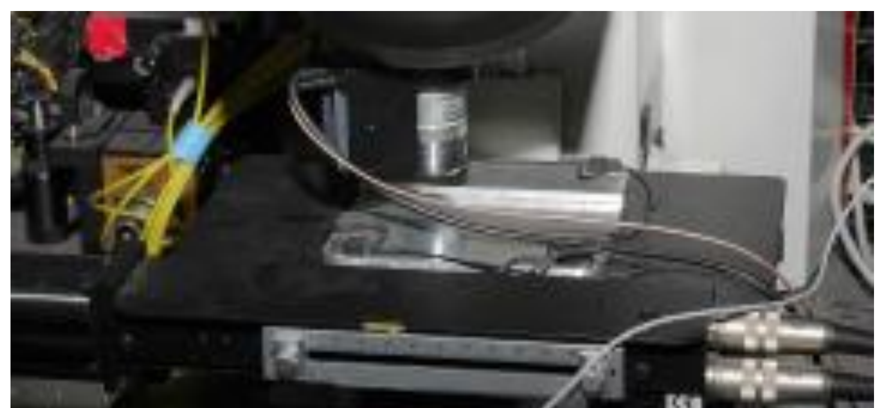
2 Colloid-polymer mixtures
- Critical point
- Crystal



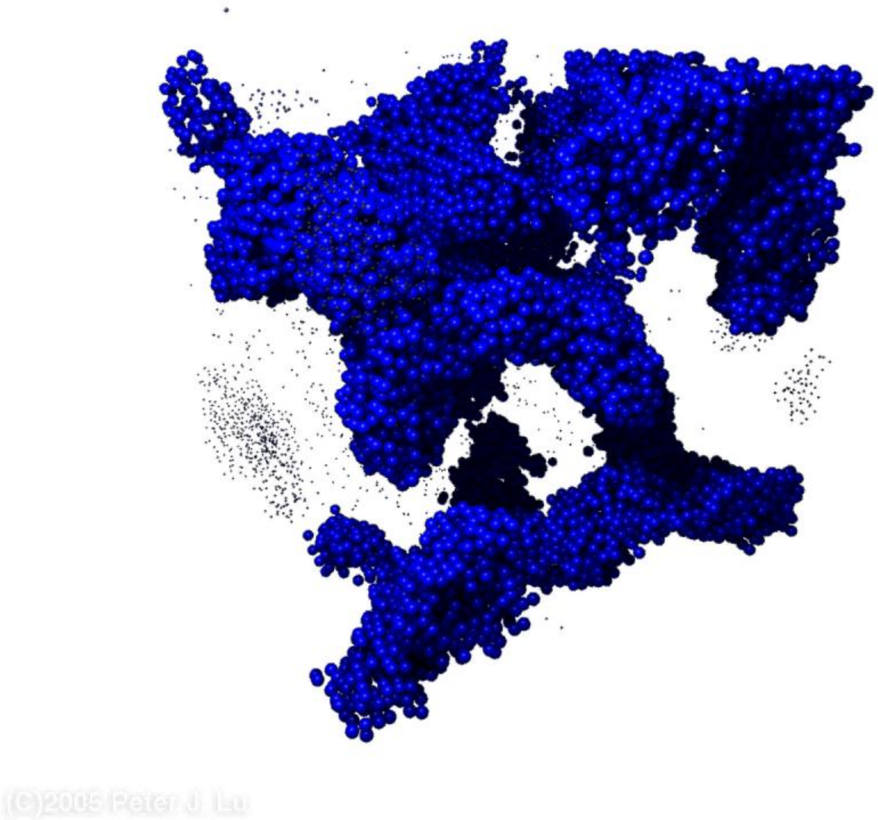
1 Colloidal Glass (Chaikin-Russel)

