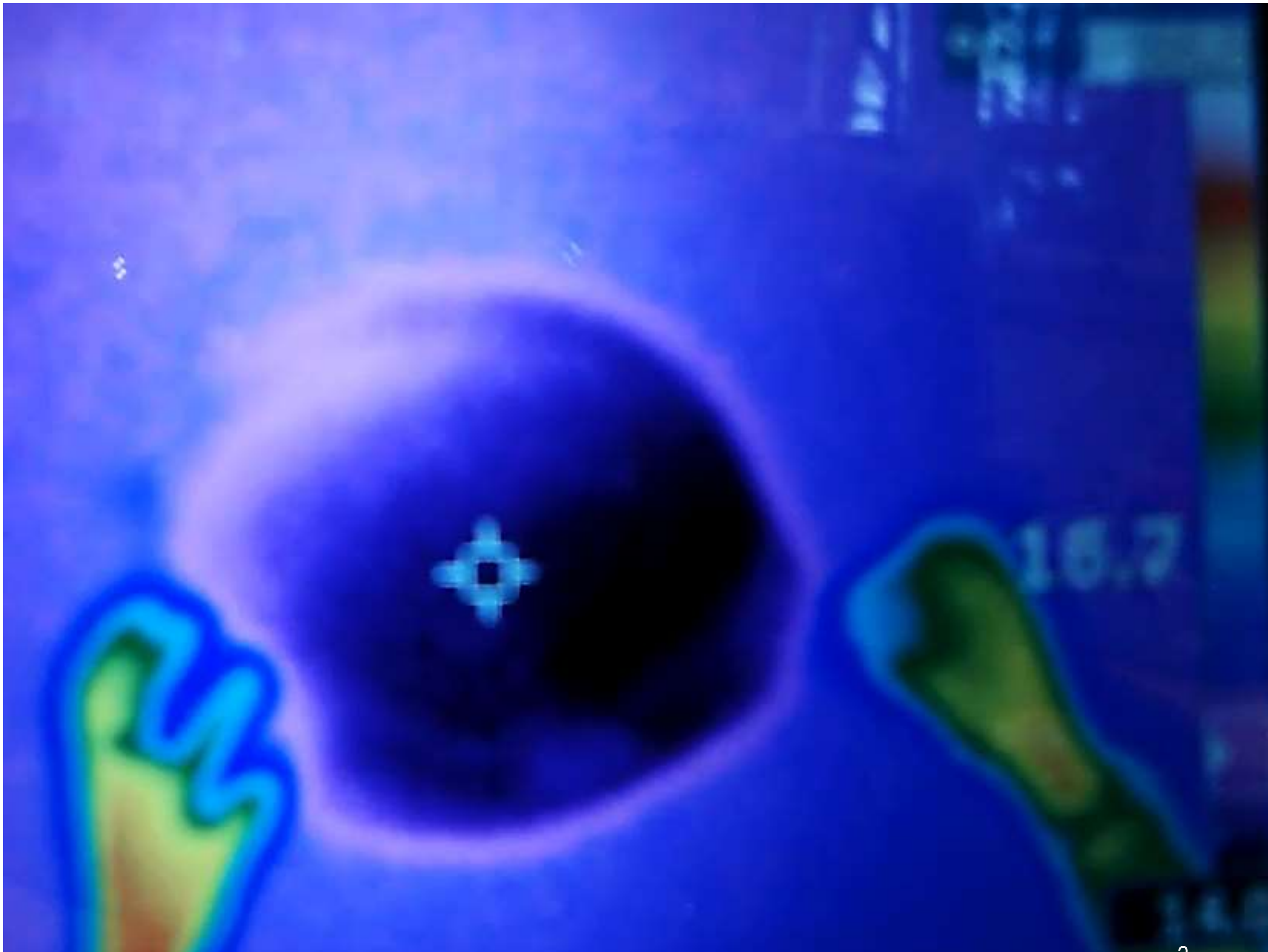
SLOVAKIA
IYPT '14

12

Cold balloon

Jakub Chudík

Cold balloon

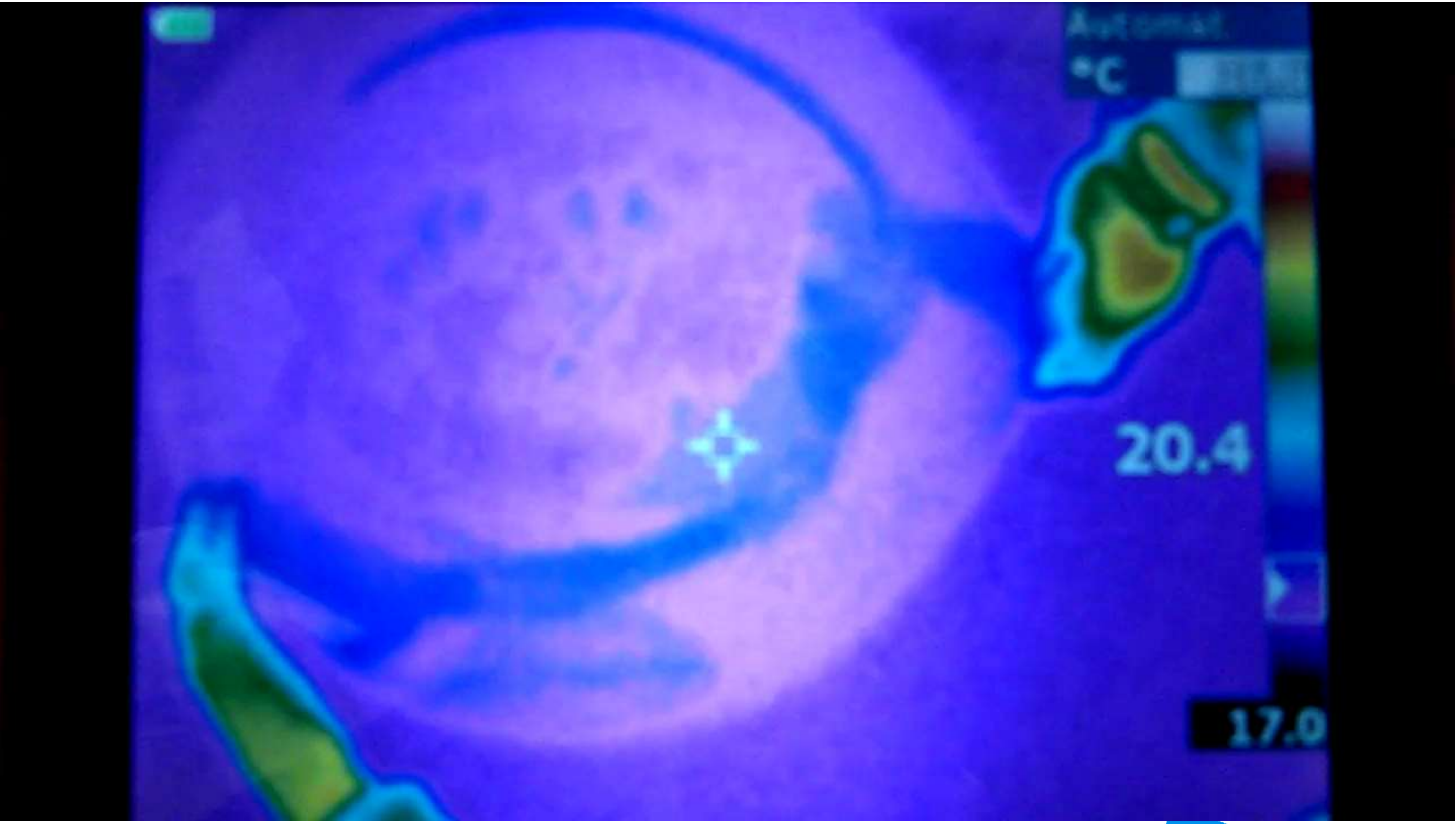


Task

As *air* escapes from an inflated rubber balloon, its surface becomes *cooler* to the touch. Investigate the parameters that affect this cooling.

What is the *temperature* of *various parts* of the balloon as a function of *relevant parameters*?

How does it look?



What causes cooling?

AIR

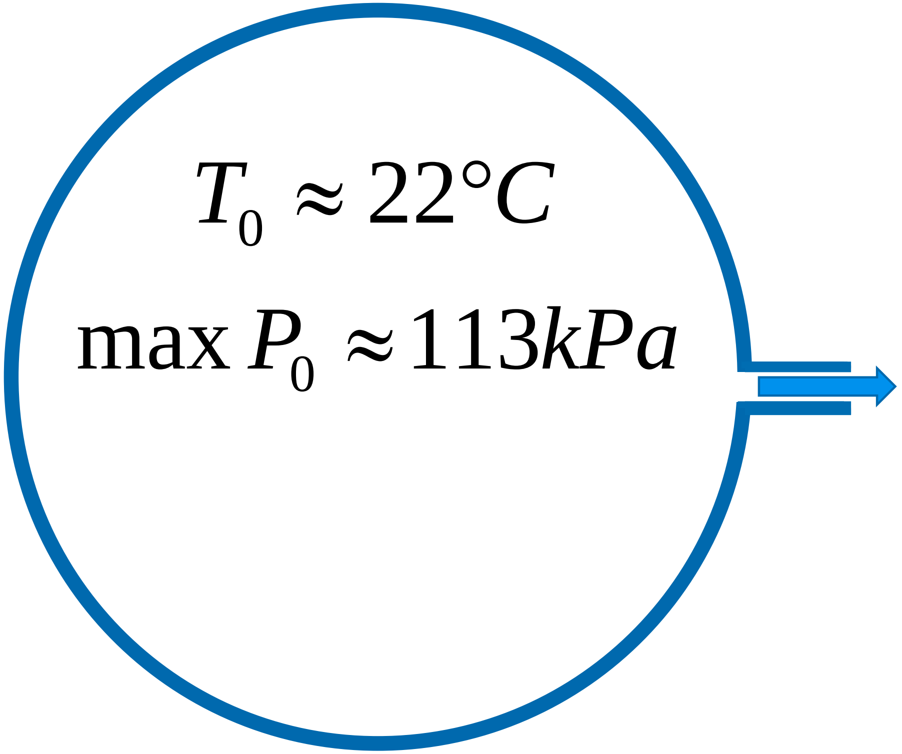
Cool down of *air*
due to expansion

RUBBER

wn of *rubber*
contraction

Can the air cause the cool down?

Escaping air expands due to pressure drop



Assuming adiabatic expansion:

$$T = T_0 \left(\frac{P_o}{P_{Atm}} \right)^{\frac{1-\kappa}{\kappa}}$$

Small balloon: $\Delta T \approx 3{,}5°C$

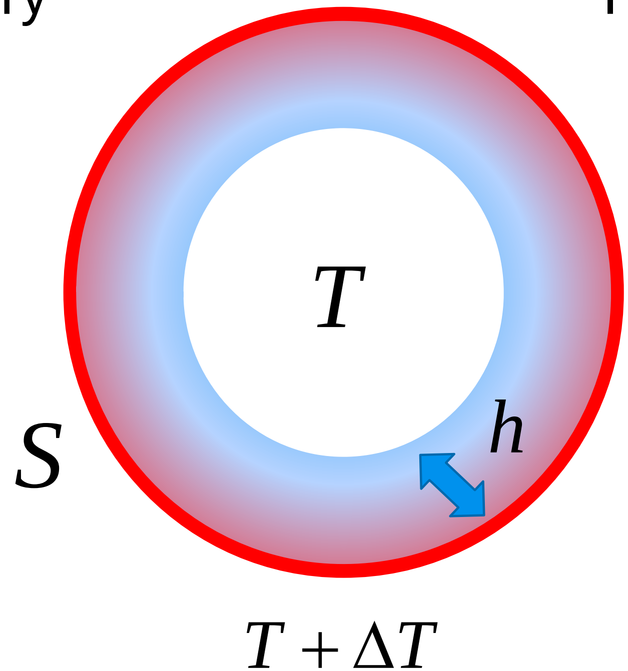
Large balloon: $\Delta T \approx 10{,}5°C$

Total heat transferred

Heat from the boundary layer

- Create temperature gradient
- Isobaric heat capacity

$$Q_2 \approx \frac{1}{2}\frac{P_0 hS}{RT} c_p \Delta T$$



Heat transferred through air

$$Q \approx tkS\frac{\Delta T}{h}$$

h Width of air layer
S Balloon surface
k Heat conductivity of air
t Time of deflation

Total transferred heat

$$Q \approx tkS\frac{\Delta T}{h} + \frac{1}{2}\frac{P_0 hS}{RT}c_p\Delta T$$

Upper estimate of total heat transferred:

$$Q \leq \Delta TS\sqrt{\frac{i+2}{T}Pkt}$$

Drop of balloon temperature:

$$\Delta T \leq \frac{Q}{mc}$$

Estimated temperature drop due to cooling effect of air expansion

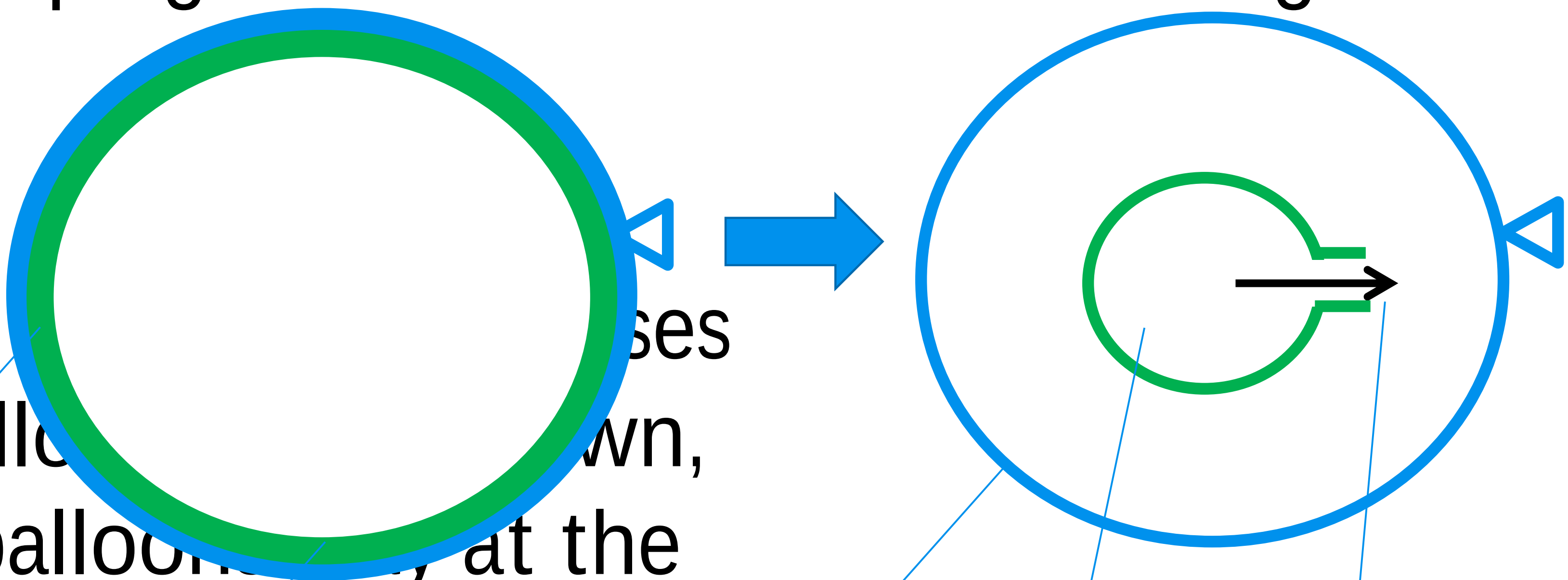
- Large balloon: $\approx 1{,}53°C$
- Small balloon: $\approx 0{,}29°C$

But balloons cool down much more!

