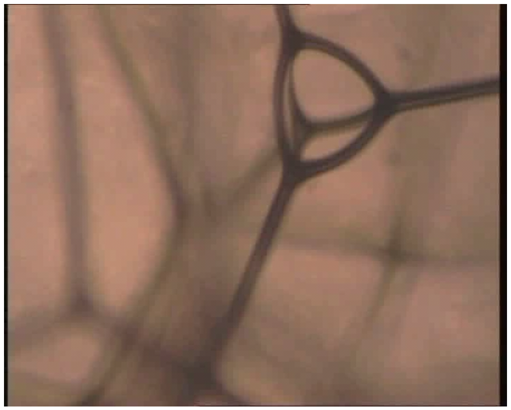
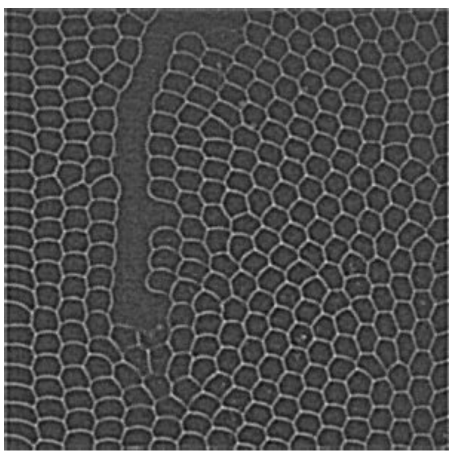
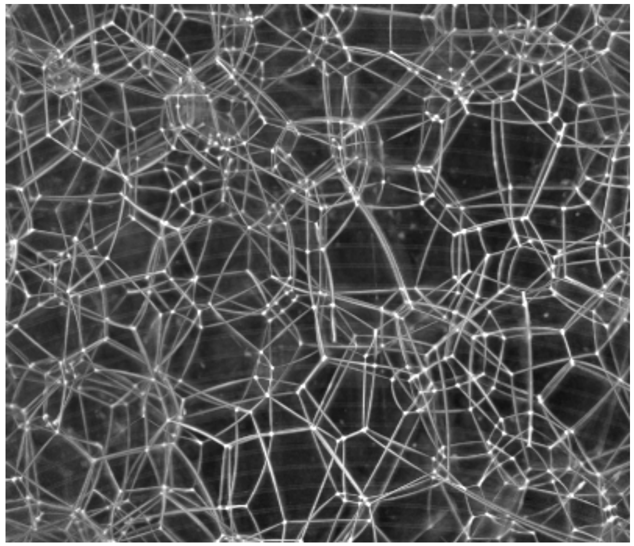
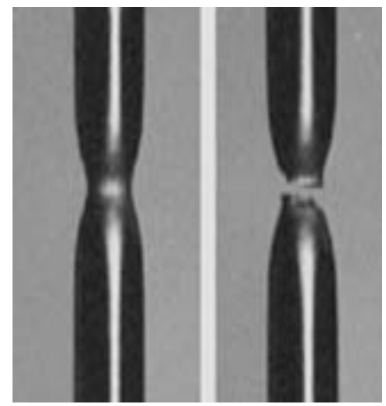
Fracture in Aqueous Foam









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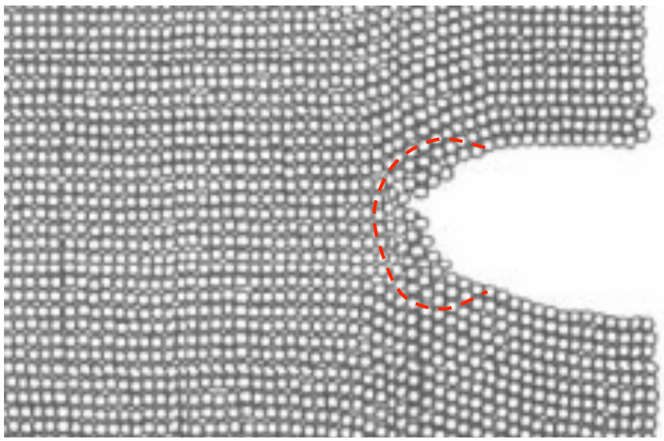
Outline

I. Bubbles as atoms: Foam
II. Understanding brittle and ductile failure
III. Understanding fracture speeds
IV. A new Brittle-to Ductile Transition

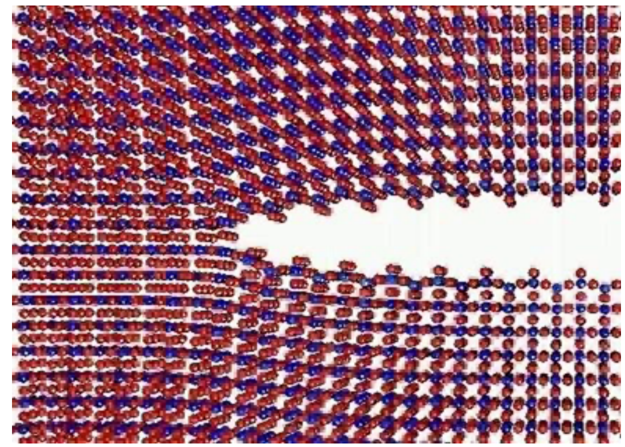
Fracture: Ductile and Brittle cracks

α-Fe [Cheung &Yip 1993]



- plastic deformation (process zone)
- blunt tip
- defects/dislocations
- generally relatively slow
- occur at low rate of applied stress

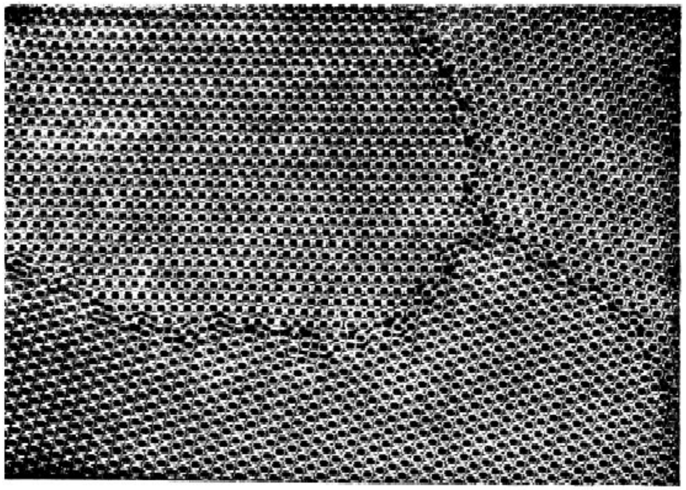
[Michael Marder 2004]



- elastic (small) deformations
- sharp tip
- no defects
- fast ($\leq c_R$), velocity gap!
- high rate of applied stress

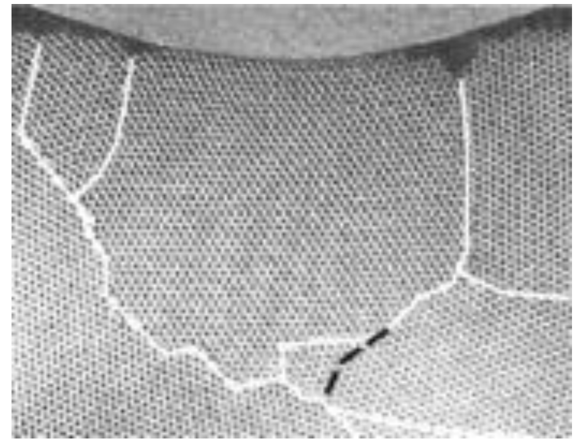
length scales nm, time scales ps!

