12

Thick lens

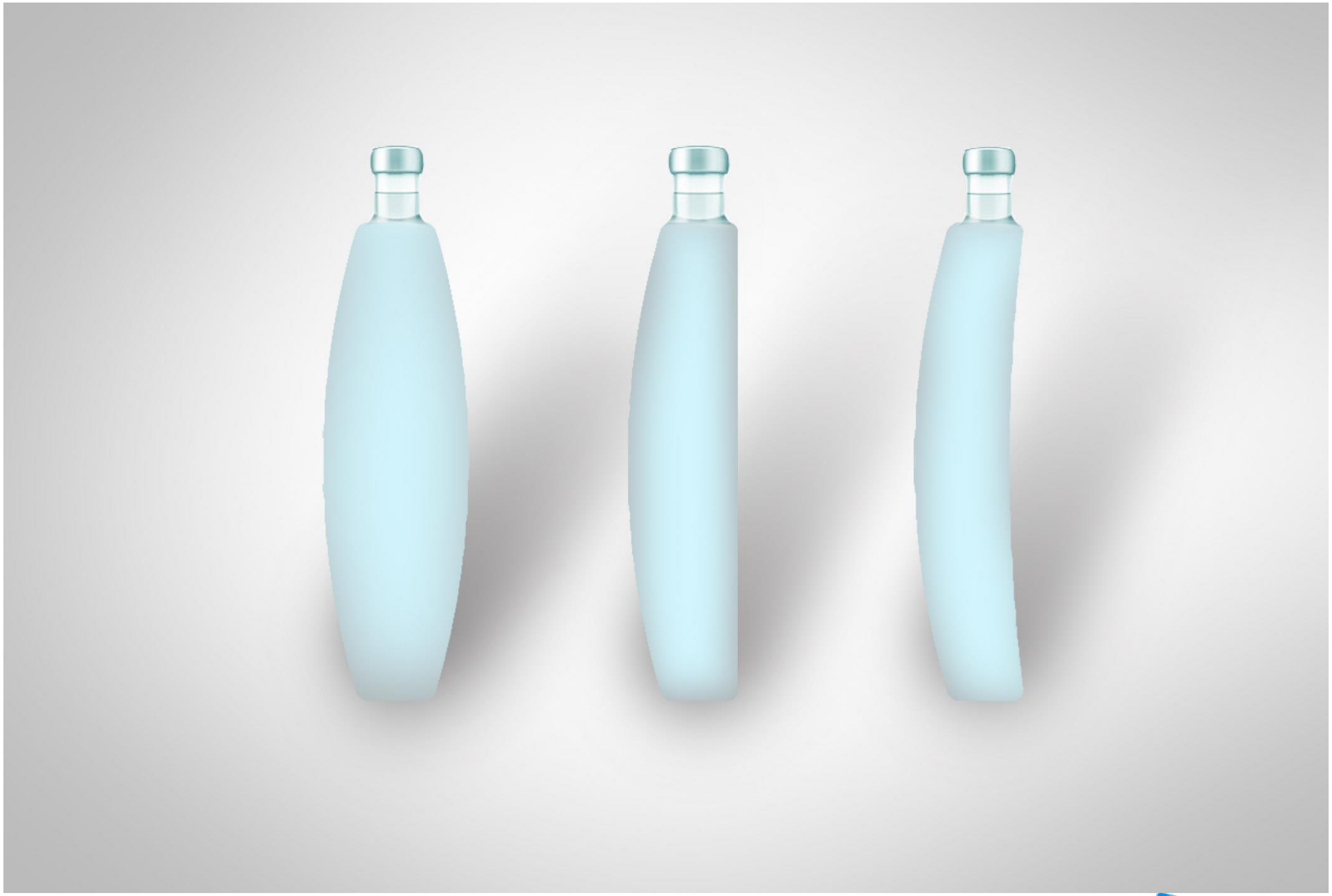
Martin Murin

12. Thick Lens:

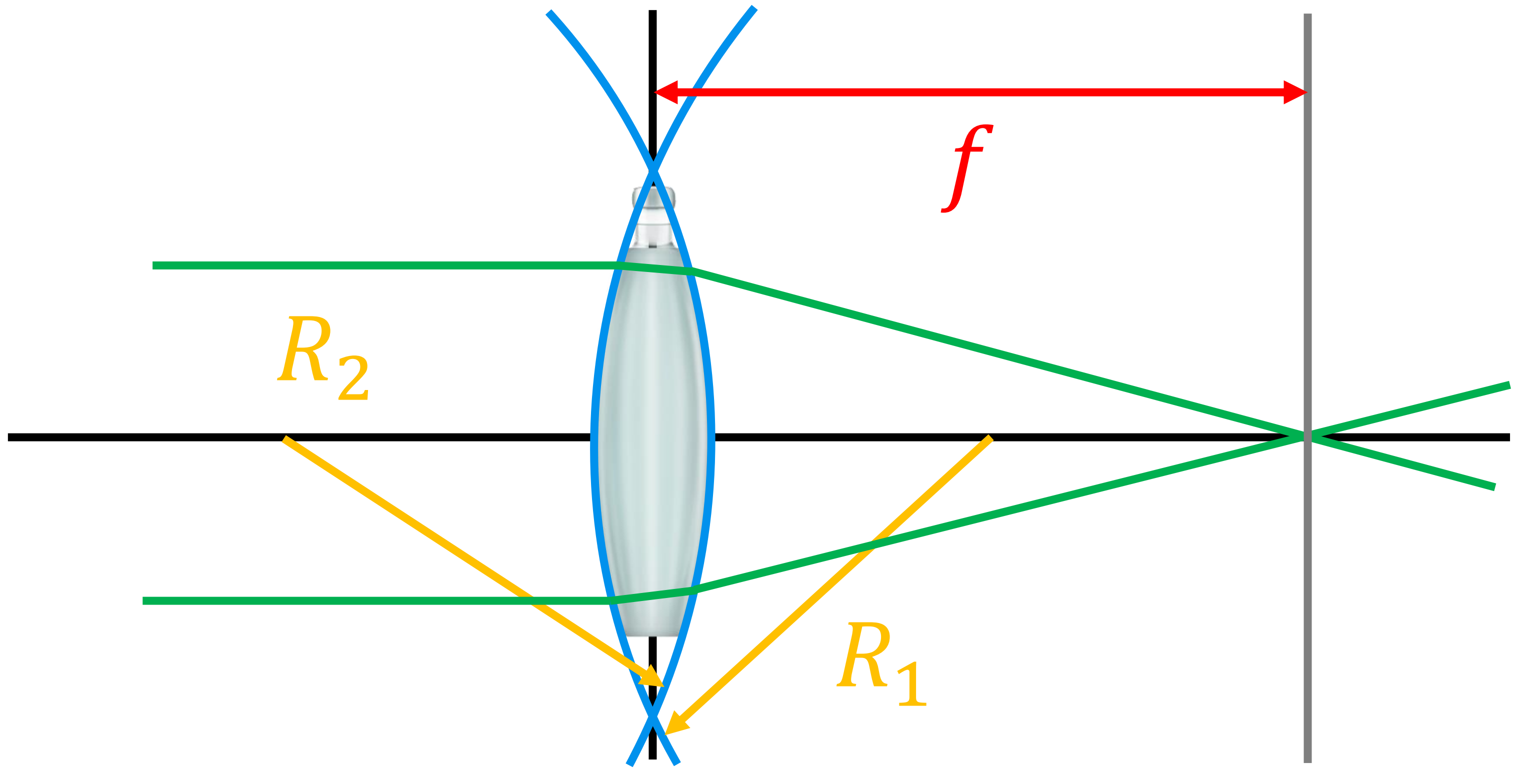
"A bottle filled with a liquid can work as a lens. Arguably, such a bottle is dangerous if left on a table on a sunny day.

Can one use such a 'lens' to scorch a surface?"