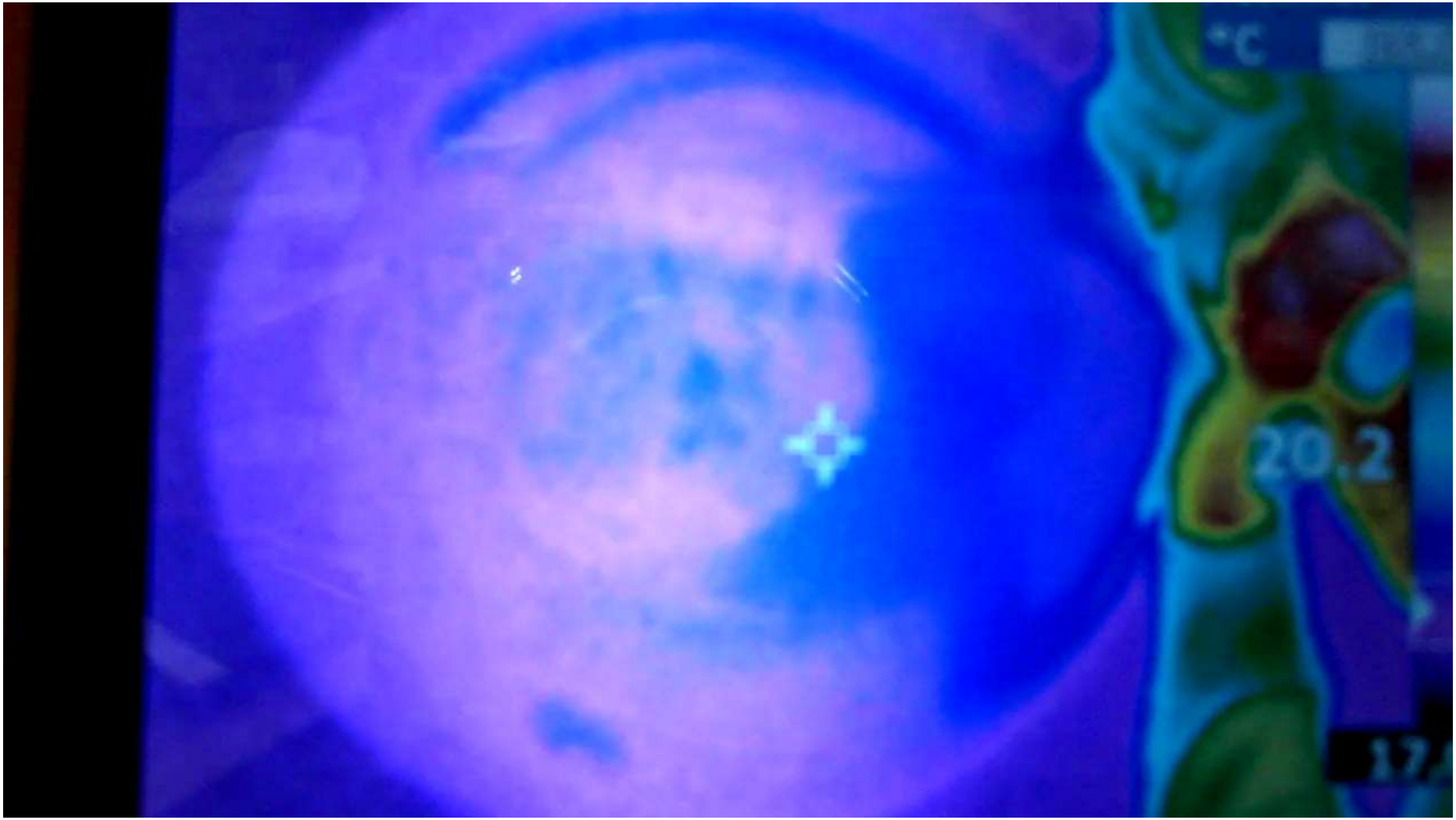
- Large balloon: $\approx 9°C$
- Small balloon: $\approx 9°C$

Experimental verification

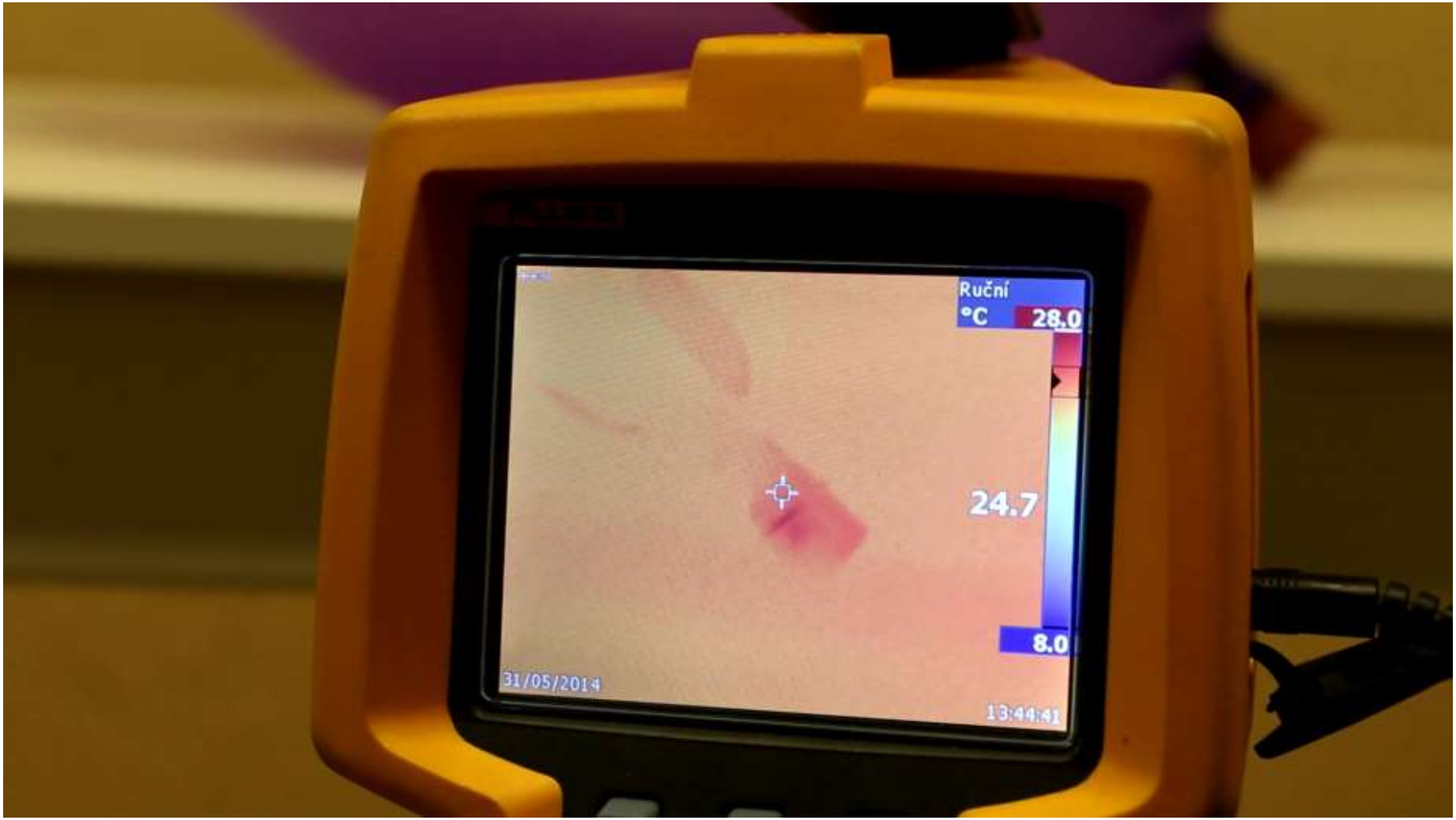
- Smaller balloon inflated inside a larger one
- Air escaping from smaller balloon into larger one
- IF cool ... ses the ballo ... wn, both balloon ... at the same temperature



Cool down of smaller balloon inside larger one

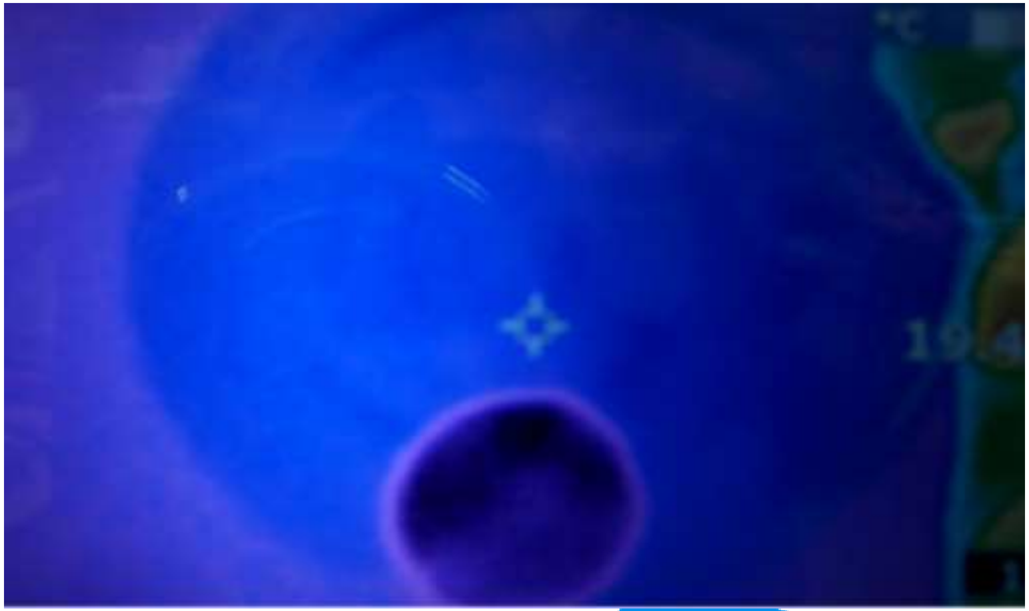


Cooling effect at the hole of balloon



Summary of the effect of air

- Mathematical model $$Q \le \Delta T S \sqrt{\frac{i+2}{T} Pkt}$$
- Calculated the cooling effect of air
  - Large balloon – $\Delta T \approx 1{,}53°C$
  - Small balloon – $\Delta T \approx 0{,}29°C$
- Two experimental verifications



What causes cooling?

Air does not cause the cooling!!!

AIR

Cool down of *air* due to expansion

RUBBER

Cool down of *rubber* due to contraction

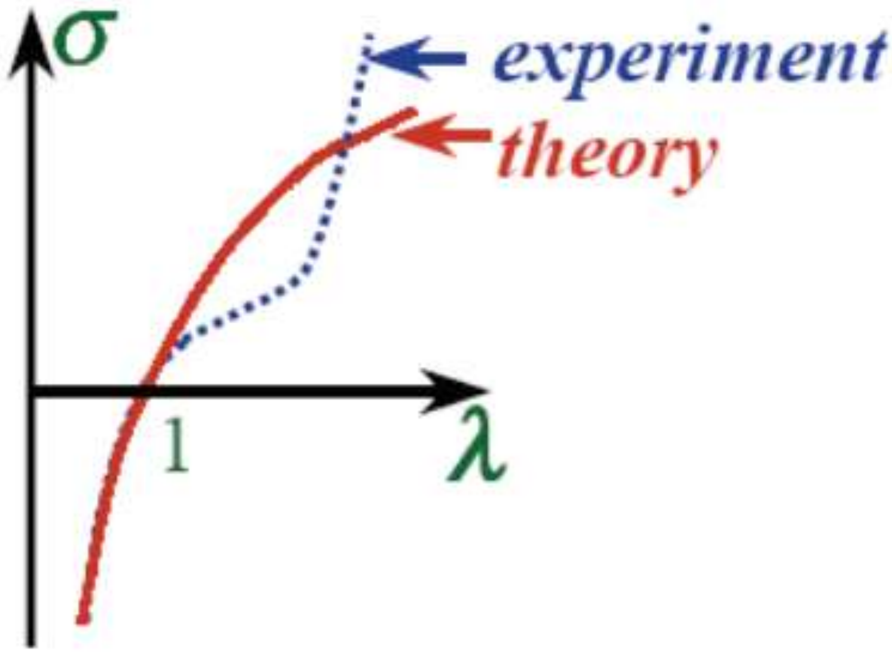
Existing theory

- Equation of state:

$$\sigma = \mathrm{kTv}\left(\lambda - \frac{1}{\lambda^2}\right)$$

- Statistical physics of polymers

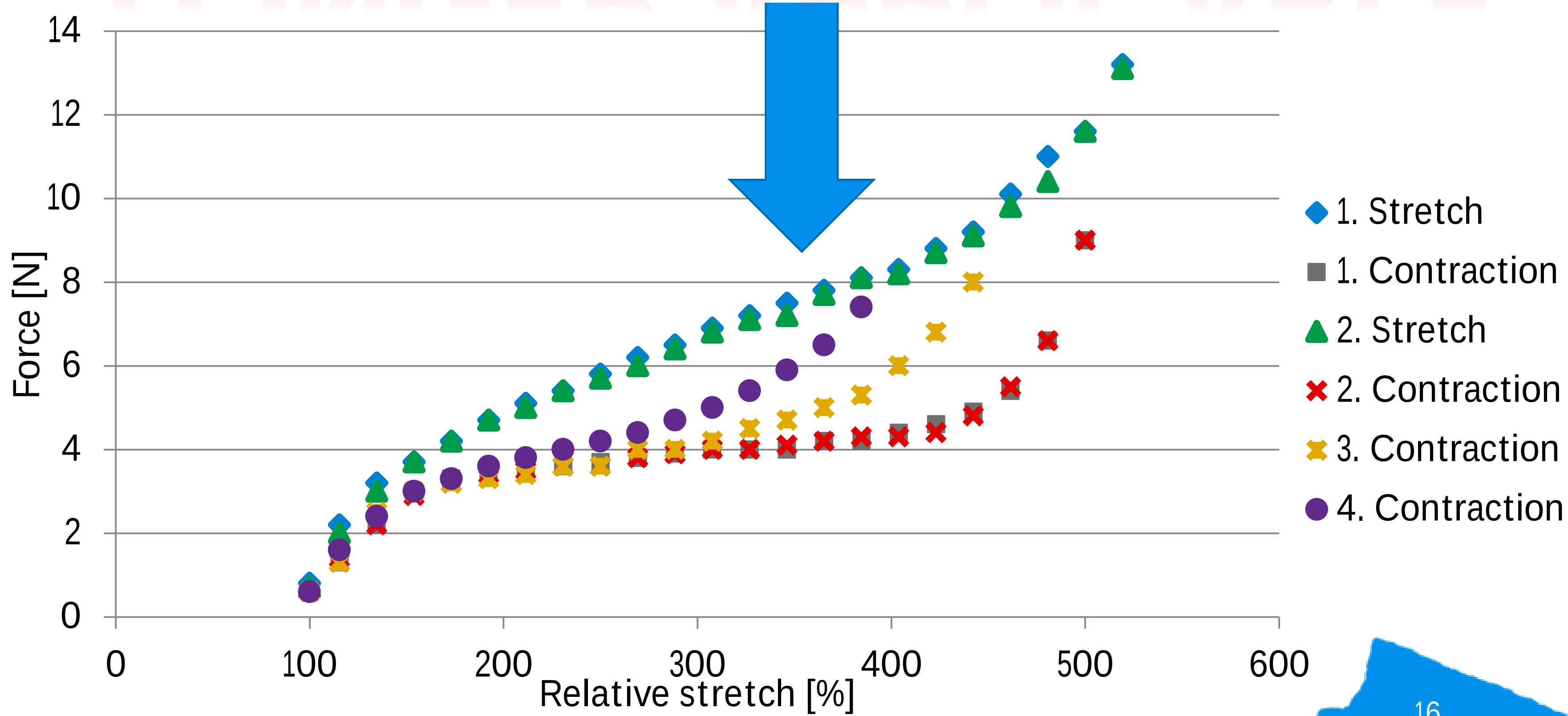
- Applicable only for small extensions
  - 40% - 120% stretch



Alexei R. Khokhlov: Lecture 3 on elastomer physics

Due to:

THIS THEORY IS NO LONGER APPLICABLE



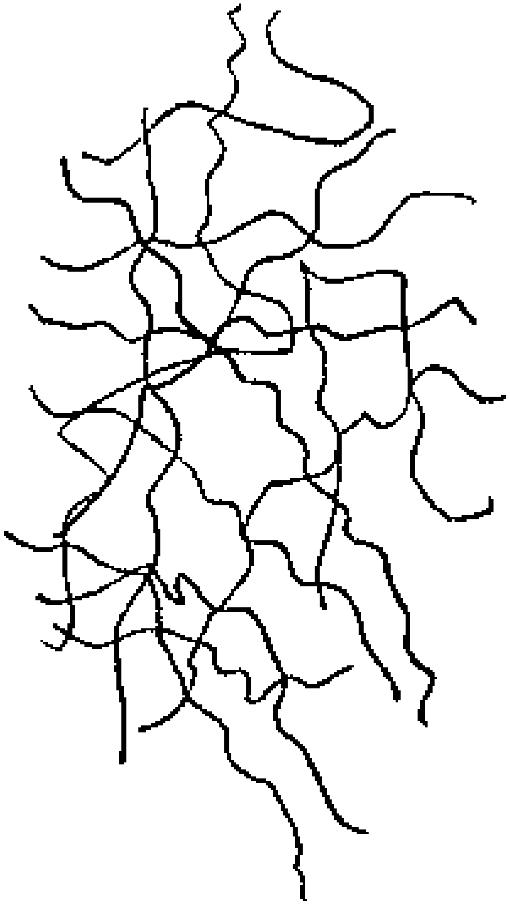
Our task now is to:

1. Explain the mechanism of heat-up and cool-down
   - Internal structure and 1st law of thermodynamics

2. Show the dependence of cool down on stretch

3. Determine the parameters affecting the stretch

Rubber elasticity

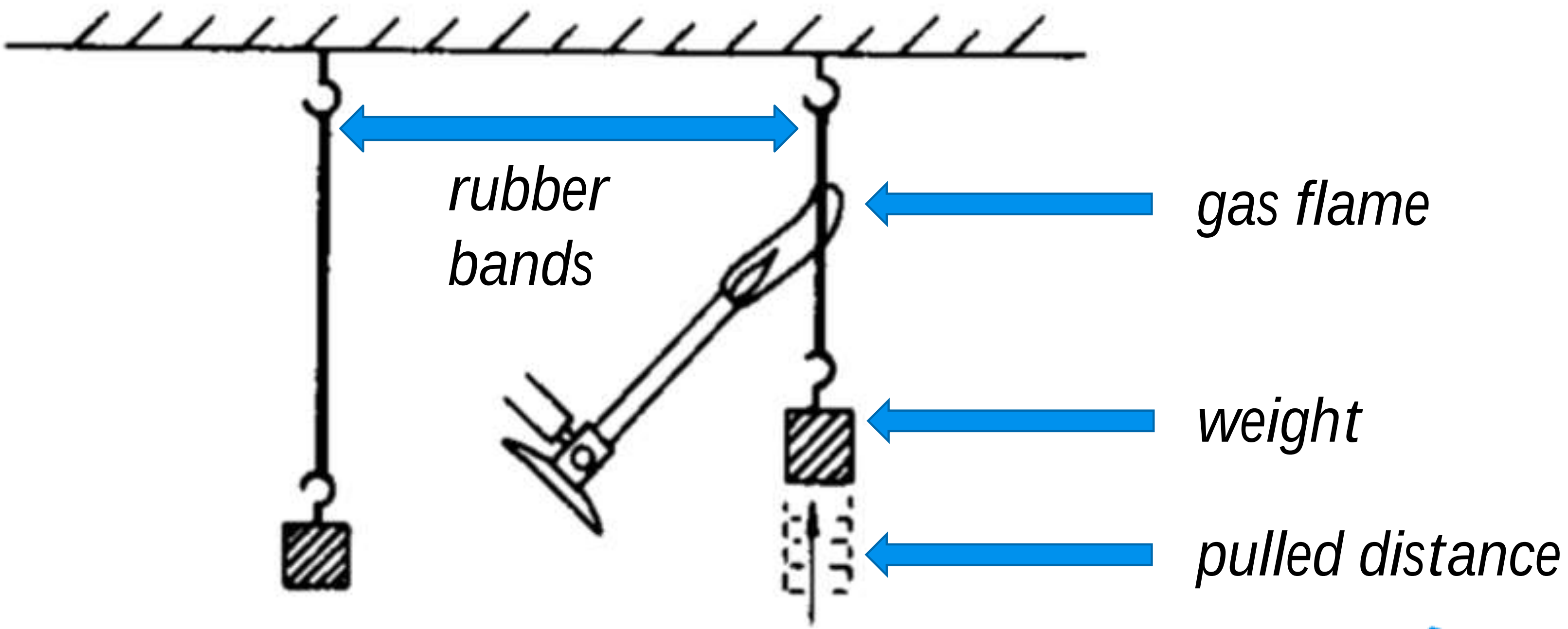


Rubber is composed of cross-linked polymer chains in constant movement

Tension in stretched rubber is caused by **thermal motion** of molecules

Rubber elasticity

- Increased temperature → increased tension
- *Known experiment:* stretched rubber with weight contracts when heated by flame
  - Heat is transformed into work



Feynman, Leighton, Sands: Feynman Lectures on Physics

Pull and release

1st law of thermodynamics: $\Delta U = Q + W$

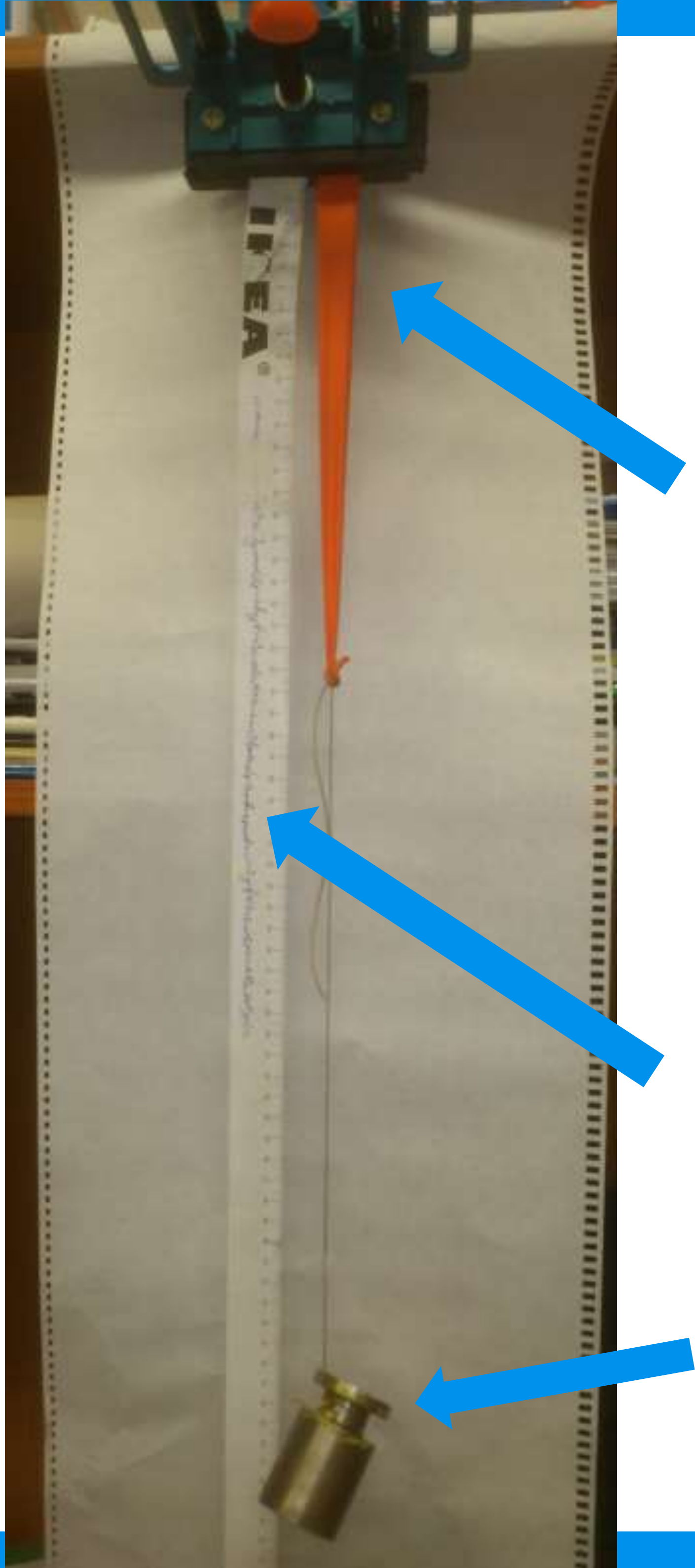
When pulled: $W > 0$ $Q = 0$

- Adiabatic expansion

When released: $W < 0$ $Q = 0$

- Adiabatic compression

Apparatus

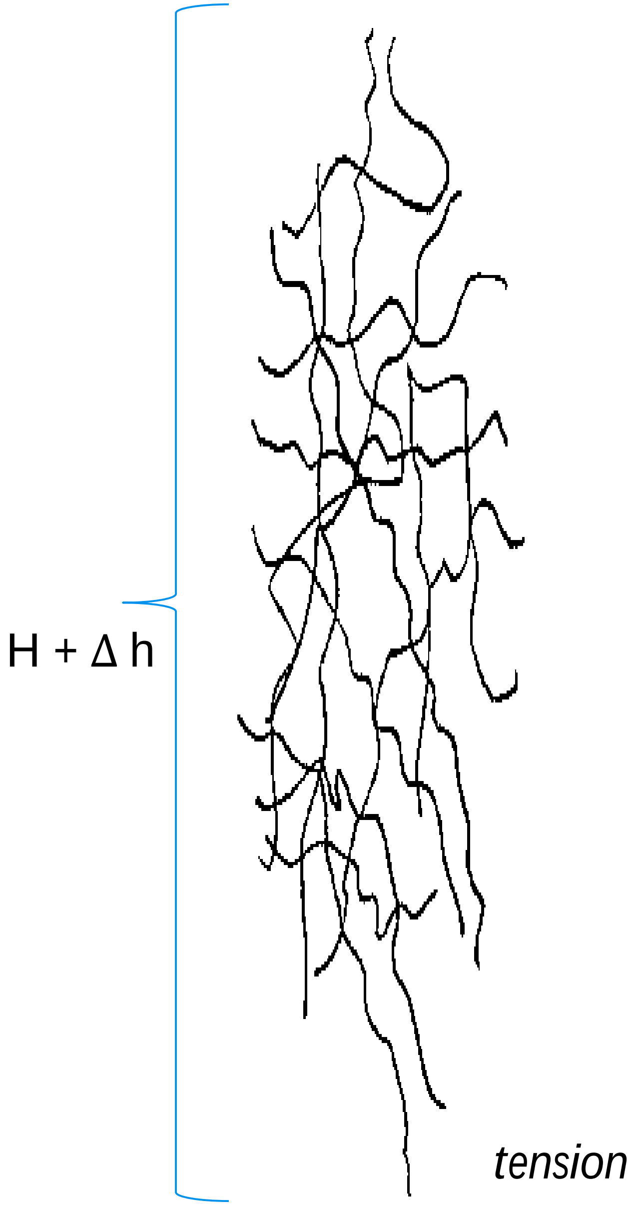


Different weights

Measuring temperature

- before and after stretch
- before and after release

Pull



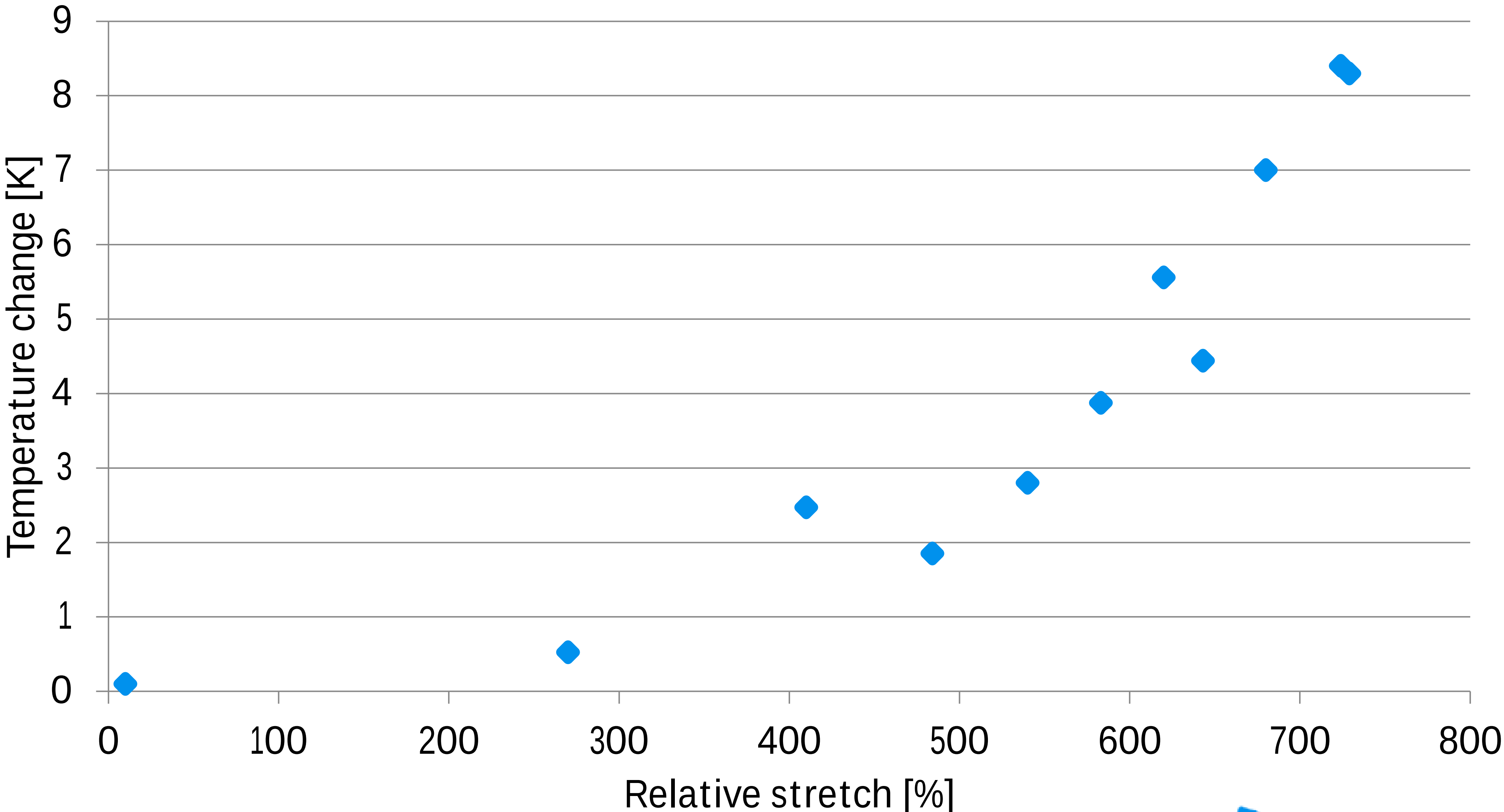
- During stretching, chains kink each other up by thermal movement

- Adiabatic expansion

$$W > 0$$
$$\Delta U = W$$

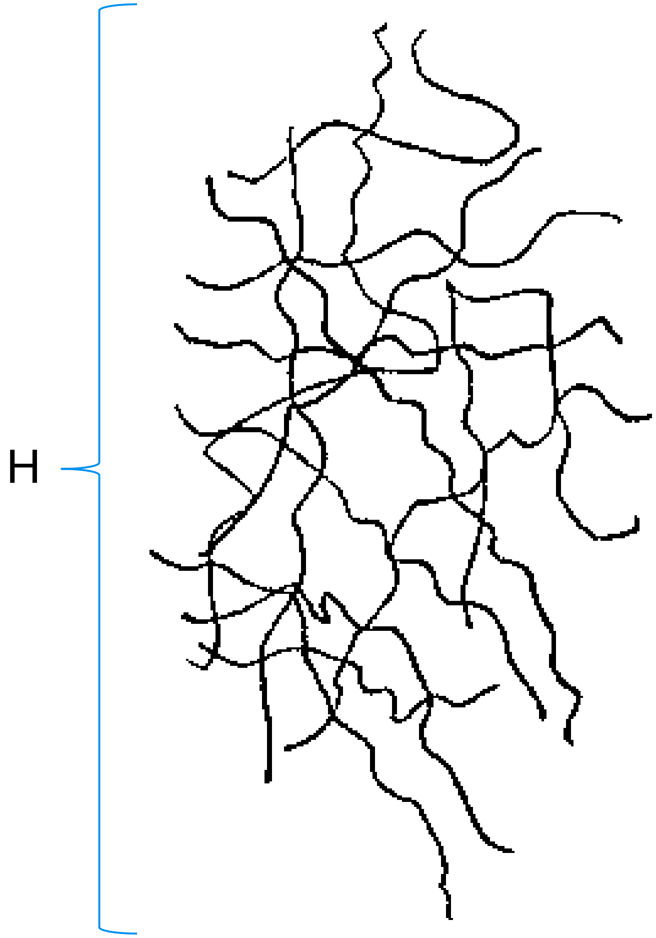
- Internal energy increases → rubber heats

