UNIVERSITAT DE BARCELONA

Urbana Champaign, May 2011

Large fluctuations during the Boiling Crisis

Eduard Vives (1), Francesc Salvat-Pujol (2) , Pol Lloveras (1,3), &
Lev Truskinovsky (3)

1 Dept. Estructura i Constituents de la Matèria
Facultat de Física, Universitat de Barcelona
Barcelona, Catalonia

2 Institut für Angewandte Physik
Technische Universität Wien
Wien Austria

3 LMS, CNRS–UMR 7649 ,
École Polytechnique,
Palaiseau, France

Outline:

- 1-Introduction
    - Thermodynamics: pool boiling
    - Classical dimensional analysis
    - Recent advances
- 2-AE experiments
    - Experimental Setup
    - Avalanche counting
    - Avalanche energy distributions
- 3-Modelling
- 4-Conclusions

Introductory references the to boiling crisis problem

-J.H.Lienhard “Snares of pool boiling research” (1995).
-V.K.Dhir “Boiling Heat Transfer”, Annu. Rev. Fluid Mech. 365-401 (1998).
-V.K.Dhir, H.S.Abarajith & G.R.Warrier “From Nano to micro to macro scales in boiling”, Microscale Heat transfer 197-216 (2005).
-V.K.Dhir “Mechanistic prediction achievable or a hopeless task?” Journal of heat Transfer 128, 1 (2006).

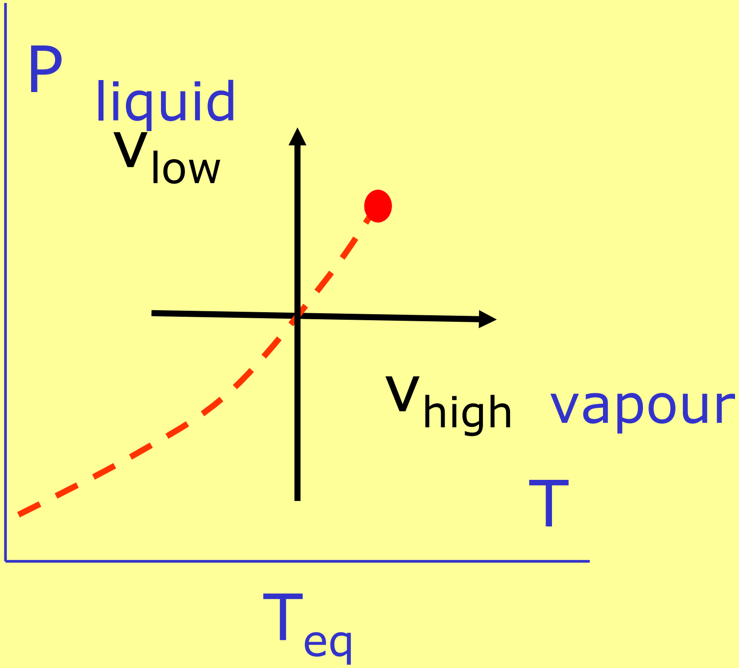
1-Introduction

Thermodynamics of boiling:

Boiling is a first-order phase transition with a scalar OP: molar volume v

Equilibrium phase diagram:

simple fluid



Phases with different v coexist exactly at T_{eq}

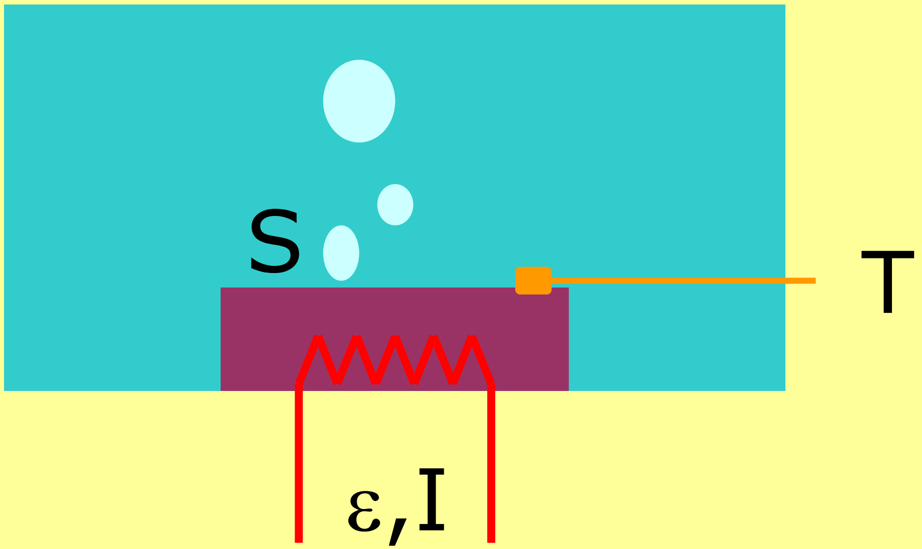
But: as many first-order phase transitions it hardly occurs in equilibrium,

It requires the creation of interfaces

bubble growth
fluid motion

Pool boiling

There are many ways of boiling a liquid. The simplest case is pool boiling (kitchen), in which convection is natural (no imposed flow) And gravity is vertical, pointing down