Bottle as a thick lens



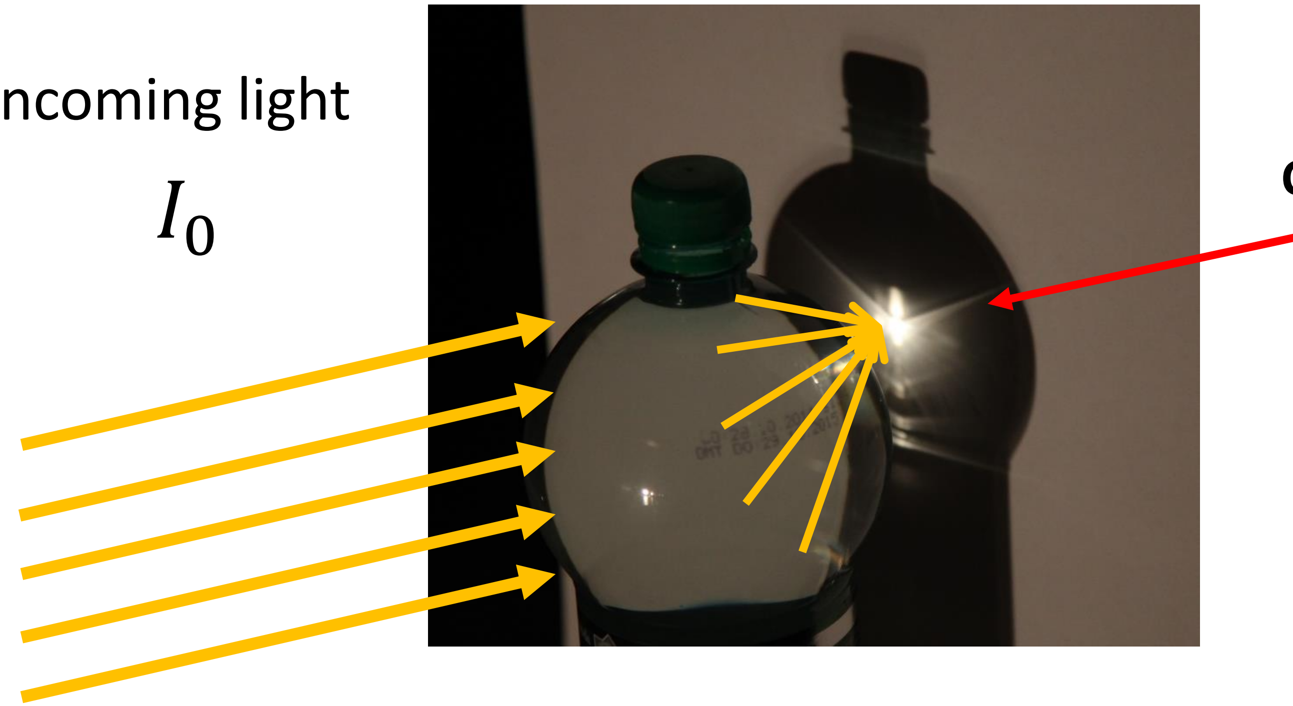
Bottle as a thick lens



How it works

incoming light

I_0

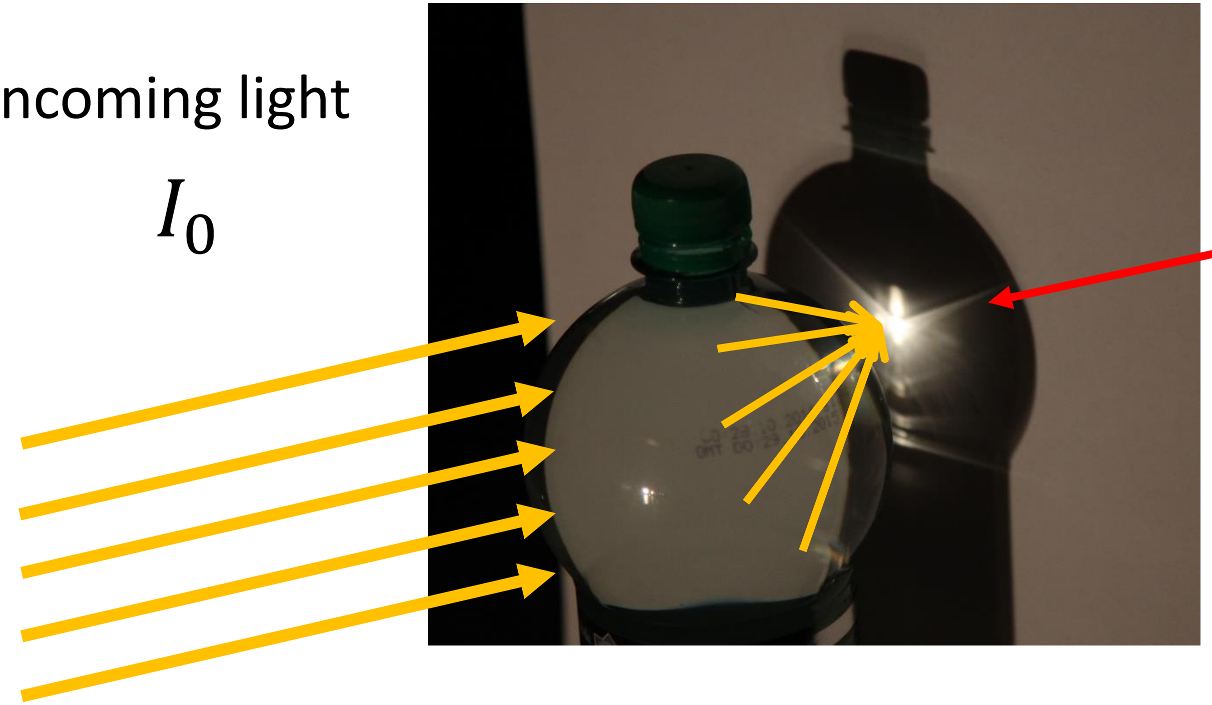


Concentrated light
= power

How it works

incoming light

I_0



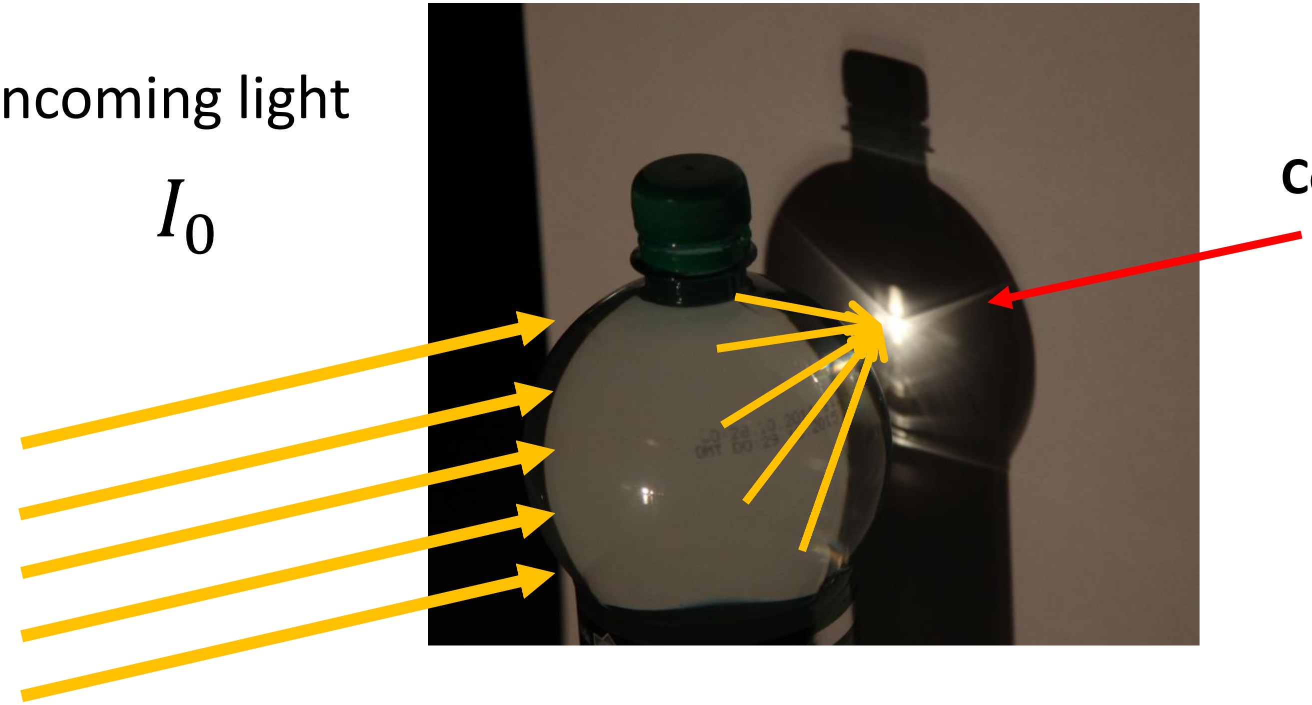
Concentrated light
= power

Material heats up

How it works

incoming light

I_0



Concentrated light
= power

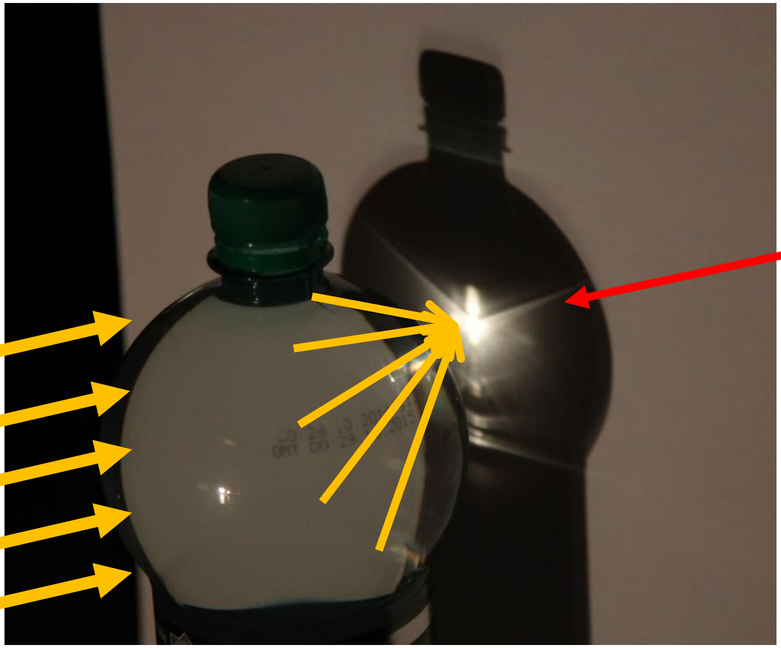
Material heats up

Ignition

How it works

incoming light

I_0



Concentrated light = power

Material heats up

Ignition

Section 1

Light passing through the bottle

Intensity of incident light

Section 2