Temperature change when stretched - heating up



Standard deviation – 1,7°C

Release



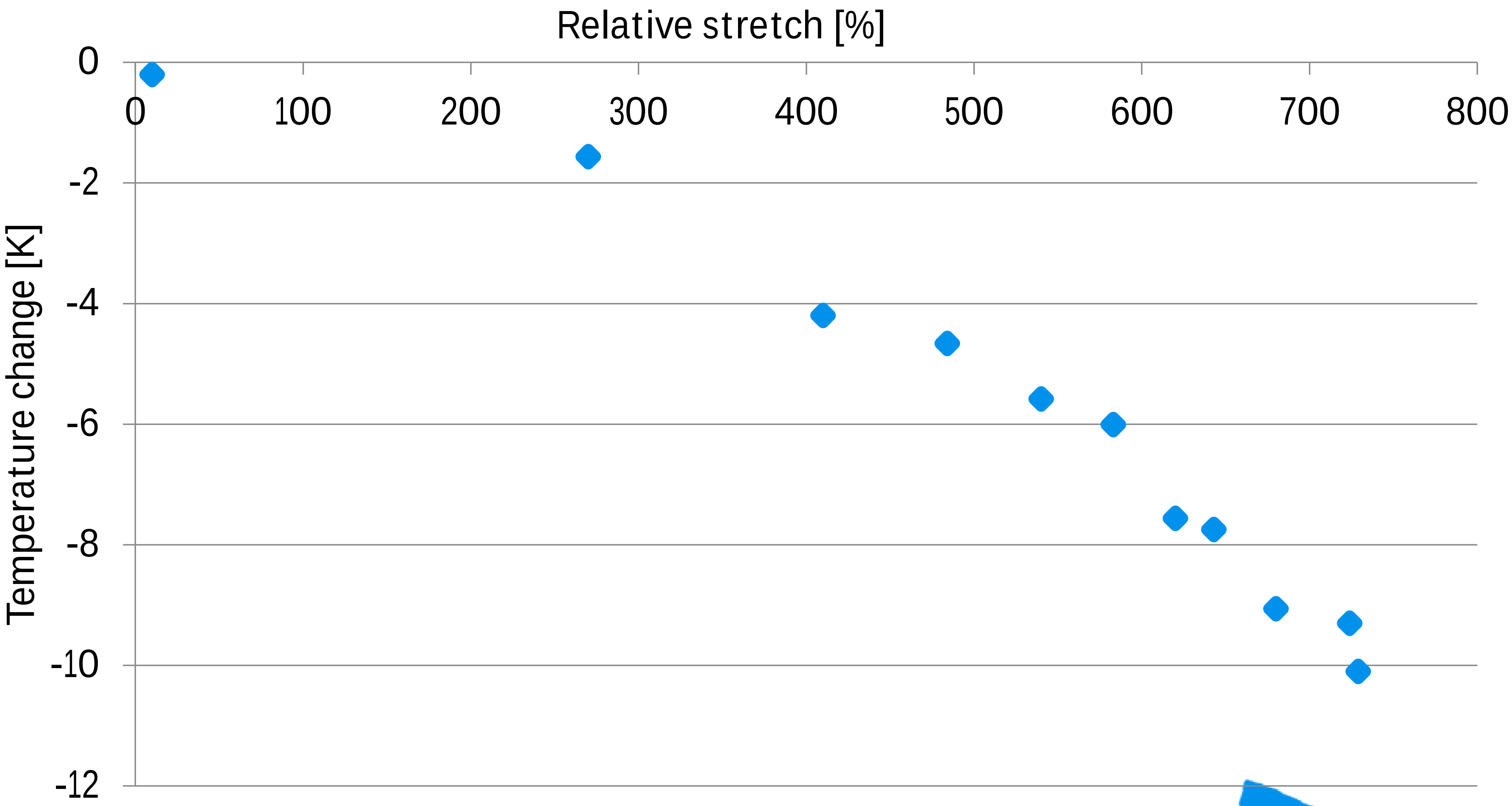
- Polymer chains become relaxed and soft
- Thermal energy is transformed into work
- Adiabatic contraction:

$$W < 0$$

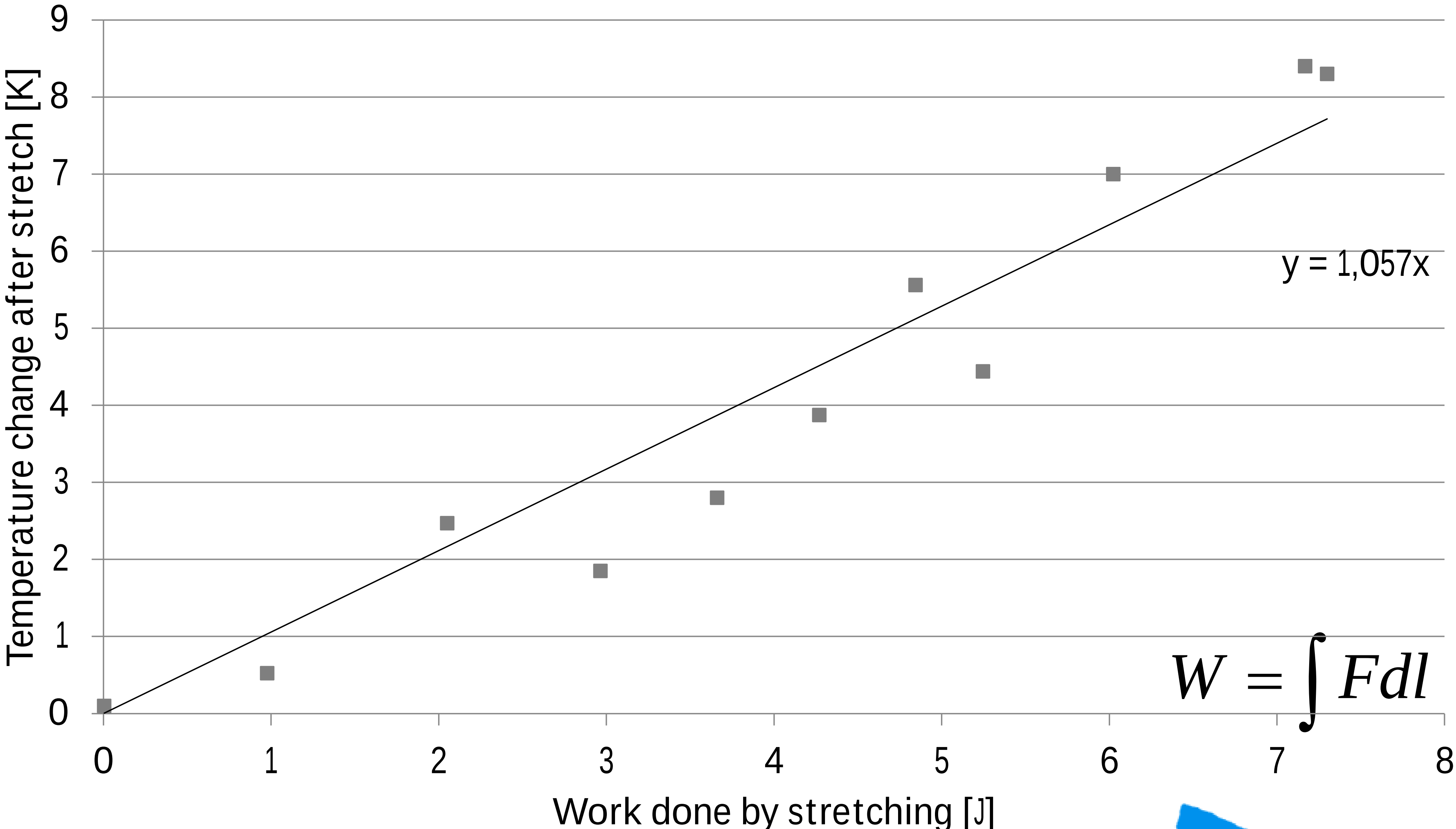
$$\Delta U = Q + W$$

- Internal energy decreases → rubber cools

Temperature change when contracted – cooling down



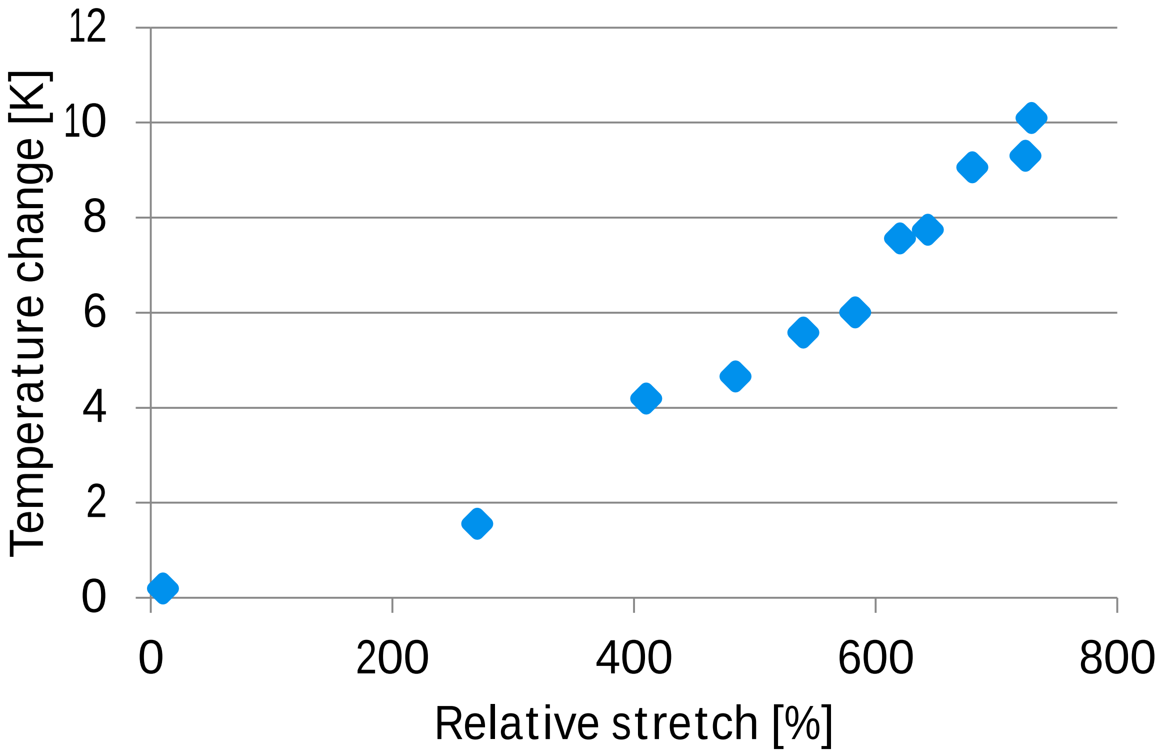
Change of temperature:



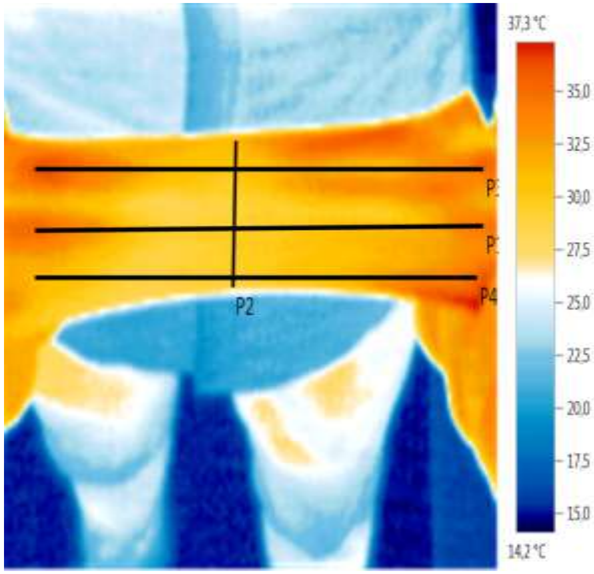
$$W = \int F dl$$

Summary

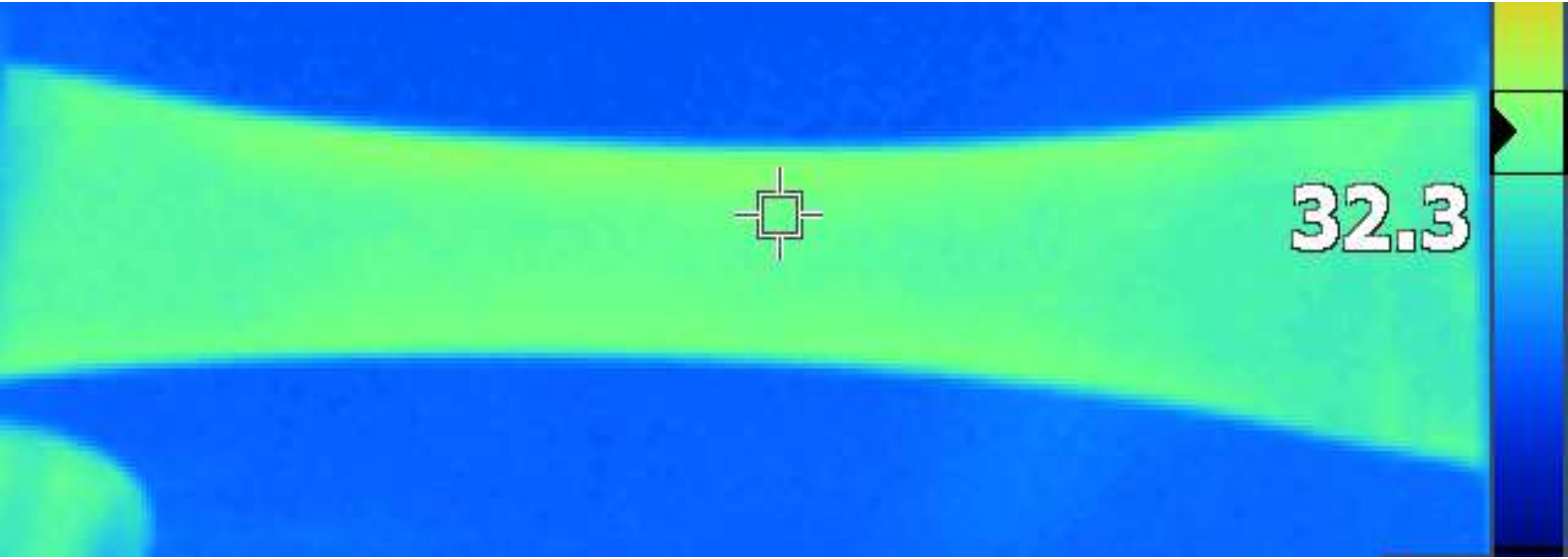
- Change of internal energy observable as heat
- Cool down depends on the amount of stretch of rubber