2-D foams: A model for atomic solids



Grains

L. Bragg,
(1947)



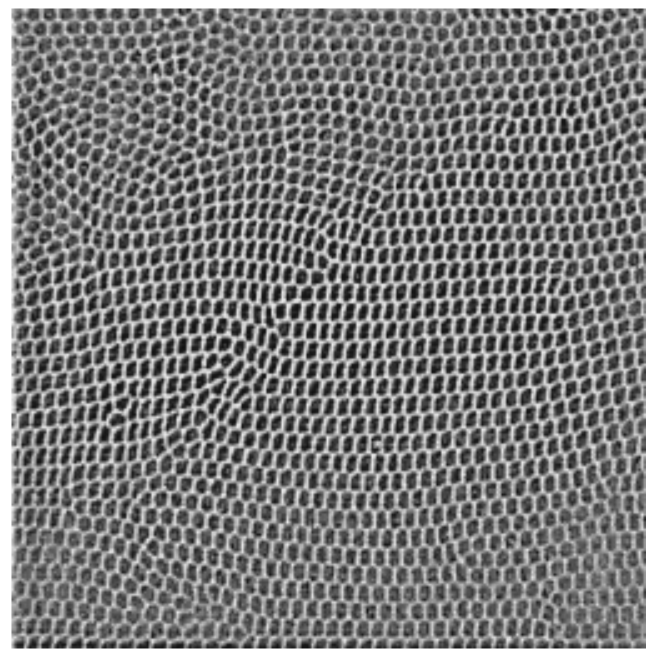
Plasticity

S. Suresh,
MIT (2004)

Can we fracture a layer of liquid foam?

Length scales: mm
Physical properties dominated by
surface tension γ and
viscosity of water μ

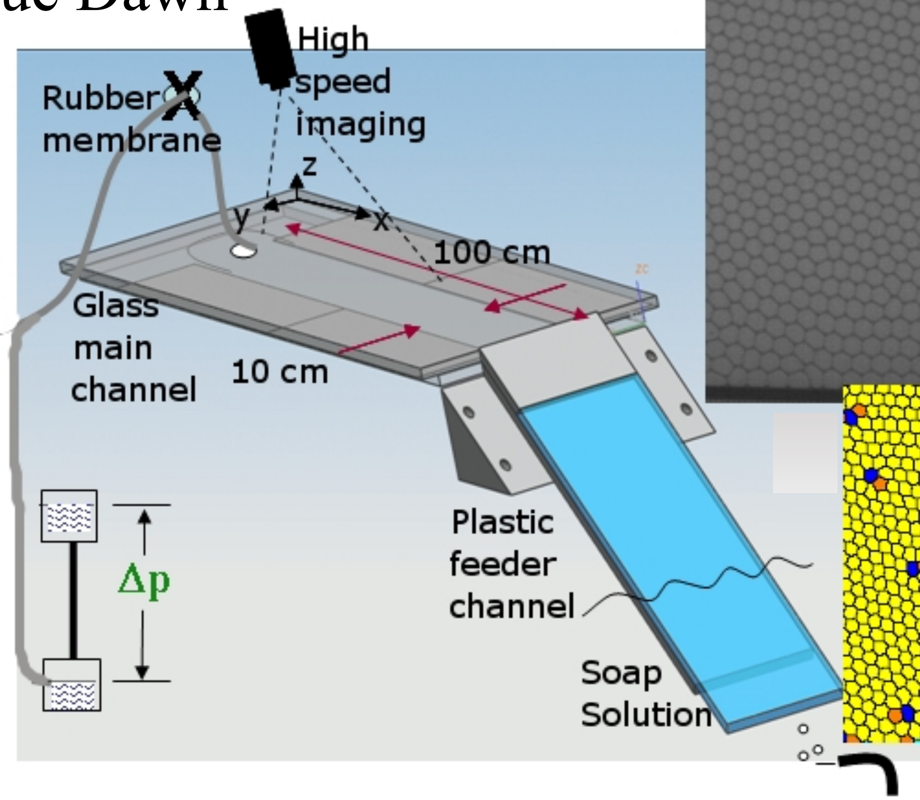
Geometry is important!

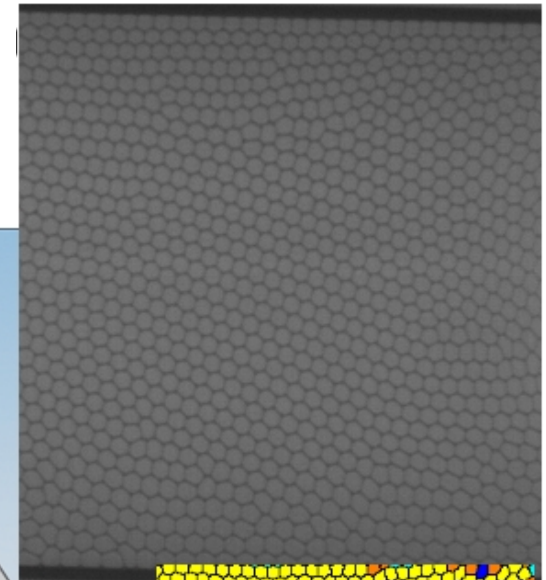


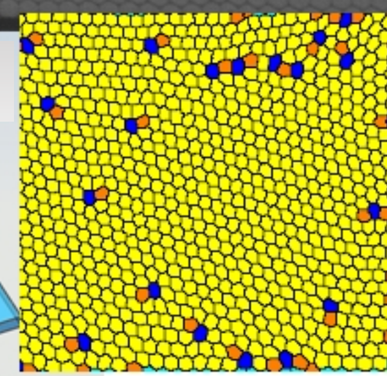
Experimental set-up

- Rectangular-channel Hele-Shaw cell,
  gap b ≈ 1mm
- Dry aqueous foam, Blue Dawn