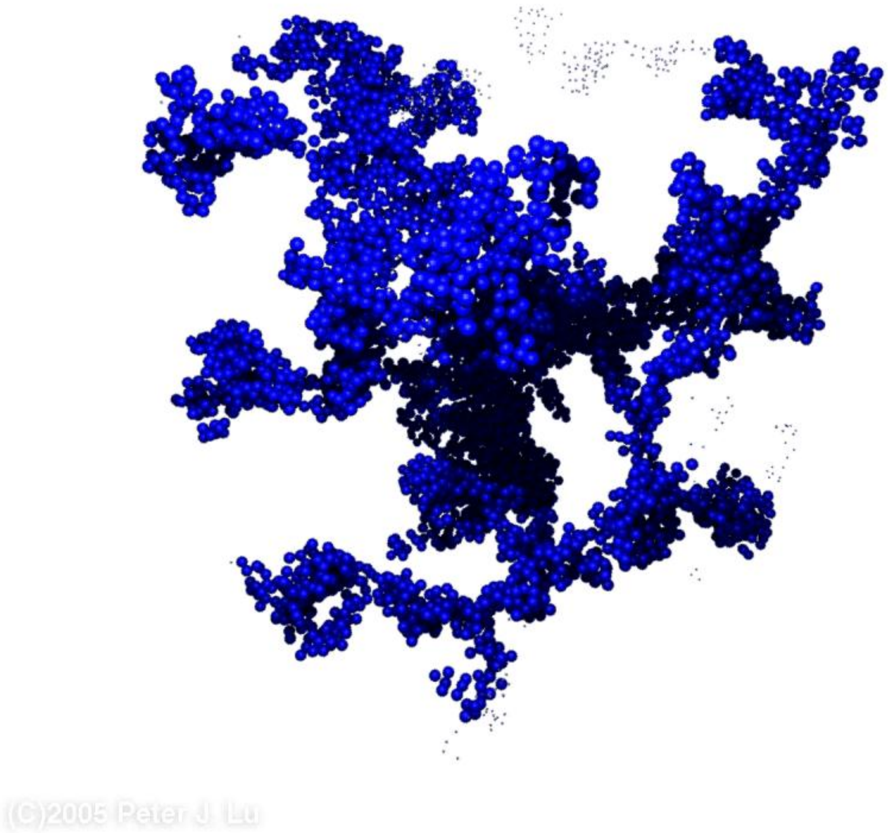
Confocal Microscopy





Phase separation leads to gelation



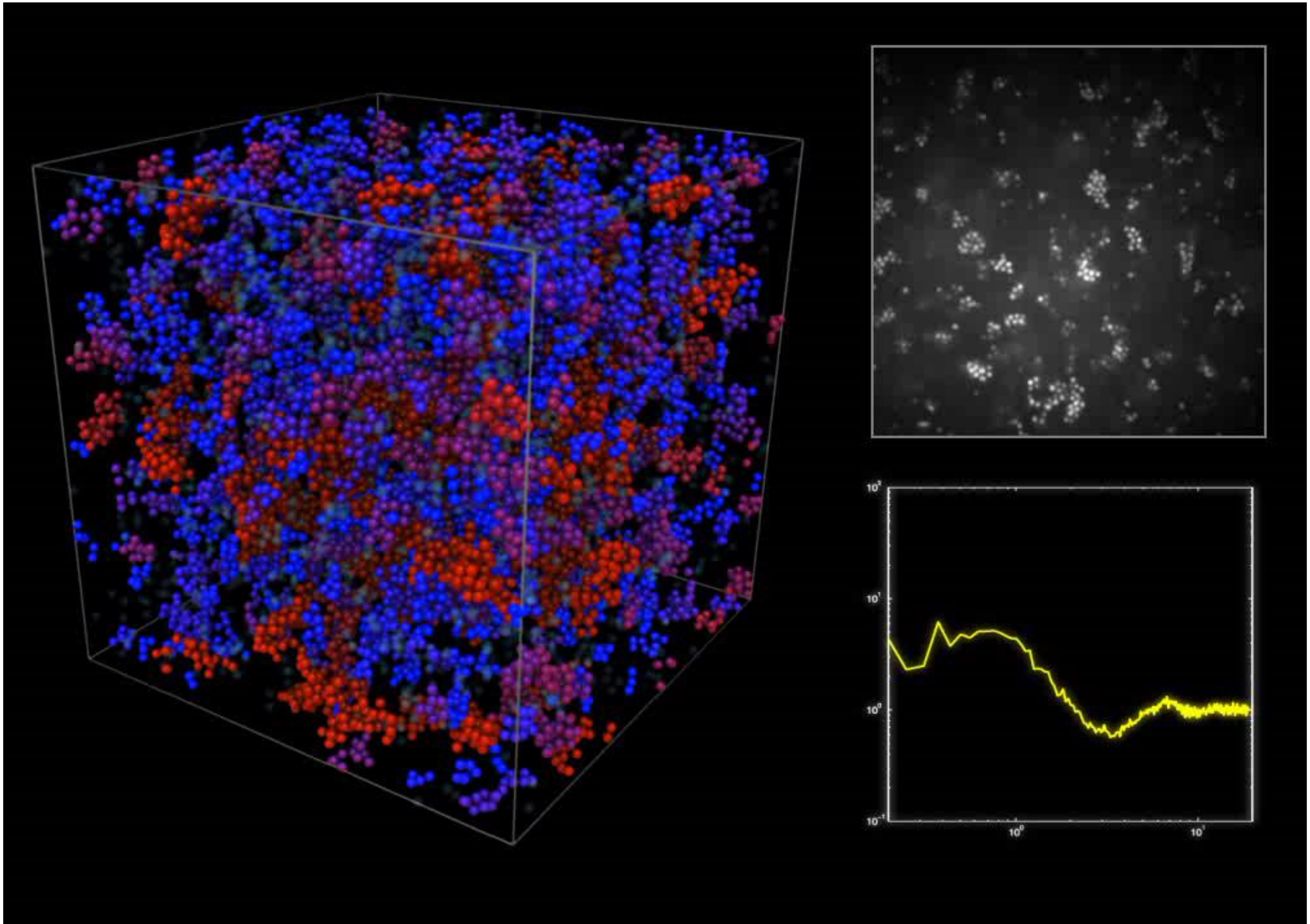


Long-range interaction

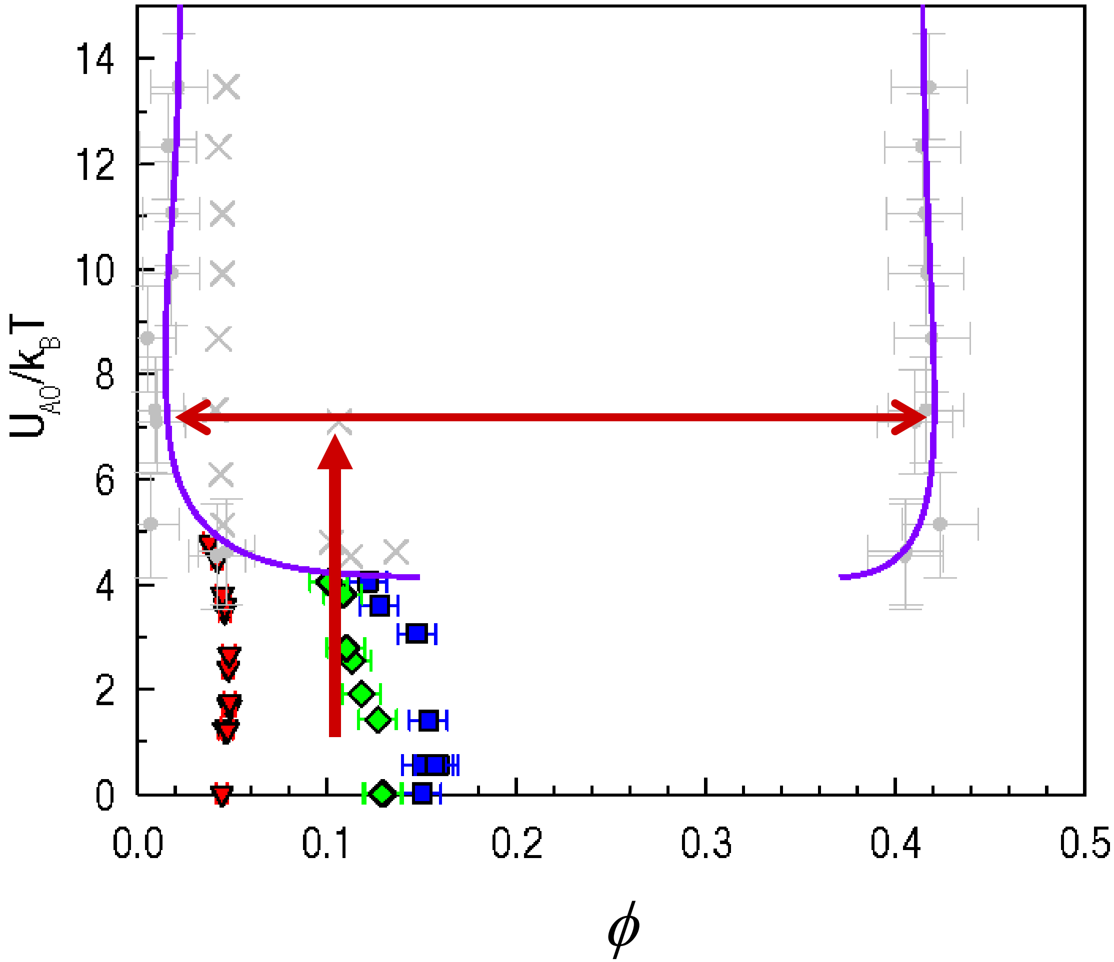
Short-range interaction

• Visualize individual particles

Gelation



Gelation phase diagram



Dynamic arrest of phase separating system

Major Results

Binary Alloys:

New, low density crystal structures

Fractal Aggregates:

Lowest density structure possible

Fundamental origin of instability

Fundamental coarsening of silica aggregates

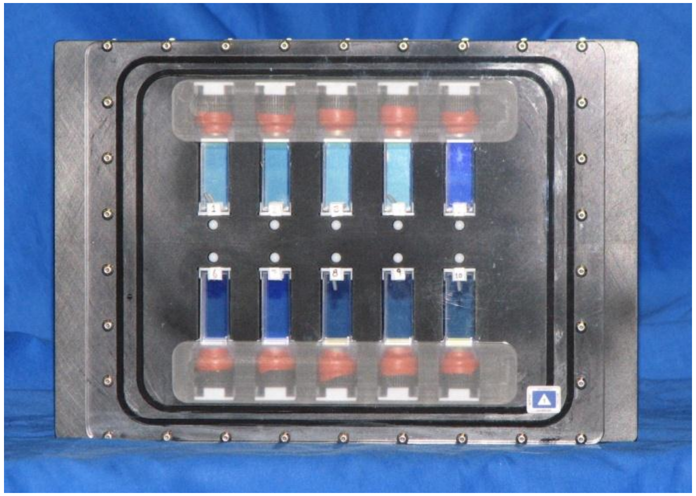
Colloid-polymer phase behavior

Fundamentals of spinodal decomposition

Colloid gelation

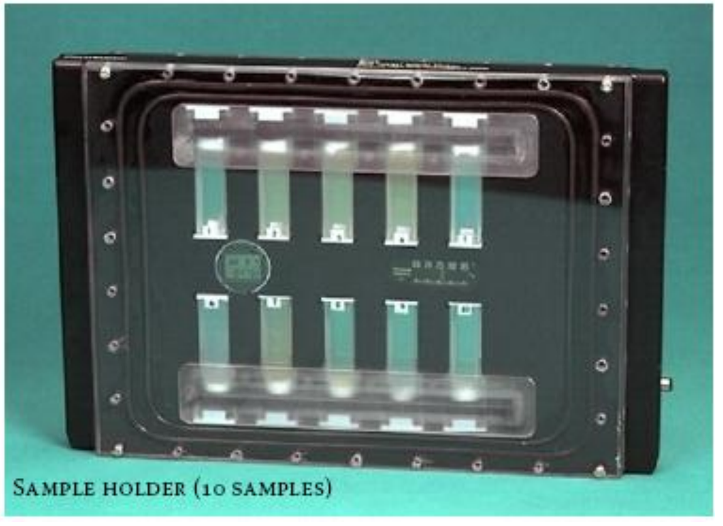
Underlying origin of gelation

Binary Colloidal Alloy Test



BCAT 3, 4, 5, 6

BCAT 3 – Use what is on ISS



Samples – small upmass

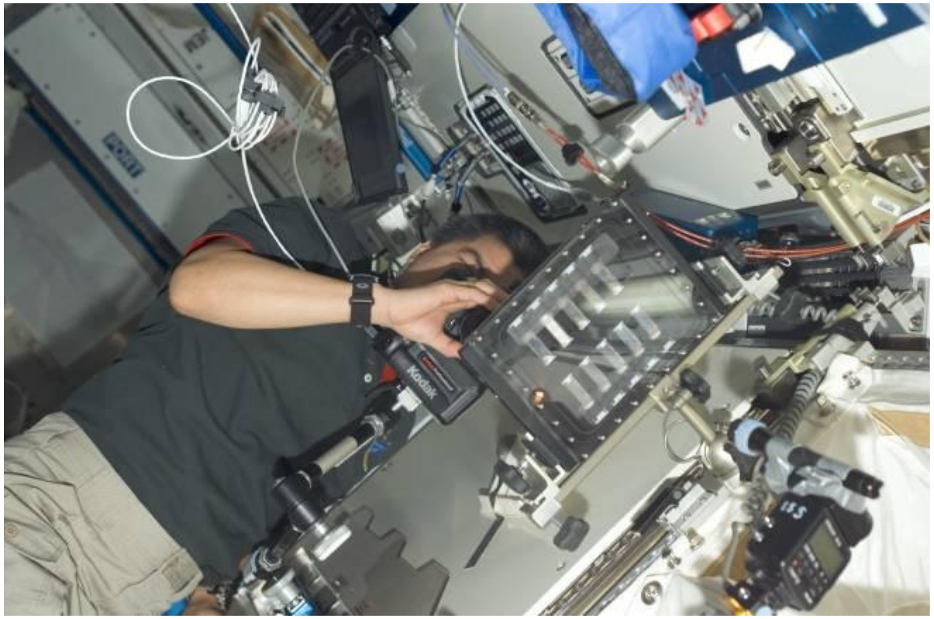
EarthKam

Binary Colloidal Alloy Crystals (BCAT)