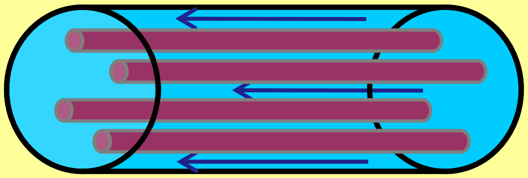


Control variable: heat flux

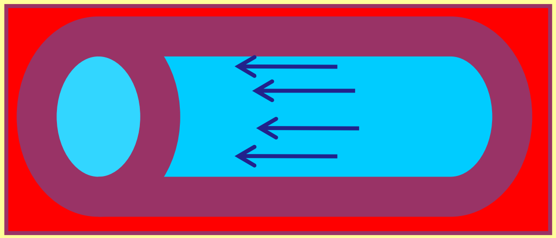
$$\Phi = \varepsilon \times I / S$$

Measured variable: temperature

$$T$$

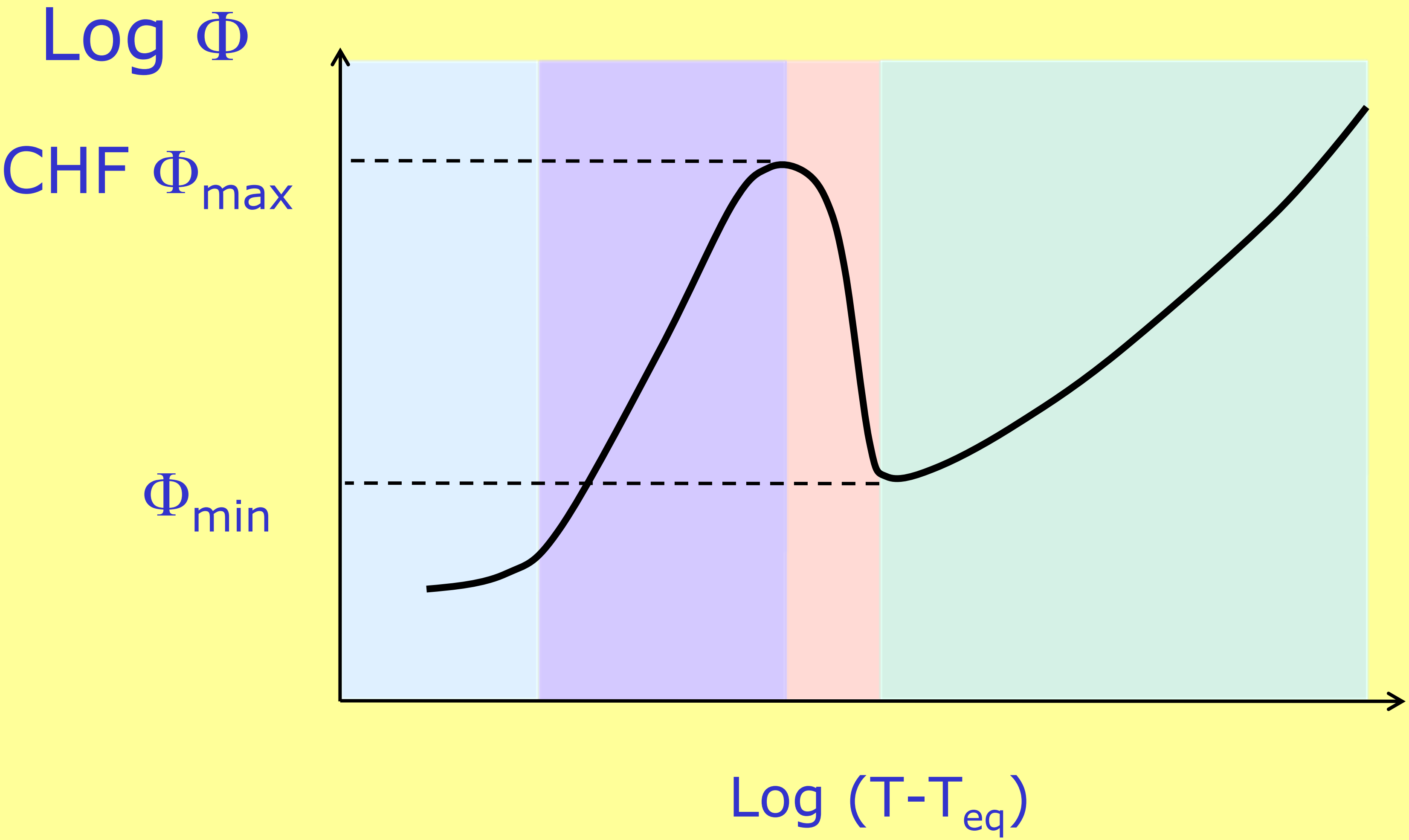


Other mechanism: external flow boiling
internal flow boiling
immersion
…



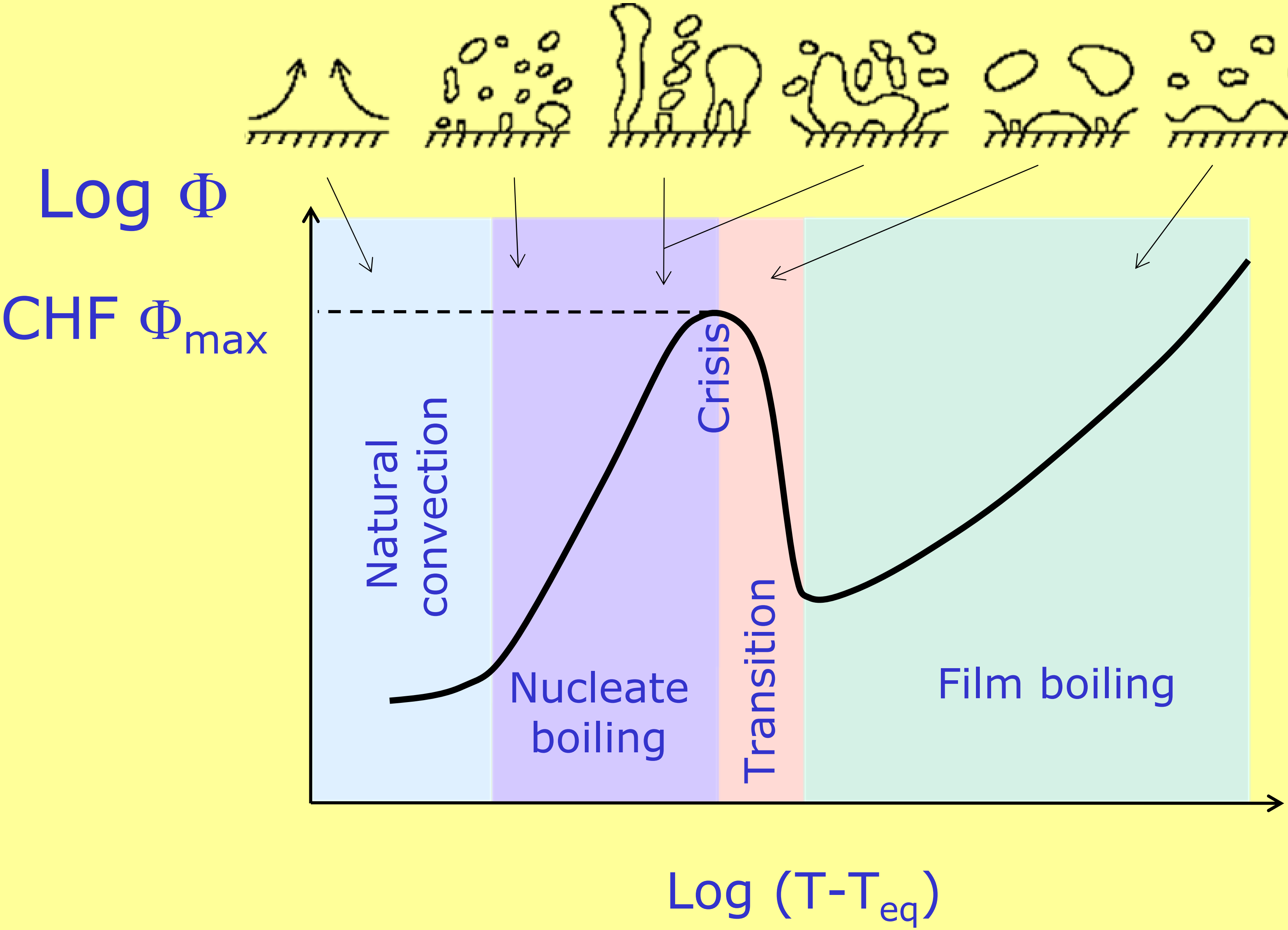
Nukiyama curve

S. Nukiyama
J. Soc. Mech. Eng. Jpn **37**, 53 & 367
(1934)



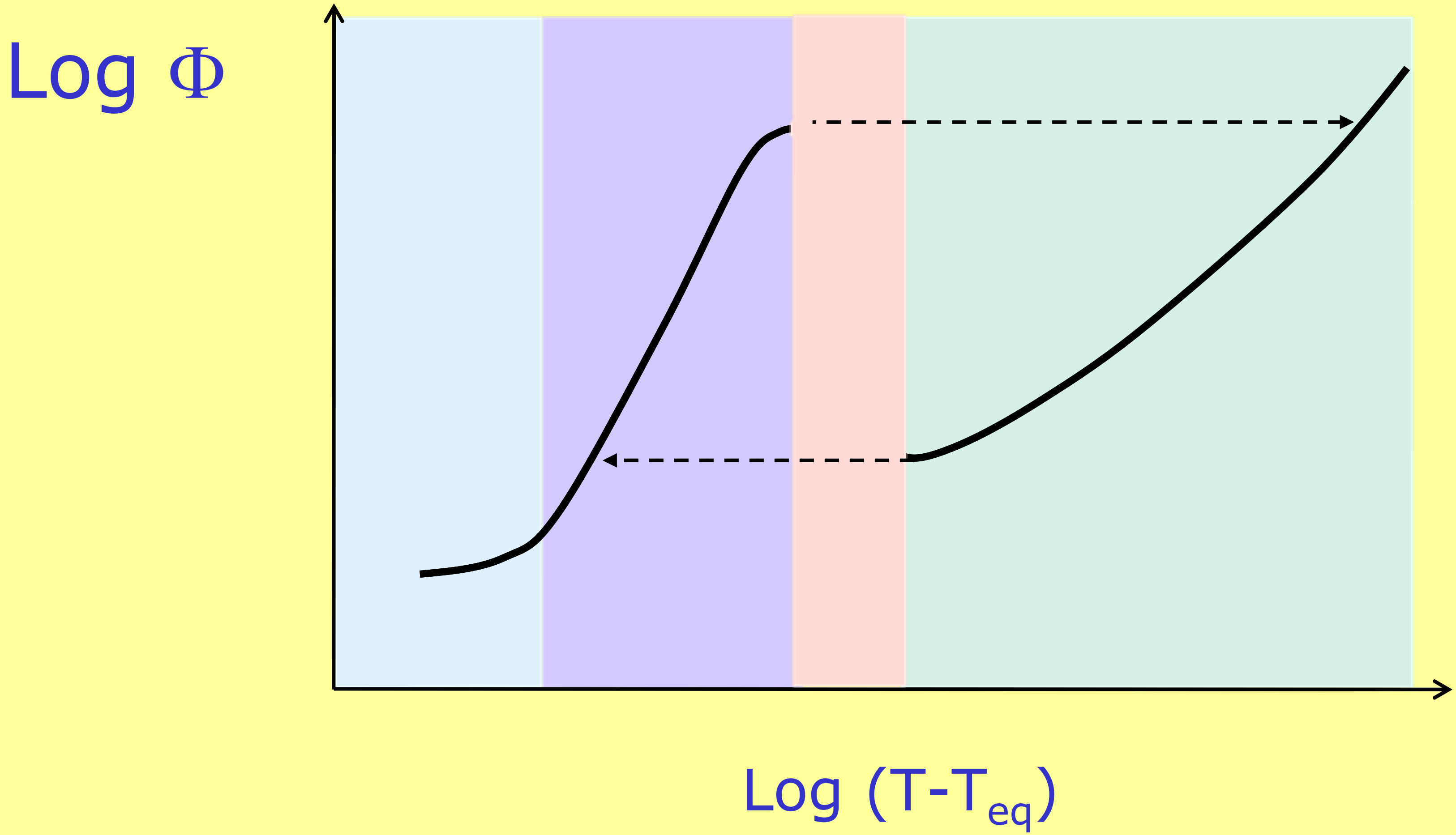
V.K.Dhir , Journal of heat transfer **128**, 1 (2006)

Boiling regimes



Driving parameter

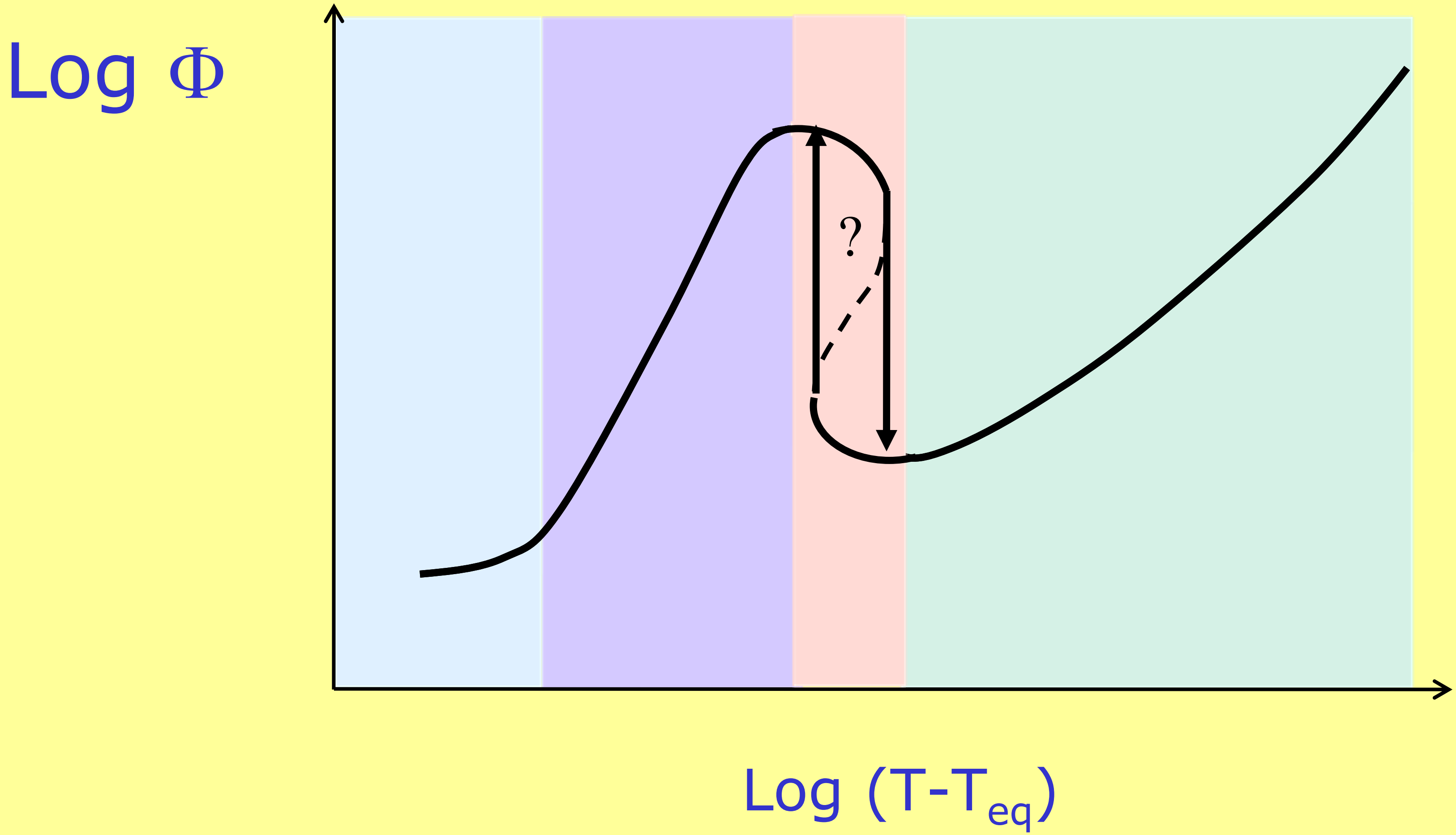
Control variable: heat flux → Hysteresis
Enormous increase of T when crisis is reached
BOILING CRISIS



Driving parameter

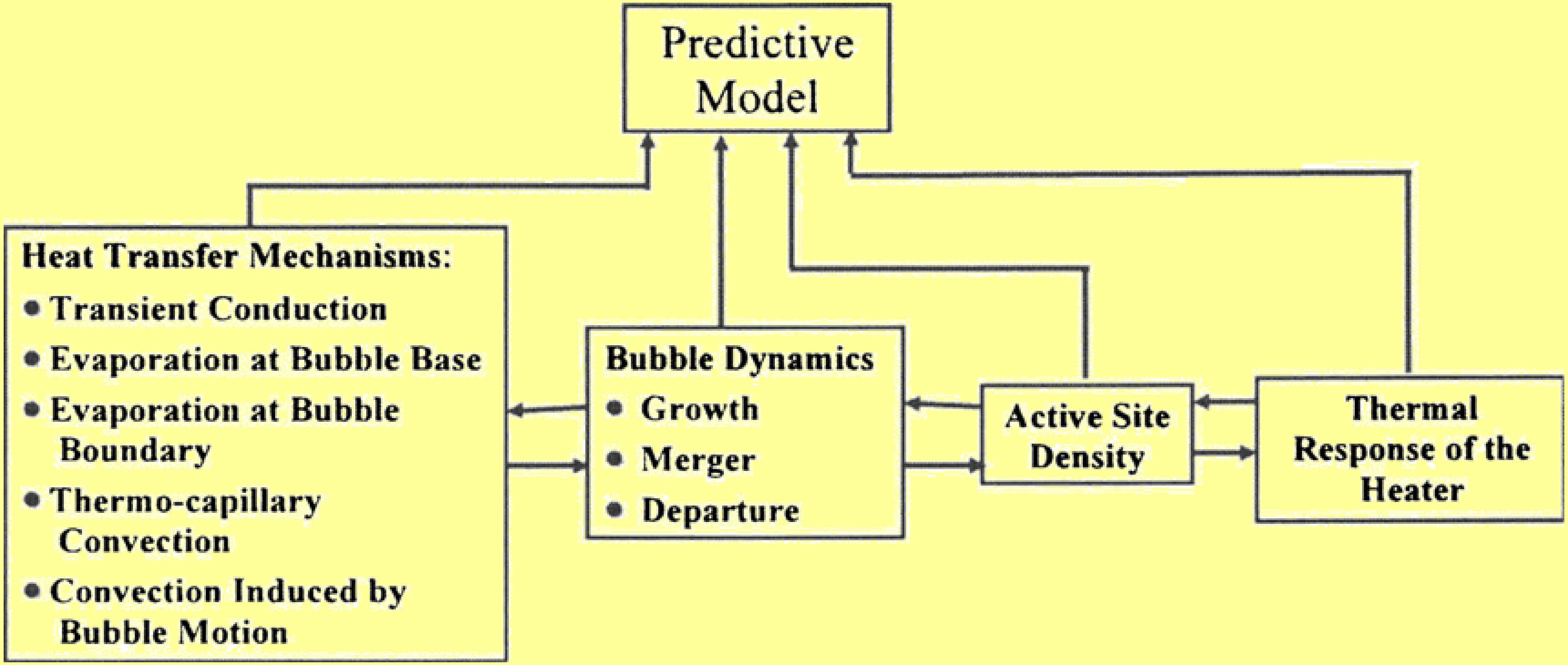
Control variable: temperature
(difficult to perform)

Hysteresis ?
Claims that no hysteresis
in well wetted conditions



Complexity of the problem

V.K.Dhir , Journal of heat transfer **128**, 1 (2006)



Predictive Model

Heat Transfer Mechanisms:

- **Transient Conduction**
- **Evaporation at Bubble Base**
- **Evaporation at Bubble Boundary**
- **Thermo-capillary Convection**
- **Convection Induced by Bubble Motion**

Bubble Dynamics

- **Growth**
- **Merger**
- **Departure**

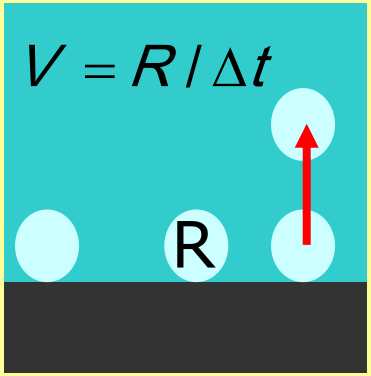
Active Site Density

Thermal Response of the Heater

$$\Phi = \Phi_{conduction} + \Phi_{convection} + \Phi_{radiation} + \Phi_{transition}$$

Dimensional analysis (1)

When approaching the crisis from low T, the main contribution to Φ: $\Phi = x\rho_G L V$



Length & time scales in the problem?
three energetic contributions:

-Excess energy for creating a bubble: $4\pi\sigma R^2$

-Potential energy (buoyancy force): $\frac{4}{3}\pi R^3 (\rho_L - \rho_G) g R$

-Kinetic energy: $\frac{1}{2}\frac{4}{3}\pi R^3 \rho_G V^2$

One can construct two equalities from these 3 terms and determine:

$$R = \sqrt{\frac{\sigma}{(\rho_L - \rho_G)g}} \qquad V = \frac{1}{\sqrt{\rho_G}}\sqrt[4]{\sigma g(\rho_L - \rho_G)}$$

Dimensional analysis (2)

The heat flux is then given by

$$\Phi = xL\sqrt{\rho_G}\sqrt[4]{\sigma g(\rho_L - \rho_G)}$$

Kutetaladze 1948

Scales:

$P=1.01105$ Pa	N_2	H_2O
Boiling T_{eq} (K)	77.35	373.13
ρ LIQUID (Kg/m^3)	806.08	958
ρ VAPOUR (Kg/m^3)	4.6	0.59
σ (N/m)	0.0089	0.0072
L (kJ/Kg)	198.38	2270
R (mm)	0.6	0.5
V (m/s)	1	2.8
Φ/X (W/cm^2)	93	380
Φ_{max} (X=0.16)	15	60