$\gamma \approx 0.025$ N/m,
$\mu \approx 10^{-3}$ Pa s



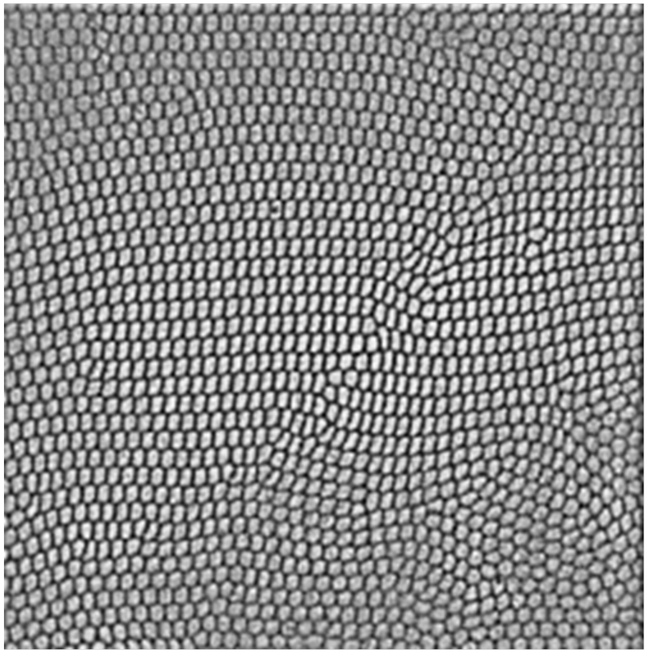


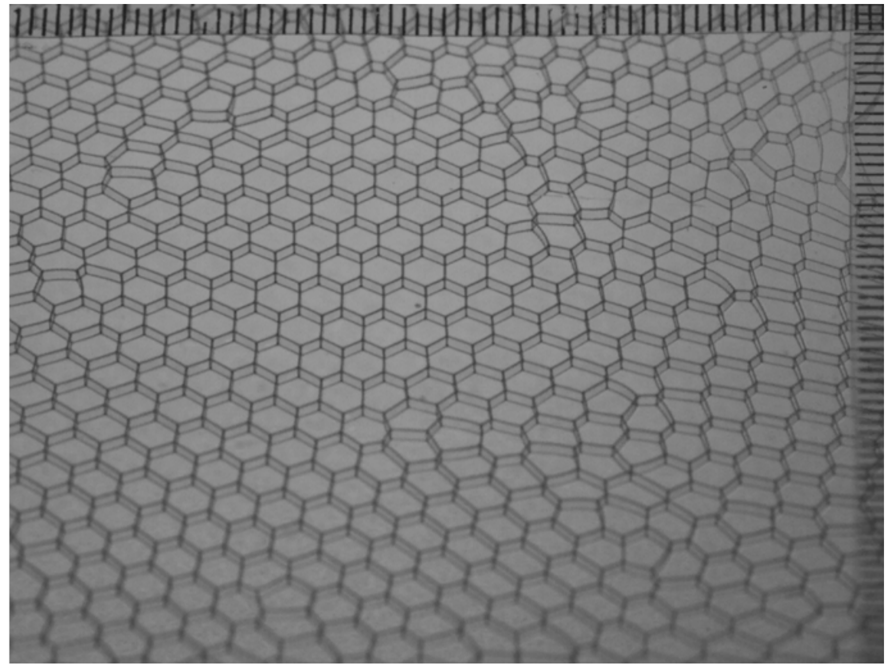


- Bubble distance
  D=3 mm → quasi-2D
- ΔP=1000…4000Pa

rise time of ΔP (rate of applied stress) controllable!

Ductile Cracks

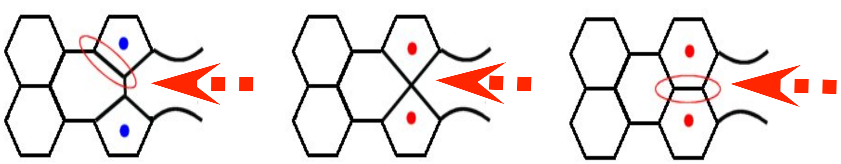




[500fps] Pressure rise time ~ 1s [100fps]

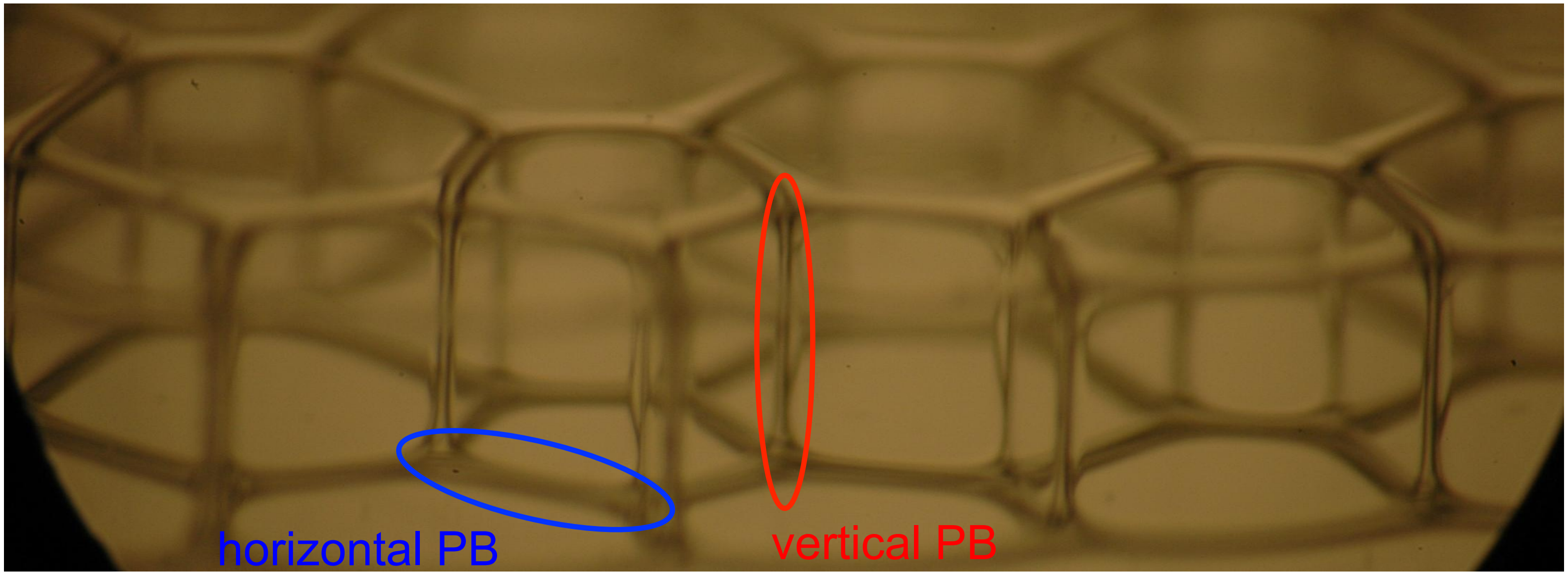
Fingering, plastic behavior!

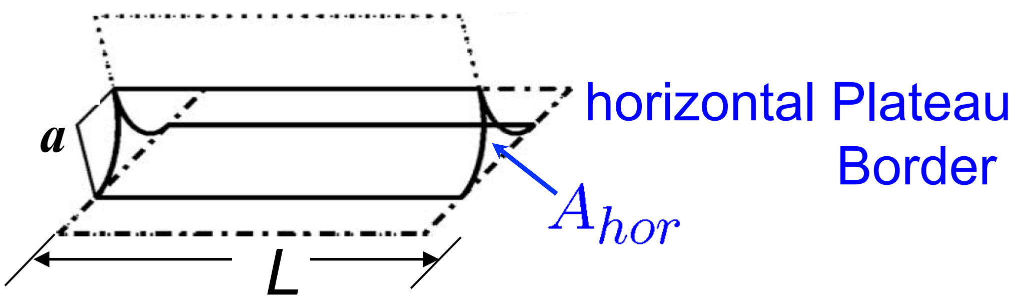
T1 process

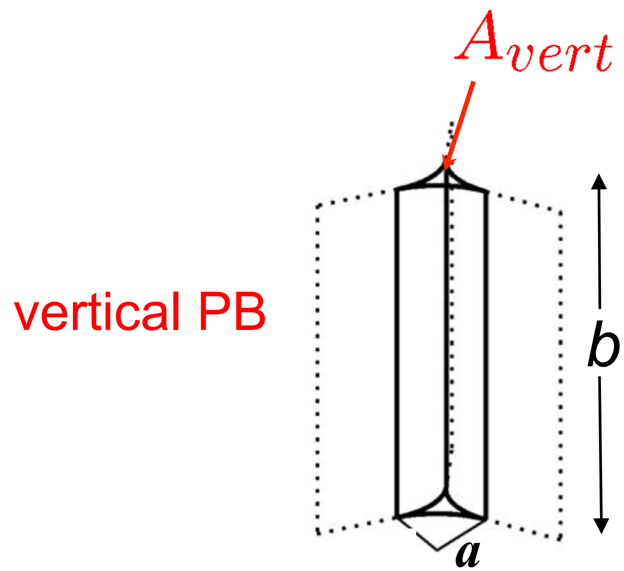


Observation: never propagates faster than ~ 0.4 m/s!