- Phase behavior of attractive colloids
  - Economic consequences – product shelf life
- Kinetics of growth of binary alloys
  - Crystals form, then anneal
- Very highly ordered colloidal crystals
  - Photonic uses – perfect crystals
    - Effective long-range interaction
  - Models for binary alloys

Crew Involvement Essential

Cathy Frey and astronaut Dan Tani at BCAT Crew Training (September 2006).



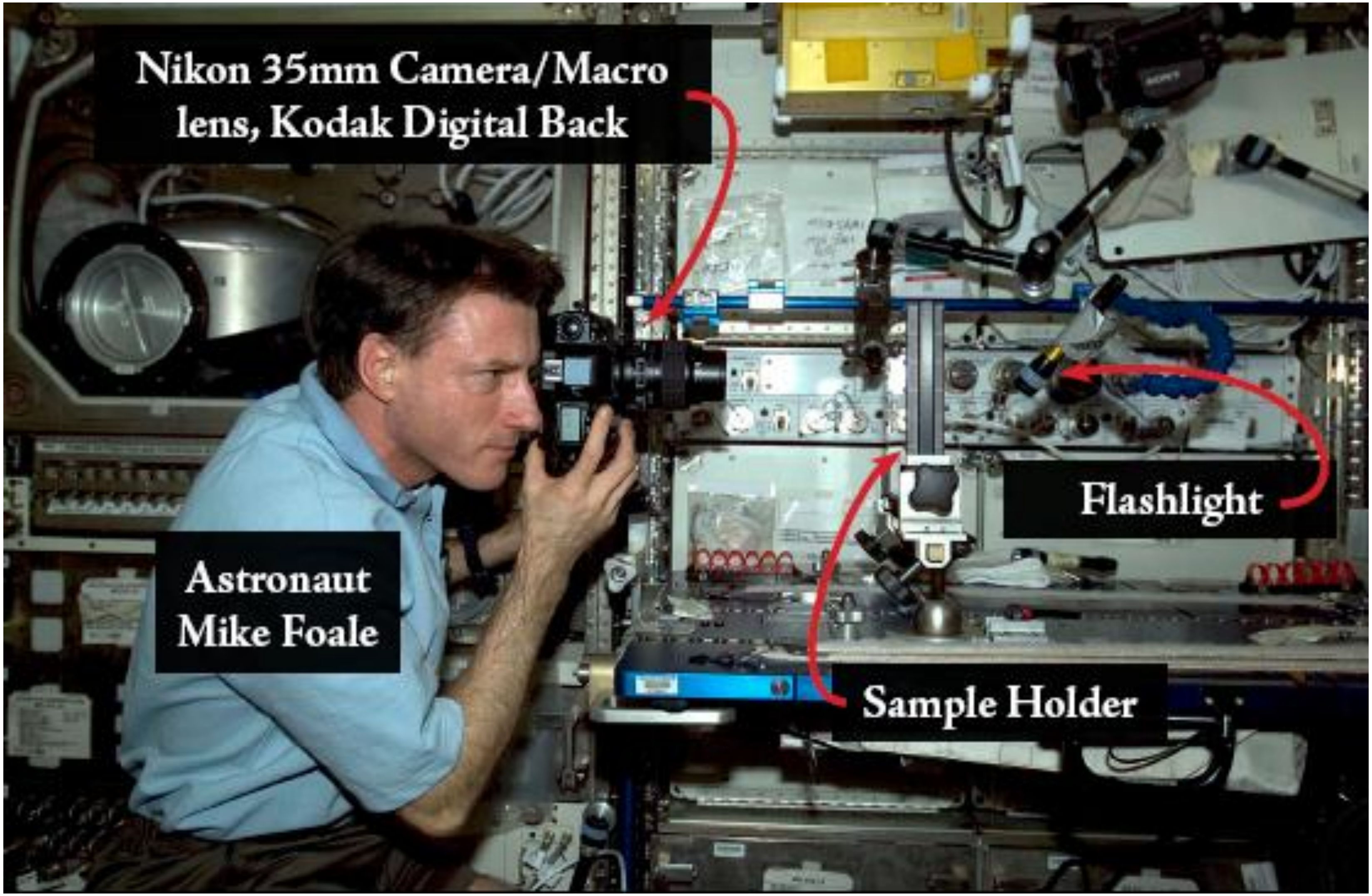
Astronaut Dan Tani on BCAT-3 (Feb. 2008).

Binary Colloidal Alloy Test-3 (BCAT-3 Operations on ISS)

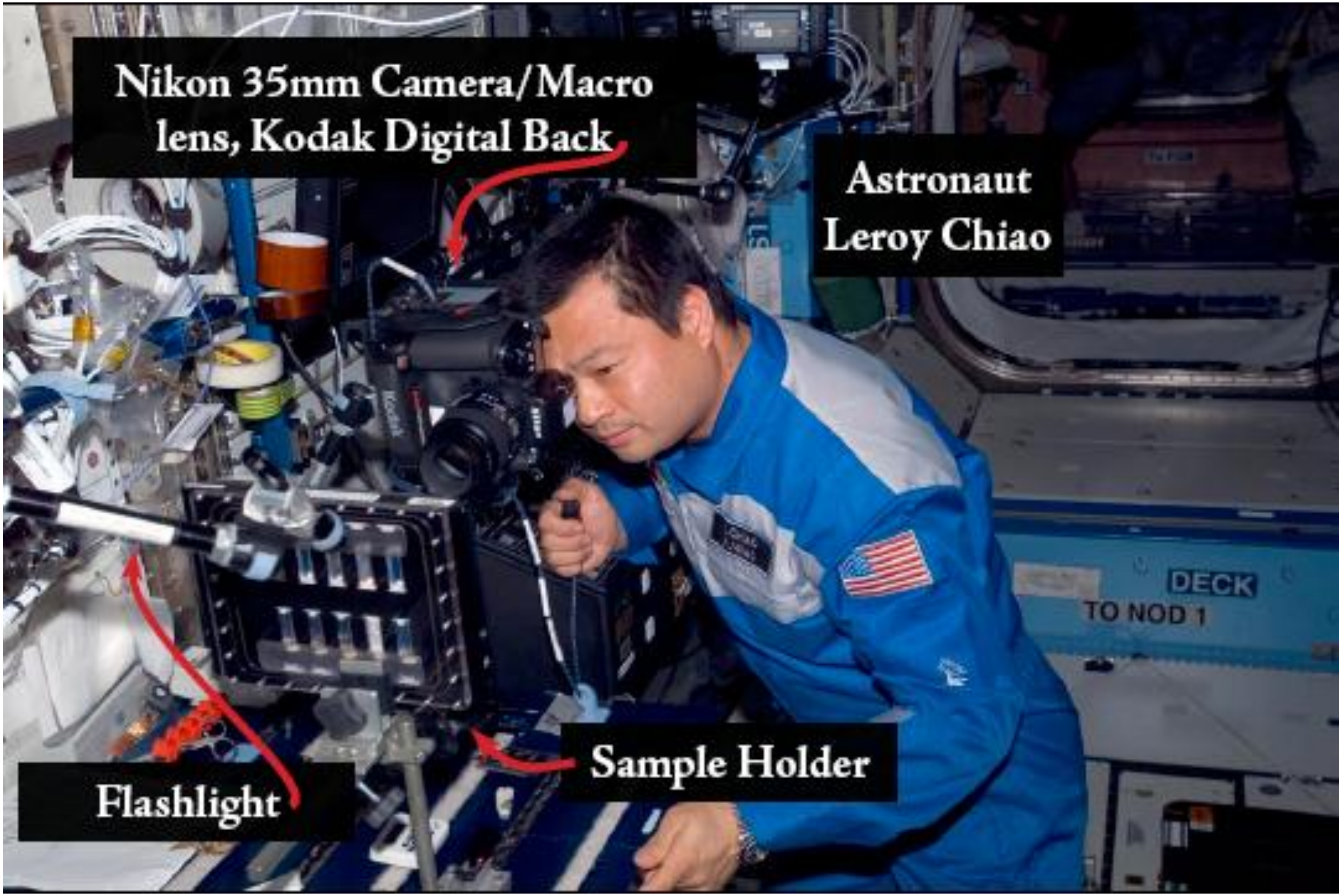
Astronaut Mike Foale photographs BCAT-3 Samples (Spring 2004).