Far-field models

Almost identical formulas can be obtained from the study of far-field models (hydrodynamics, instability of a vapor jet, etc..) Zuber 1959

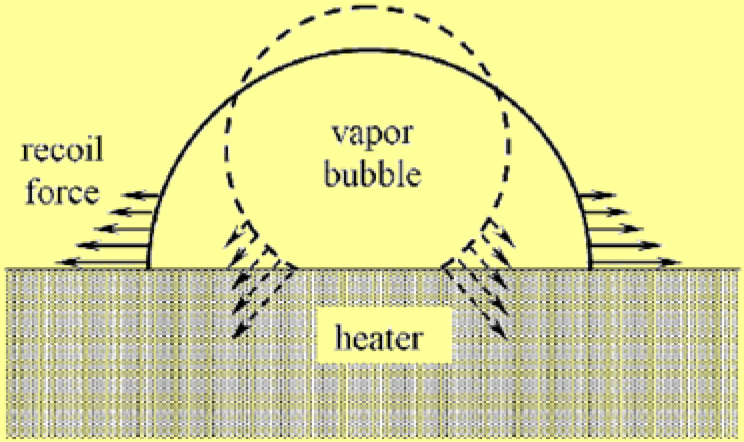
The parameter X contains, besides the fraction of surface covered by vapour, all the other adimensional dependences, geometrical factors and other “correction” coefficients (wettability, aging of the heater surface, etc…)

Experimentally, critical heat flux Φ_{max} in flat surfaces, corresponds to $X = 0.01 - 0.16$

Recent advances: near surface models

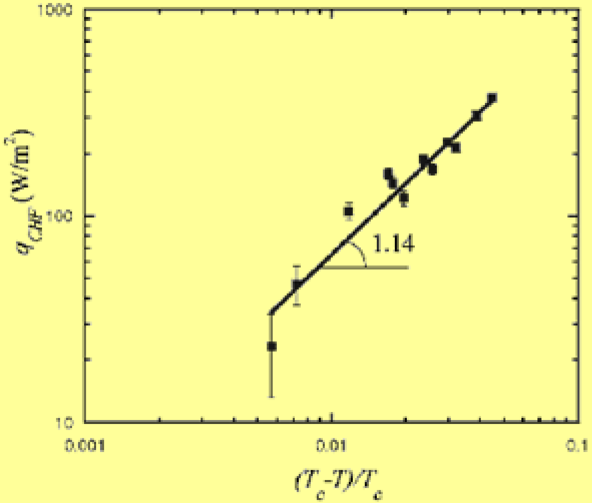
Recoil force mechanism

Nikolayev et al. PRL **97**, 184503 (2006)



Recoil force increases with the evaporation rate and is opposed to bubble detaching. When this force "wins", the gas film spreads and produces the crisis

Dependence of Φ_{max} when approaching the critical point



$$\Phi_{max}^{K-Z} \propto L\left[\sigma\left(\rho_L-\rho_G\right)\right]^{1/4}\alpha\left(T_{eq}-T\right)^{\varpi}$$

$$\Phi_{max}^{Nikolayev}\alpha\left(T_{eq}-T\right)^{\varpi'}$$

➡ smaller scales play a role

Gravity dependence

Very important for space-crafts

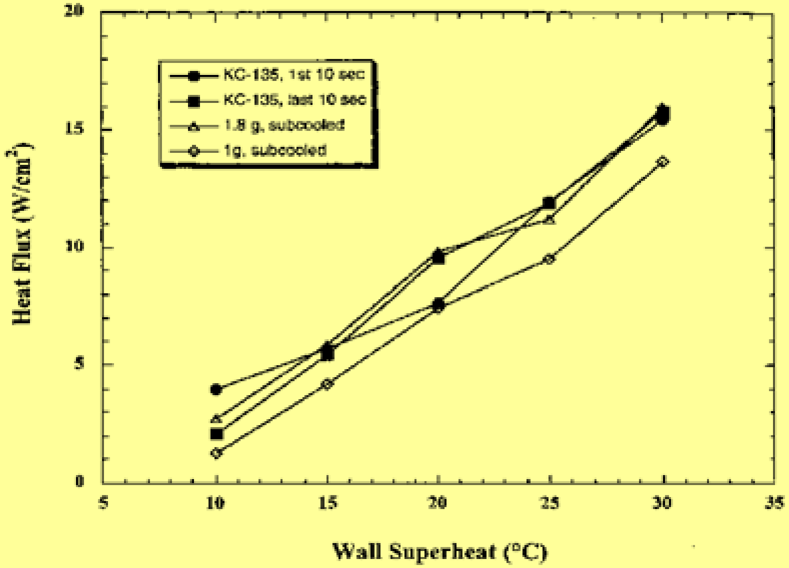
Some results do not agree with the $\Phi_{\text{max}} \propto \sqrt[4]{g}$ dependence

-Relative fluctuations $\Delta\Phi_{\text{max}}/\Phi_{\text{max}} \propto {}^{1}\!/_{4}(\Delta g/g)$

But measurements at low g (large fluctuations) are rather stable

-Spatially resolved heat flux, shows that in the boiling regions the flux is independent of gravity

The effect of gravity is on the dry surface x(g)



Kim & Benton Int. J. Heat Fluid Flow 23, 497 (2002)

Burnout experiments (1)

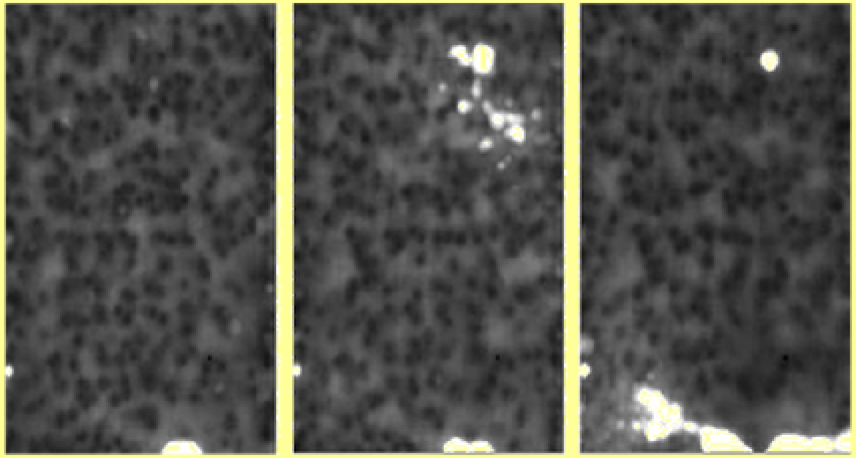
Urbana Champaign, May 2011

Theofanous et al. Experimental Thermal and Fluid Science **26**, 775 & 793 (2002)

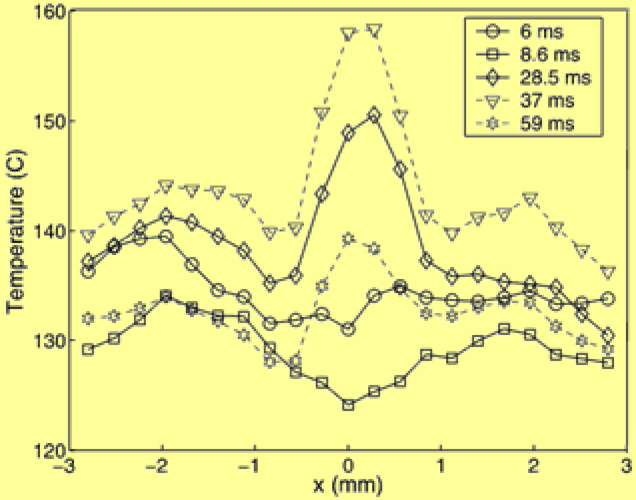
Powerful imaging techniques (Optical microscopy, thermography, and X-rays) with spatial and temporal resolution

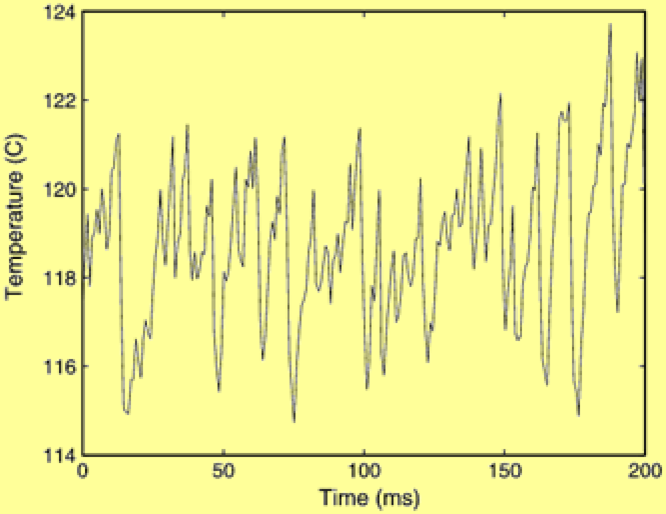
- Cold, Hot & Dry spots

-Strong temperature fluctuations: (larger than 10%)



Water 122 W/cm^2



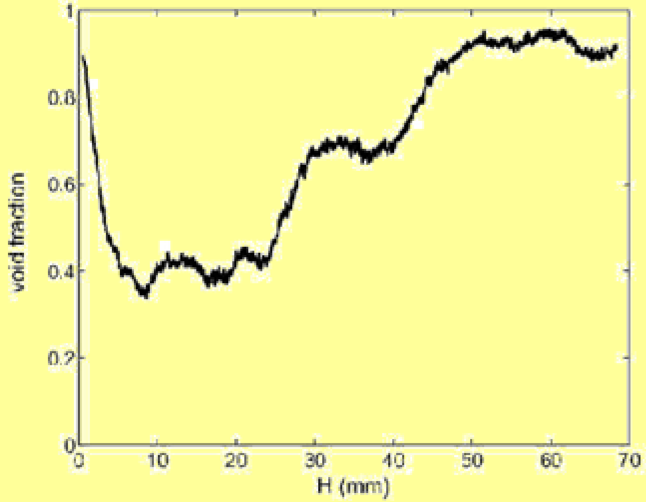


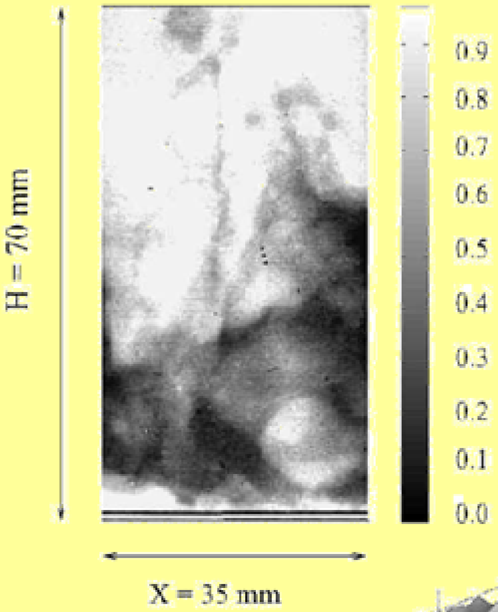
Burnout experiments (2)

Theofanous, Tu, Dinh & Dinh Experimental Thermal and Fluid Science **26**, 775 & 793 (2002)

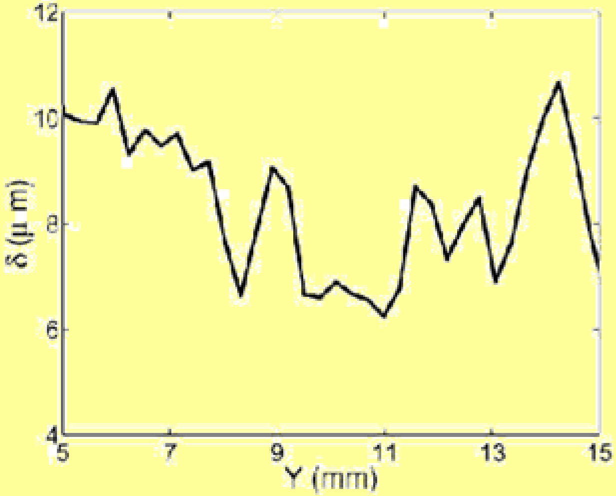
- Existence of a liquid microlayer

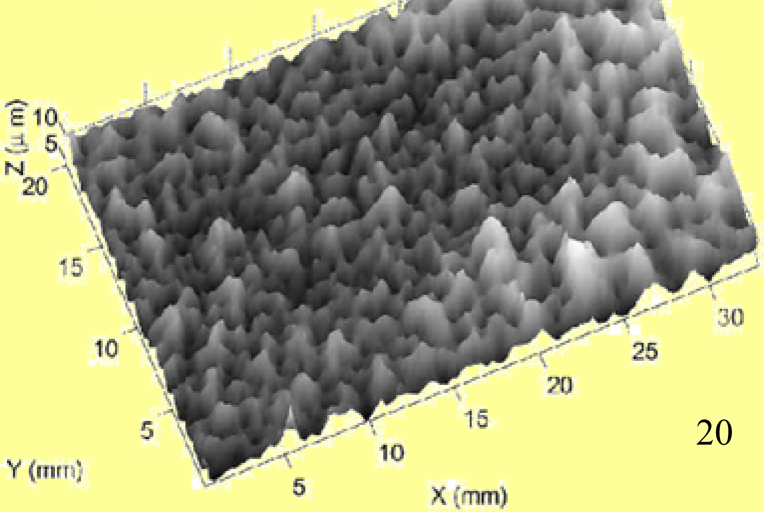
Water
100 W/cm²





Water
150 W/cm²





Experiments

Acoustic Emission

Scruby J.Phys.E: Sci Instr. **20** (1987)

Sources of AE (detected on the metal):

- Liquid flow → Continuous signals

- Nucleation of a bubbles (creation of interfaces)
- Acceleration of liquid-gas interface

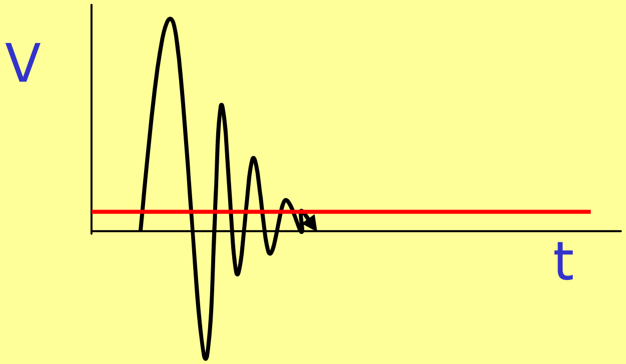
} → Intermittent bursts

Standard analysis:

AE is used for monitoring industrial processes.
Most studies focus on spectral analysis.