Energy of light

Reflection, absorption, dissipation

Different shapes of bottles

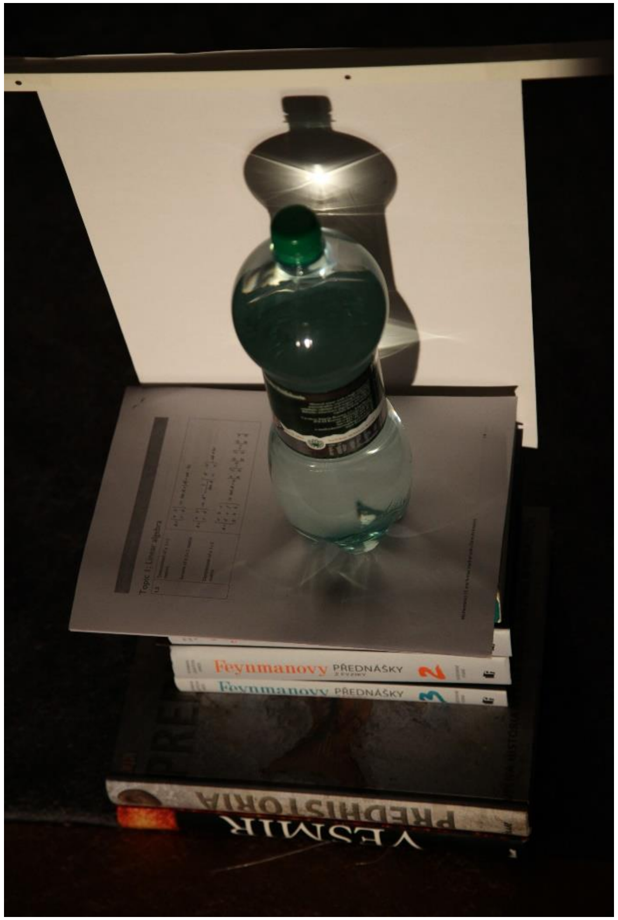
Undefined shape

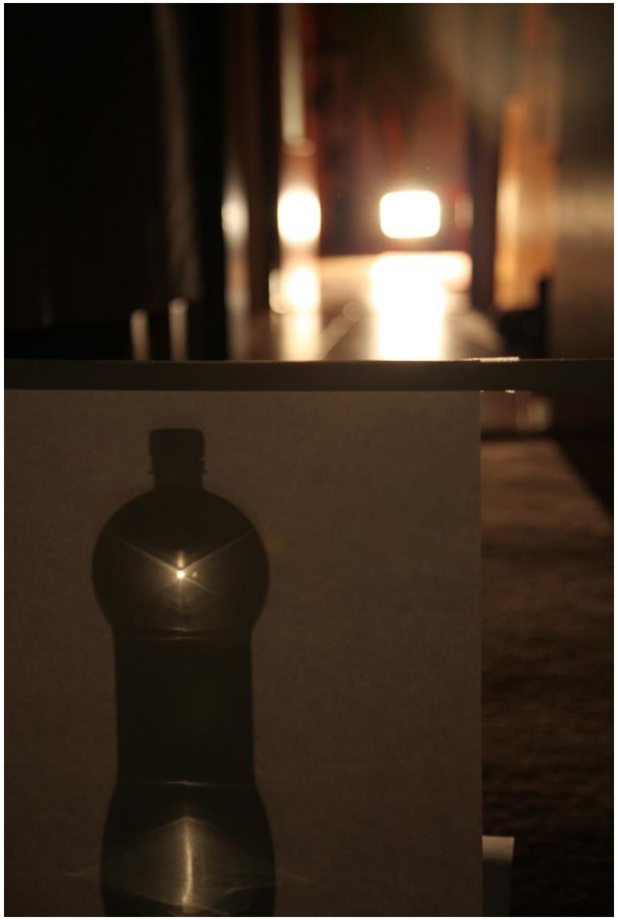
Cylinder

Top view:

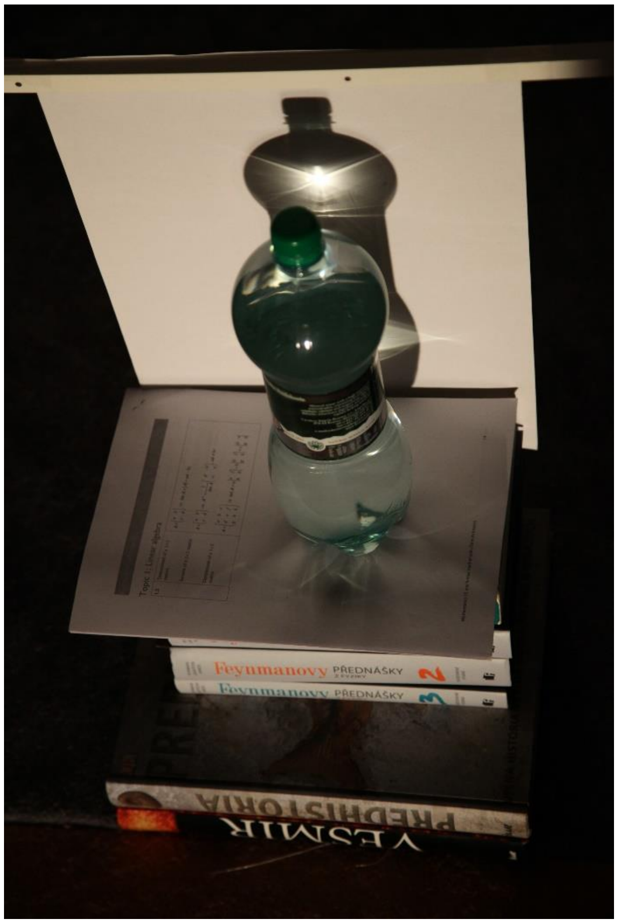
Sphere

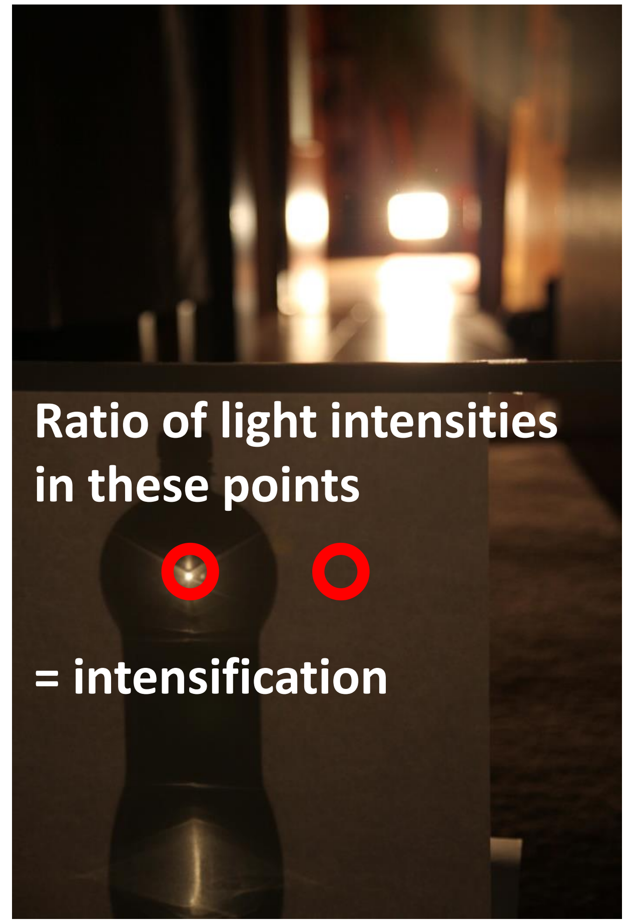
Intensification of light - **experiment**



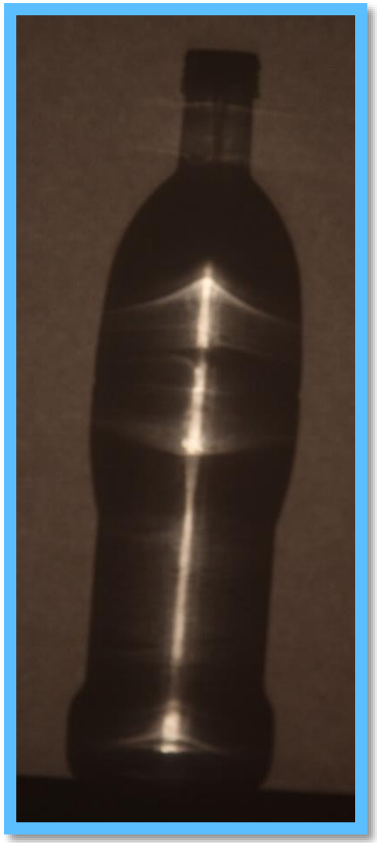


Intensification of light - **experiment**





Patterns and intensifications observed



Patterns and intensifications observed

5×

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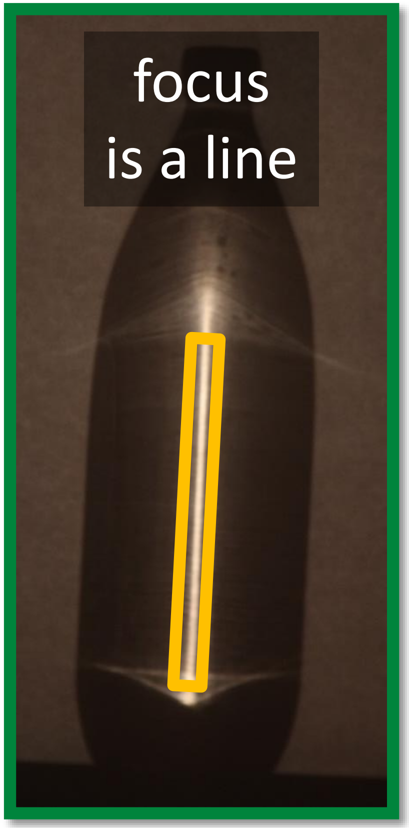
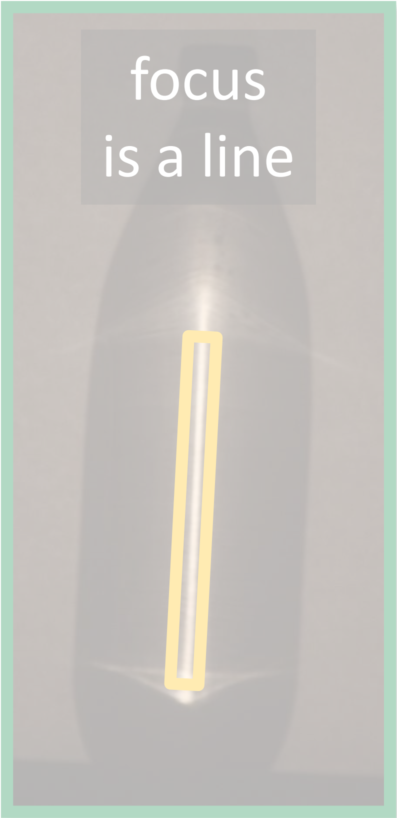