BCAT-3 Sample Module on the International Space Station (ISS).

Astronauts are part of the science team



Astronauts are part of the science team



Contributing astronauts

Gregory E. Chamitoff

Leroy Chiao

Mike Fincke

Michael Foale

Sandra Magnus

Daniel Tani

Peggy Whitson

Jeffrey Williams

BCAT-4 team:

PI: Prof. David Weitz , Harvard University

Co-I: Peter Lu, Harvard University

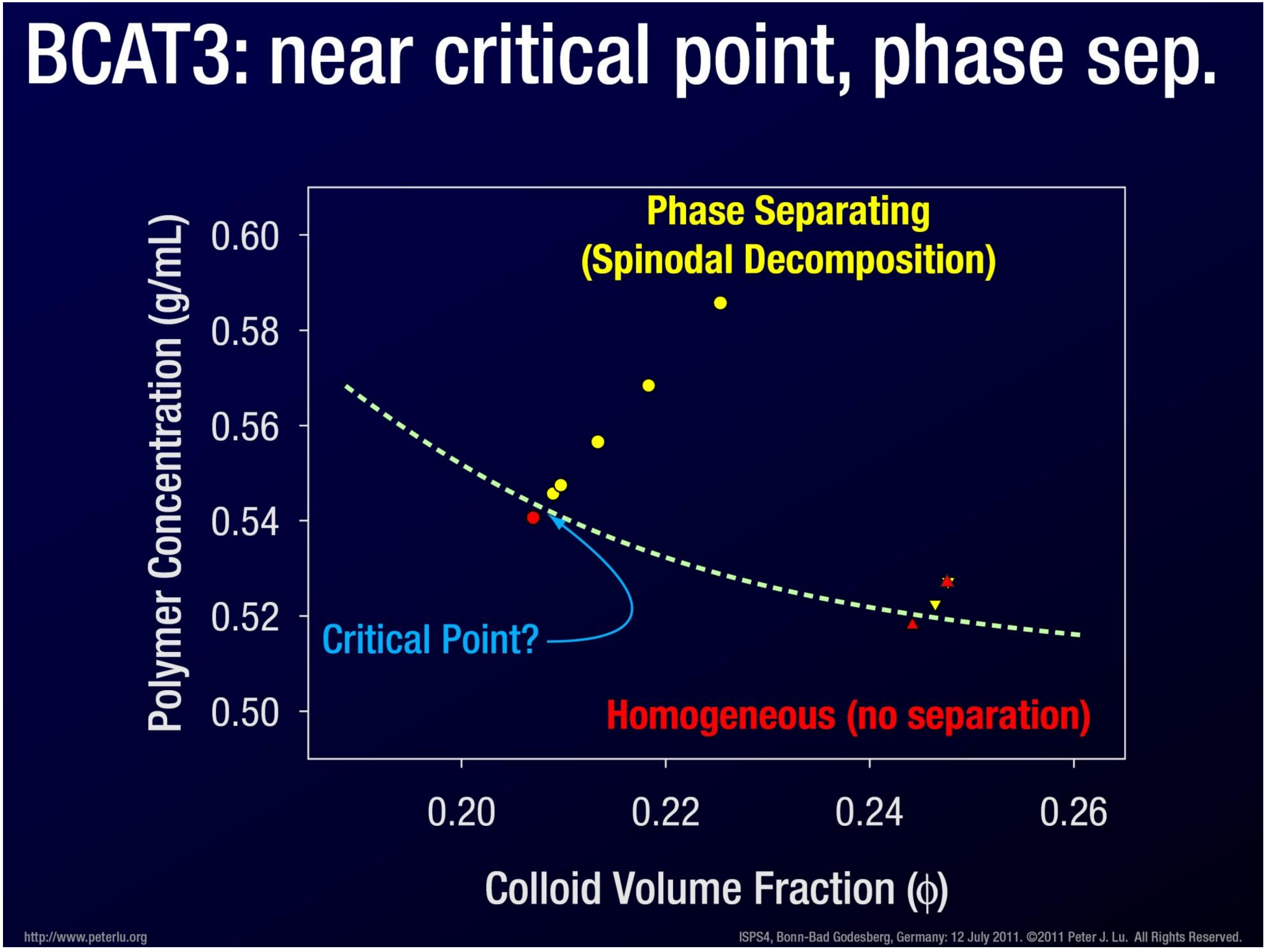
Co-Is: Prof. Paul Chaikin and Dr. Andrew Hollingsworth,
New York Unversity (NYU)

***Co-Is*:** Prof. Barbara Frisken / Dr. Arthur Bailey,
Simon Fraser University, Canadian Space Agency (CSA)

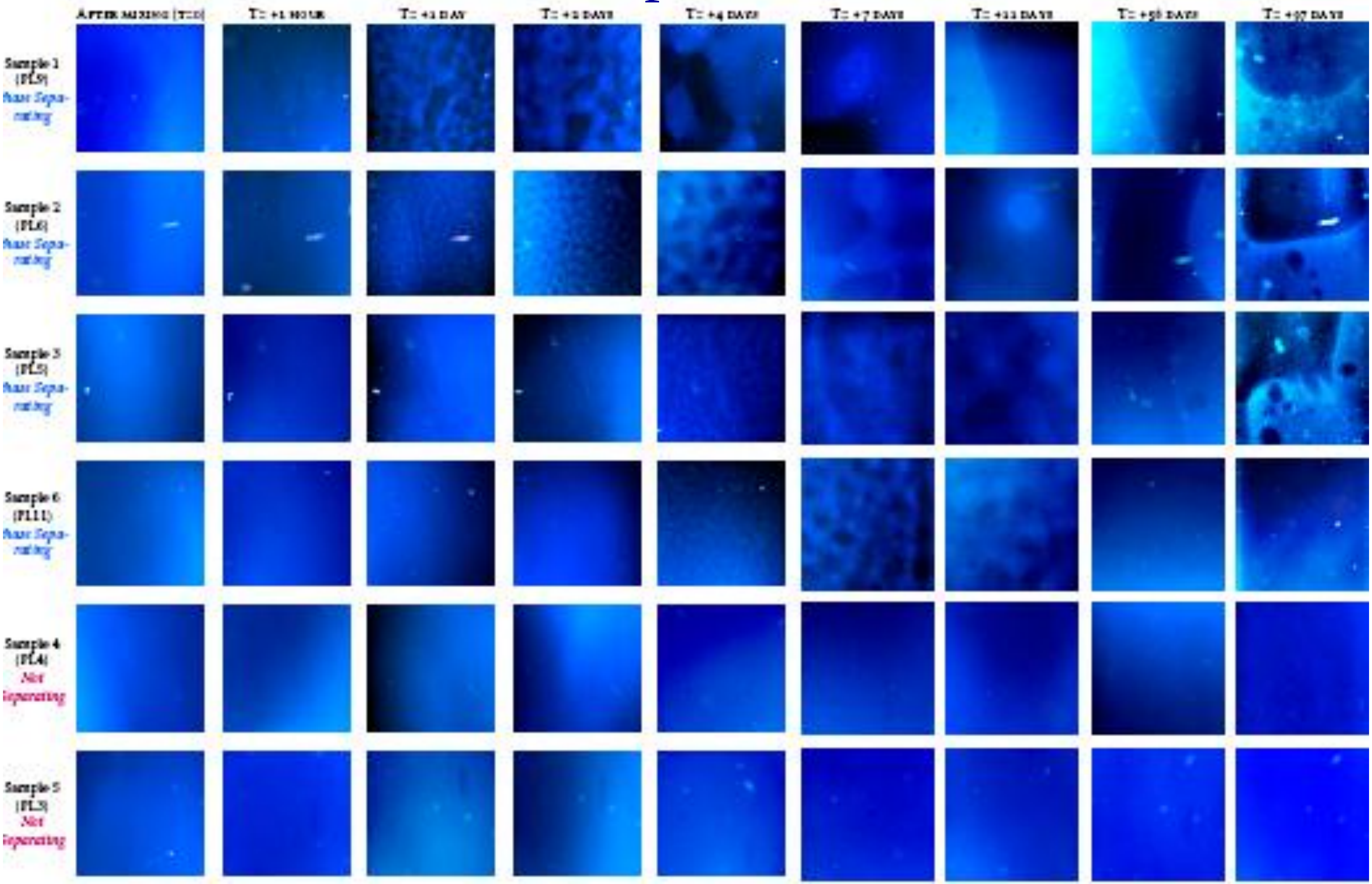
PS: Dr. William Meyer, NCSER at NASA GRC