Avalanche analysis

-separate the continuous noise
-identify pulses → statistical analysis

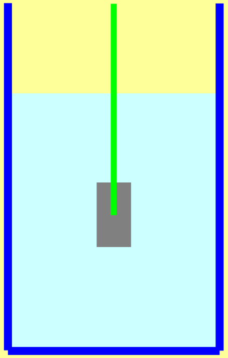


$$E = \frac{1}{R}\int_0^D [V(t)]^2 dt$$

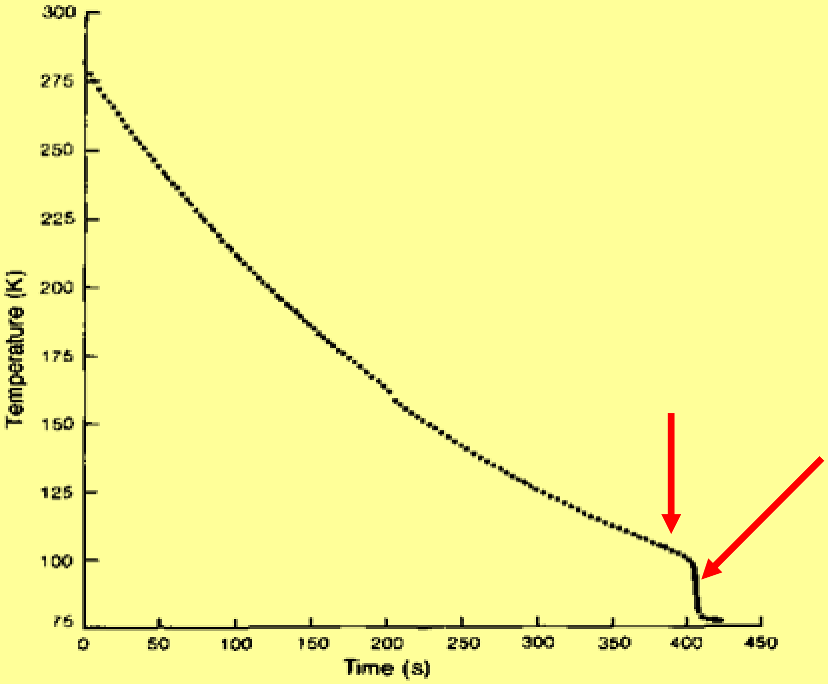
Boiling by immersion

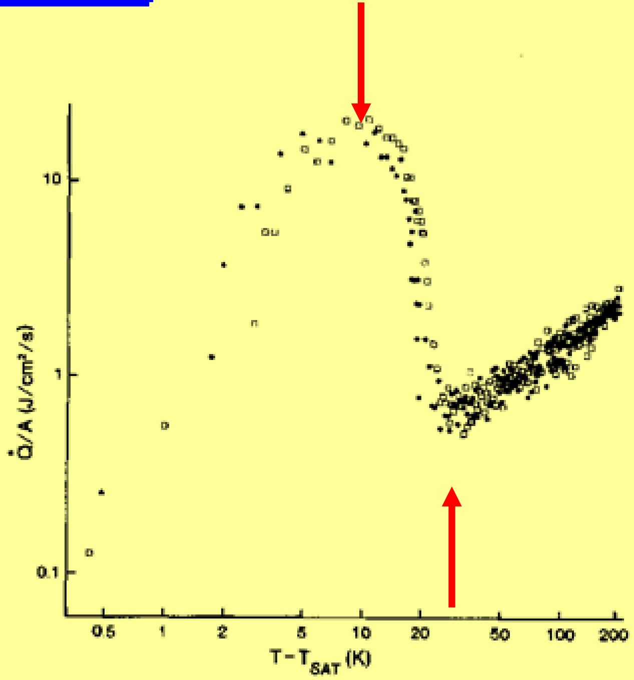
Immersing a hot metal into a liquid is an easy way to access the boiling Φ(ΔT) curve

T.W.Listerman et al. AJP 54, 554 (1986)



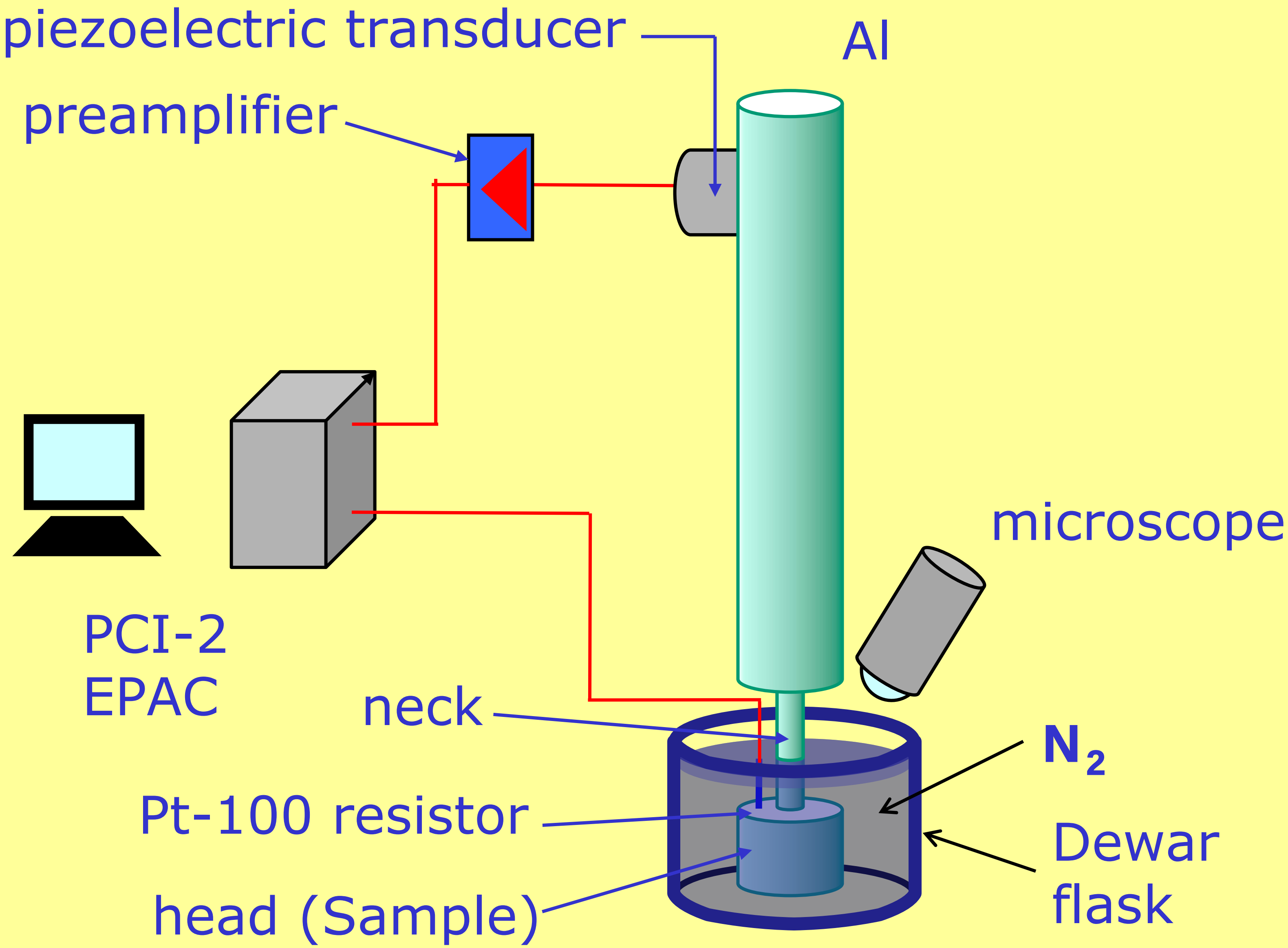
Al cylinder at room T
in a liquid N_2 bath