5× 5×

Patterns and intensifications observed



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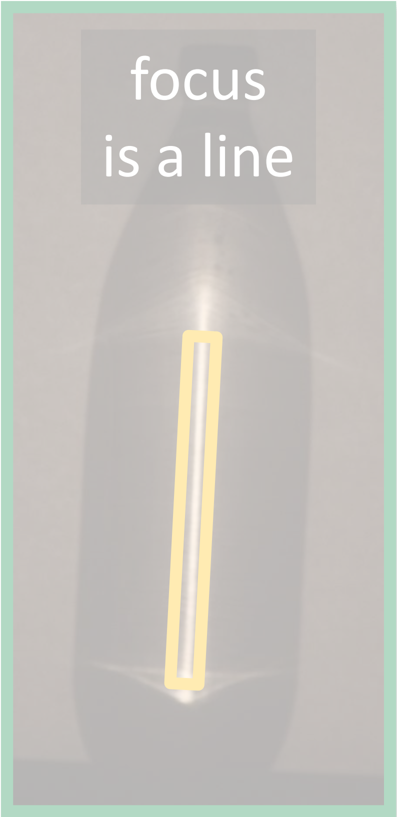
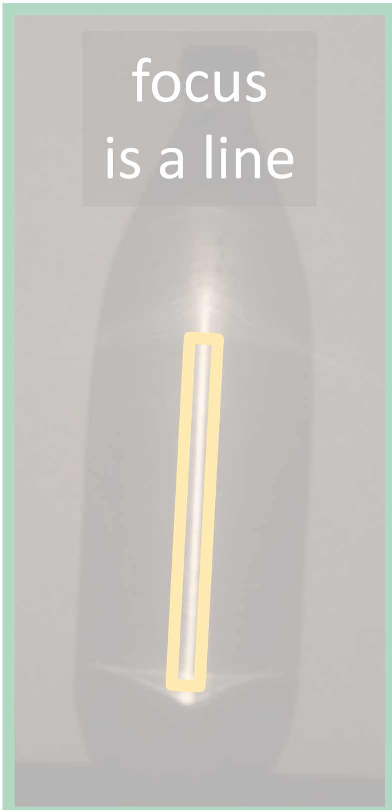
Patterns and intensifications observed



5× 5× 25×

Patterns and intensifications observed

5×

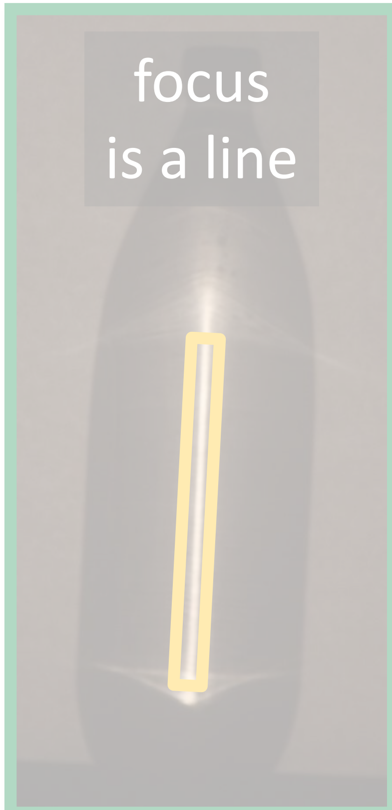


5×

25×

Patterns and intensifications observed

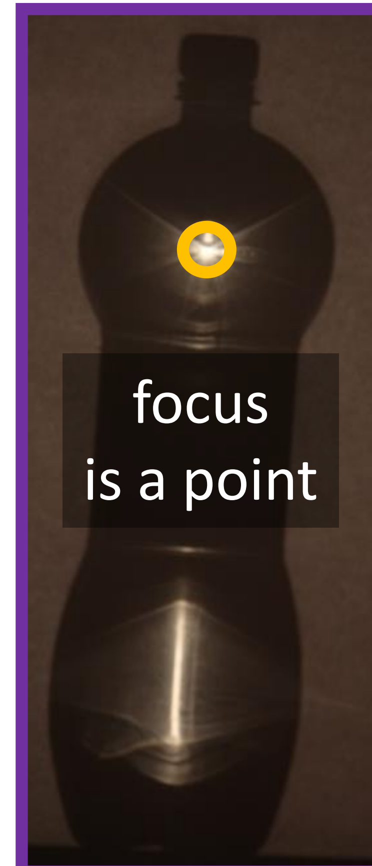
5×



5×

25×

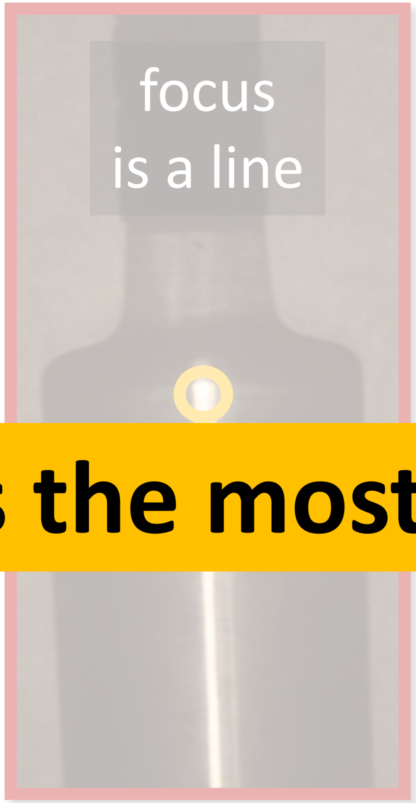
1500×



Patterns and intensifications observed

5×

5×



25×

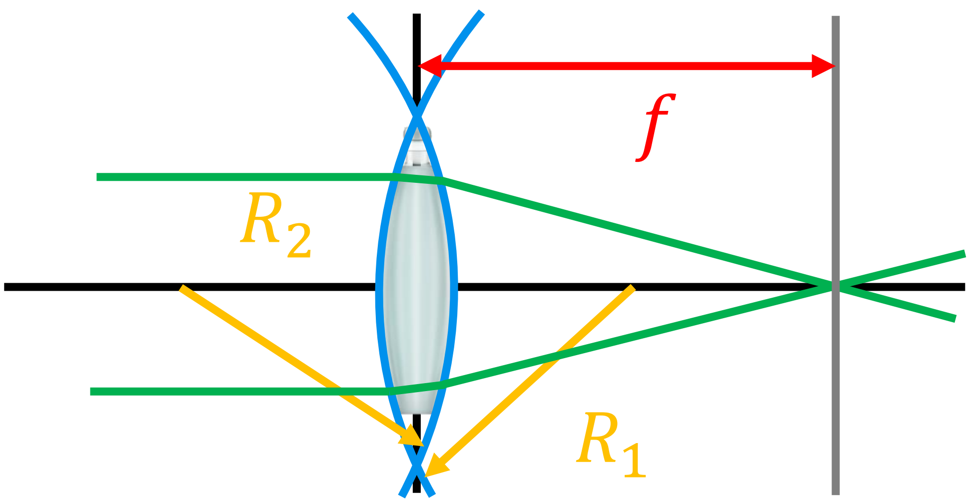
1500×

Spherical bottle is the most dangerous

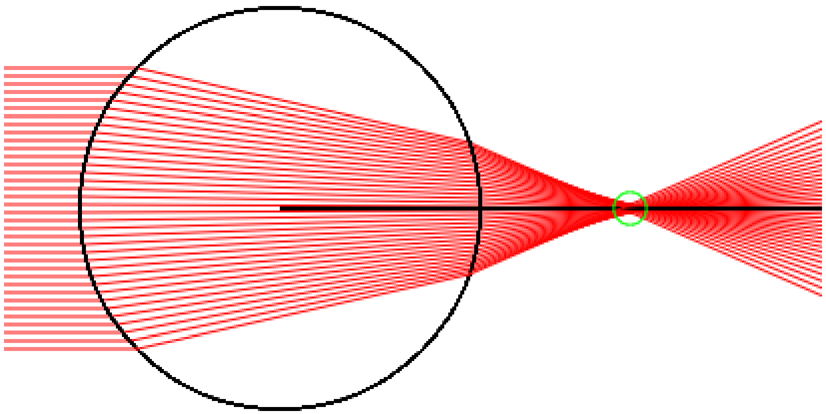
Section 1:
Theoretical estimate of intensification

Two theoretical models

Geometrical model



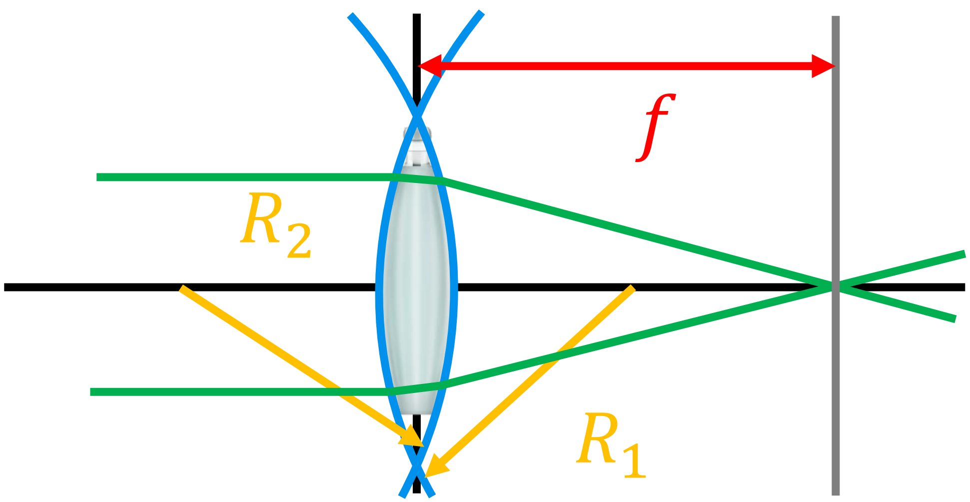
Numerical ray tracing

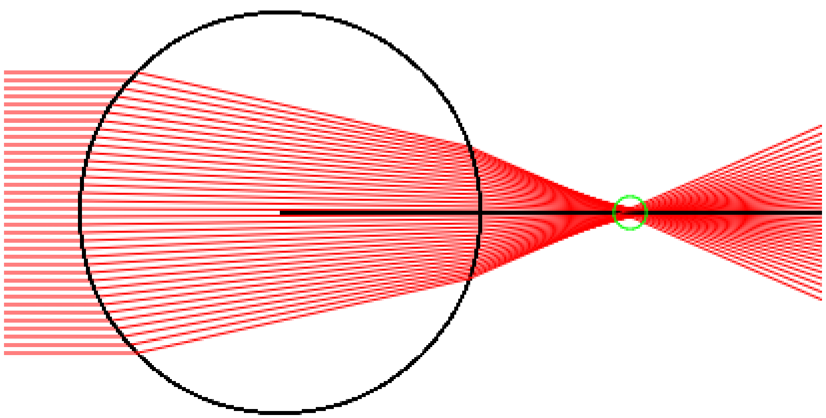


Section 1:
Theoretical estimate of intensification

Two theoretical models

Geometrical model ➡ Numerical ray tracing





GEOMETRICAL MODEL

Focus of a sphere

"Lensmaker's equation"