PM: Ronald Sicker, NASA GRC

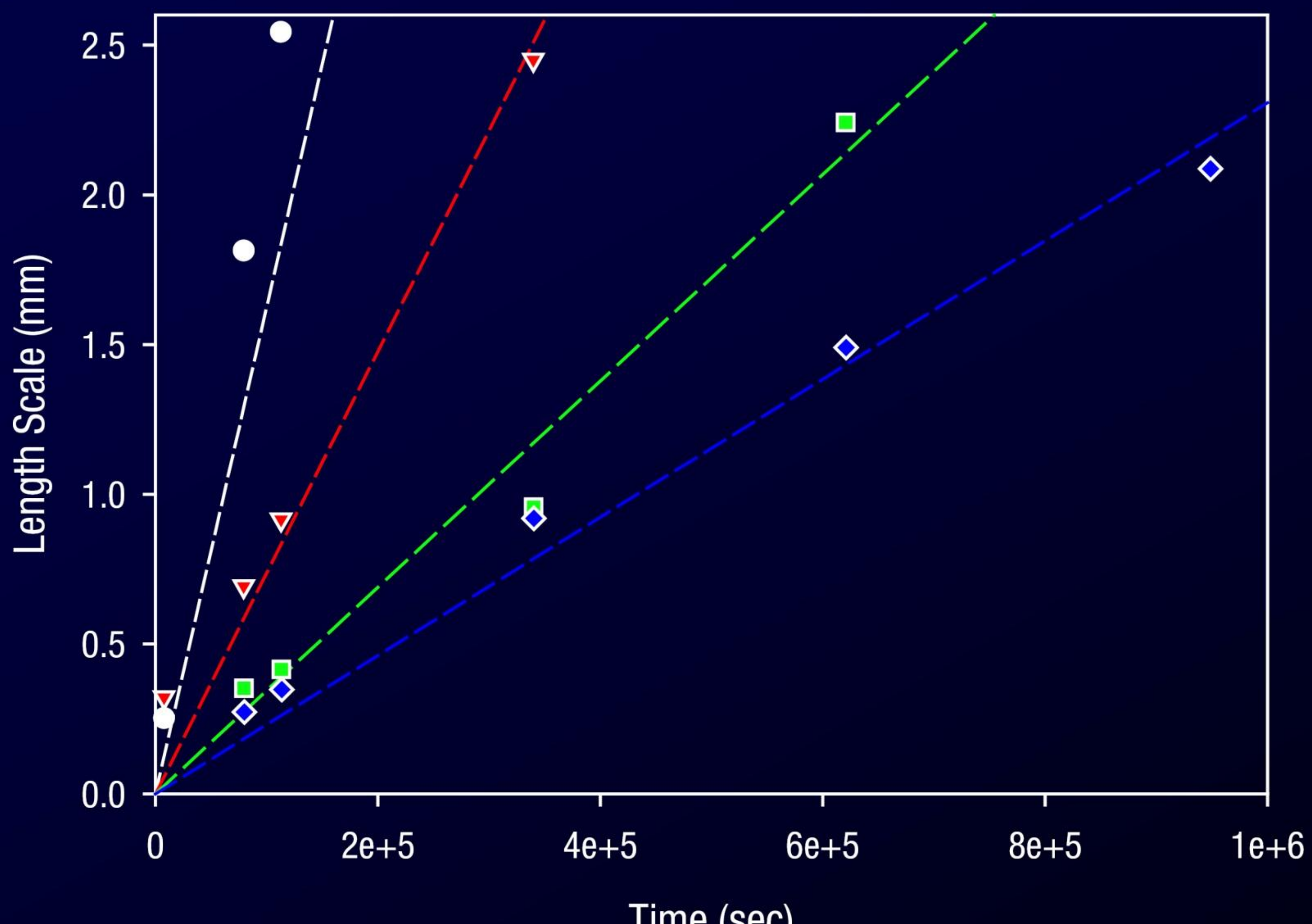
Engineering Team: ZIN Technologies, Inc.; SAIC


BCAT3: near critical point, phase sep.
Phase Separating
(Spinodal Decomposition)
Critical Point?
Homogeneous (no separation)
Polymer Concentration (g/mL)
0.60
0.58
0.56
0.54
0.52
0.50
0.20
0.22
0.24
0.26
Colloid Volume Fraction (ϕ)
http://www.peterlu.org
ISPS4, Bonn-Bad Godesberg, Germany: 12 July 2011. ©2011 Peter J. Lu. All Rights Reserved.