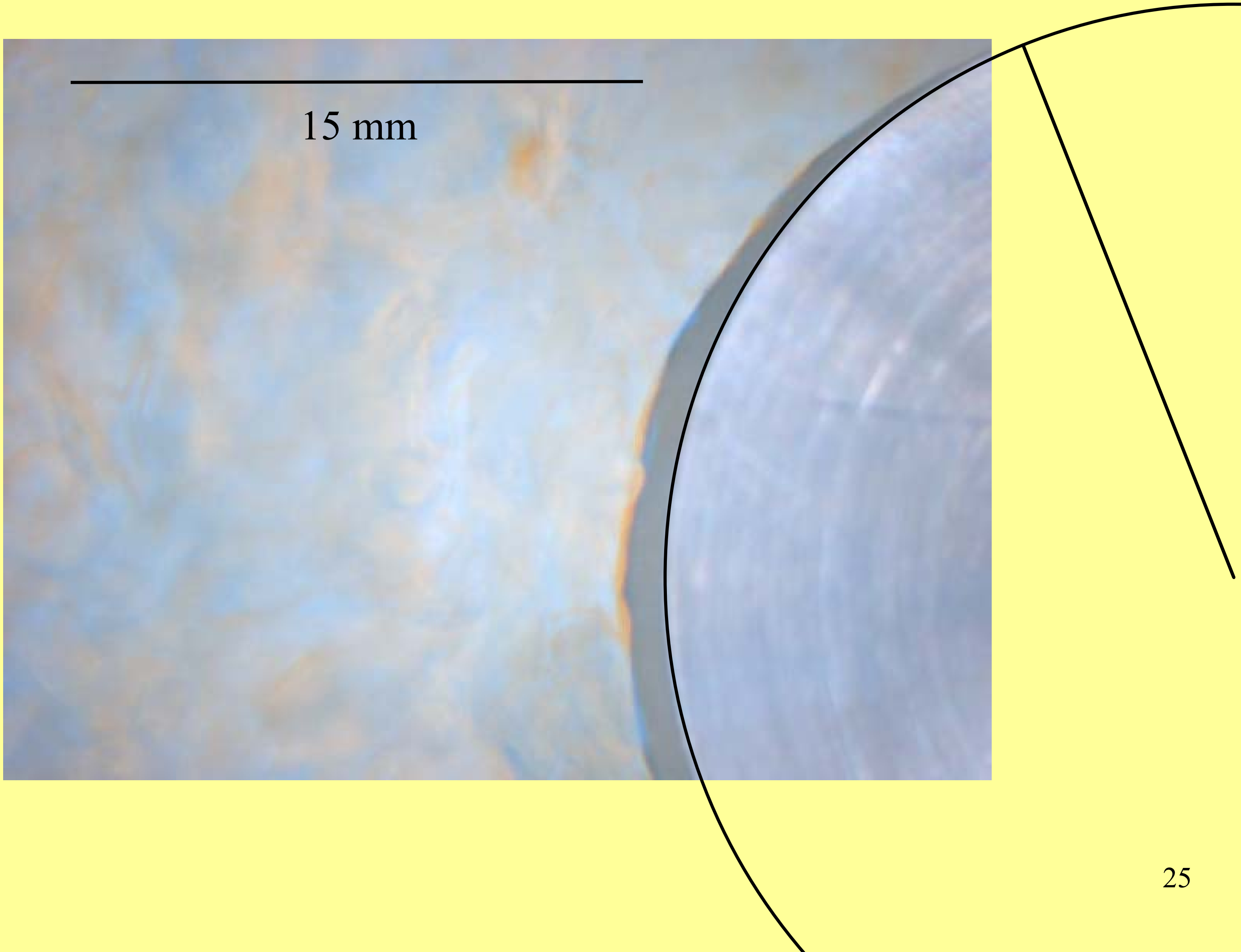


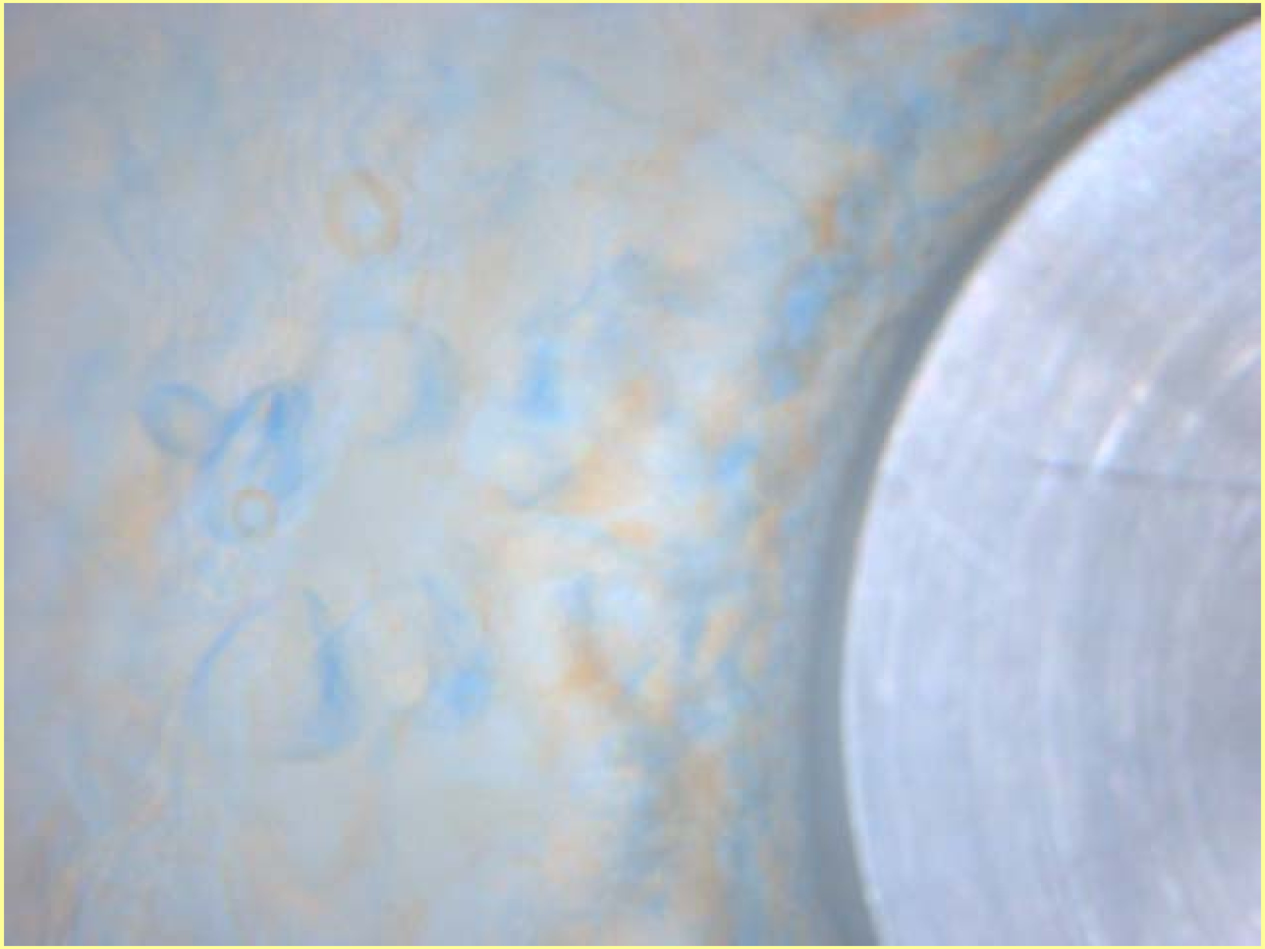
$$\Phi = \frac{1}{S}\frac{dQ}{dt} = \frac{mC_p(T)}{S}\frac{dT}{dt}$$

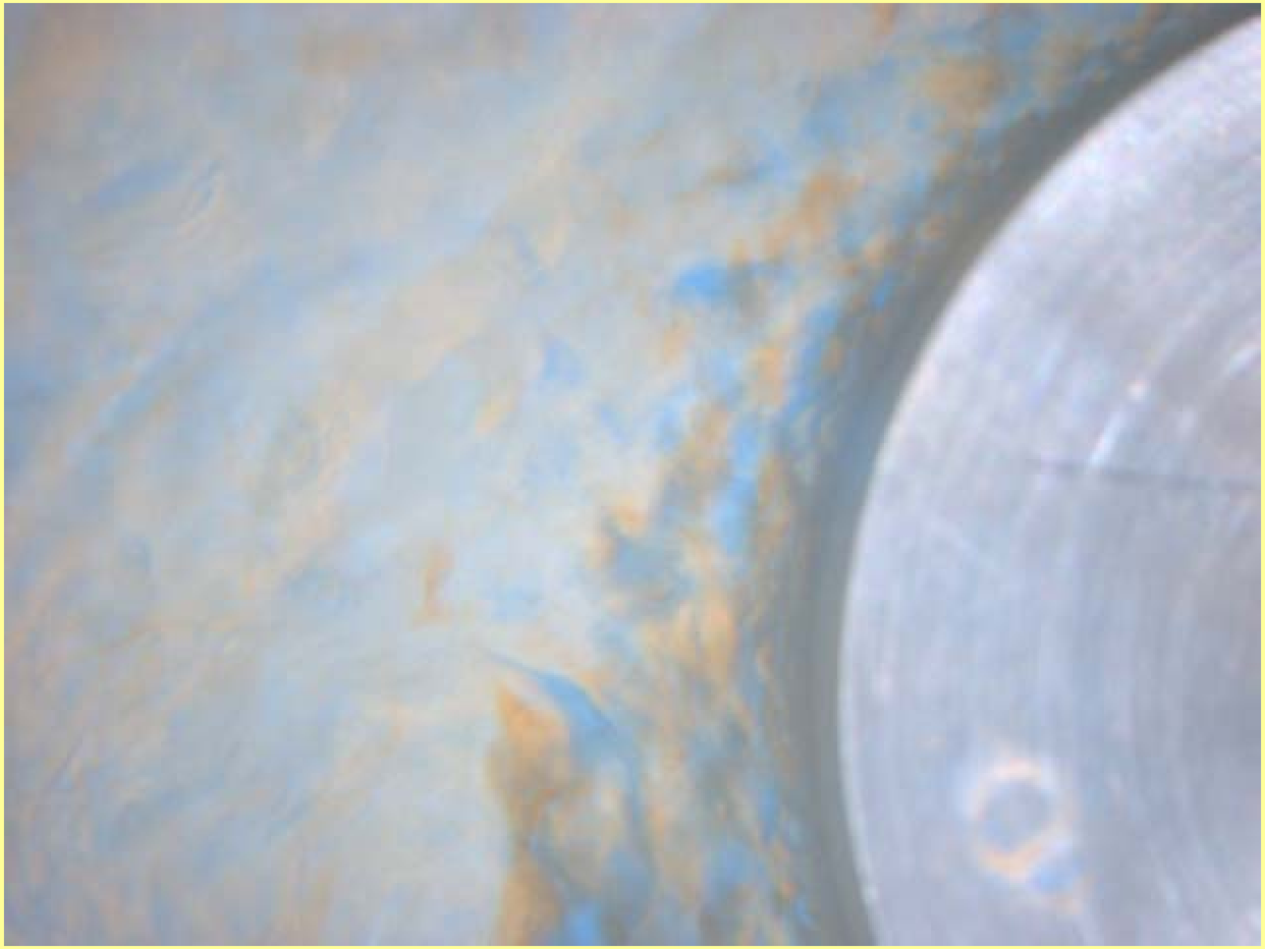
Experimental setup:

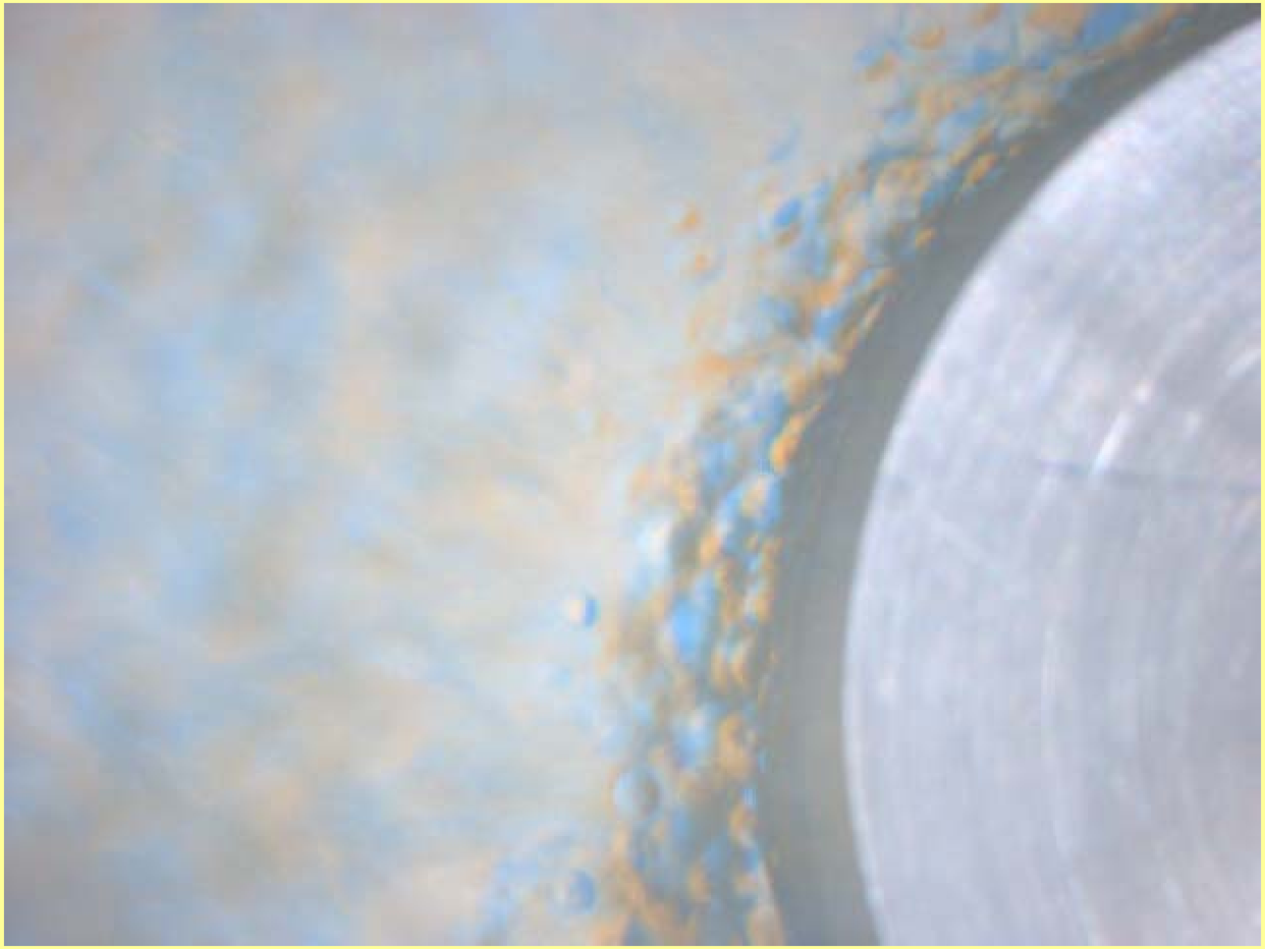


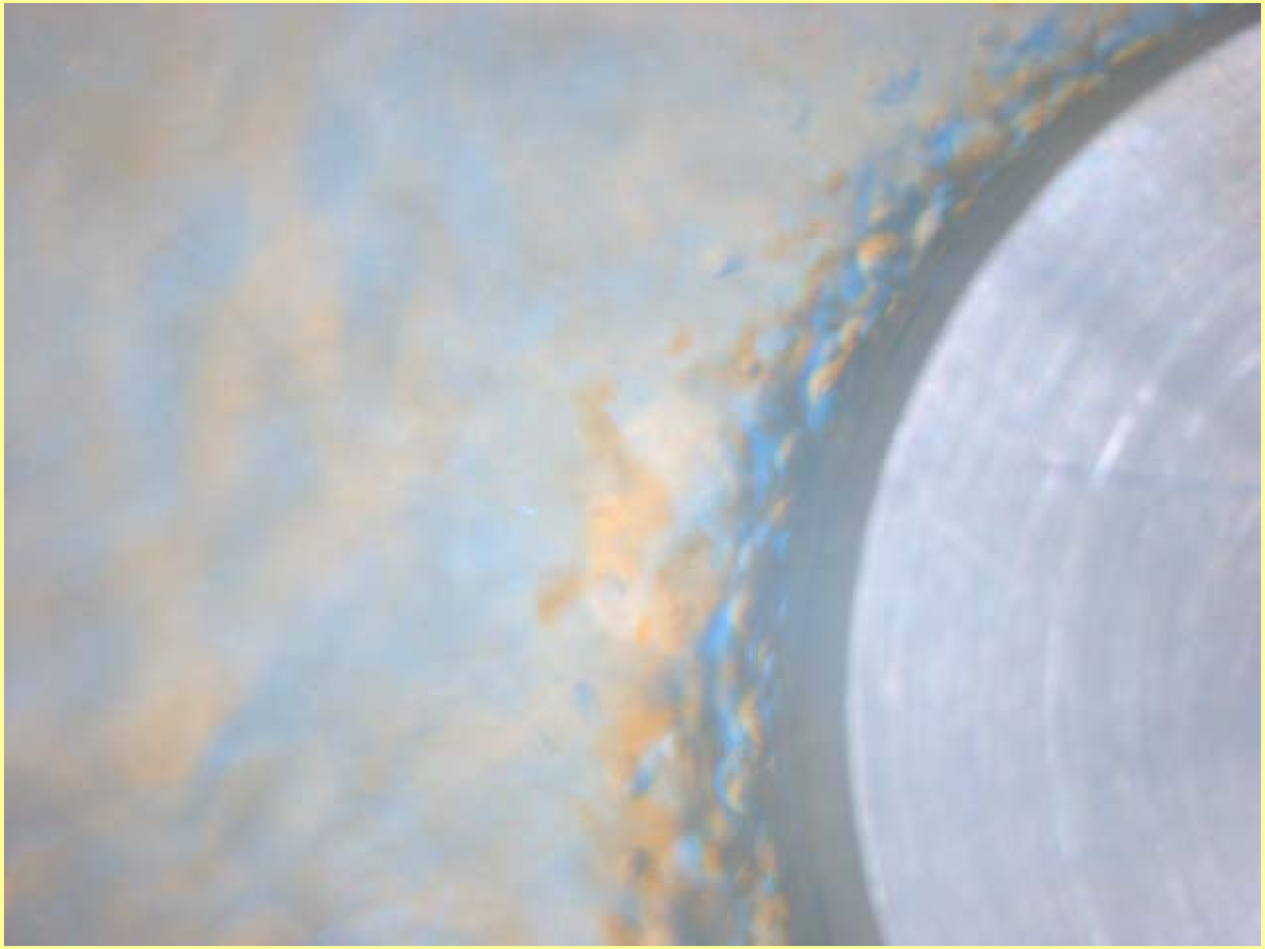
Optical images ($\Delta t=1$s)