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right]$$

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(For a sphere: $R_2 = -\mathrm{R}_1 = -\mathrm{R}$ $\quad d = 2R$)

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For water

$$f = \frac{nR}{2n-2} \longrightarrow n = 1.33 \approx \frac{4}{3} \longrightarrow \boxed{f = 2R}$$

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$$f = \frac{nR}{2n-2} \longrightarrow$$

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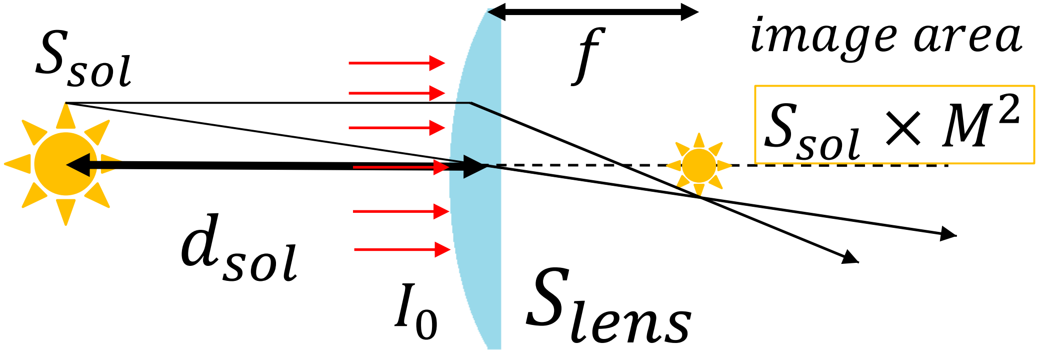
$$n = 1.33 \approx \frac{4}{3} \longrightarrow \boxed{f = 2R}$$

EXPERIMENTALLY CONFIRMED

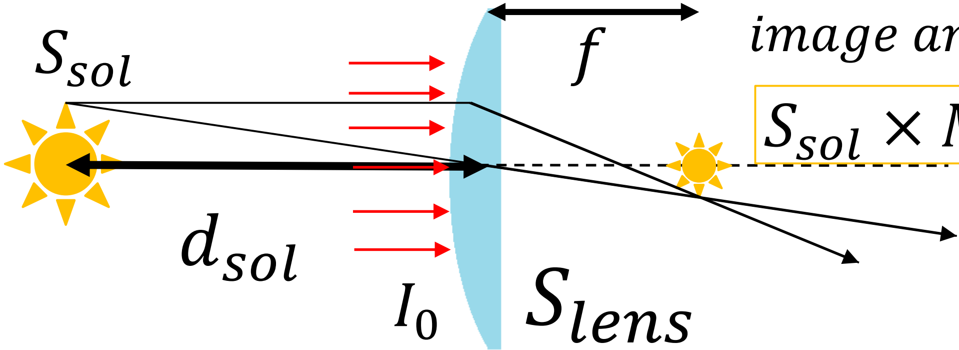
Maximum achievable intensity?



$$image\ area = Solar\ area \times magnification^2$$

$$magnification = \frac{f}{f - d_{sol}}$$

Maximum achievable intensity?



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(power is conserved)

$$I = k\, I_0 \frac{S_{lens}}{S_{sol} M^2}$$

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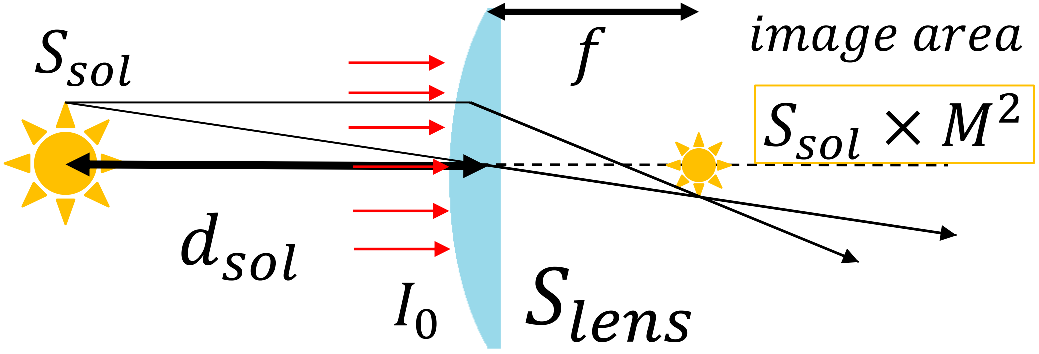

$$magnification = \frac{f}{f - d_{sol}}$$

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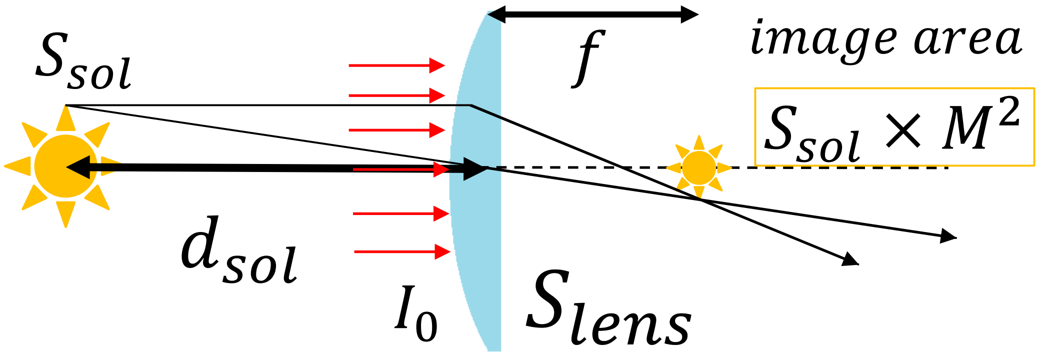
$$I = k\, I_0 \frac{S_{lens}}{S_{sol} M^2}$$

$$I = k\, I_0 \frac{S_{lens}}{S_{sol}} \frac{d_{sol}^2}{f^2}$$

Maximum achievable intensity?



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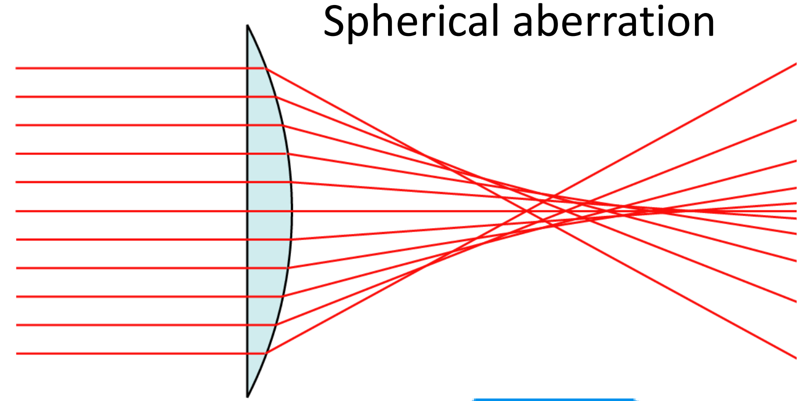
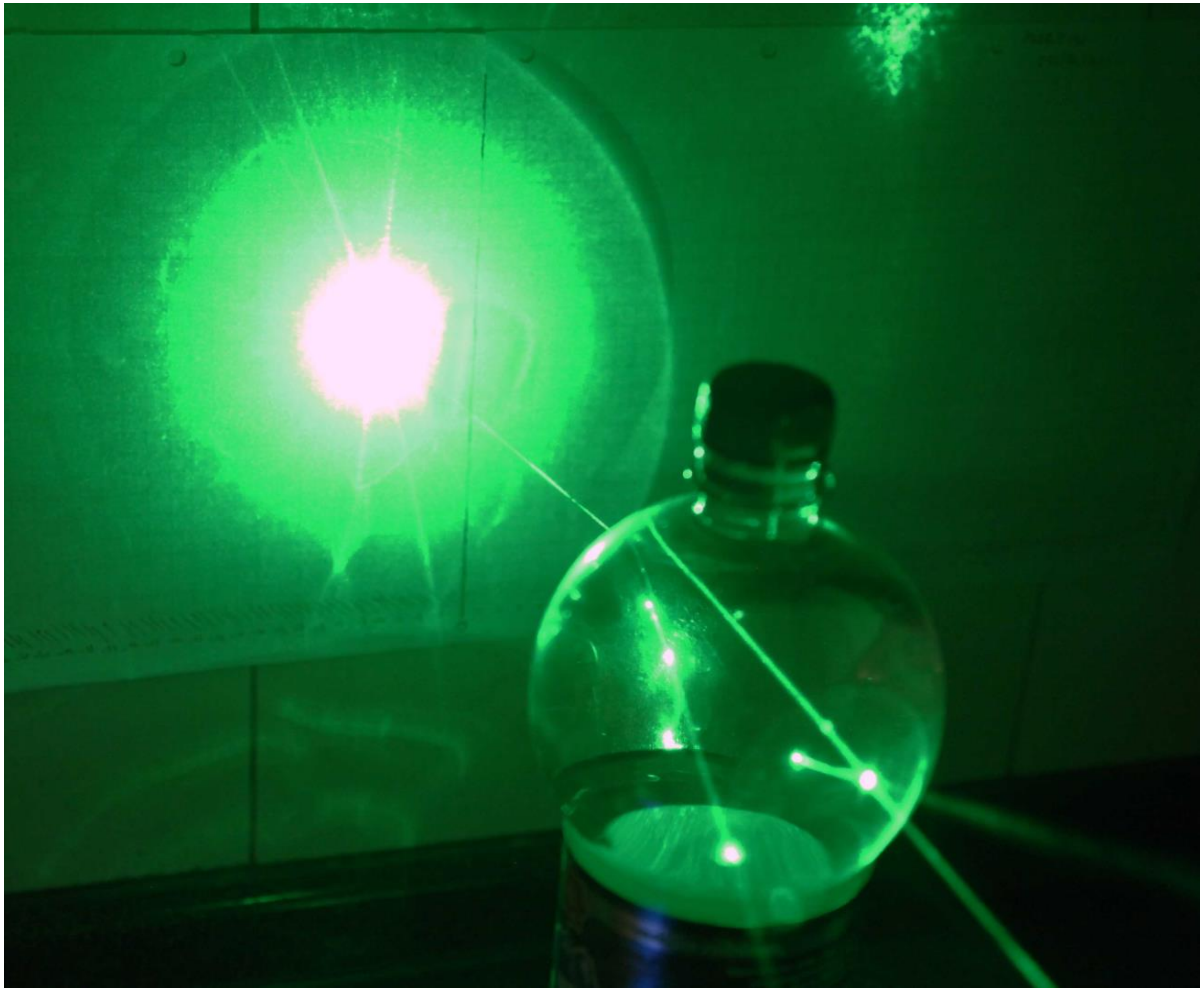
Spherical aberration