Quasi-2D foam geometry

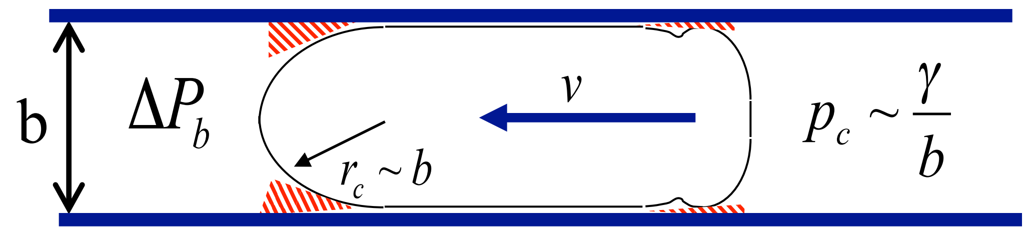






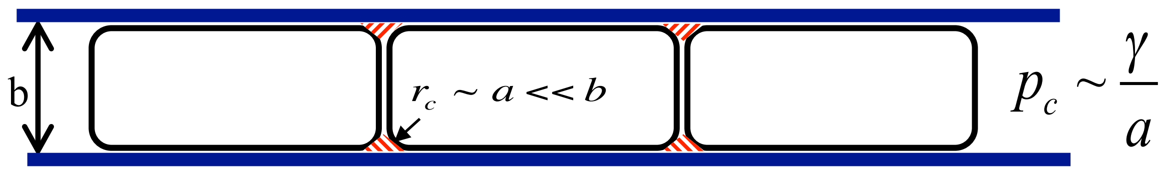
Quasi-2D foam rheology

Bretherton’s (1961) single bubble



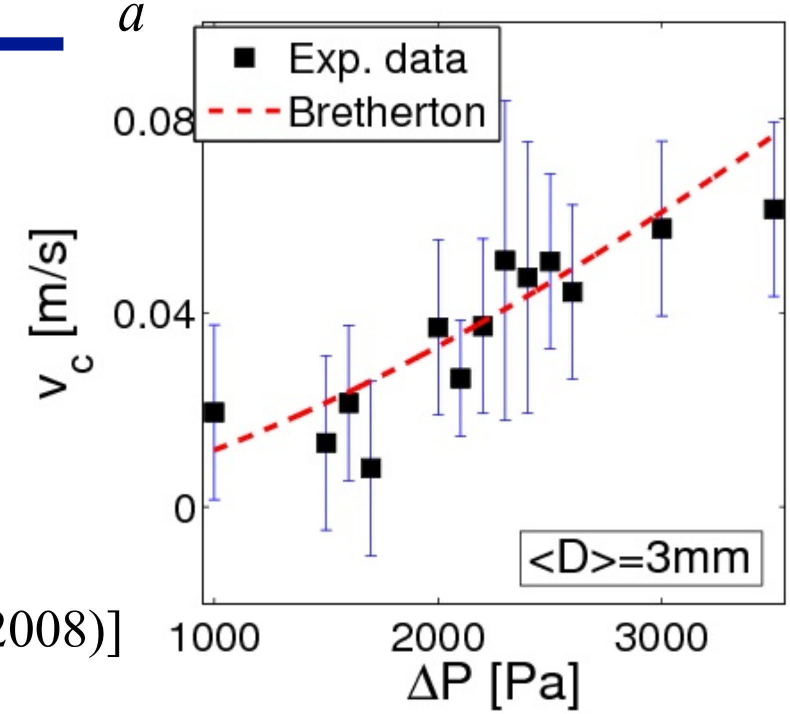
$$Ca = \frac{\mu v}{\gamma}$$

Monolayer of dry foam



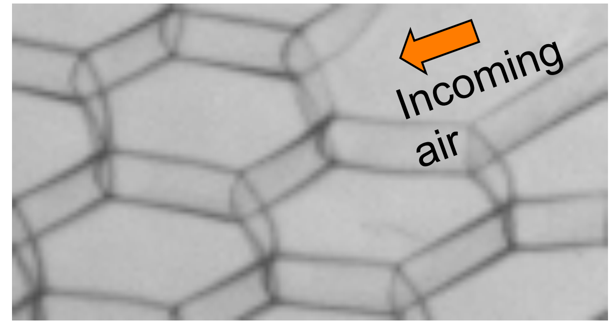
$$\Delta P_b = 4.70\, p_c Ca^{2/3}$$

Bretherton theory
quantitatively valid!



[SH, S. Arif, JC Tsai , Phil. Trans. Roy. Soc. A (2008)]