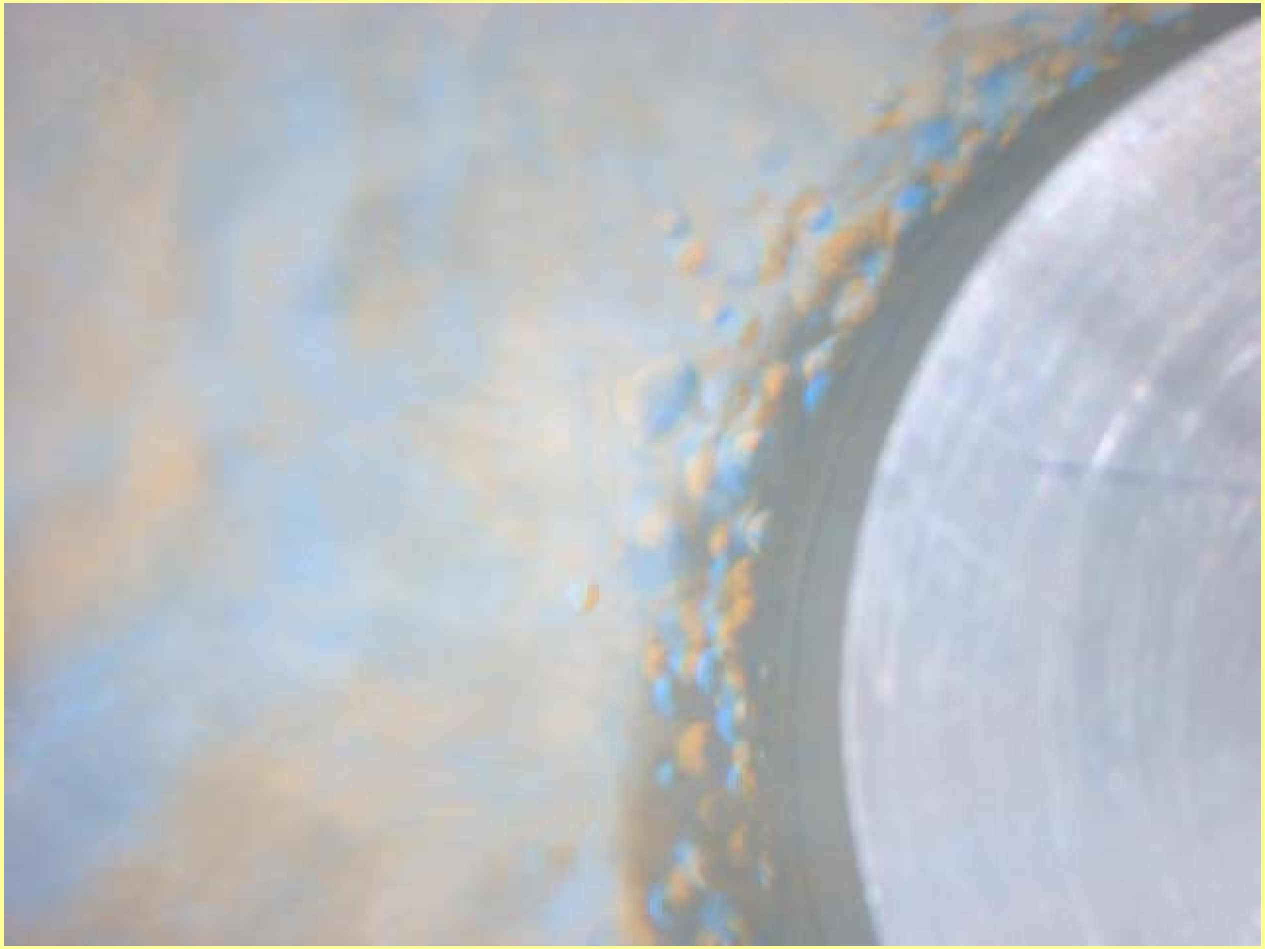


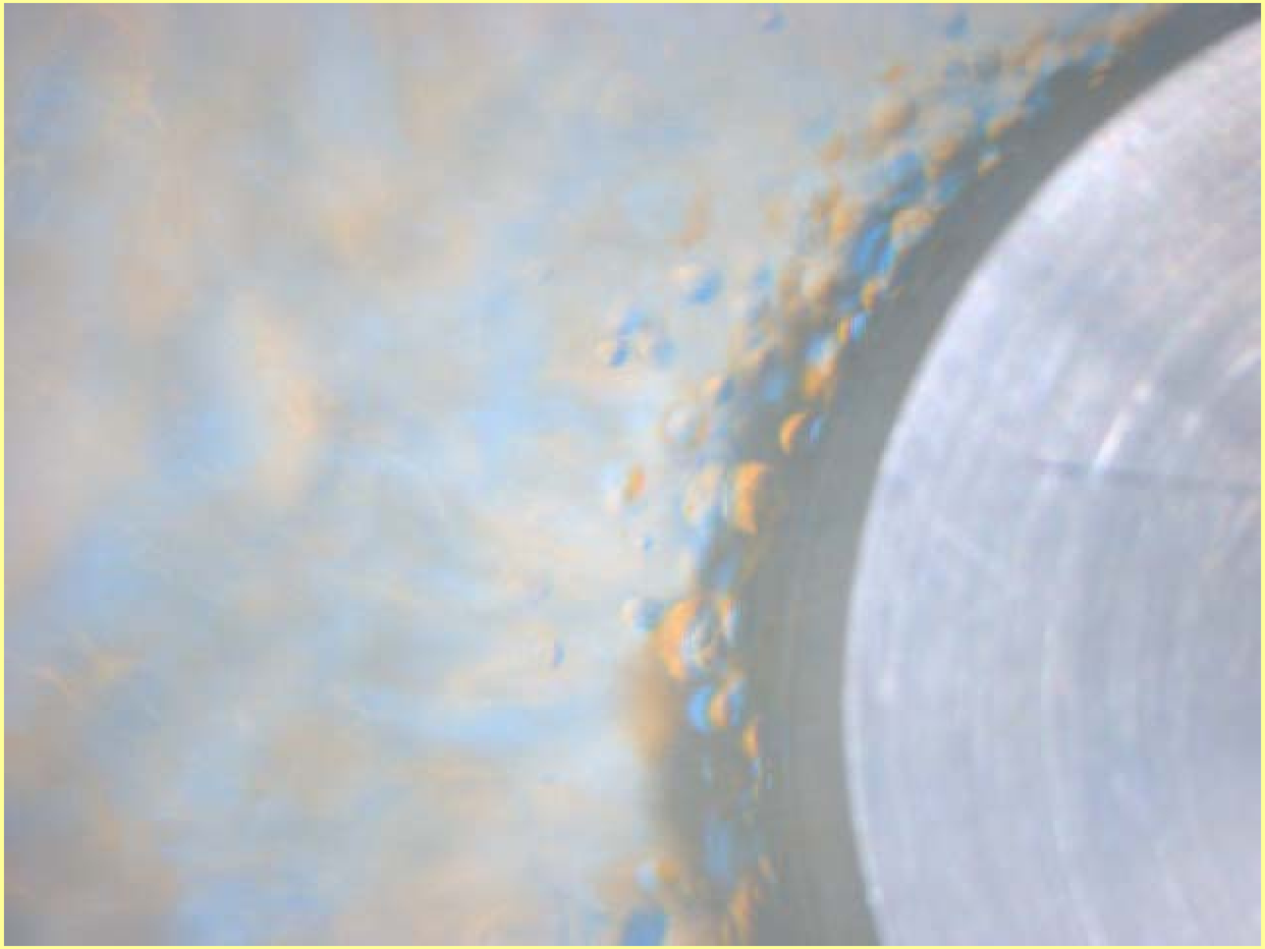


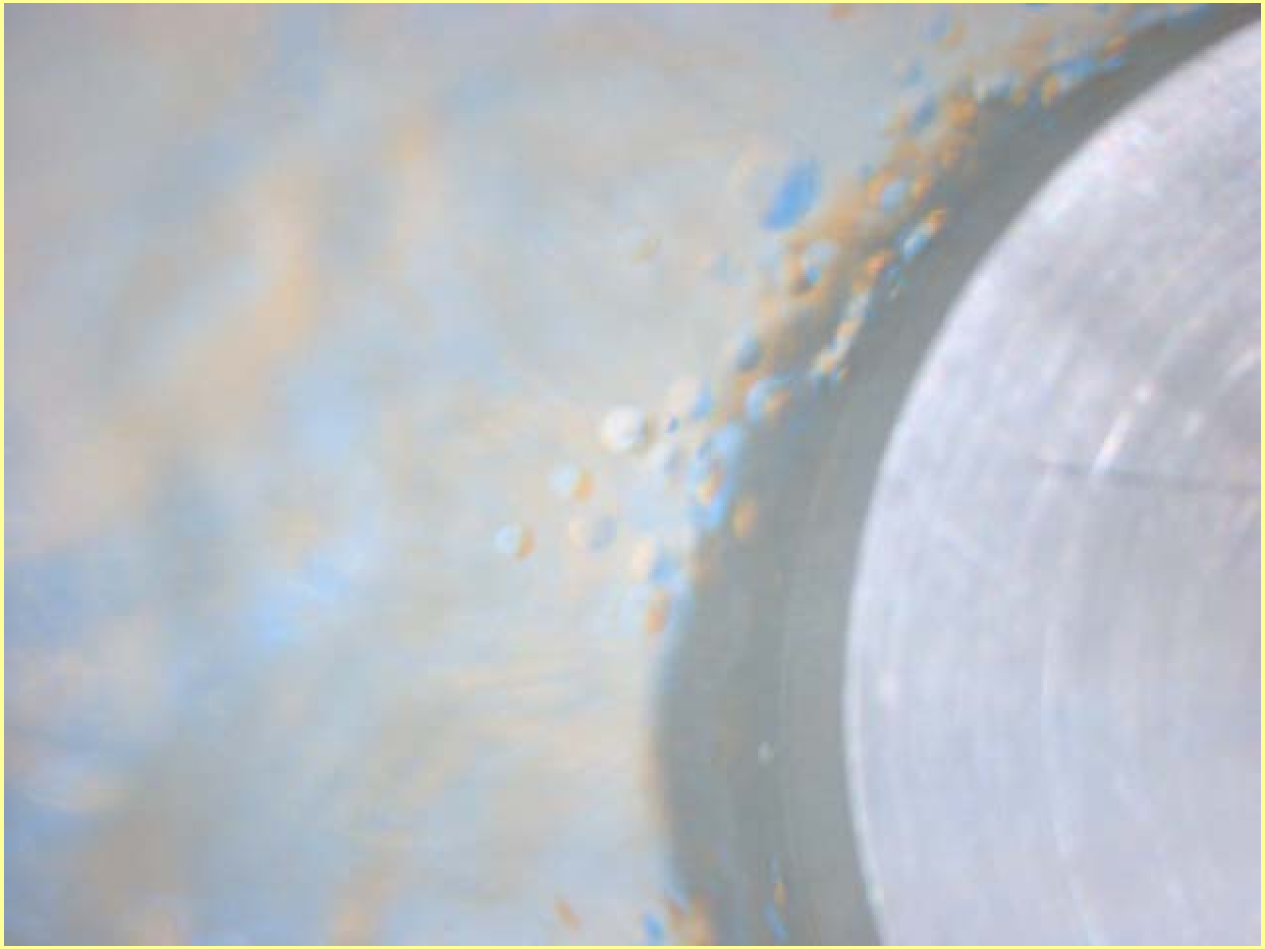












Experimental Nukiyama curve

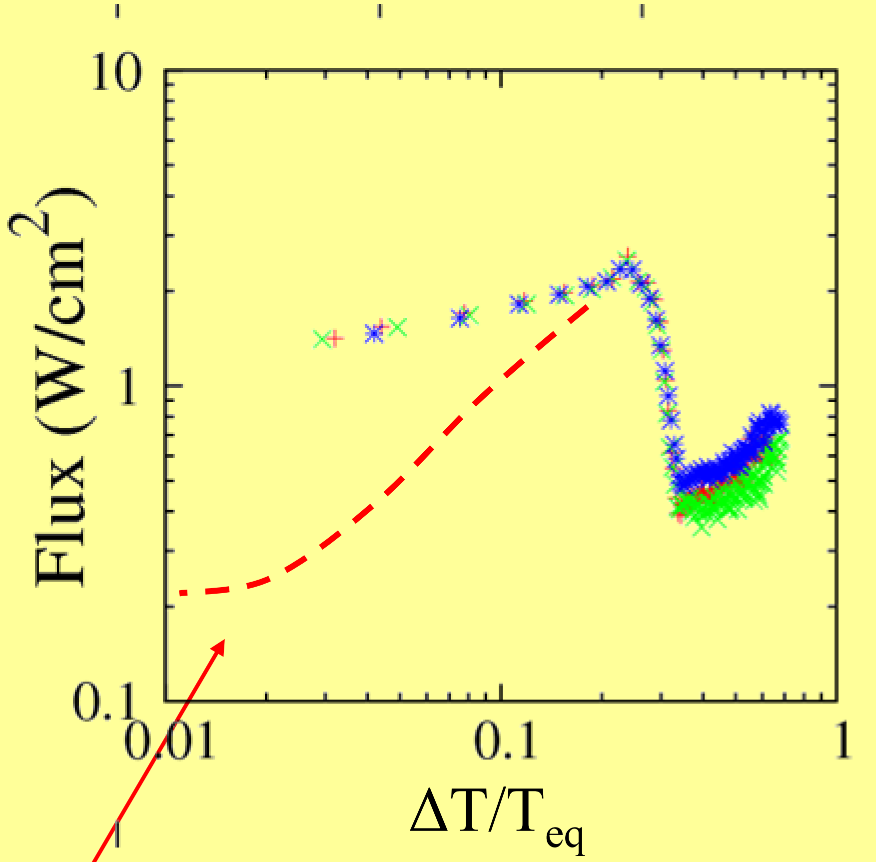
$$\Phi = \frac{1}{S}\frac{dQ}{dt} = \frac{mC_p(T)}{S}\frac{dT}{dt}$$