ABERRATION EXPERIMENT



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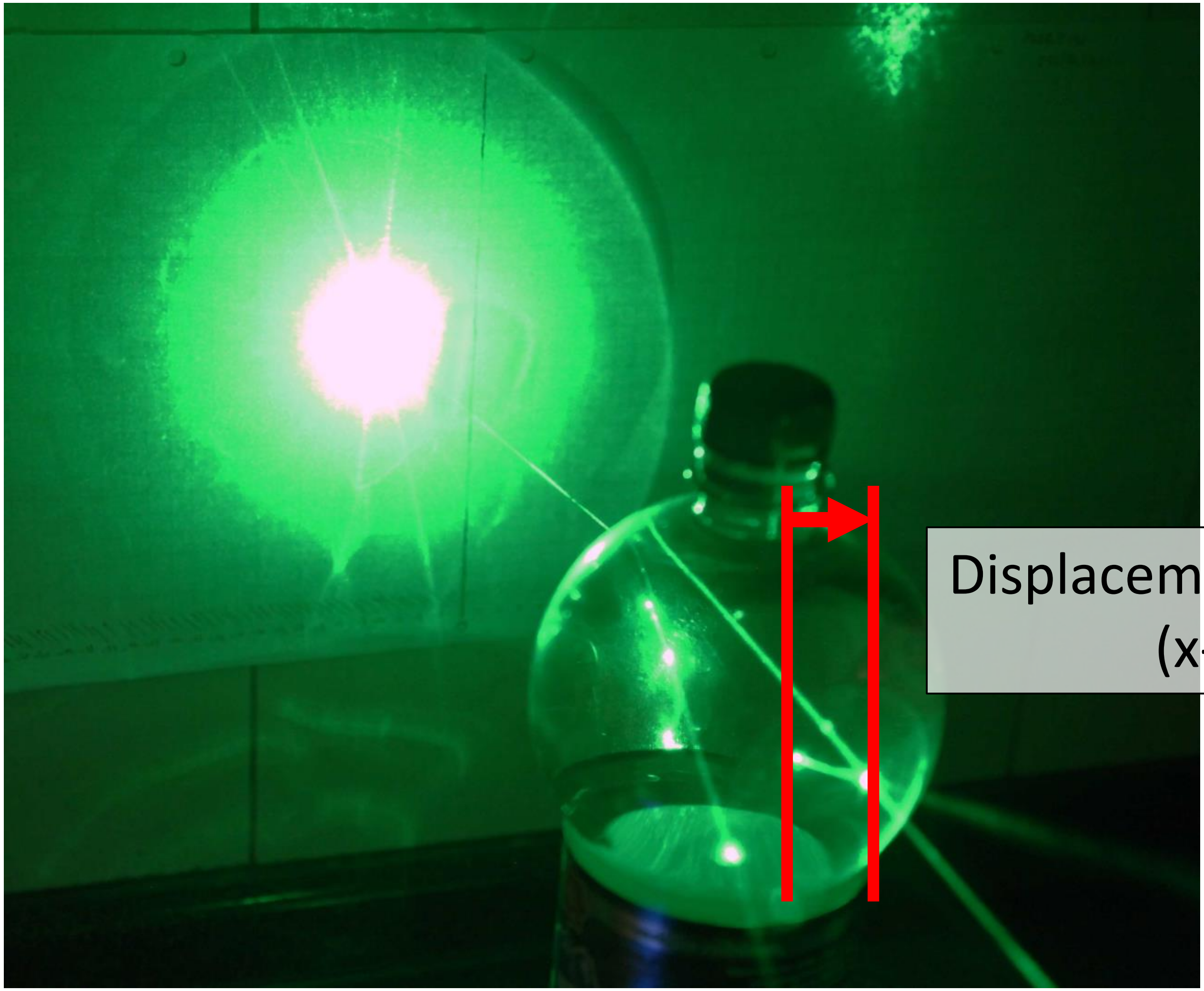
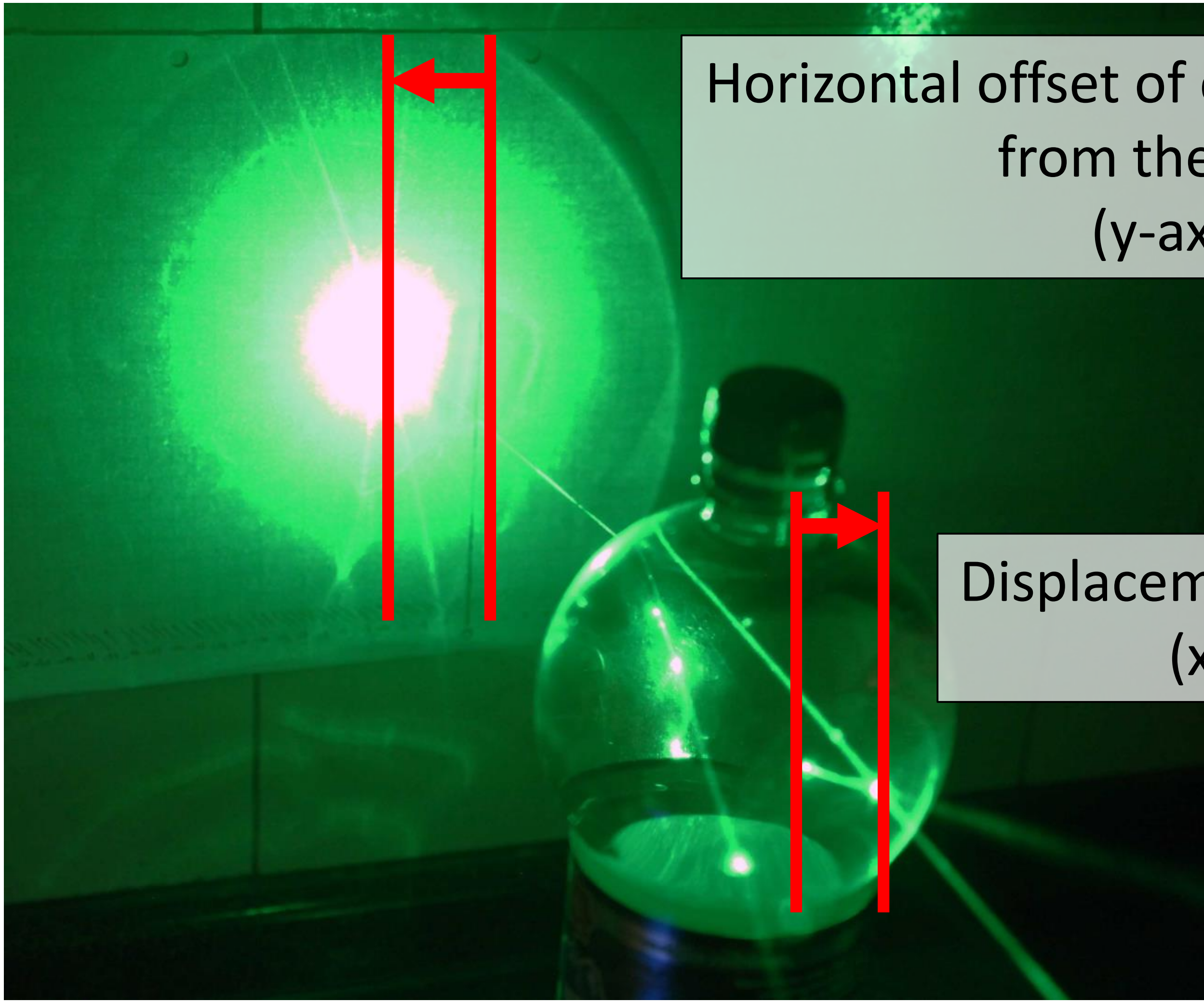


Displacement of the ray (x-axis)