Ductile threshold velocity

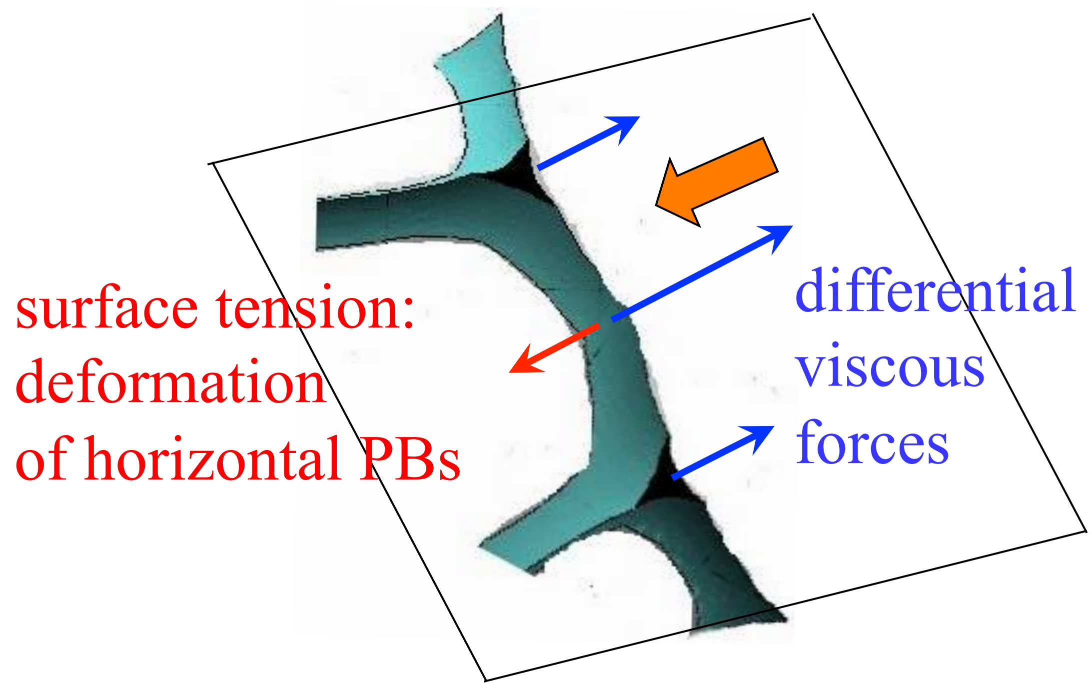


$$\frac{2\gamma}{L} = 4.70\,\frac{\gamma}{2a}\,Ca^{2/3}$$

$$Ca_c = \left(\frac{4a}{4.70L}\right)^{3/2}$$

$$v_c = 0.36\,m/s$$

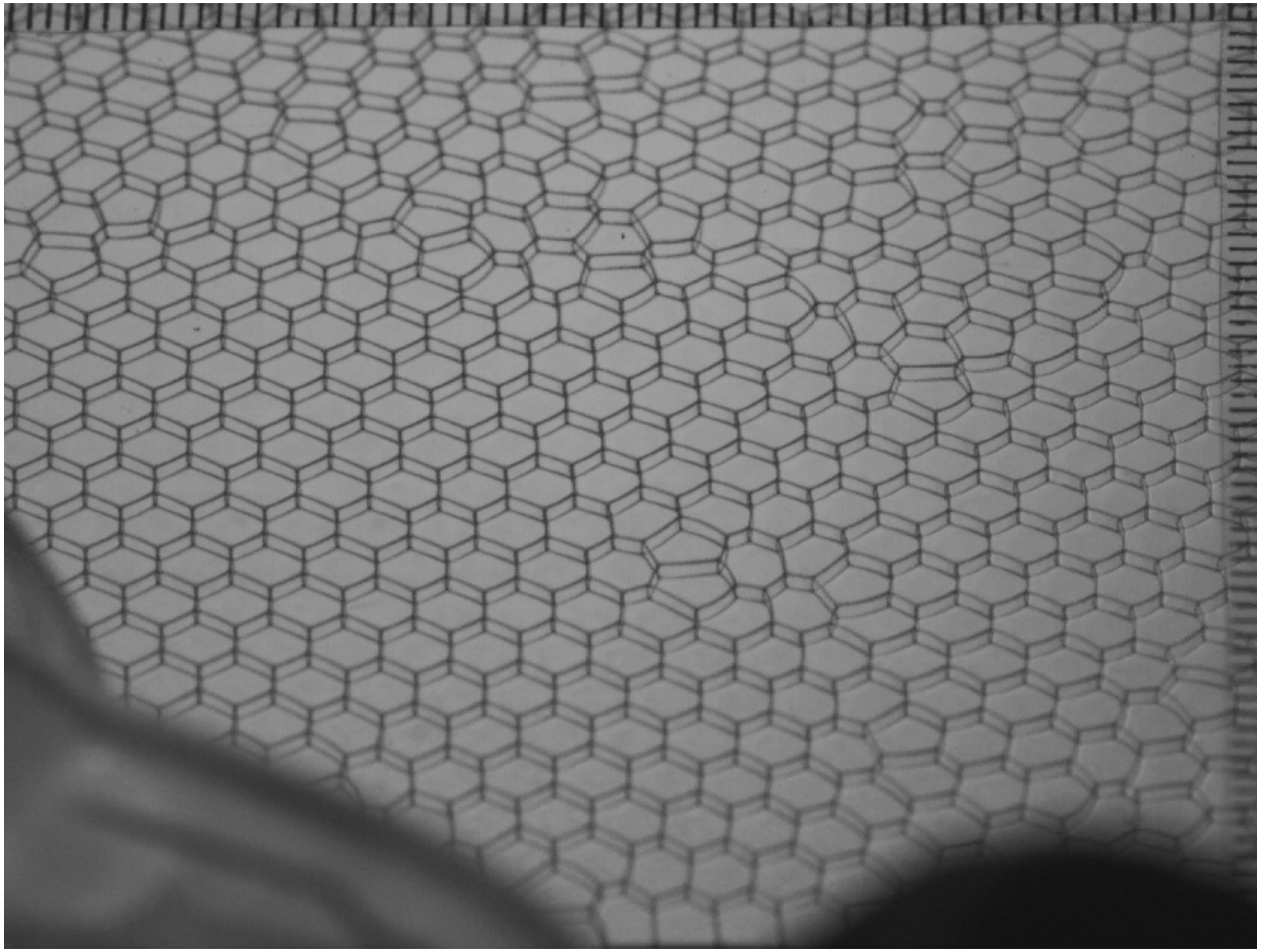
confirmed
experimentally



Establishes upper speed limit for ductile propagation mode

[SH, S. Arif, JC Tsai , Phil. Trans. Roy. Soc. A (2008)]

Brittle Cracks

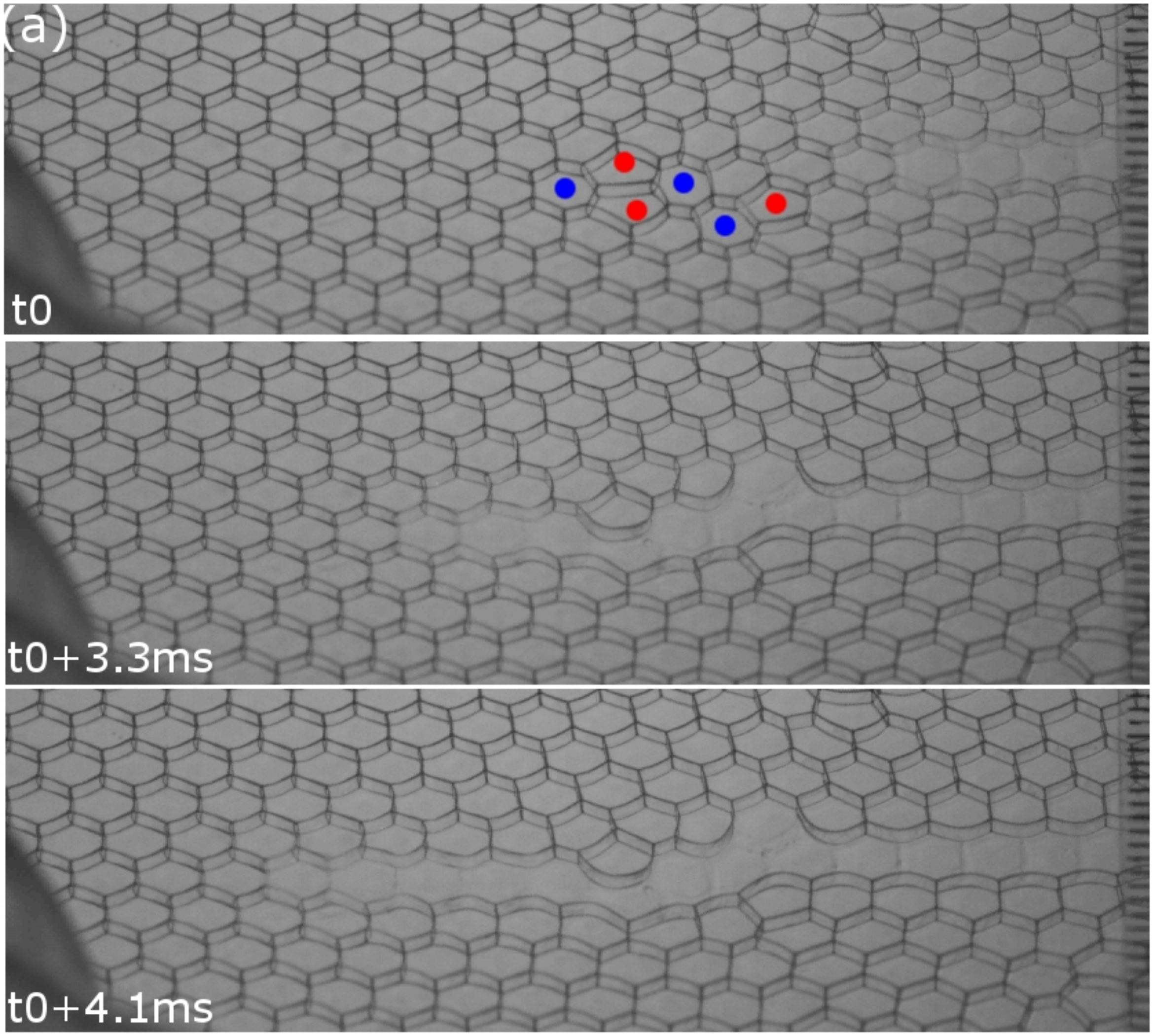


[2400fps]

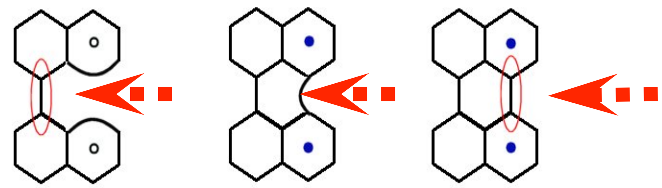
Pressure rise time < 1ms

Straight cleavage, elastic behavior!