The experiment is not designed for a pool-boiling Nukiyama curve

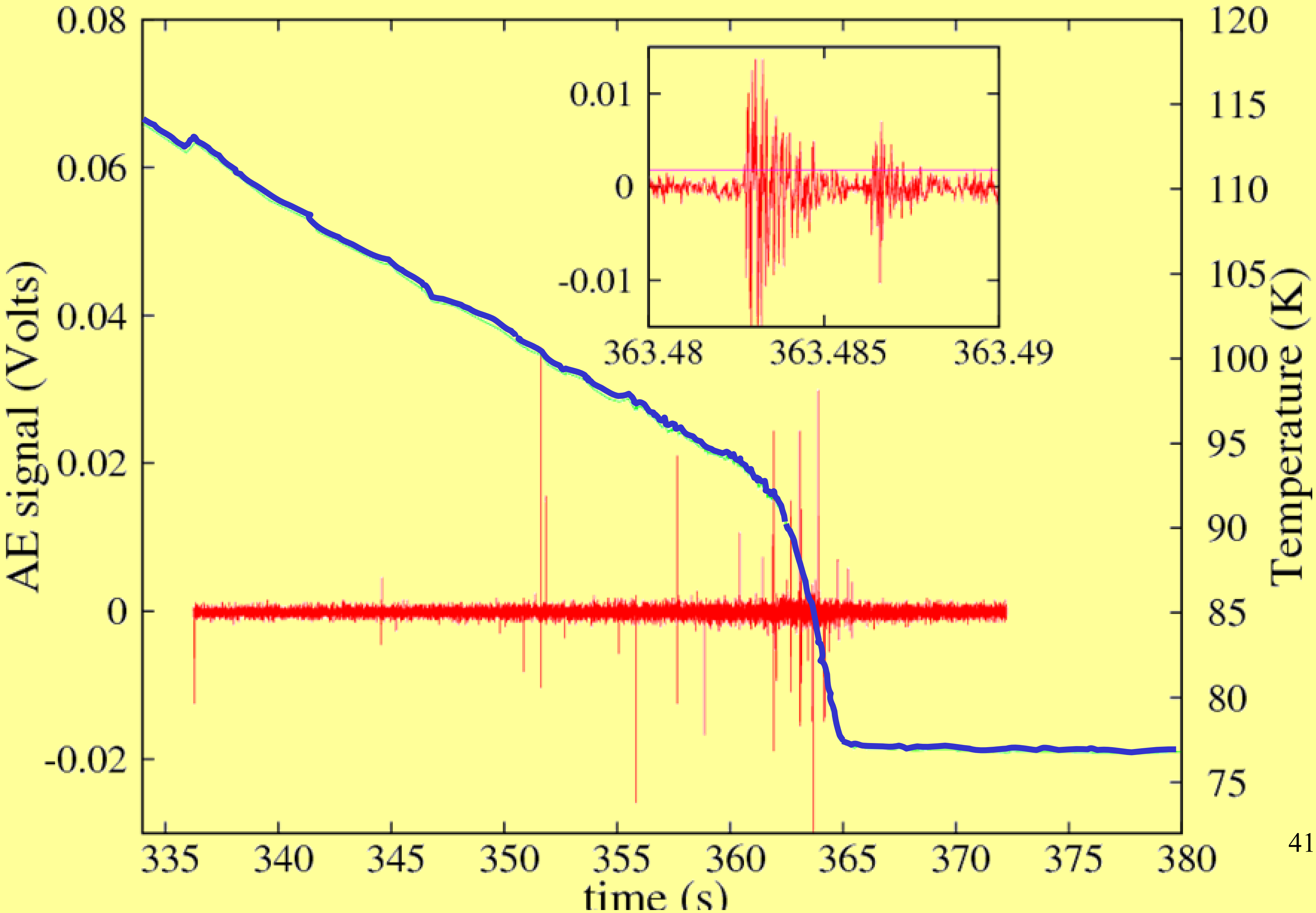
-Dynamic experiment: Delay with respect to the stationary curve

-Cylindrical geometry: Different regimes simultaneously for vertical and horizontal faces

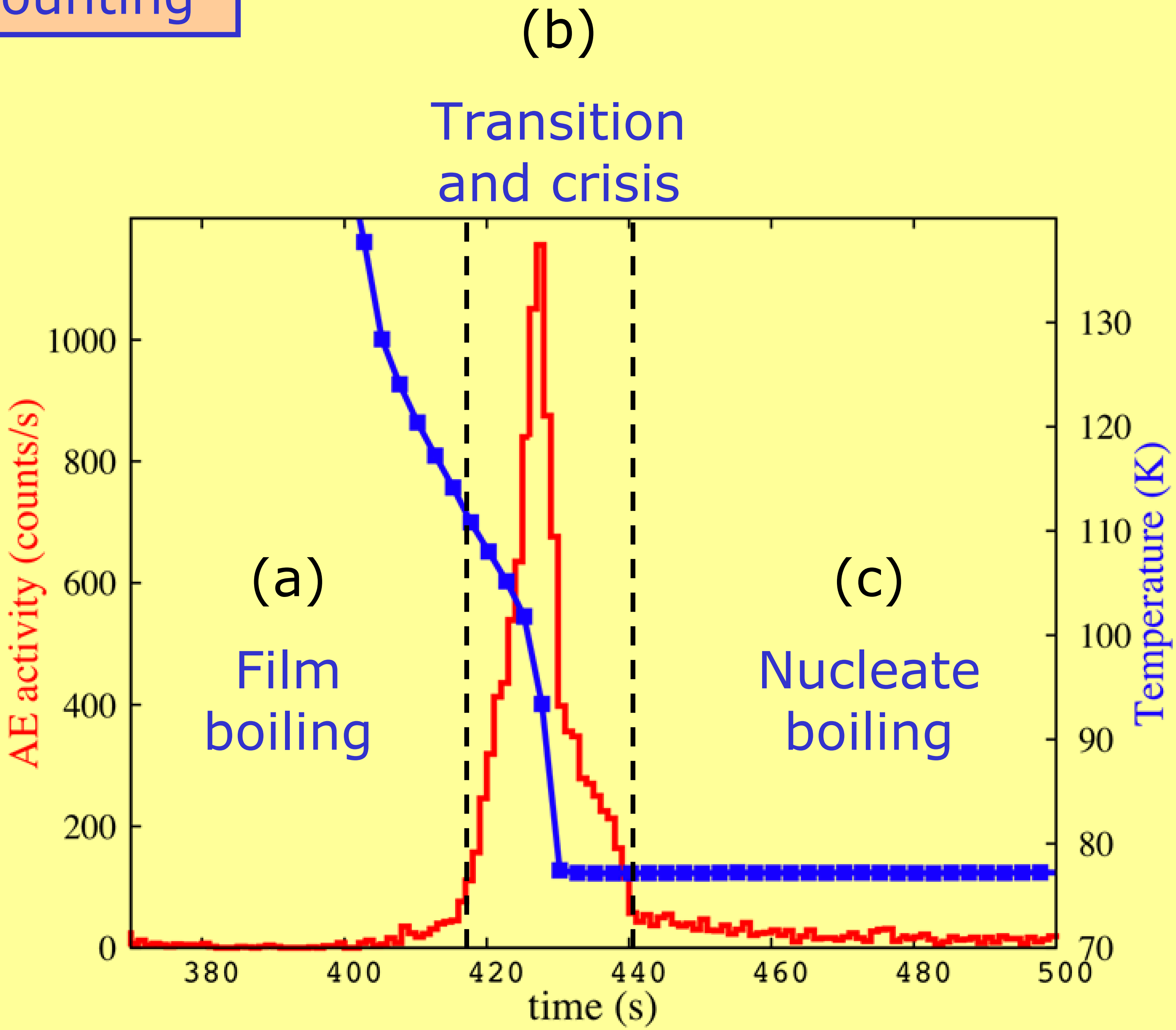
-Heat transfer through the neck: Pure natural convection regime and early stages of nucleate boiling regime are never reached



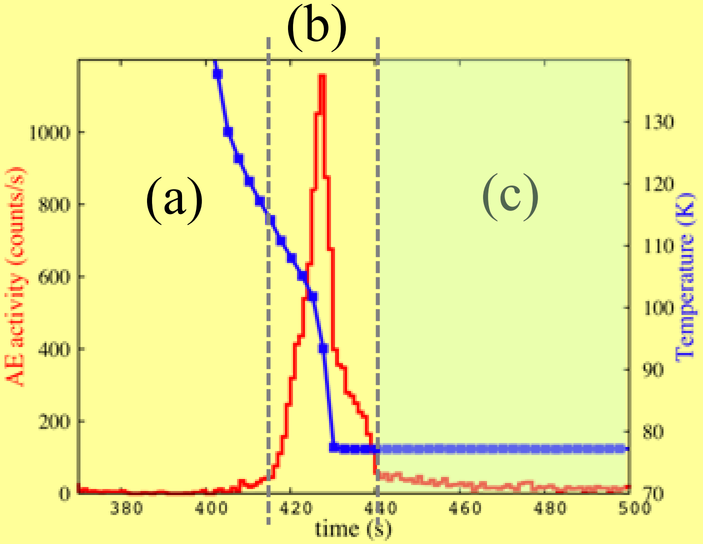
AE raw signal: typical result

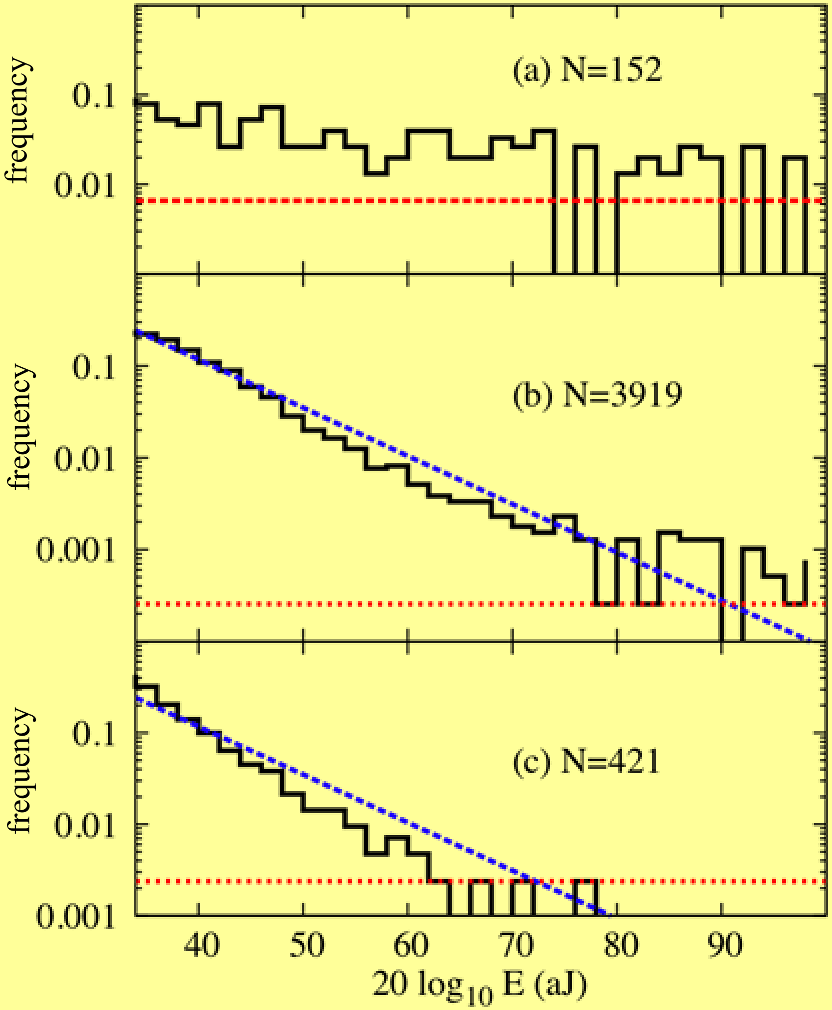


Pulse counting



Energy distributions P(E)