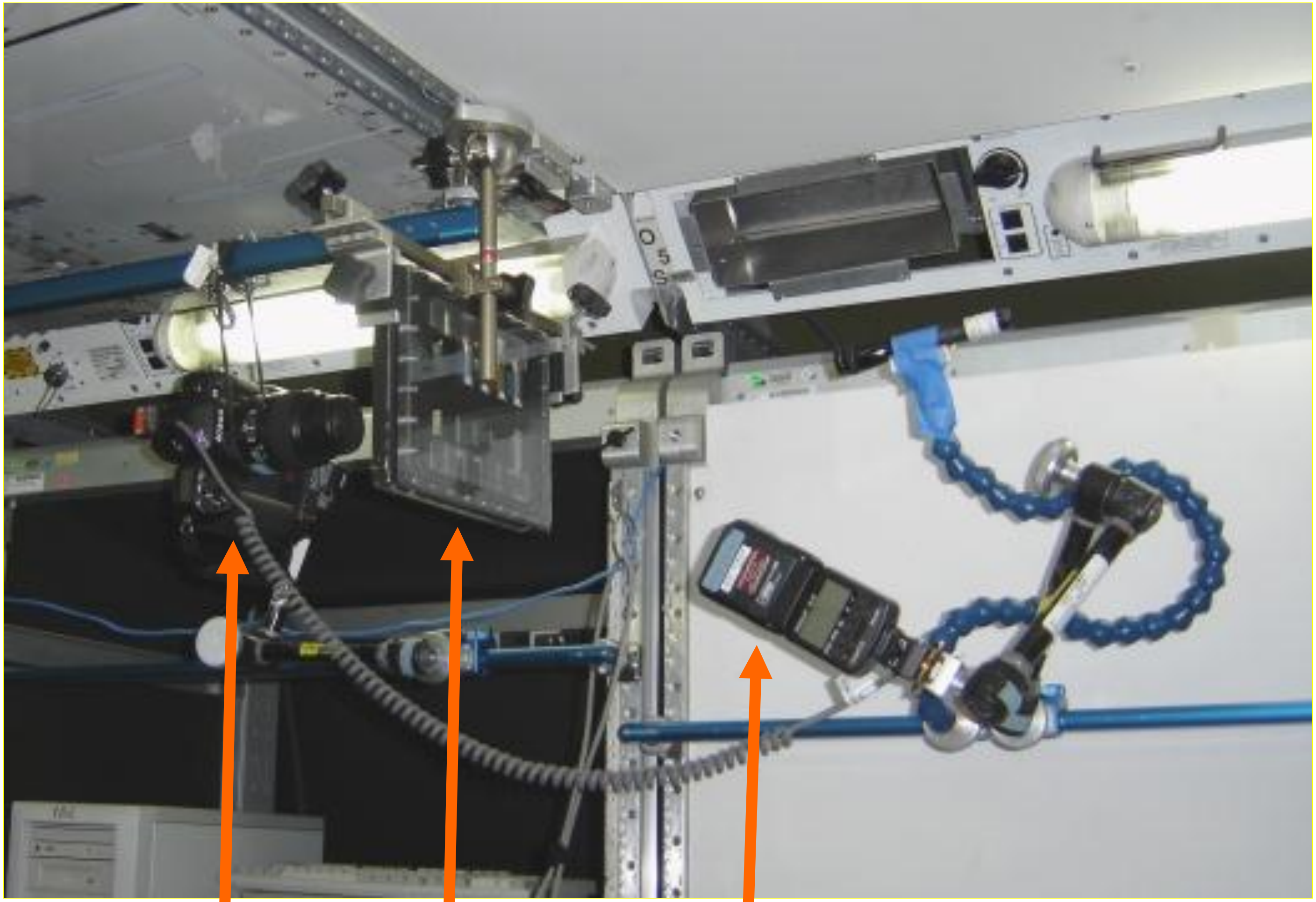
Phase separation



BCAT3: Original data

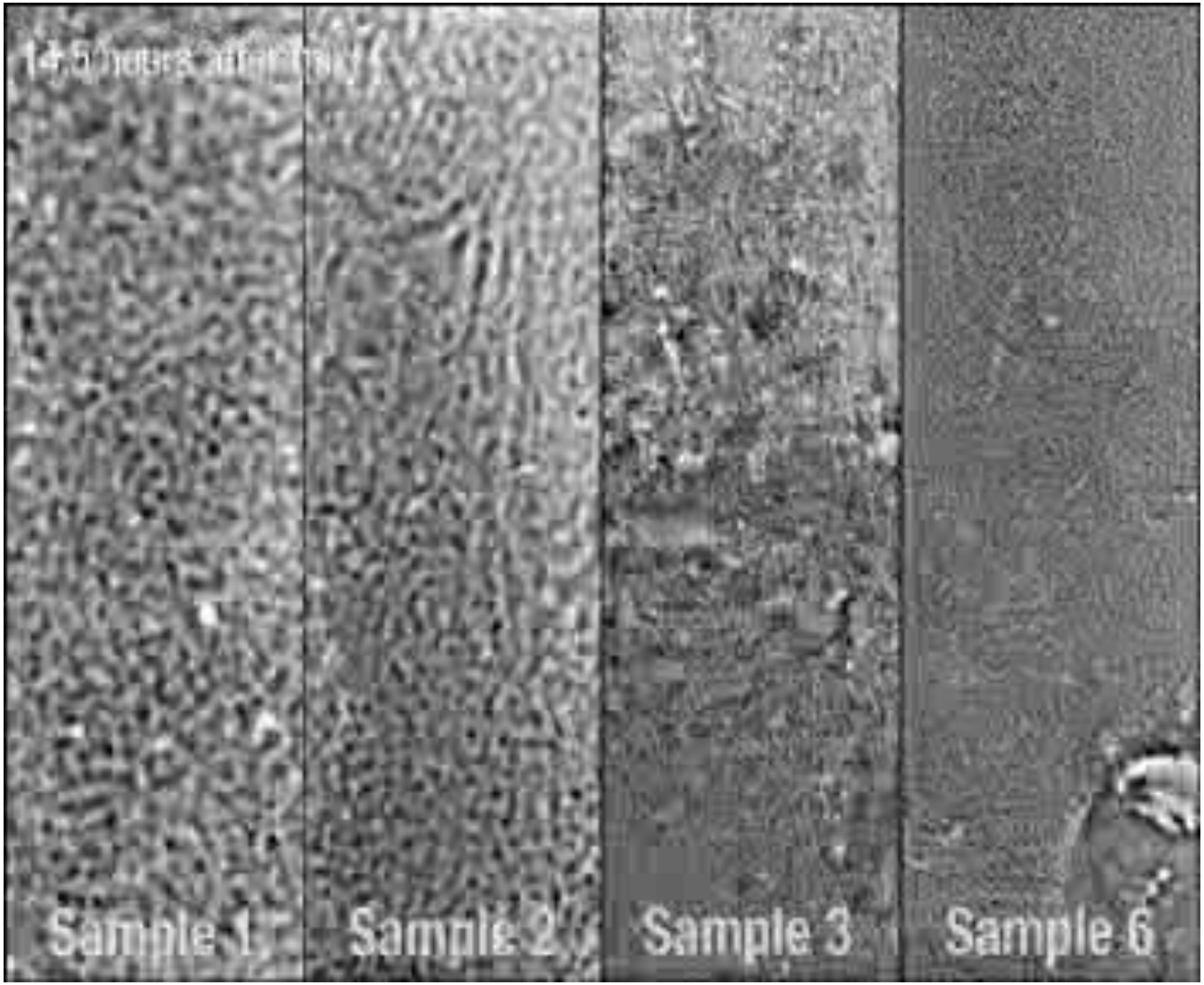


BCAT 3: Set-up evolves with astronaut contributions

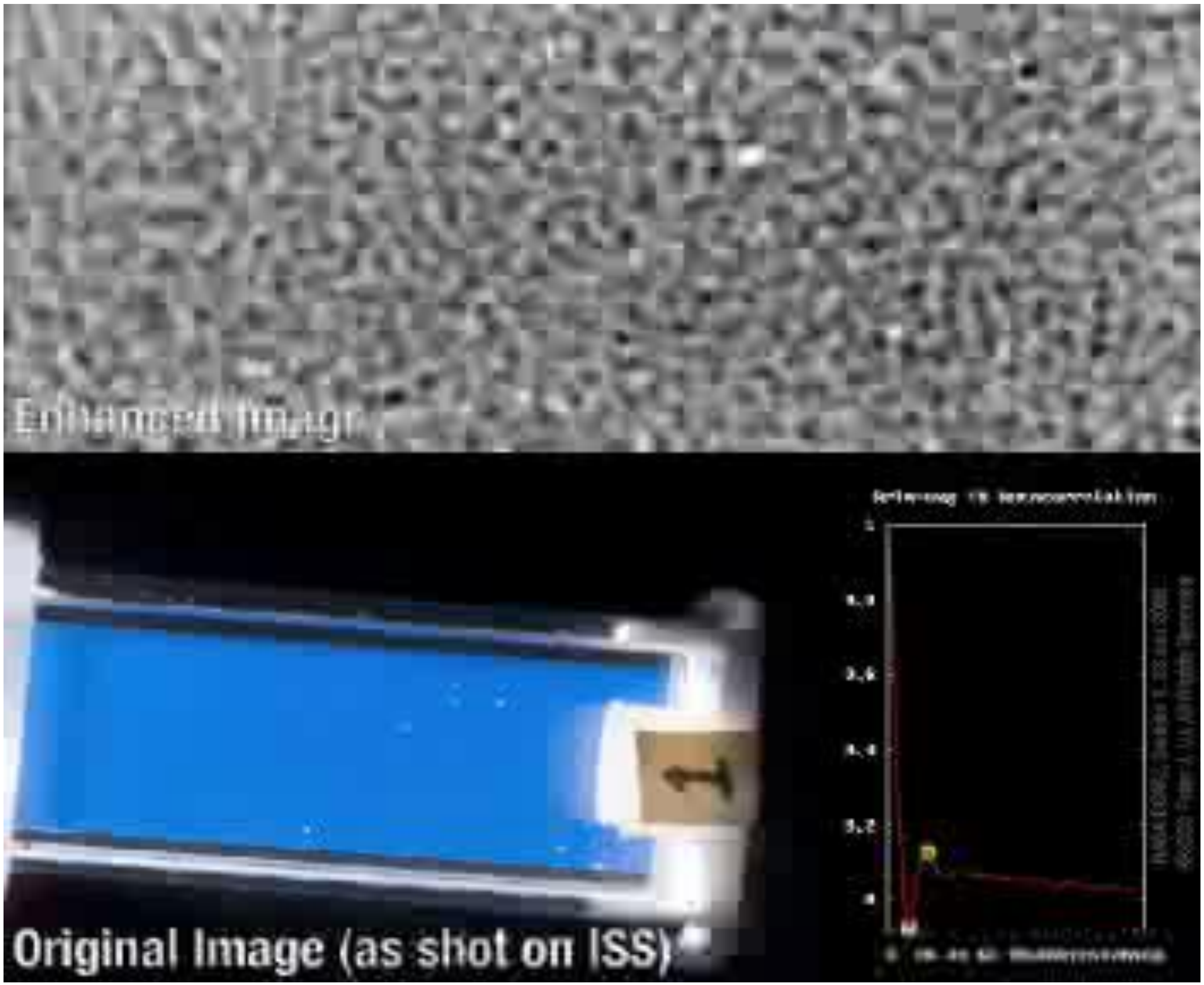


Camera Samples Flash

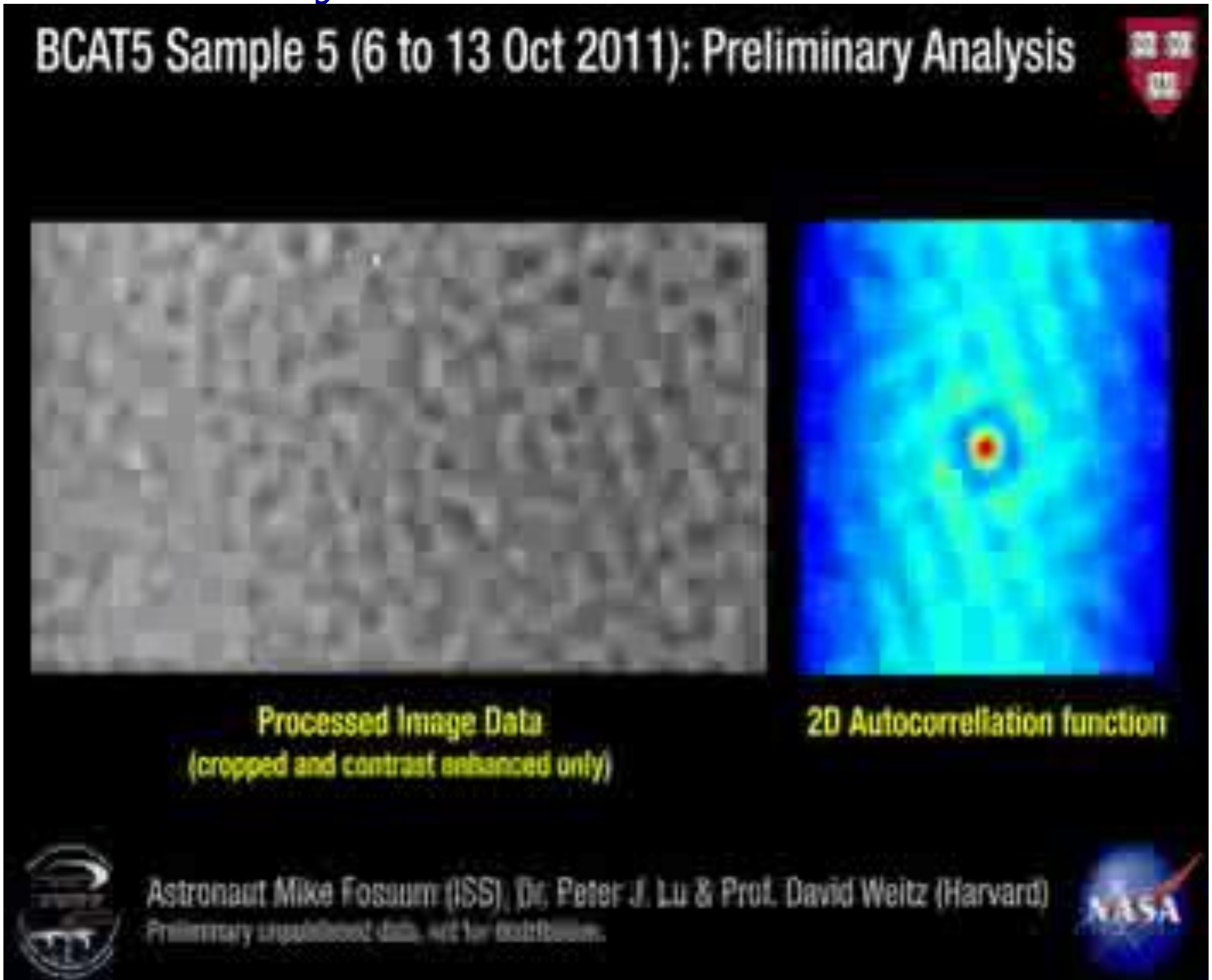
Raw data from BCAT3



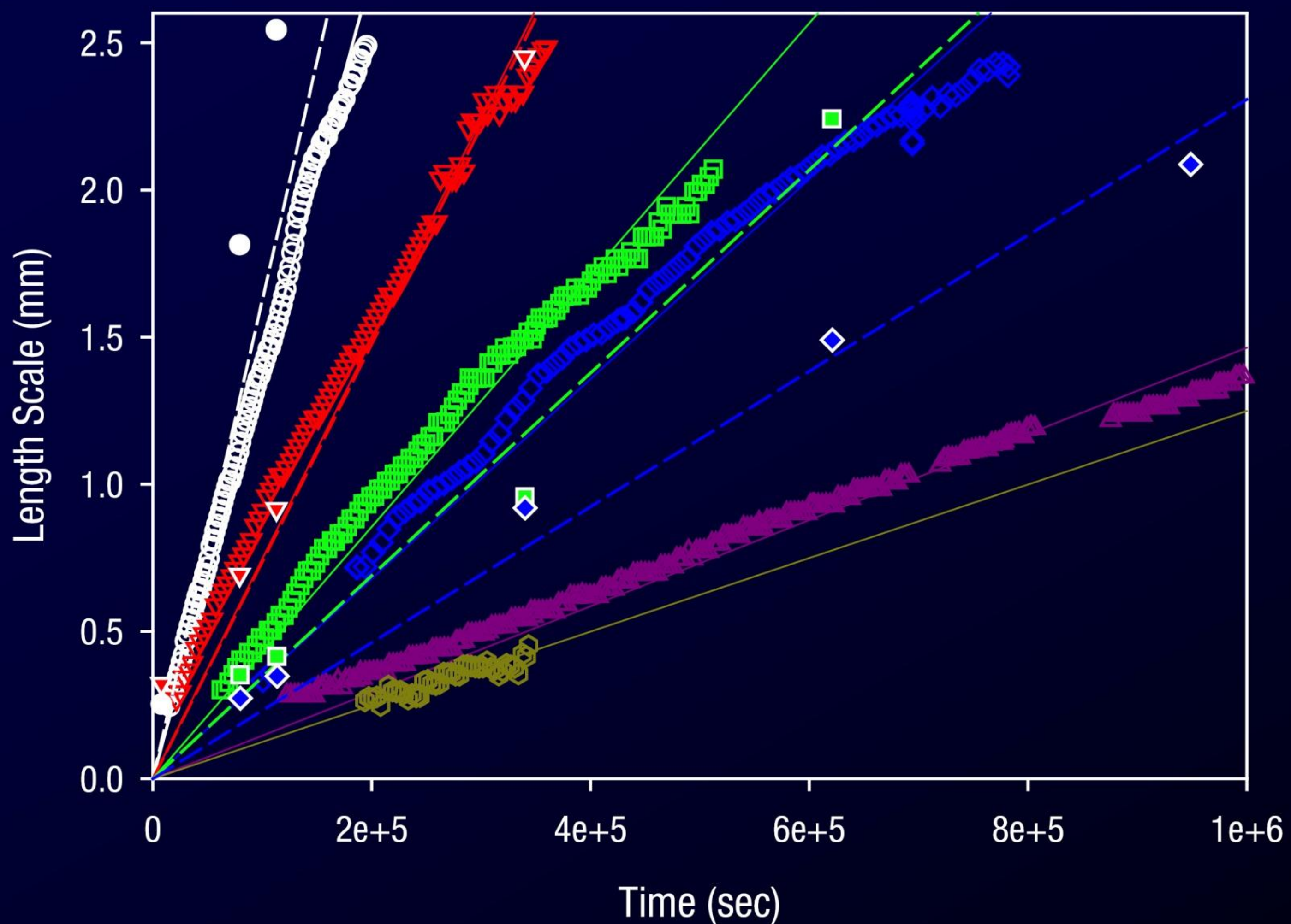
Analyzed data from BCAT3



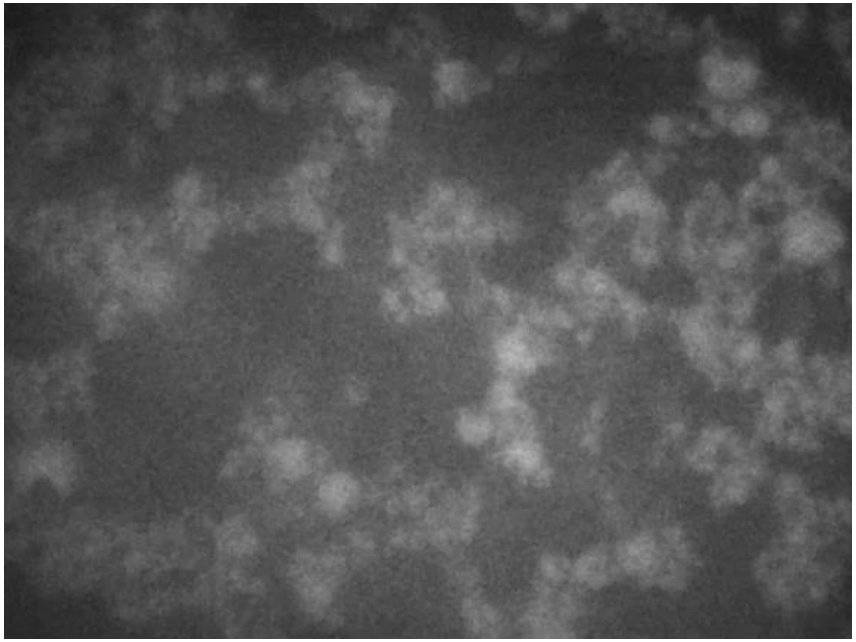
Analyzed data from BCAT5

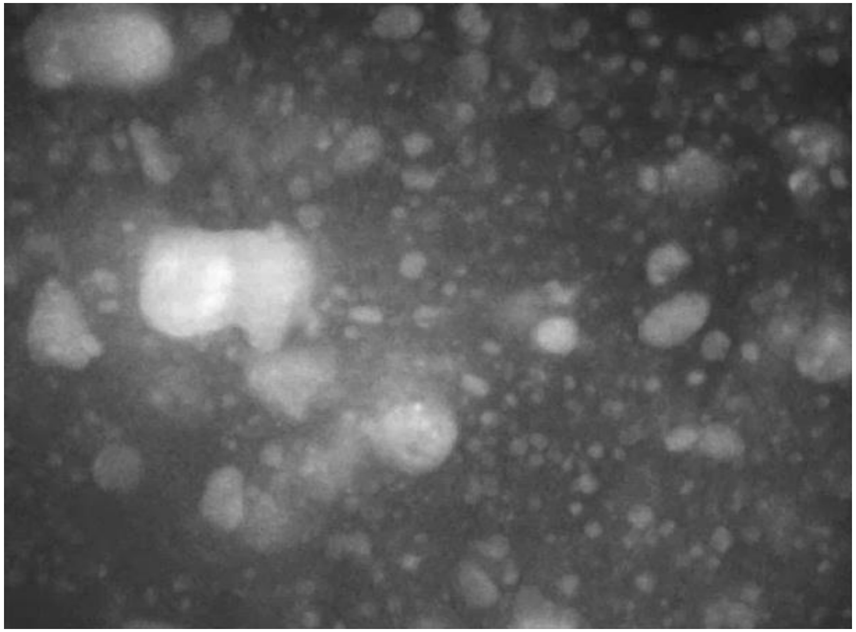


BCAT3: Automation with EarthKAM



Phase separation is important for the stability of many products

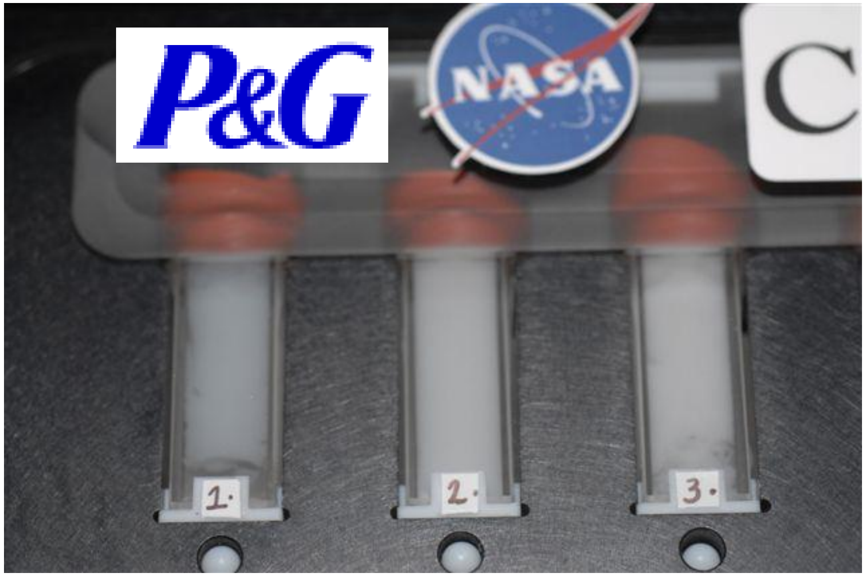




Matt Lynch, P&G

P&G Samples currently on ISS

BCAT-5 Sample Module



P&G BCAT-5 samples on ISS

Sample publications

PRL 95, 238302 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Glasslike Arrest in Spinodal Decomposition as a Route to Colloidal Gelation

S. Manley,[1,*] H. M. Wyss,[1] K. Miyazaki,[2,†] J. C. Conrad,[1] V. Trappe,[3] L. J. Kaufman,[2,†]
D. R. Reichman,[2,†] and D. A. Weitz[1]

PRL 95, 048302 (2005) PHYSICAL REVIEW LETTERS week ending 22 JULY 2005

Time-Dependent Strength of Colloidal Gels

S. Manley,[1] Benny Davidovitch,[2] Neil R. Davies,[1] L. Cipelletti,[1,*] A. E. Bailey,[1,†] R. J. Christianson,[1] U. Gasser,[1,‡]
V. Prasad,[1,§] P. N. Segre,[1,||] M. P. Doherty,[3] S. Sankaran,[3] A. L. Jankovsky,[3] B. Shiley,[4] J. Bowen,[4] J. Eggers,[4] C. Kurta,[4]
T. Lorik,[4] and D. A. Weitz[1]

PRL 94, 218302 (2005) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2005

Gravitational Collapse of Colloidal Gels

S. Manley, J. M. Skotheim, L. Mahadevan, and D. A. Weitz