Brittle Cracks

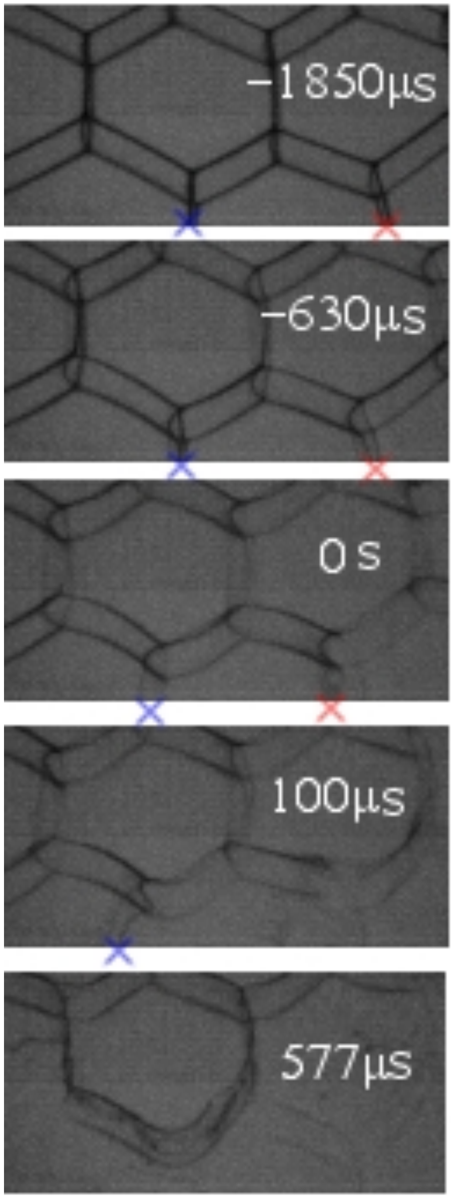


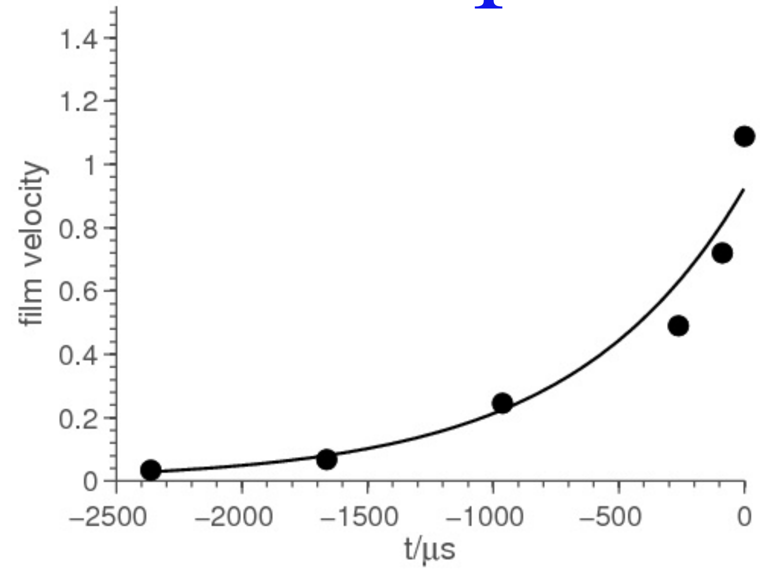
Film rupture

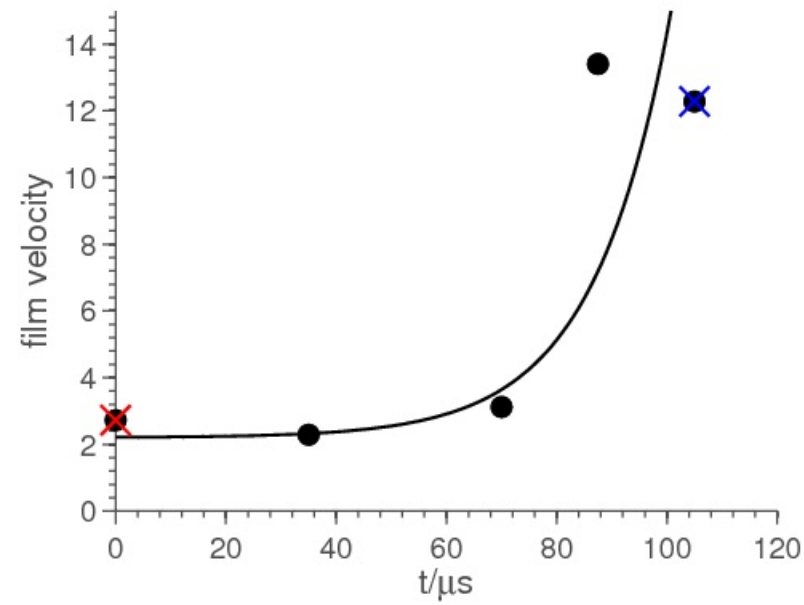


Observation: never propagates slower than ≈10 m/s: velocity gap!

A close look at film rupture

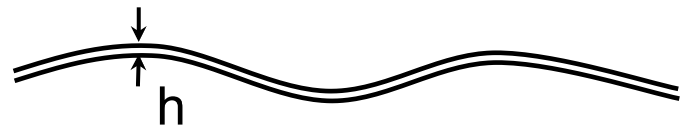






acceleration up to $10^5 m/s^2$!

Film stability



$$\tilde{\omega}_{im} = \left(-\tilde{k}^3 \coth(\tilde{k}) \left\{ 1 - \left[1 - \left(1 - \frac{\tilde{k}_c^4}{\tilde{k}^4} \right) \tanh^2(\tilde{k}) \right]^{1/2} \right\} \right)^{1/2}$$

$$\tilde{k} = kh \qquad \tilde{k}_c = (\rho a_f/\gamma)^{1/2} h^2$$

$$\tilde{k}, \tilde{k}_c \ll 1 \Rightarrow \omega_{im}(k_m) \approx (\rho/2\gamma)^{1/2} h^{1/2} a_f$$

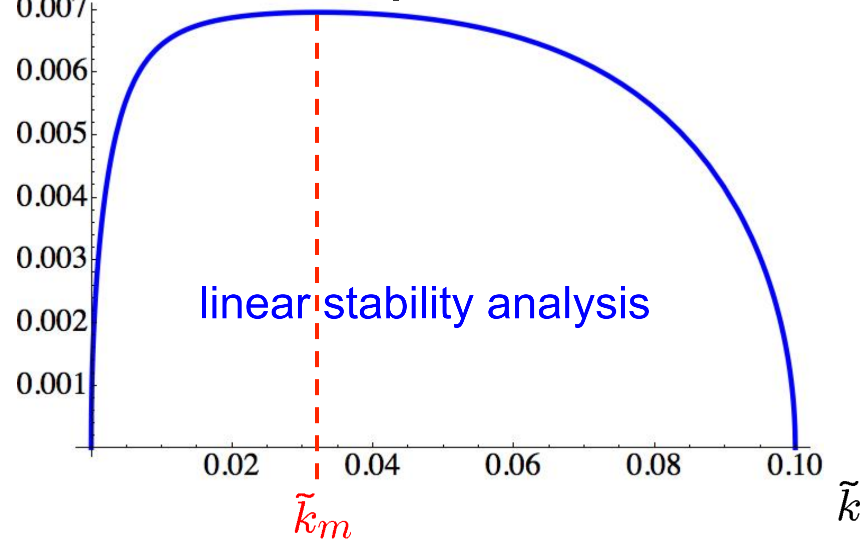
film acceleration:

$$a_f = \Delta P/(\rho h) \propto h^{-1} \Rightarrow \omega_{im} \propto 1/h^{1/2}$$

thinner films are more unstable!