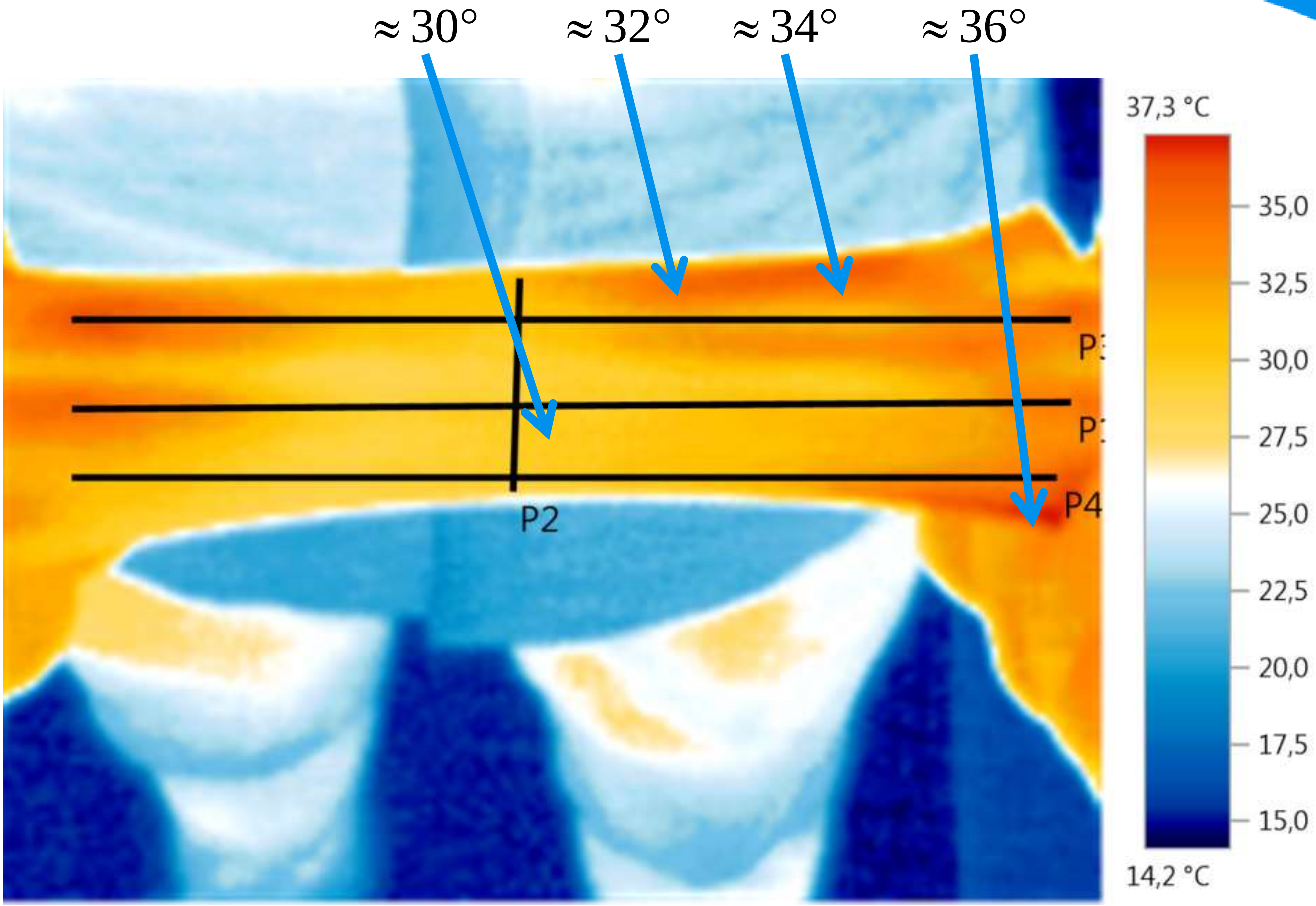


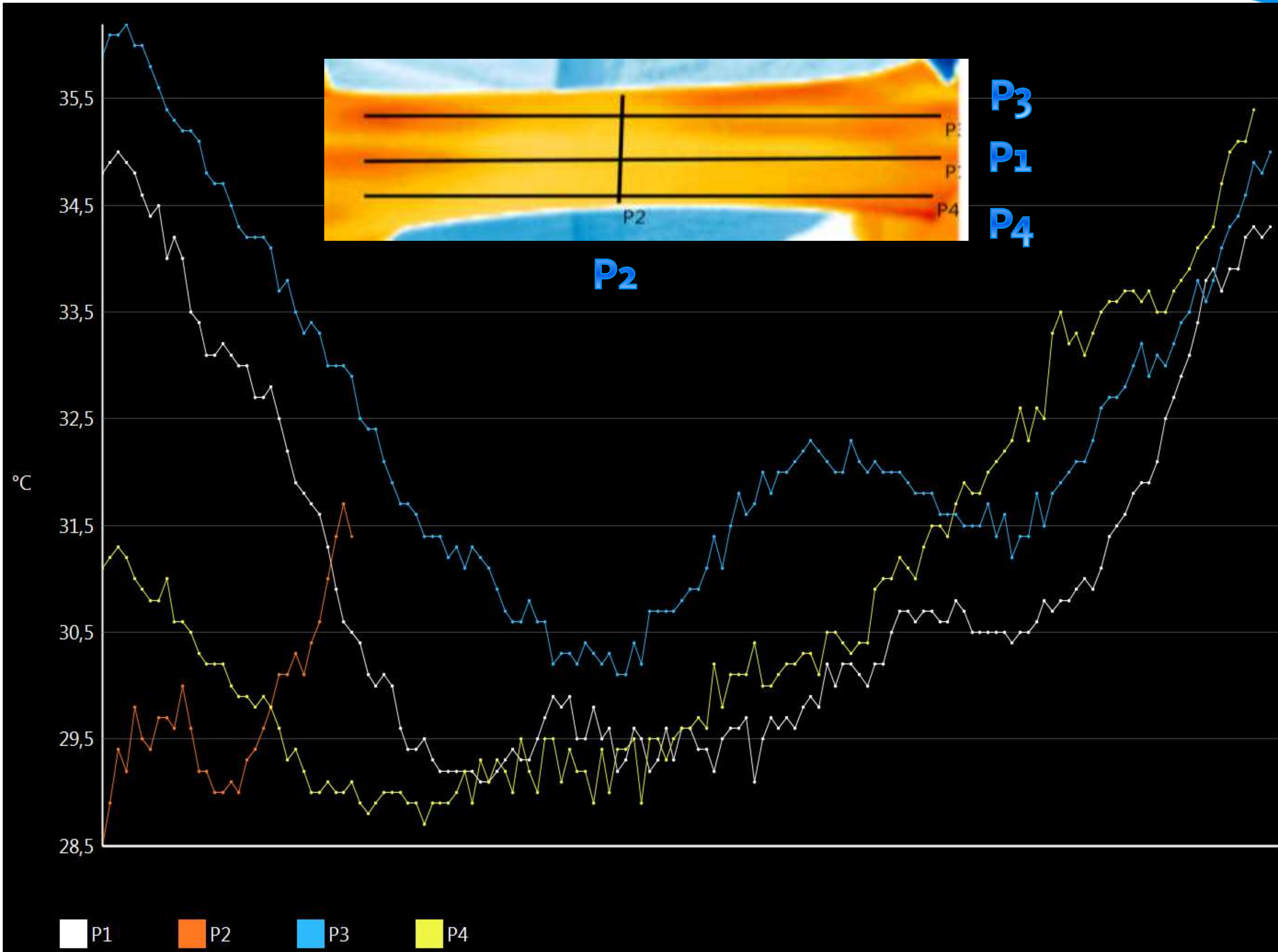
Different parameters affecting the stretch

Grip	Thickness	Curvature
		

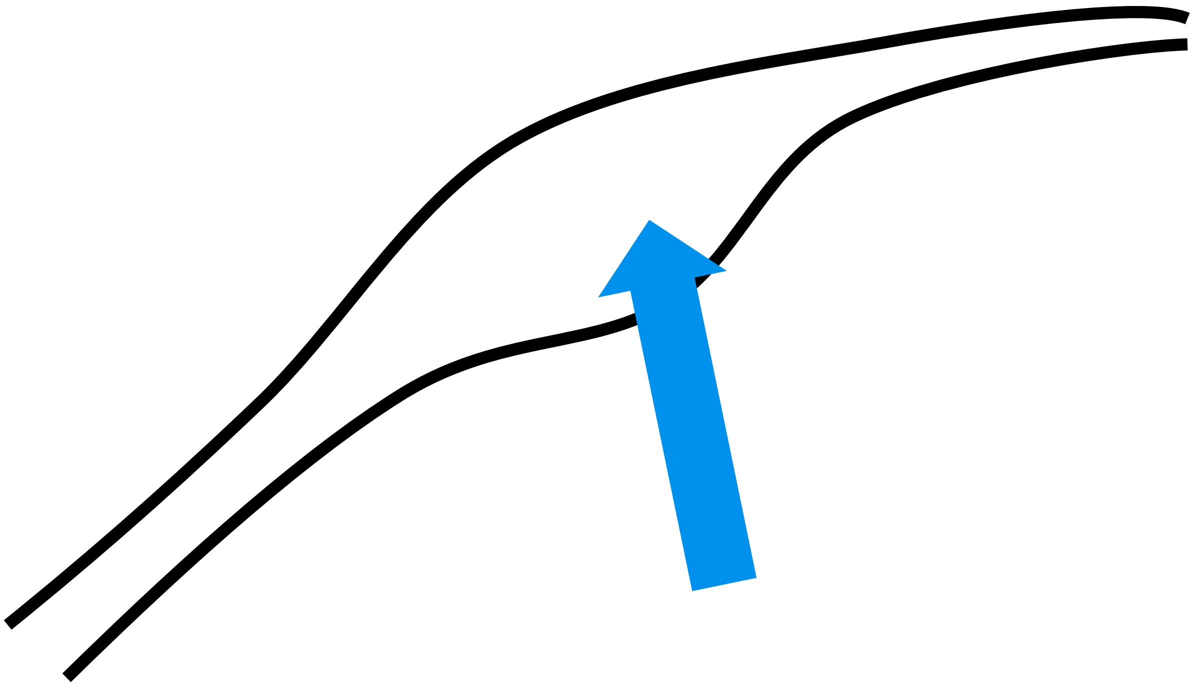
Grip




≈ 30°
≈ 32°
≈ 34°
≈ 36°
P2
P4
37,3 °C
35,0
32,5
30,0
27,5
25,0
22,5
20,0
17,5
15,0
14,2 °C


P3
P1
P4
P2
35,5
34,5
33,5
32,5
31,5
30,5
29,5
28,5
°C
P1
P2
P3
P4

Thinner / thicker

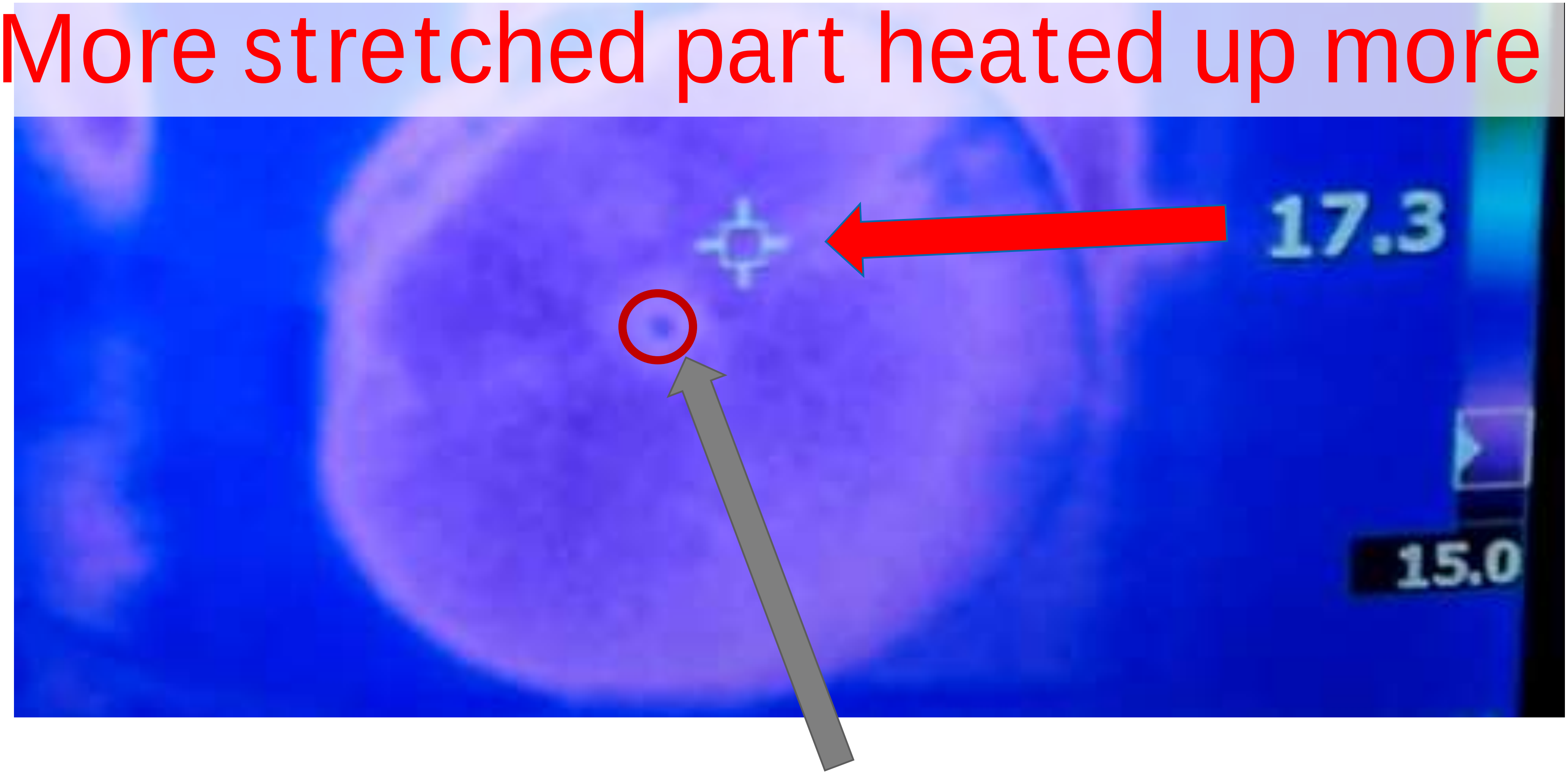


Thicker layer of rubber –
stiffer, less strain

Thinner / thicker

Thinner / thicker

More stretched part heated up more

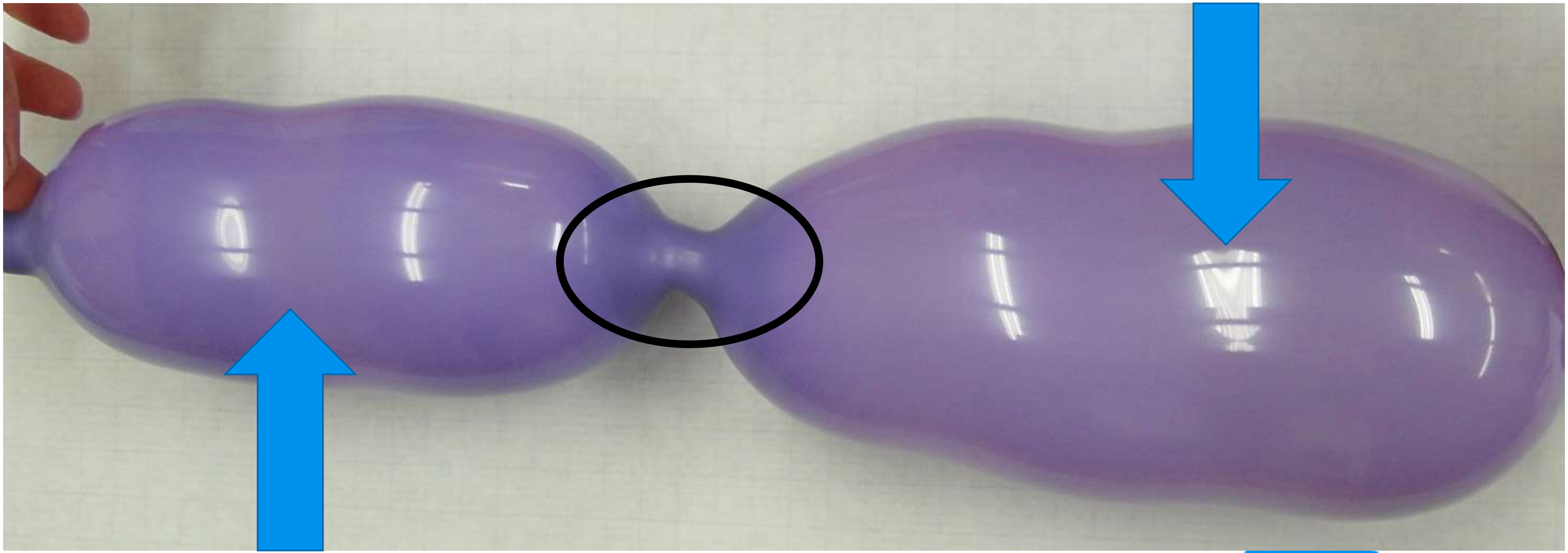


$\approx 16°C$

Shape of the balloon

After air escaped:

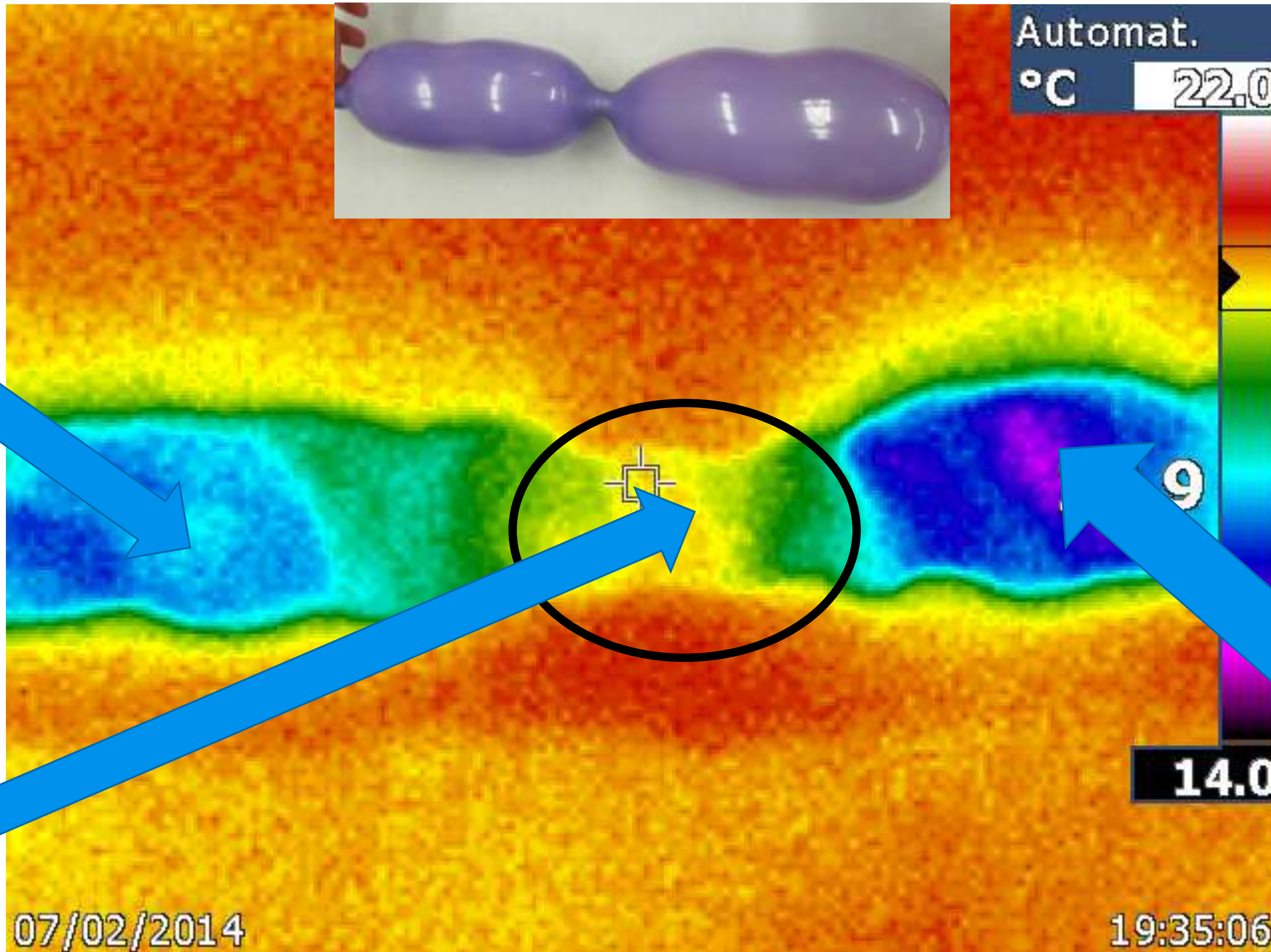
- Less stretched parts are warmer
- Stretched parts are cooler