VOLUME 93, NUMBER 10 PHYSICAL REVIEW LETTERS week ending 3 SEPTEMBER 2004

Limits to Gelation in Colloidal Aggregation

S. Manley,[1] L. Cipelletti,[1,*] V. Trappe,[2] A. E. Bailey,[1,†] R. J. Christianson,[1] U. Gasser,[1,‡] V. Prasad,[1,§] P. N. Segre,[1,||]
M. P. Doherty,[3] S. Sankaran,[3] A. L. Jankovsky,[3] B. Shiley,[3] J. Bowen,[4] J. Eggers,[4] C. Kurta,[4] T. Lorik,[4] and D. A. Weitz[1]

Sample publications

Vol 453|22 May 2008|doi:10.1038/nature06931 nature

Gelation of particles with short-range attraction

Peter J. Lu[1], Emanuela Zaccarelli[3,4], Fabio Ciulla[3], Andrew B. Schofield[5], Francesco Sciortino[3,4] & David A. Weitz[1,2]

PRL 99, 028303 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

Gravitational Stability of Suspensions of Attractive Colloidal Particles

Chanjoong Kim,[1,2] Yaqian Liu,[3] Angelika Kühnle,[3,*] Stephan Hess,[3] Sonja Viereck,[3]
Thomas Danner,[3] L. Mahadevan,[2] and David A. Weitz[1,2]

PRL 99, 205701 (2007) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2007

Spinodal Decomposition in a Model Colloid-Polymer Mixture in Microgravity

A. E. Bailey,[1,*] W. C. K. Poon,[2] R. J. Christianson,[1,†] A. B. Schofield,[2] U. Gasser,[1,‡] V. Prasad,[1,§] S. Manley,[1,||]
P. N. Segre,[1,§] L. Cipelletti,[1,¶] W. V. Meyer,[3] M. P. Doherty,[4] S. Sankaran,[3] A. L. Jankovsky,[4] W. L. Shiley,[5] J. P. Bowen,[5]
J. C. Eggers,[5] C. Kurta,[5] T. Lorik, Jr.,[5] P. N. Pusey,[2] and D. A. Weitz[1]

J Real-Time Image Proc
DOI 10.1007/s11554-009-0133-1

ORIGINAL RESEARCH PAPER