[Keller & Kolodner, J. Appl. Phys. 1954]

[Bremond & Villermaux, JFM 2005]



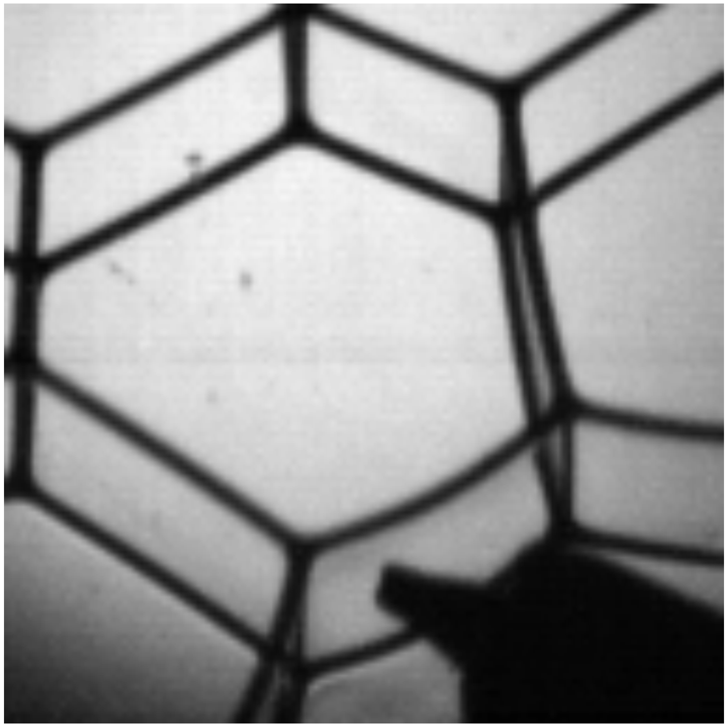
breakage time scale:

$$\tau_{break} = \ln(h/\zeta_0) \frac{(2\rho\gamma h)^{1/2}}{\Delta P}$$

For typical h~1μm, ΔP=2000Pa: $\tau_{break} \sim 100\mu s$

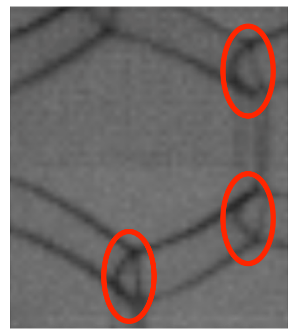
Predicts growth of crack speed with D, ΔP, $1/h^{1/2}$ (confirmed experimentally)

Film breakage and waves



Wave propagates around bubbles through unbroken films

Measured: c ≈ 10.4m/s



Oscillating mass in vertical PBs!

[57000fps]

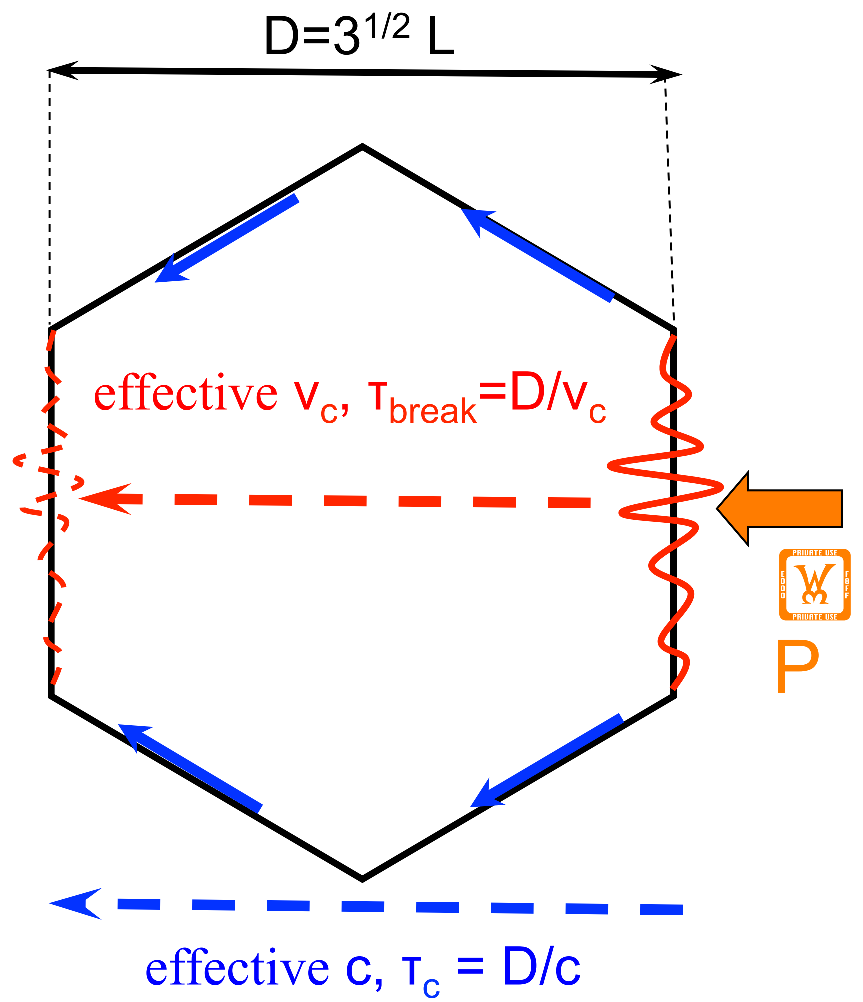
2D theory:

$$c \approx \left(\frac{6\gamma}{\varepsilon_2 \rho L}\right)^{1/2}$$

[Schwartz & Princen, JCIS 1987]

For our a ≈140μm, b=1mm, L=2mm:
ε_2≈0.001, c ≈ 9.8 m/s !

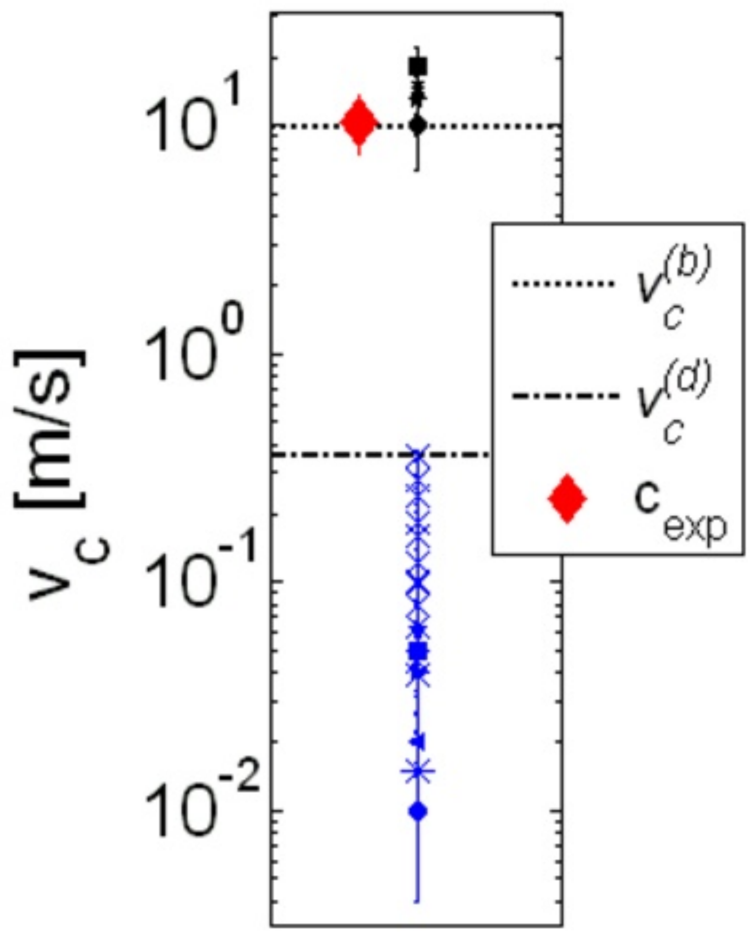
Brittle threshold velocity



if $\tau_{break} > \tau_c$, ΔP cannot be maintained: no brittle crack !