~uniform

~power law

~power law

(+ cutoff)

one count

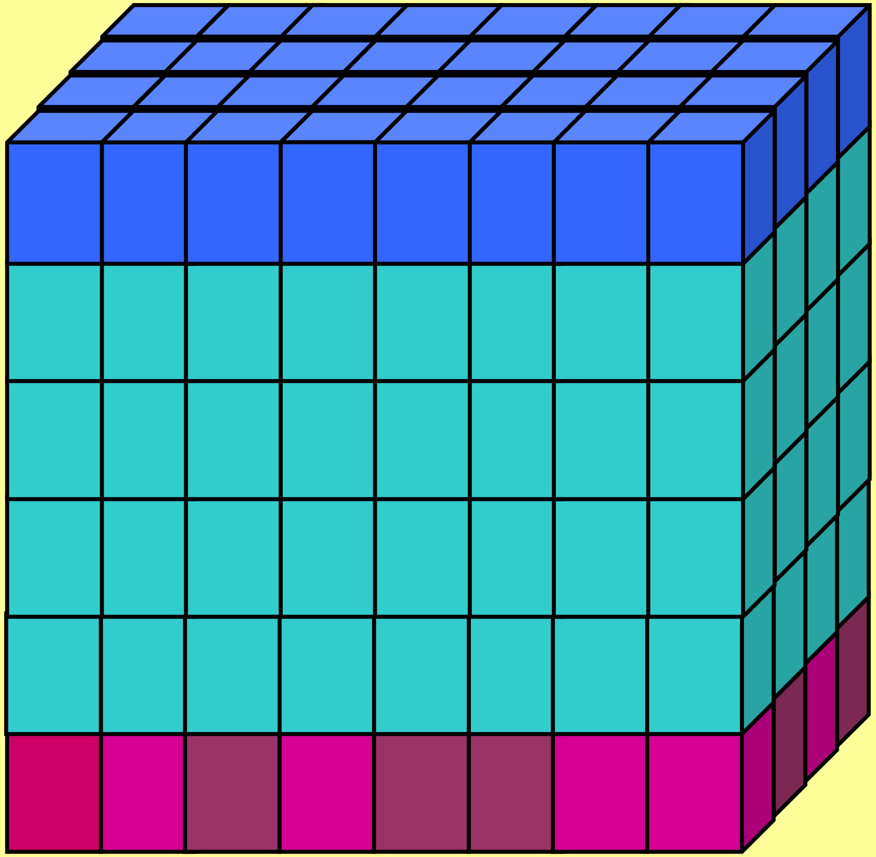
$$p(E)\,dE \propto E^{-\tau}\,dE$$

where $\tau \approx 2.05 \pm 0.1$

Simulations

Model

Lattice model
(Lx=50)x(Ly=50)x(Lz=20)



Liquid reservoir

Fixed temperature T_{eq}

Liquid/Vapor

$S_i=-1,1$

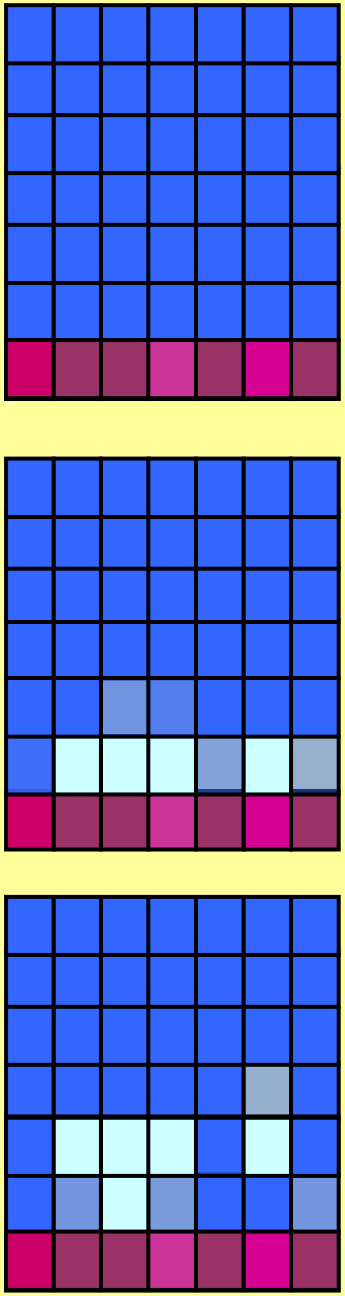
Initially
$T_i=T_{eq}, S_i=-1$

Heater

Quenched Gaussian distribution of T around $T_M \pm \sigma$

with $T_M > T_{eq}$

Simulation steps



Initial condition: all sites liquid at T_t

1 Thermal equilibration:

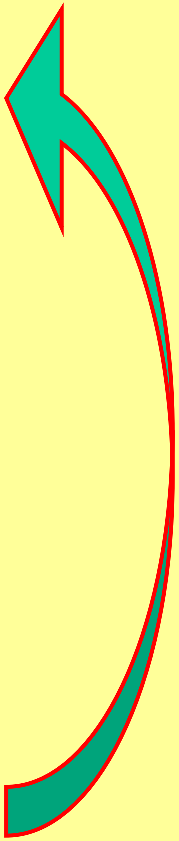
A-Heat transfer (Fourier equation)

B-Decision on transition/overcooling/overheating

C-Phase transition + new T

2 Mechanical equilibration:

Drift + filling the voids



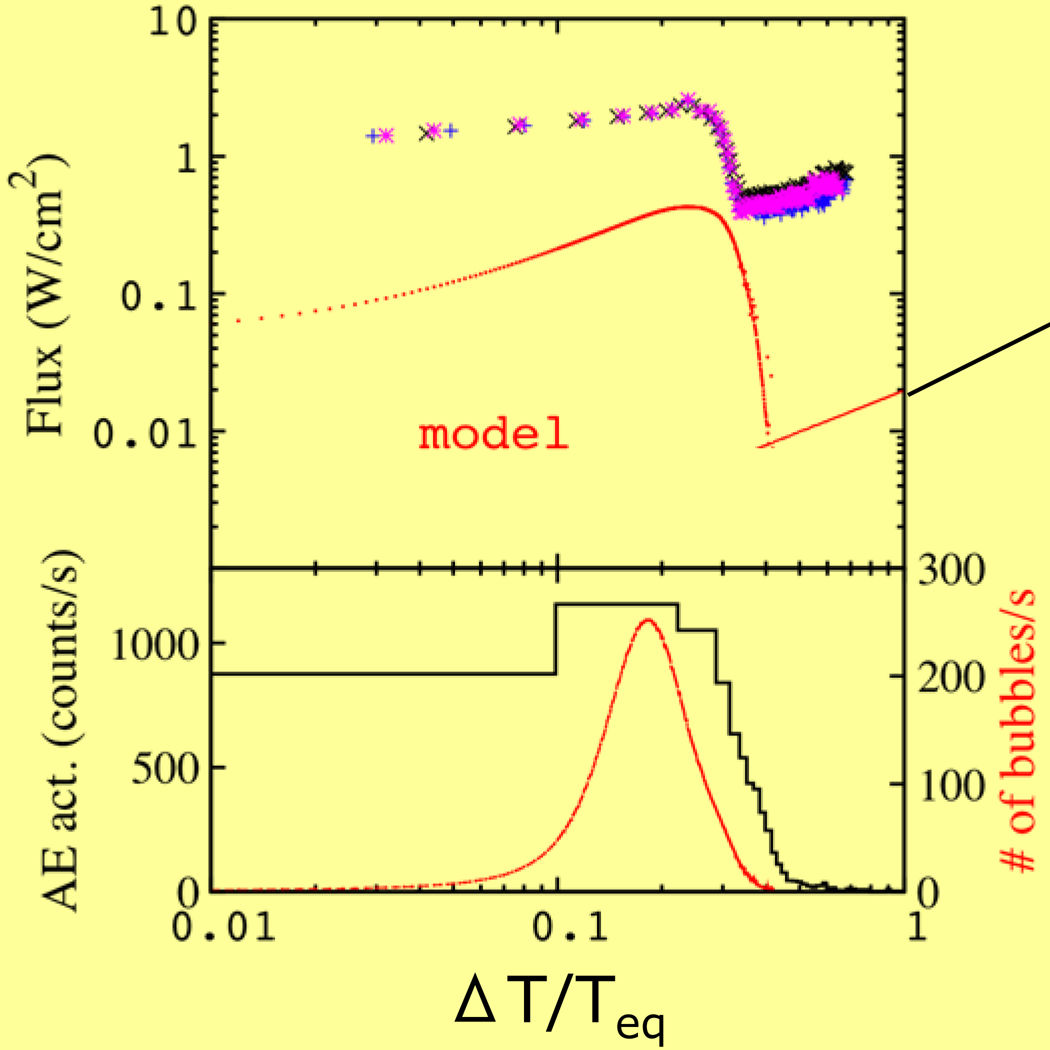
Model parameters: N_2 at atmospheric pressure

	N_2
Boiling T_{eq} (K)	77.35
ρ LIQUID (Kg/m^3)	806.08
ρ VAPOUR (Kg/m^3)	4.6
τ (N/m)	0.0089
K LIQUID (J/mKs)	0.139
K VAPOUR (J/mKs)	0.026
C LIQUID (J/Kg K)	2042
C VAPOUR (J/Kg K)	741.5
L (kJ/Kg)	198.38

Free:

T_M
$\sigma = 0.1$
$a = 1mm$
$\Delta t = 1ms$

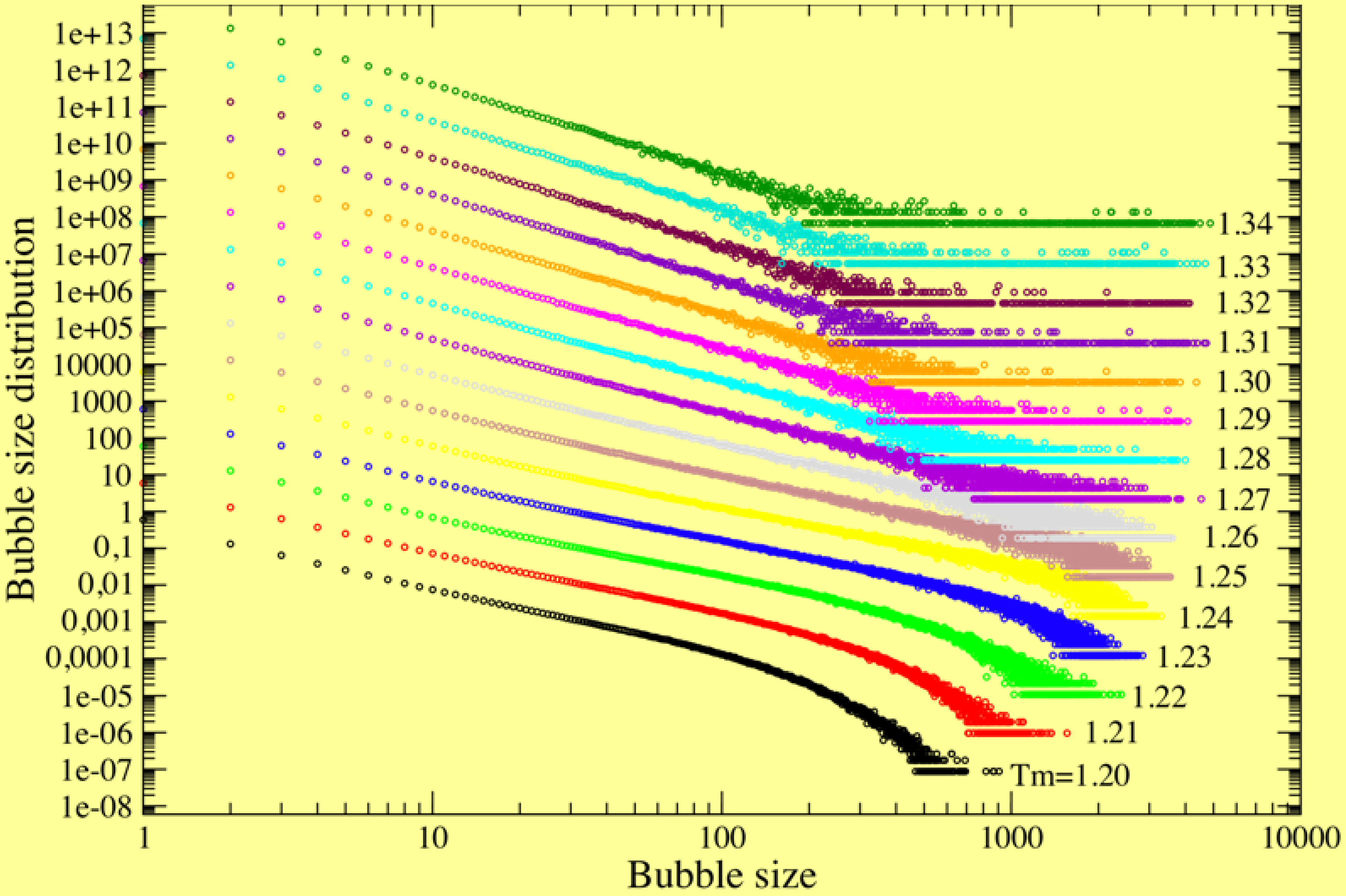
Simulation results



Convection and radiation not included

We associate each acoustic signal to a single numerical bubble

Critical distribution of bubble sizes at the crisis



Conclusions

Conclusions

- Experimental analysis of acoustic emission activity during the boiling crisis as an avalanche process

- Energy distribution of acoustic signals has no characteristic scale, approximating well to a power-law behavior with exponent

$$p(E) \propto E^{-\tau} \qquad \tau \approx 2.05 \pm 0.1$$

- This is indicative of the existence of critical phenomena associated with the boiling crisis

- Simple "near hot surface" model describes well the lack of characteristic scale in the bubble size when approaching the crisis.

- It supports the origin of the boiling crisis to lie just close to the hot surface (percolation of bubbles)

- The agreement with experimental exponent suggests that energy of acoustic signals only depends on the contact area between bubble and hot surface