Shape of the balloon

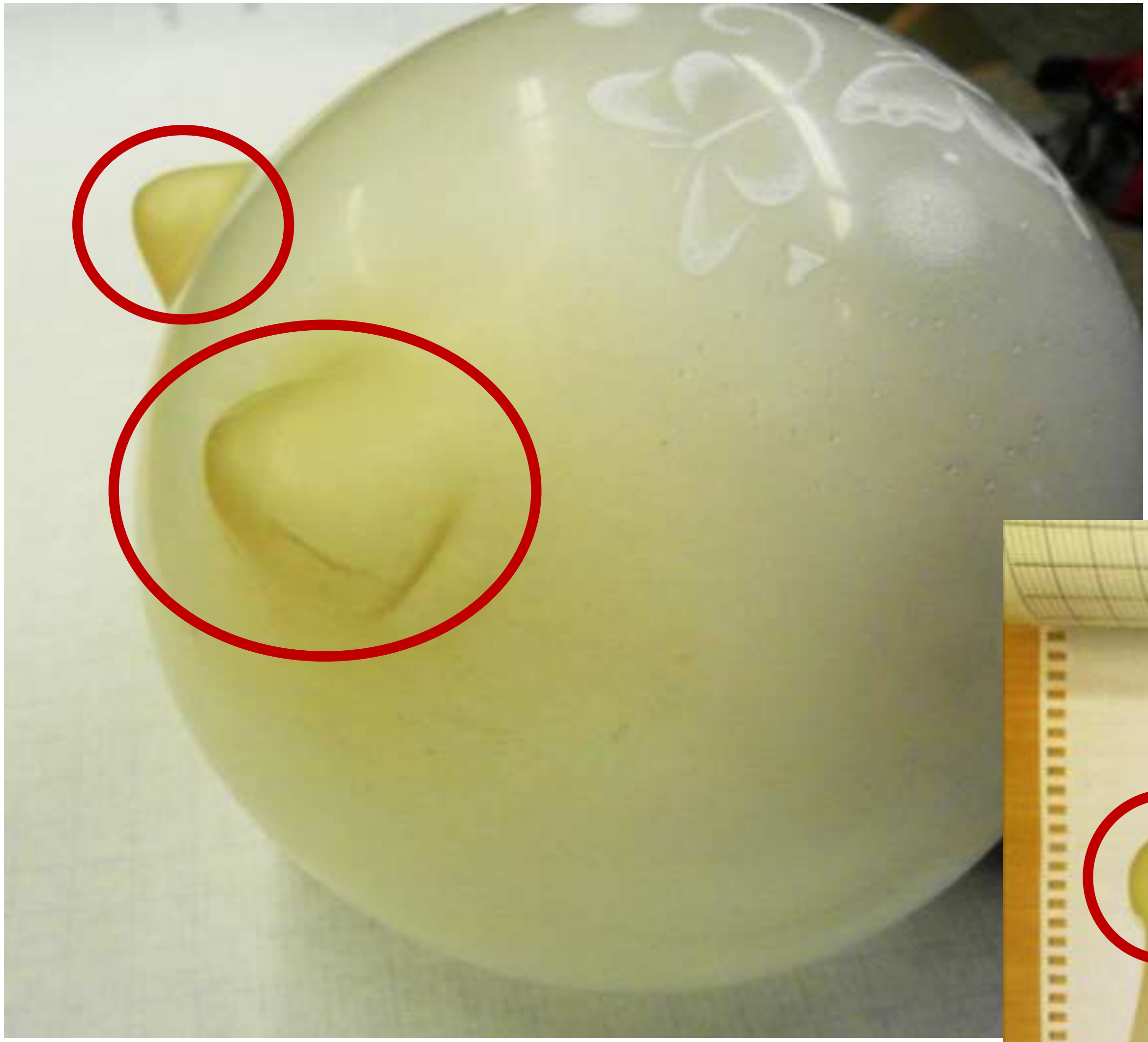
≈ 17°

≈ 20°



≈ 16°

Curved

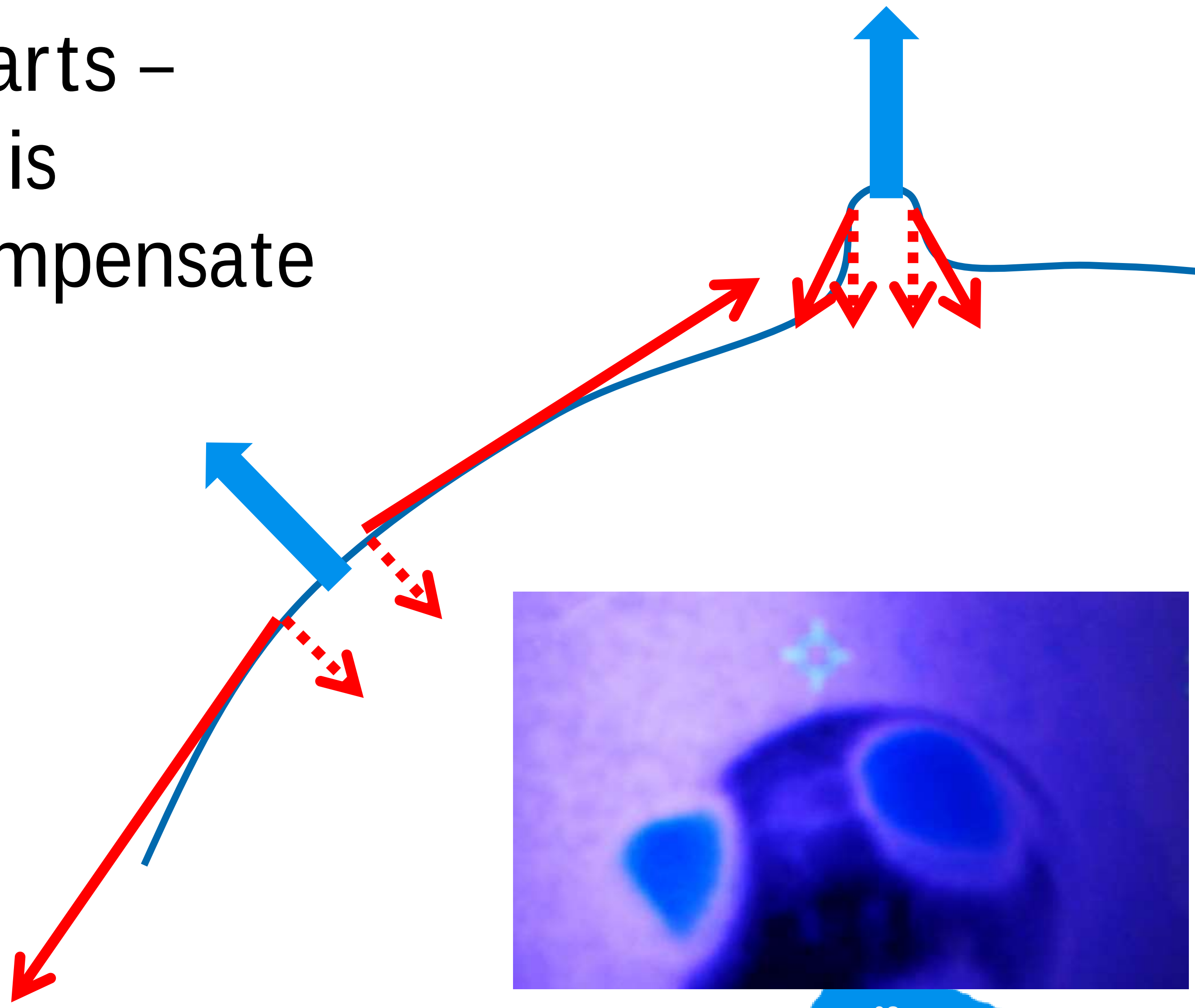


More curved are less stretched

Less stretched cool down less

Curved

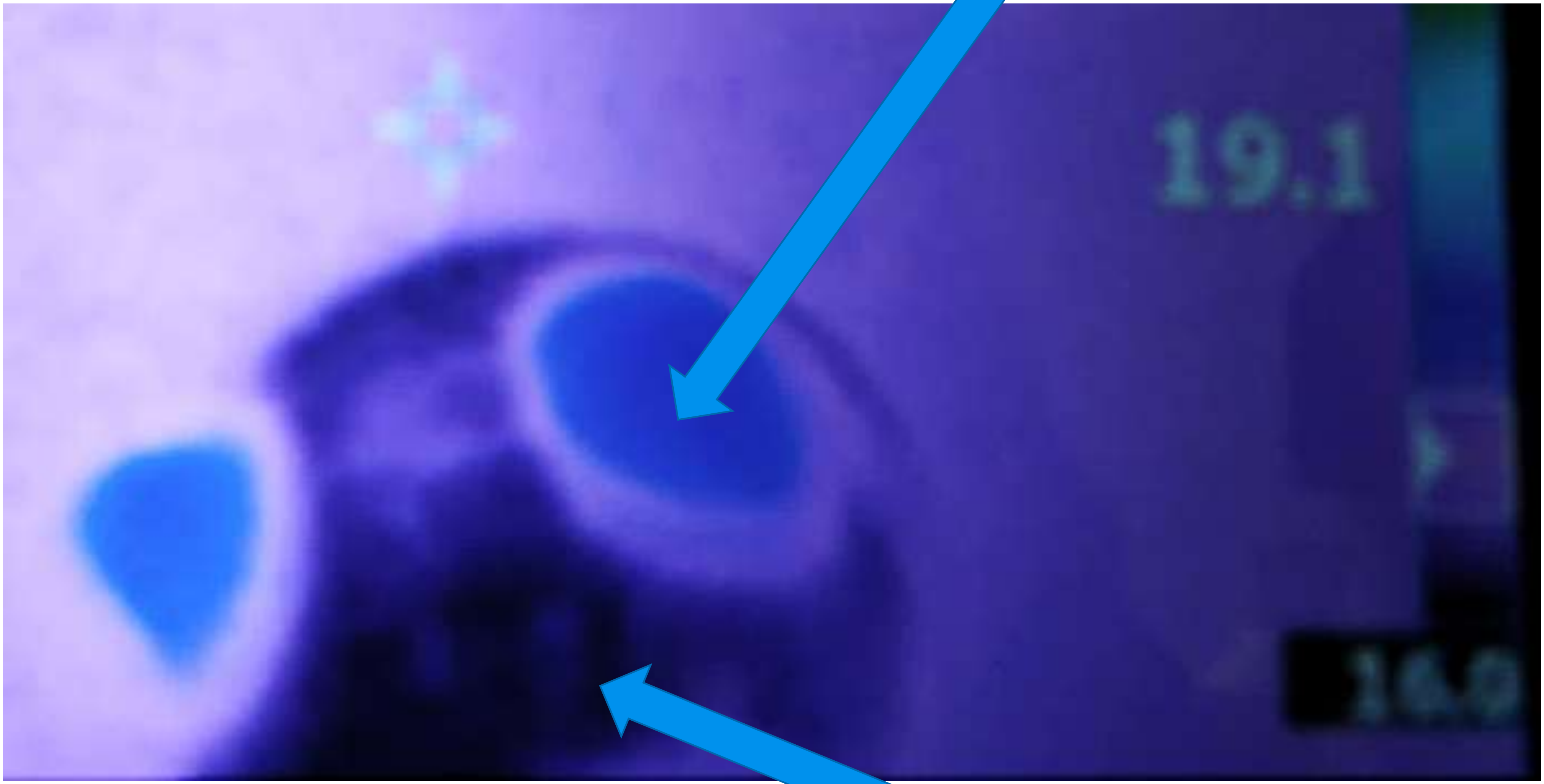
- More curved parts – smaller tension is sufficient to compensate air pressure
  - Less strain



Tension of rubber
Normal component of the tension
Air pressure

Curved – less cooled

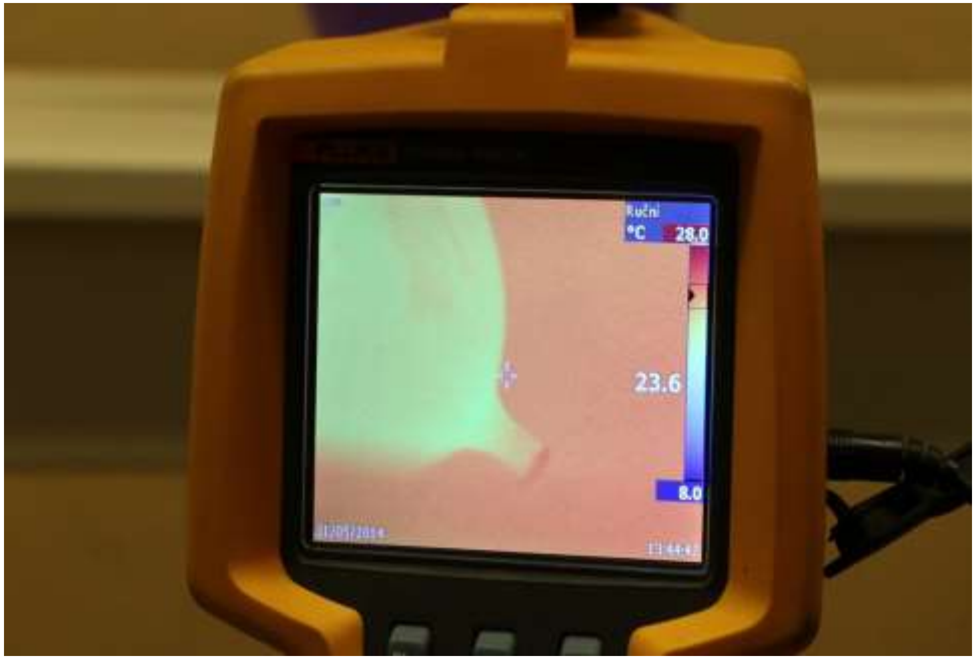
$\approx 19°C$

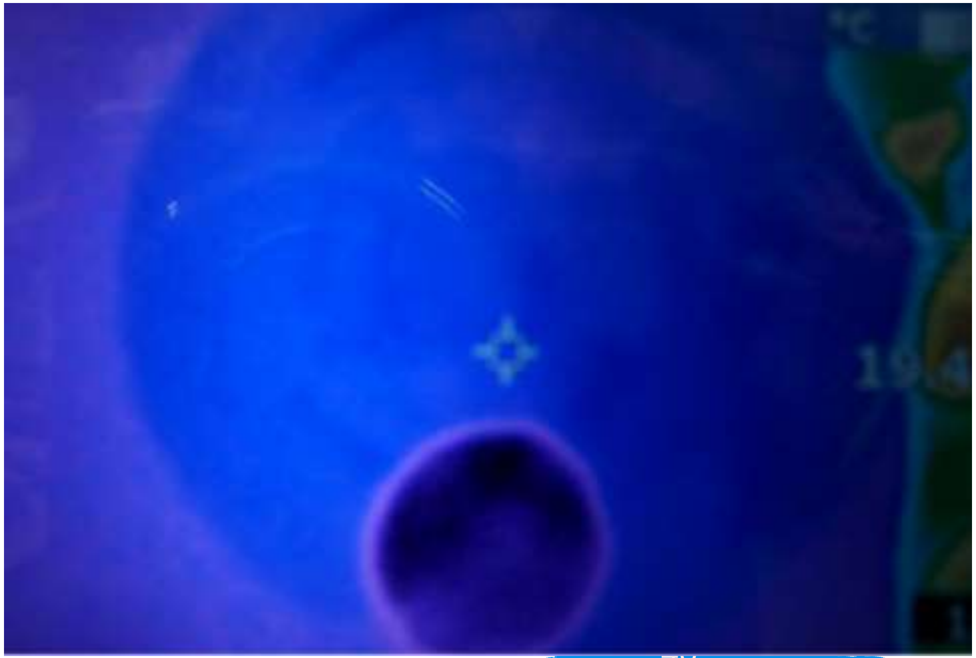


$\approx 17°C$

Conclusion - air

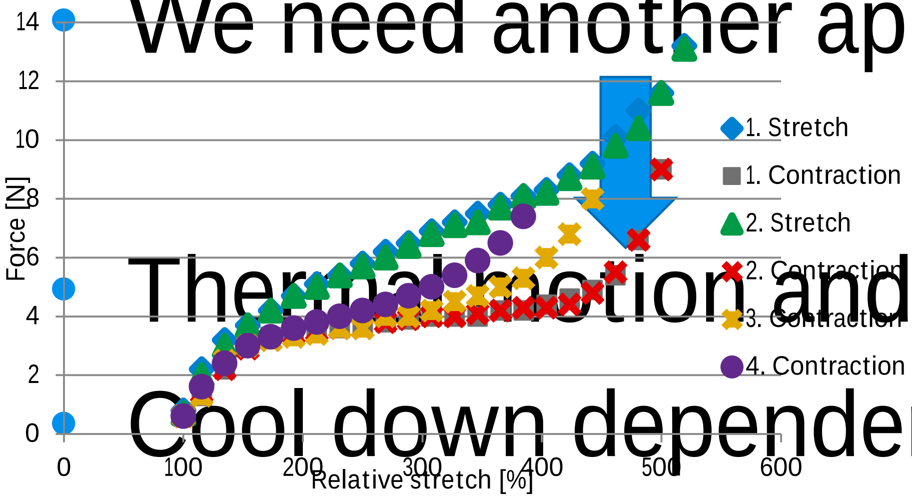
- Mathematical model $$Q \leq \Delta T S \sqrt{\frac{i+2}{T} Pkt}$$
- Calculated maximal effect
  - Large balloon – $\Delta T \approx 1{,}53°C$
  - Small balloon – $\Delta T \approx 0{,}29°C$
- Two experimental verifications