minimum (lower bound) speed: $v_c^{(b)} = c$, brittle cracks are supersonic

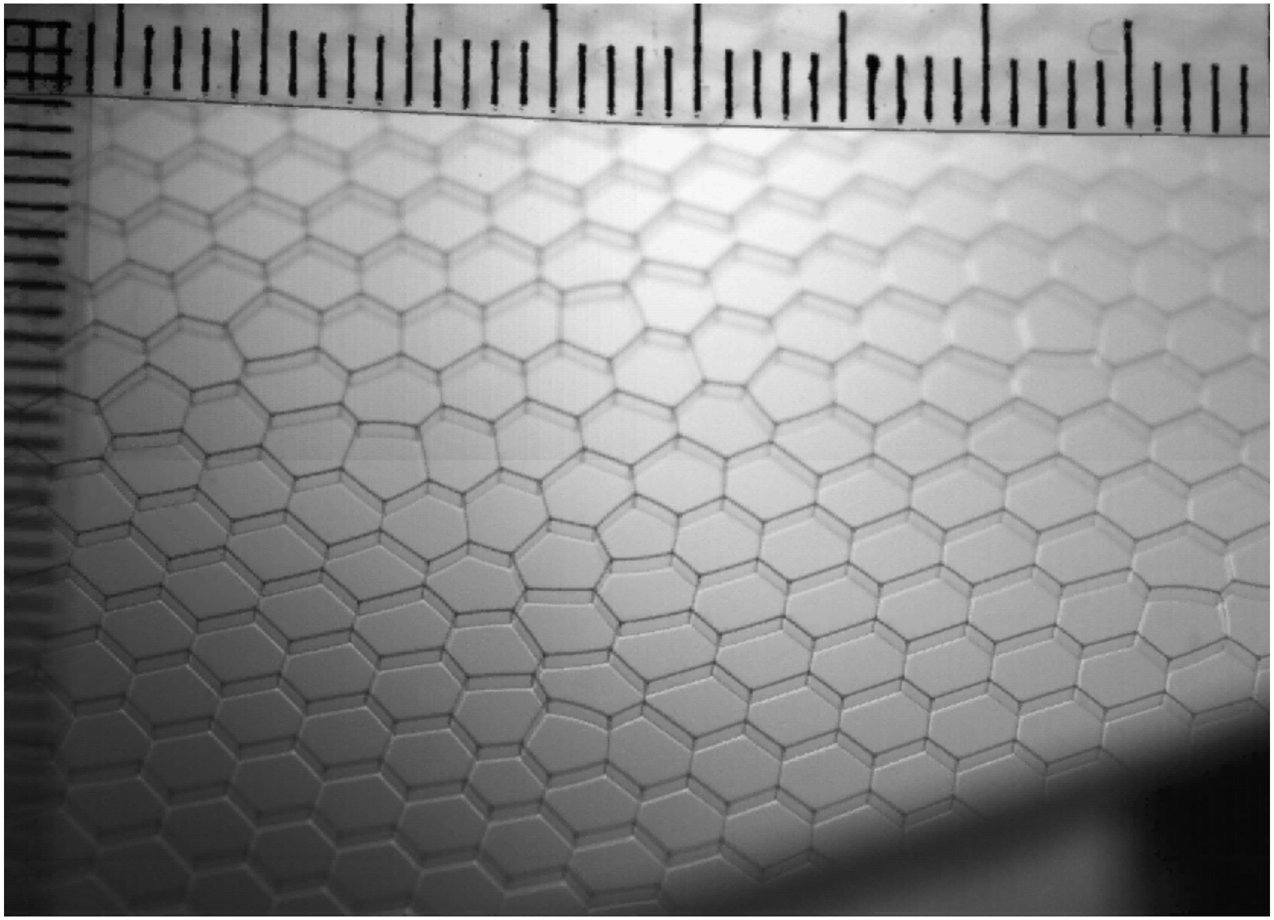
The velocity gap



- All ductile velocities below $v_c^{(d)}$
- All brittle velocities above $v_c^{(b)}$
- All brittle velocities supersonic

[S. Arif, JC Tsai, SH, Europhys. Lett. (2010)]

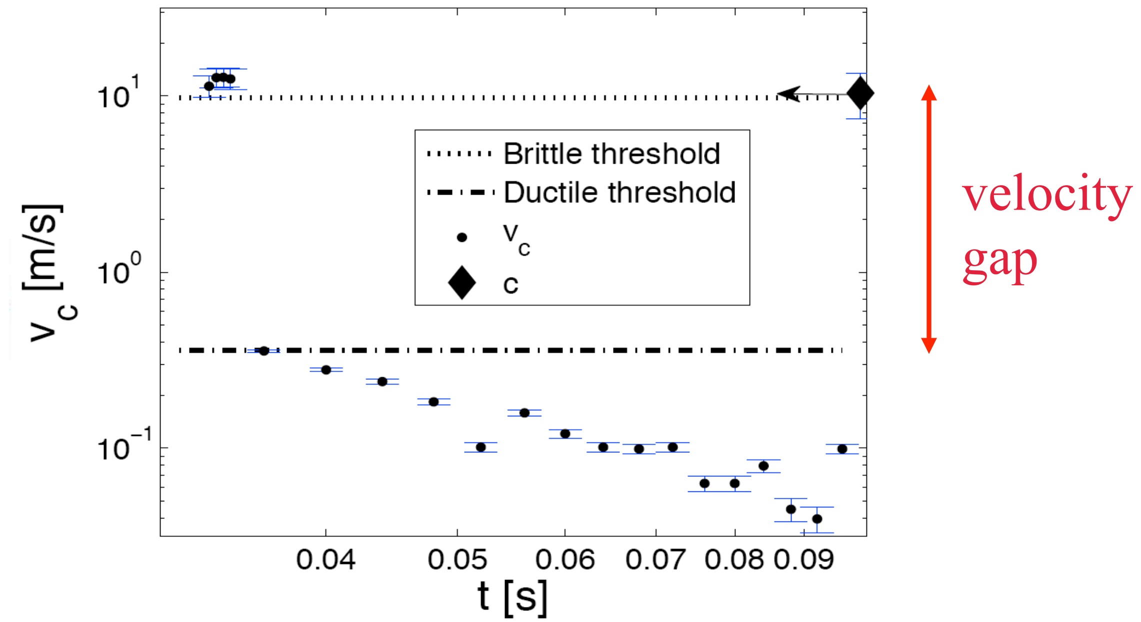
Spontaneous Brittle-to-Ductile Transition



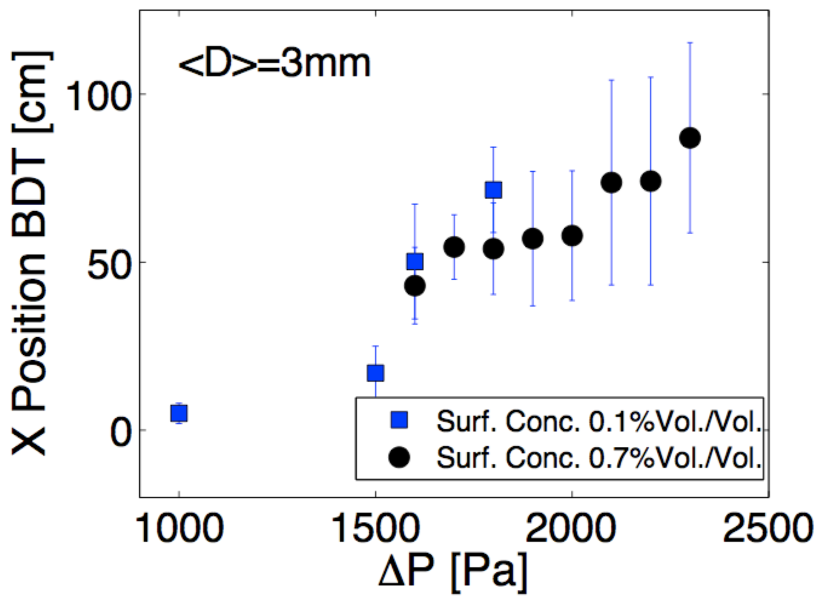
[2400fps]

Spontaneous Brittle-to-Ductile Transition

Dynamics obeys velocity gap!



Location of BDT varies with ΔP



Conclusions

- Quasi-2D foam displays two distinct failure modes – brittle and ductile
- Fracture velocities are explained from first principles
- Velocity gap: a consequence of limiting velocities
- Spontaneous Brittle-to-Ductile transition because of dissipative effects

Future work: Effects of defects, microstructure