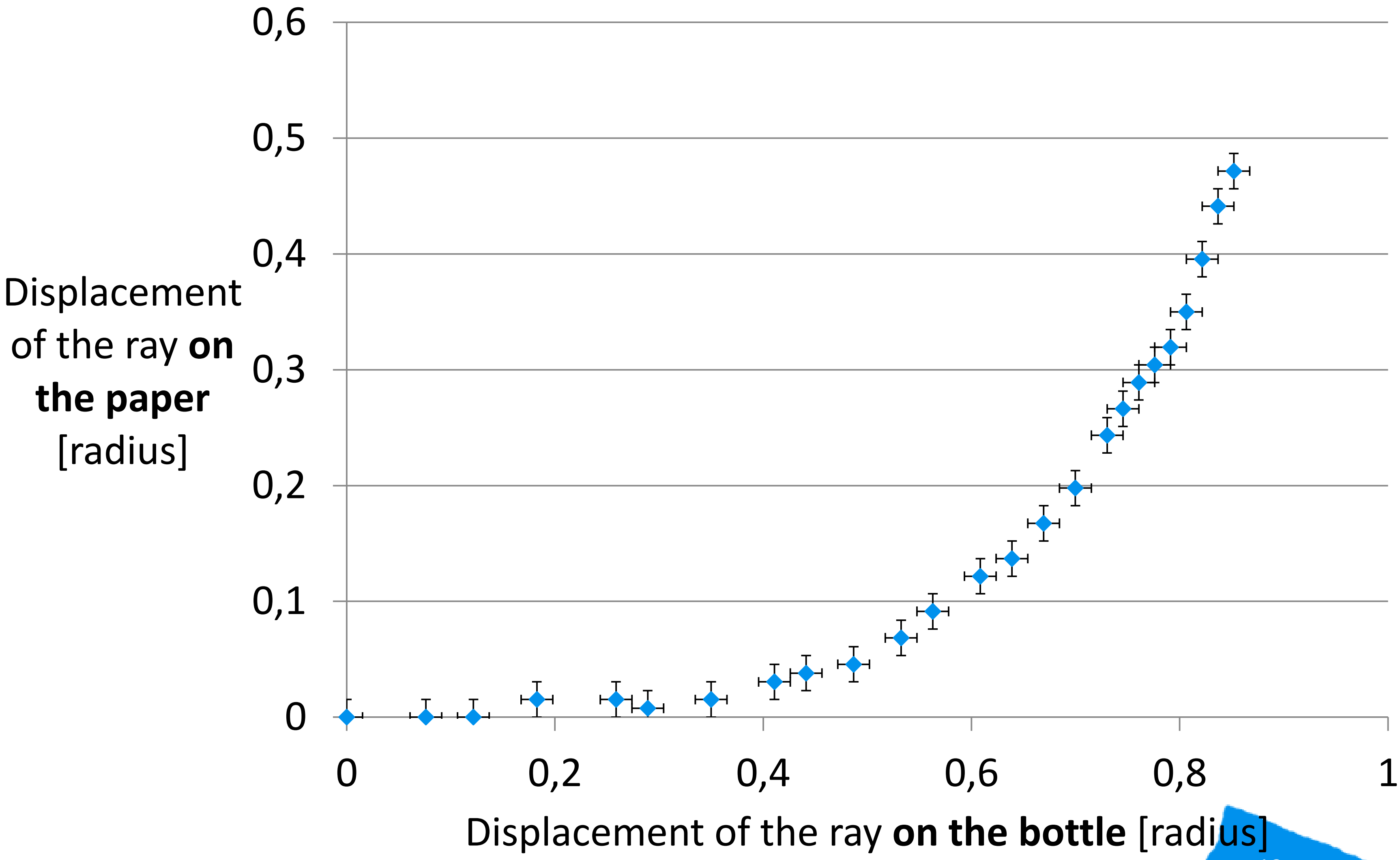
ABERRATION EXPERIMENT



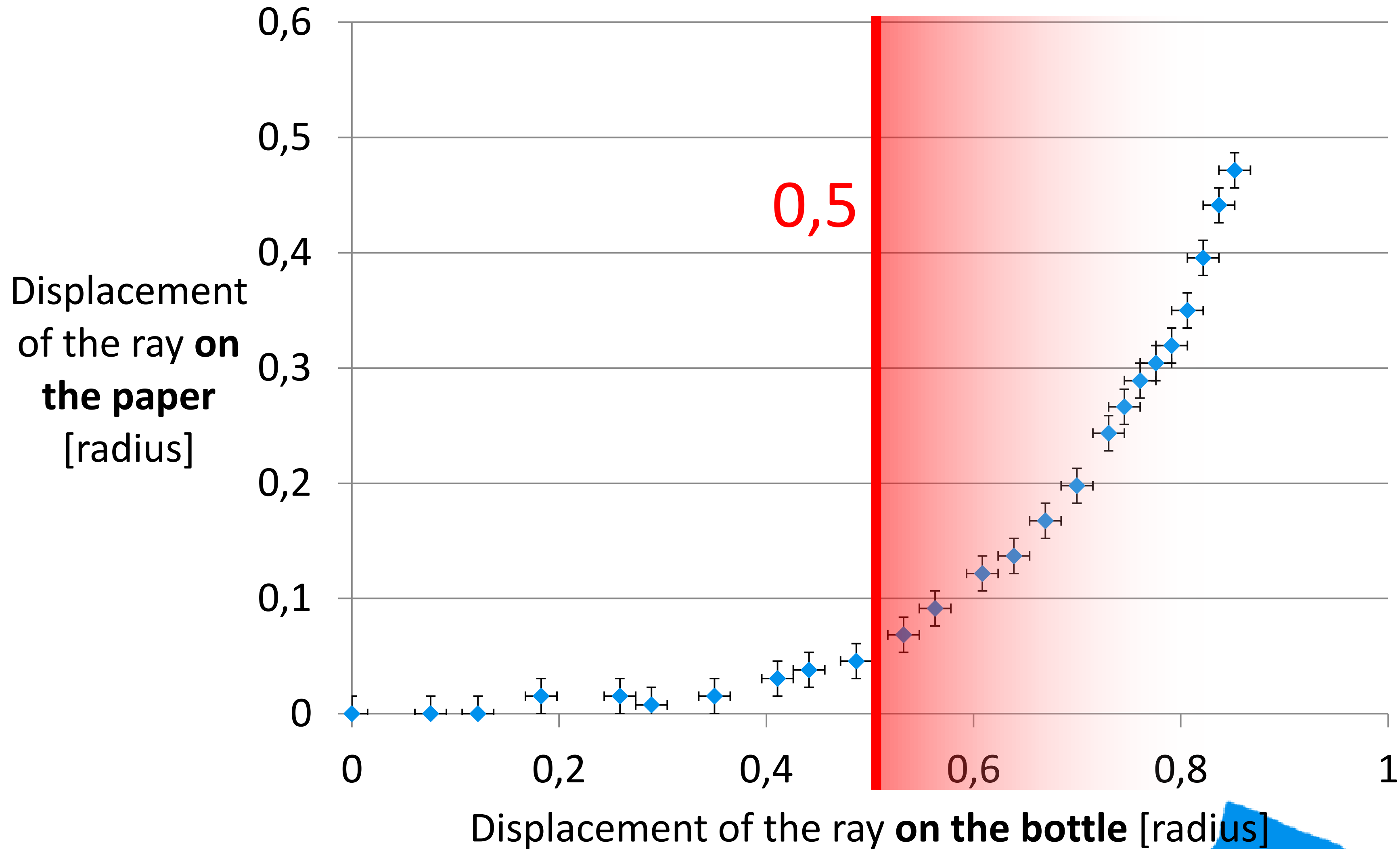
Horizontal offset of concentrated light from the focus (y-axis)

Displacement of the ray (x-axis)

Effective area – **ABERRATION EXPERIMENT**



Effective area – **ABERRATION EXPERIMENT**



Theoretical prediction of maximal intensity

$$I = k\, I_0 \frac{S_{lens}}{S_{sol}} \frac{d_{sol}^2}{f^2}$$

$$I = k\, I_0 \frac{\frac{\pi R^2}{4}}{S_{sol}} \frac{d_{sol}^2}{4R^2}$$

$$\frac{d_{sol}^2}{S_{sol}} \cong 14000$$

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$$\frac{d_{sol}^2}{S_{sol}} \cong 14000$$