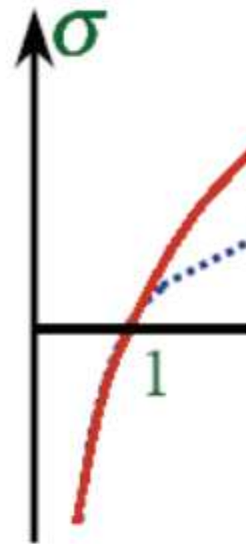


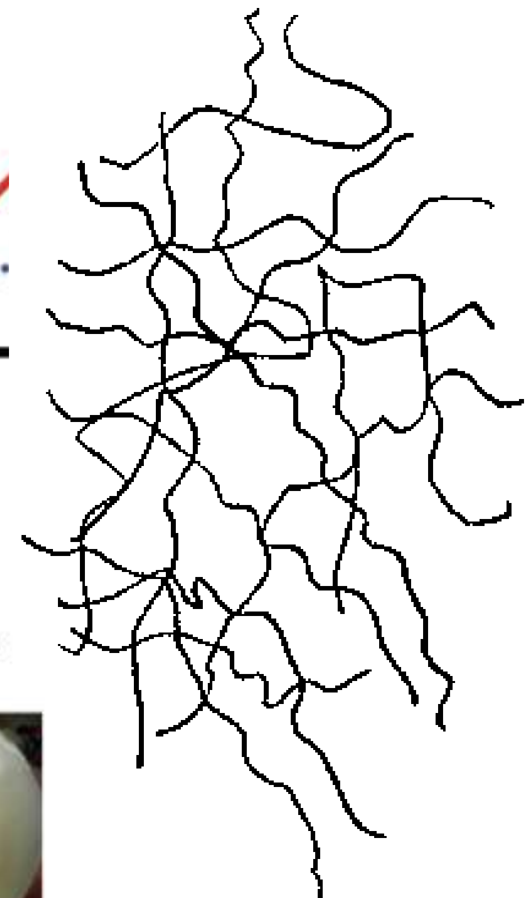


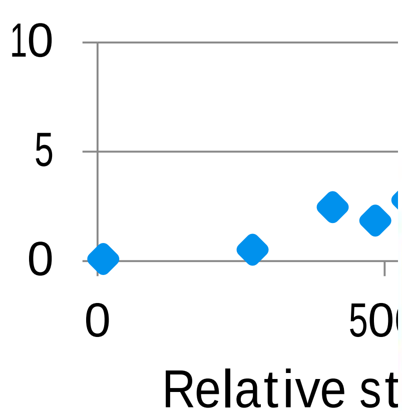
Conclusion - theory

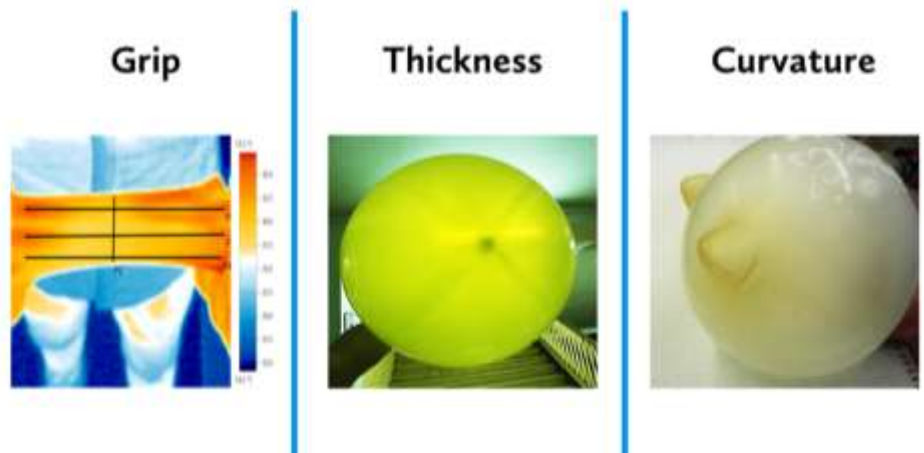
- Existing theory is not sufficient
- We need another approac
- Thermal motion and tensi
- Cool down dependence o







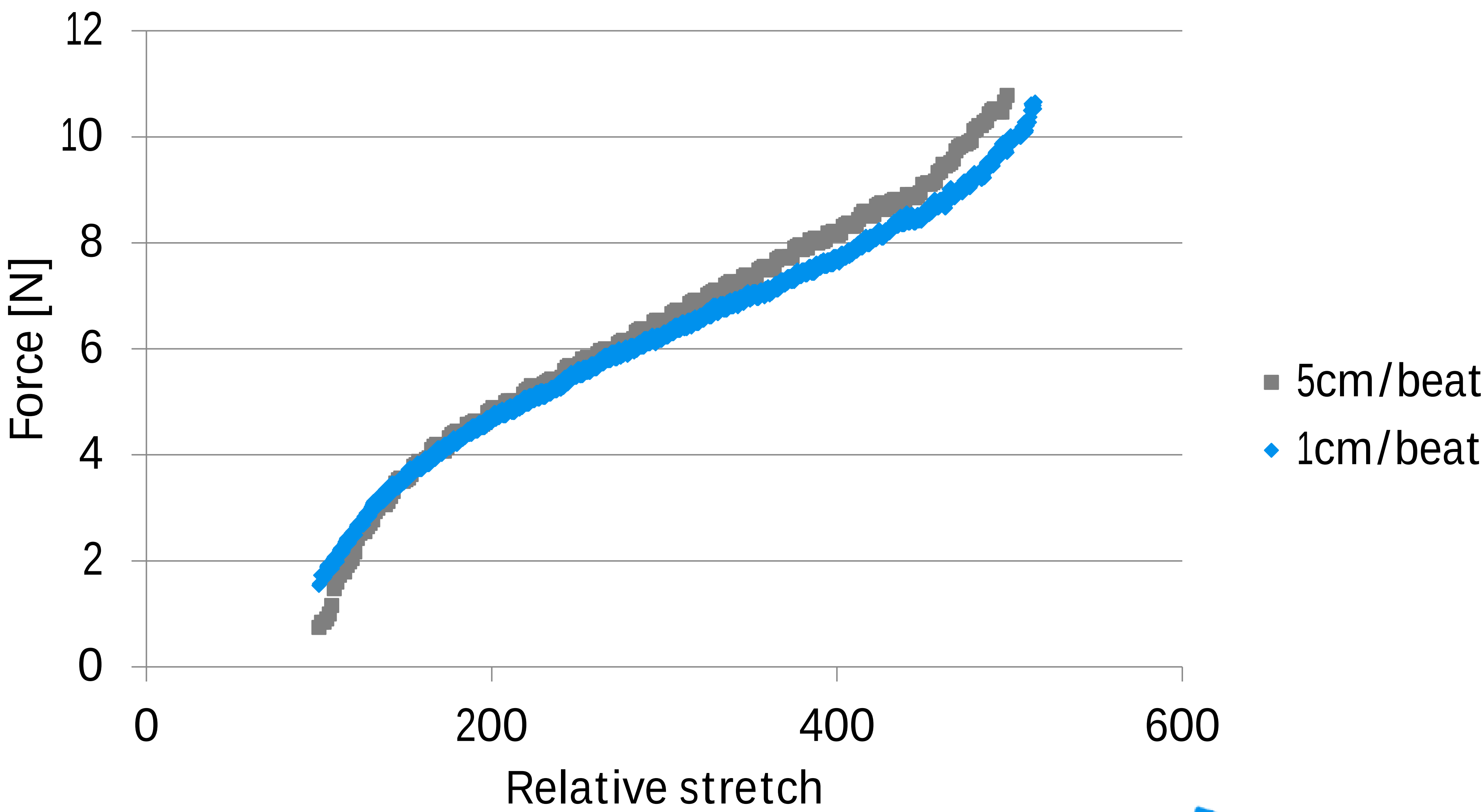




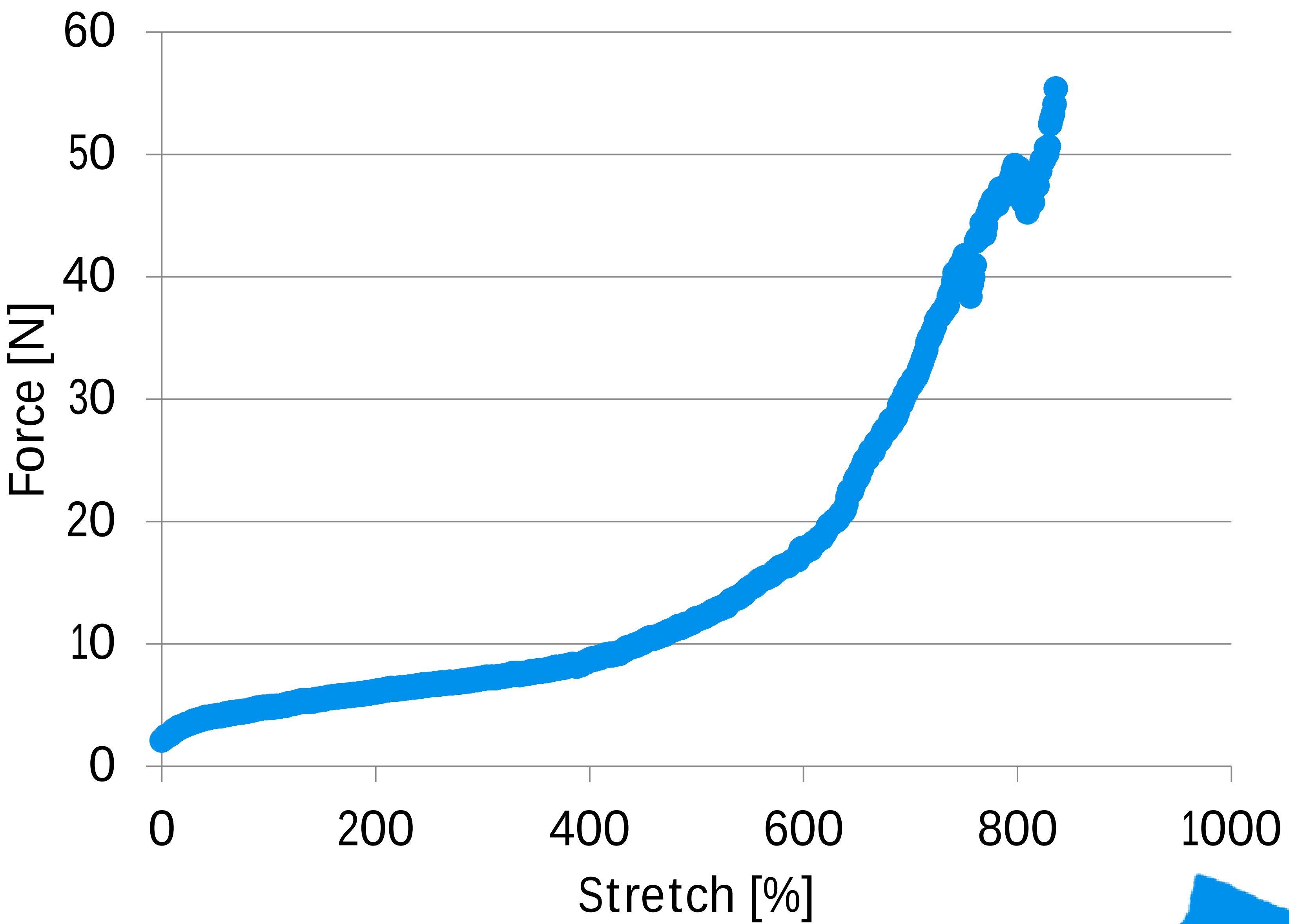
ve stretch [%]