Orders-of-magnitude performance increases in GPU-accelerated correlation of images from the International Space Station

Peter J. Lu · Hidekazu Oki · Catherine A. Frey · Gregory E. Chamitoff · Leroy Chiao ·
Edward M. Fincke · C. Michael Foale · Sandra H. Magnus · William S. McArthur Jr. ·
Daniel M. Tani · Peggy A. Whitson · Jeffrey N. Williams · William V. Meyer · Ronald J. Sicker ·
Brion J. Au · Mark Christiansen · Andrew B. Schofield · David A. Weitz

Eur. Phys. J. E (2009)
DOI 10.1140/epje/i2008-10390-7

Gravitational compression of colloidal gels

J.J. Liétor-Santos[a], C. Kim[b], P.J. Lu, A. Fernández-Nieves[a,c], and D.A. Weitz

Successes of the NASA Colloid Effort

•Highly trained scientists and engineers

- Eric Weeks, professor, Emory
- Itai Cohen, professor, Cornell
- Phil Segre, teacher, Atlanta
- John Crocker, professor UPenn
- Tony Dinsmore, professor, UMass
- Tom Mason, professor UCLA
- Rebecca Christianson, professor, Olin College
- Zhengdong Chen, professor Texas A&M
- Vikram Prasad, research scientist, Dow Chemicals
- Suliana Manley, professor, EPFL, Lausanne
- Jaci Conrad, professor, University of Houston
- Urs Gasser, staff scientist, PSI, Switzerland
- Luca Cipelletti, professor, Montpellier France
- Art Bailey, SFU, Canada
- Toshimitsu Kanai, Yokohama National University

Successes of the NASA Colloid Effort

- Very strong impact on industry
- Strong interactions with industry
- Start-up companies
- Strong contribution to economic competitiveness

Successes of the NASA Colloid Effort

- Very strong impact on industry
- Strong interactions with industry

Thank you for your attention

- Strong contribution to economic competitiveness