THANK YOU FOR YOUR ATTENTION

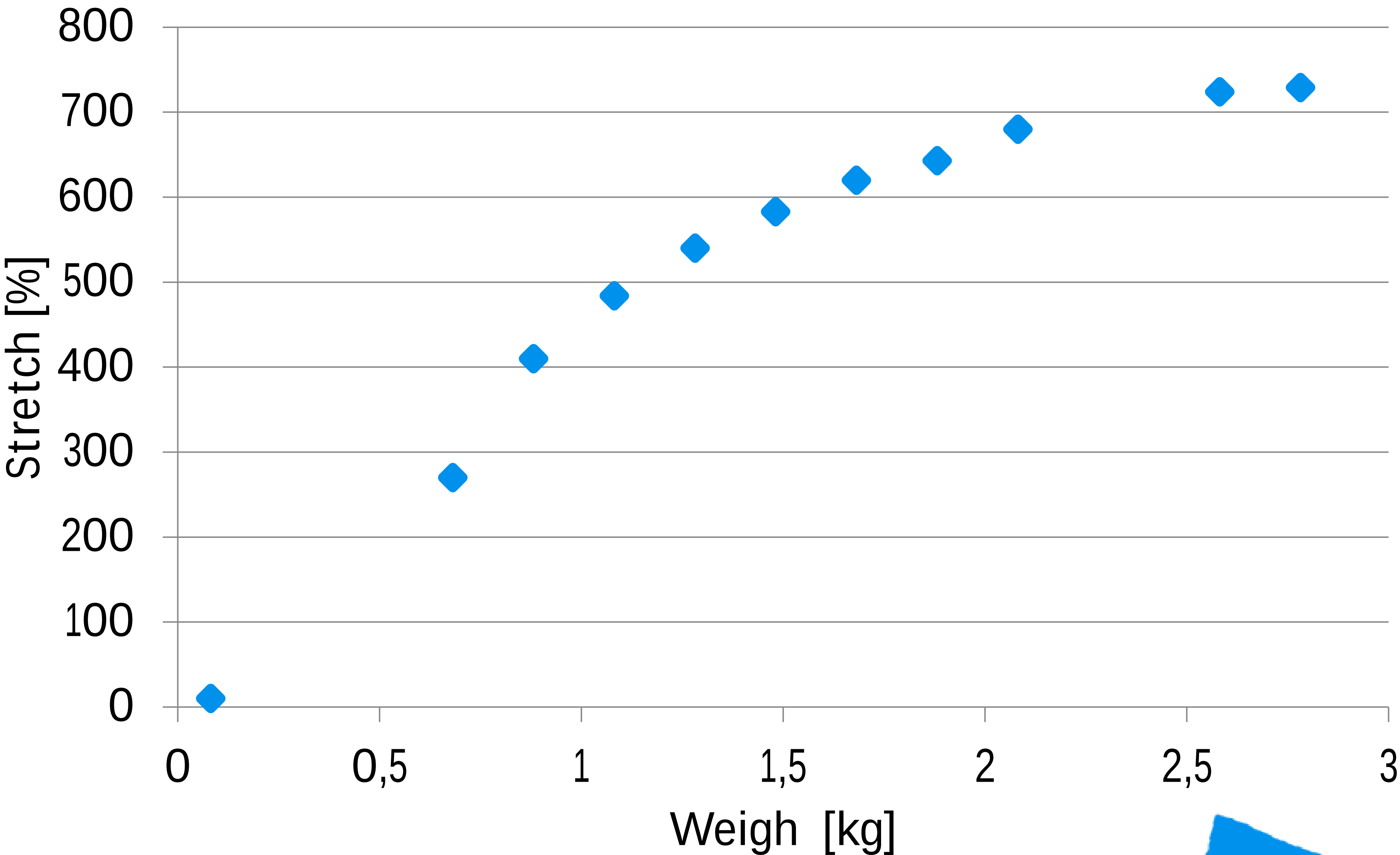
Force dependence on speed of stretch



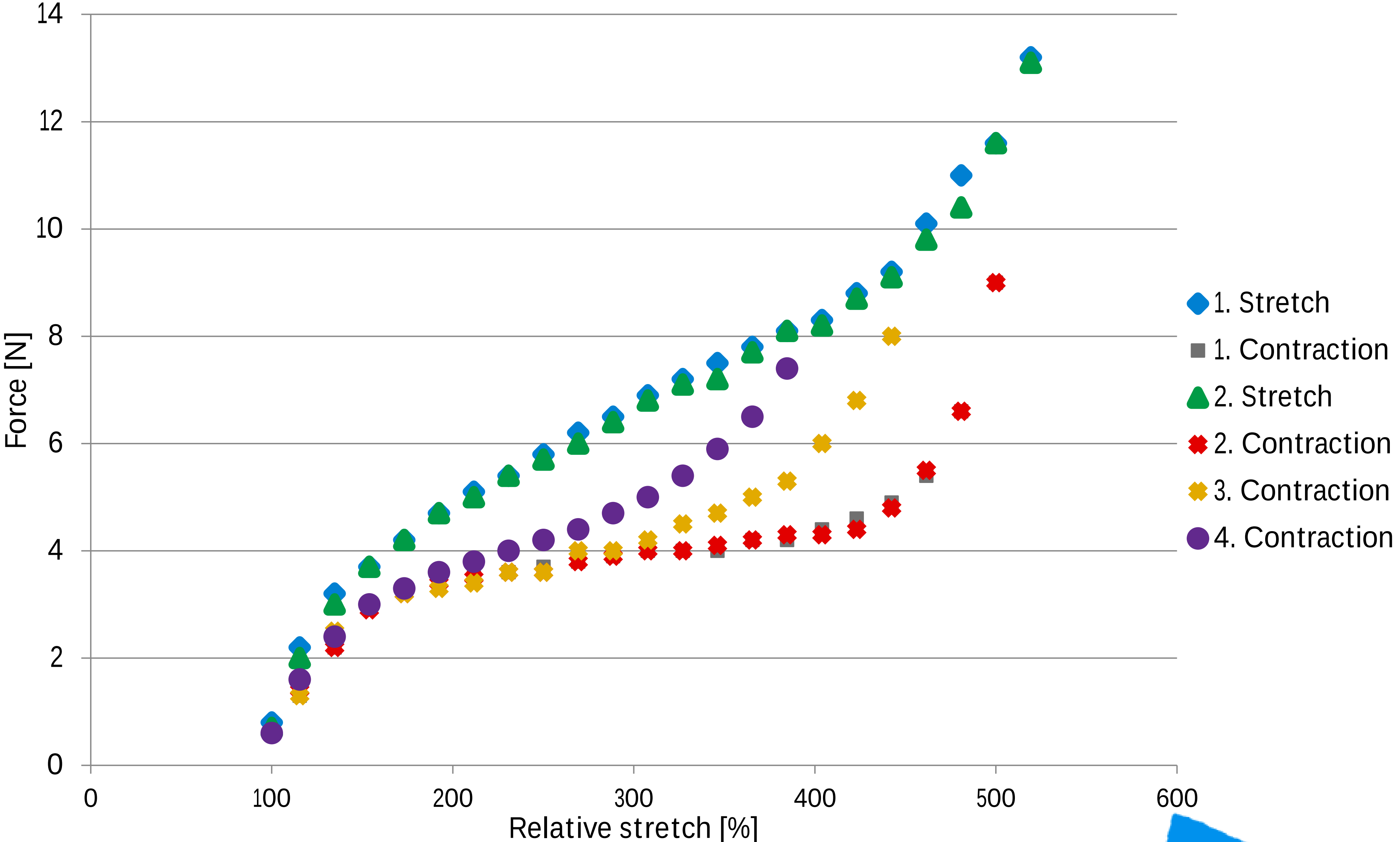
Maximal stretch/force dependance



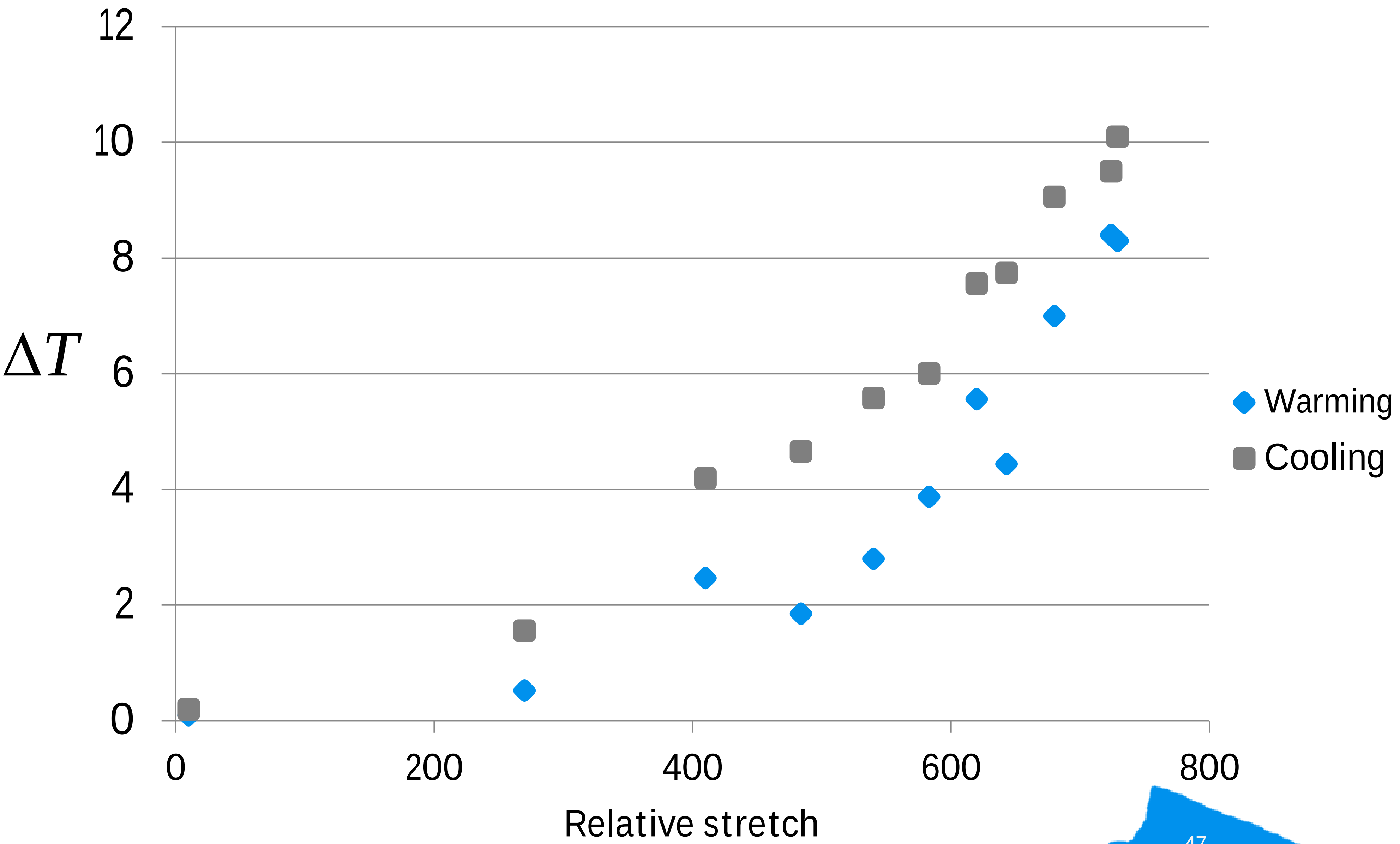
Stretch dependence on weight



Hysteresis of rubber



Dependence of temperature change on stretch

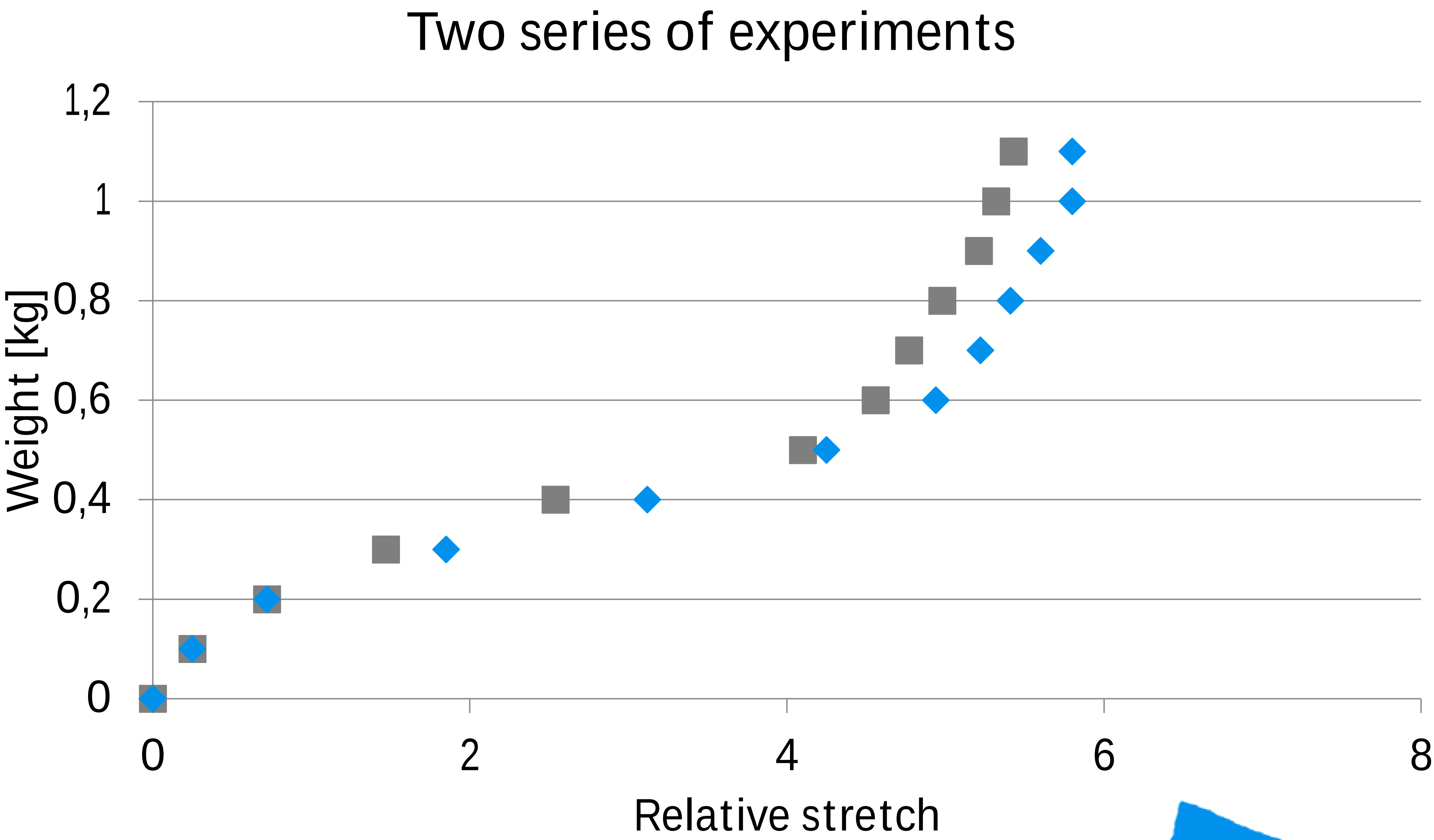


$$Q \approx \frac{1}{2} hS \frac{i+2}{2} \frac{P_O}{T} \left(T_O - T\right) + tkS \frac{T_O - T}{h}$$

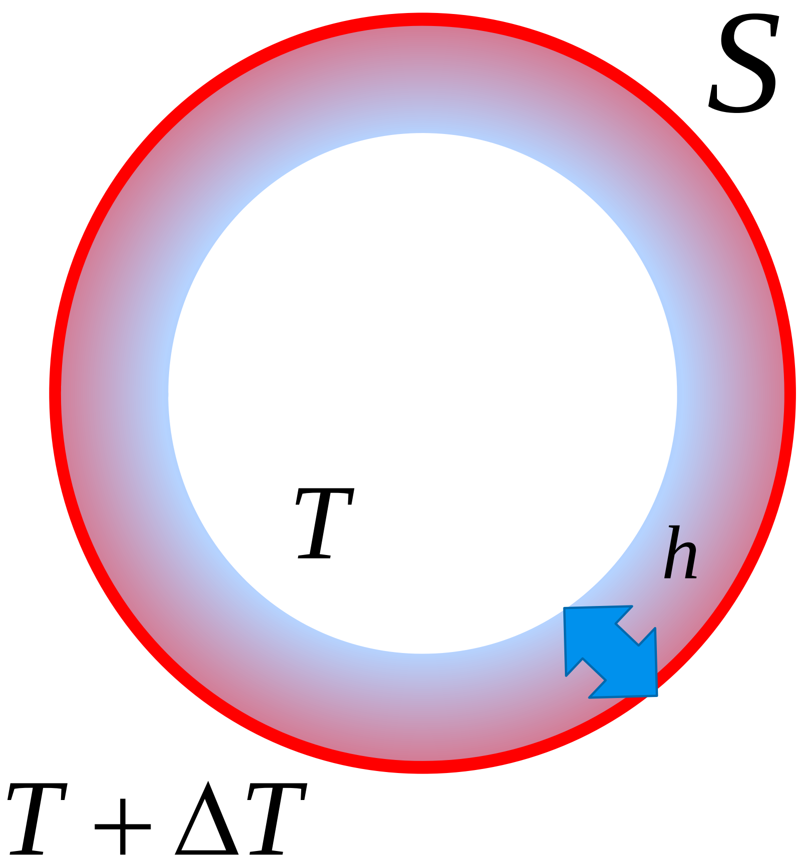
$$Q \le \sqrt{\frac{1}{2} \frac{i+2}{2} hS \frac{P}{T} \Delta T kS \frac{1}{h} \Delta T t}$$

$$Q \le \Delta T S \sqrt{\frac{i+2}{T} Pkt}$$

Attrition of rubber



Heat transferred through air



h Width of air layer

S Balloon surface

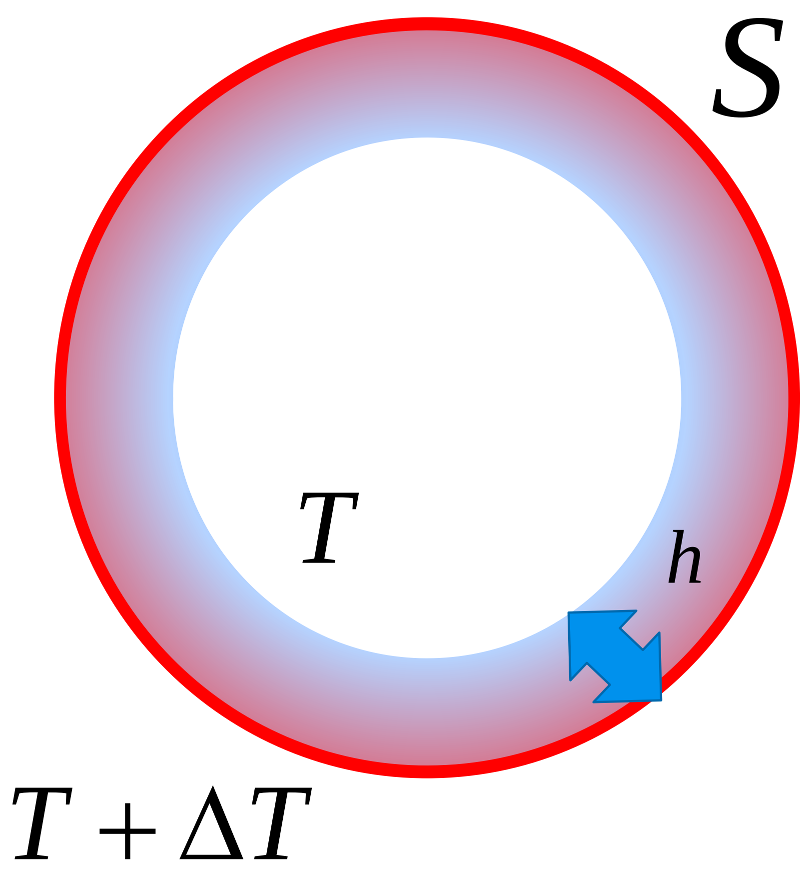
k Heat conductivity of air

t Time of deflation

$$Q \approx tkS \frac{\Delta T}{h}$$

To create the gradient $\frac{\Delta T}{h}$,
some heat had to be transferred first..
(with higher gradient)

Heat from the boundary layer



Based on (isobaric) heat capacity c_p
this heat has to be transferred
to create the gradient: $\frac{\Delta T}{h}$

$$Q_2 \approx \frac{1}{2} \frac{P_0 h S}{RT} c_p \Delta T$$

Temperature drop in the rubber

More realistic estimate

- ½ surface
- ½ time
- Adjust heat capacity

Then

- Small balloon ~~$\approx 1{,}29\,°C$ / $\approx 0{,}32\,°C$~~
- Large balloon ~~$\approx 1{,}53\,°C$ / $\approx 6{,}8\,°C$~~

Our equipment – Fluke TiR

- Measurement range: -20°C to 120°C
- Accuracy: $\pm 2°C$
- Thermal sensitivity: ≤ 0.09 °C at 30 °C
- Image frequency: 9Hz refresh rate