$$I = k \frac{14000\pi}{16} I_0 \cong 2750 k\, I_0$$

Comparison with the experiment

$$I = k\frac{14000\pi}{16} I_0 \cong 2750k\, I_0$$

Permeability constant includes

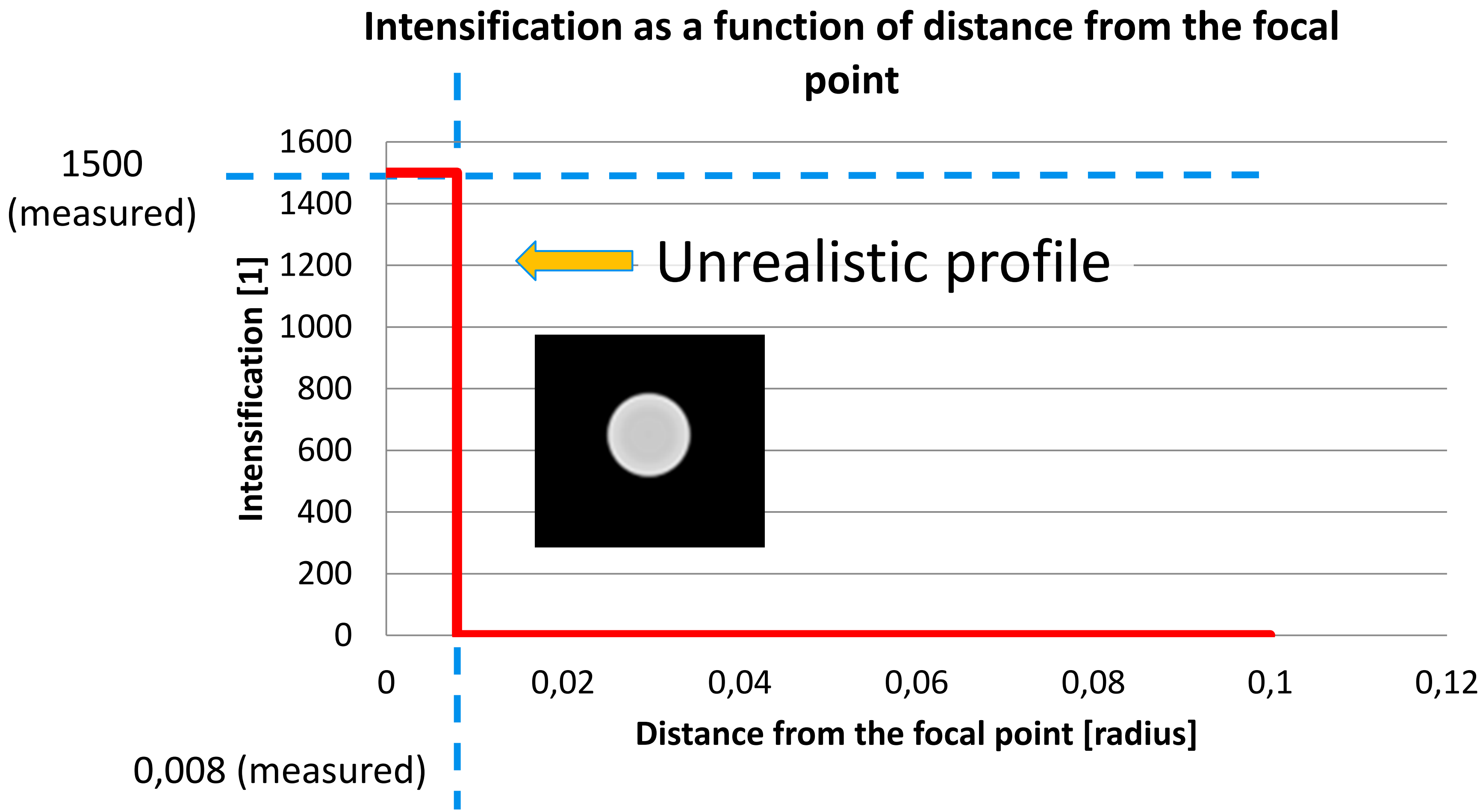
- Reflection on plastics-air interface
- Reflection on plastics-liquid interface (2x)
- Scattering in the liquid
- Absorption in the liquid (depends on the frequency of the light)

1500×

+ other undeterminable losses

$$k \cong 0.55$$

Motivation for better model



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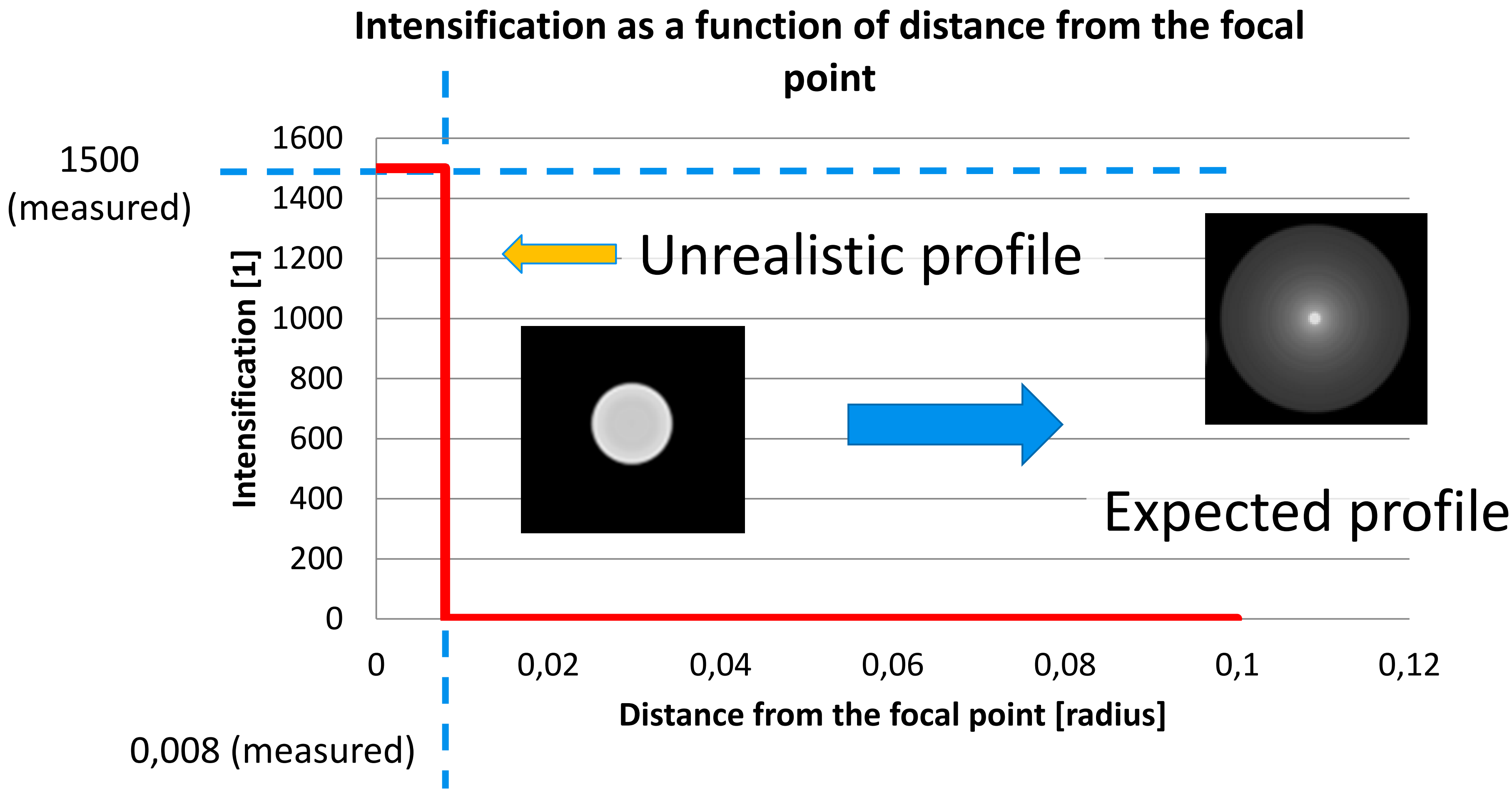


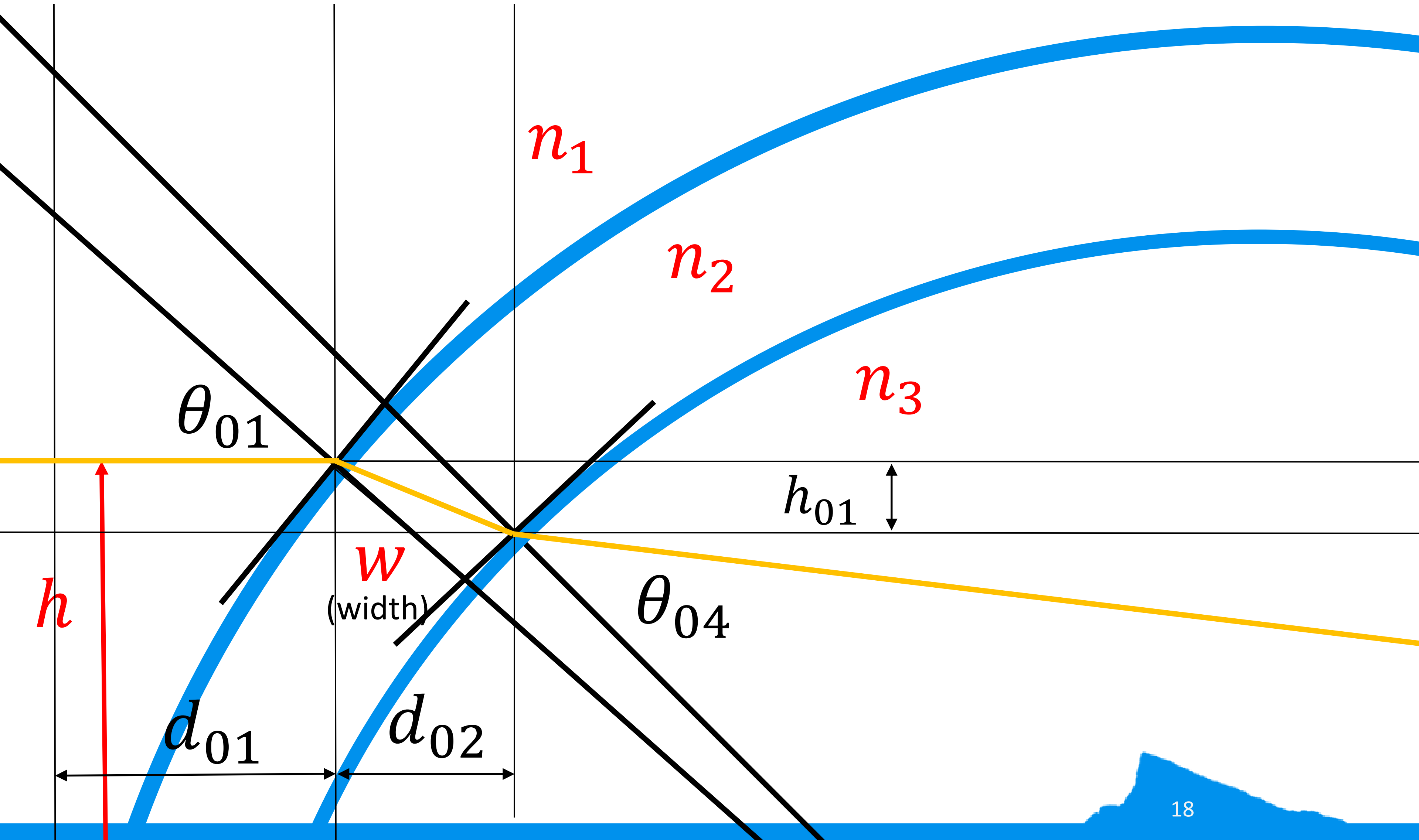
NUMERICAL RAY TRACING

Advantages:

accuracy – spherical aberration, reflection, dispersion <u>were assumed</u>

results – full image of intensity profile curve

Reflection + refraction at the interfaces



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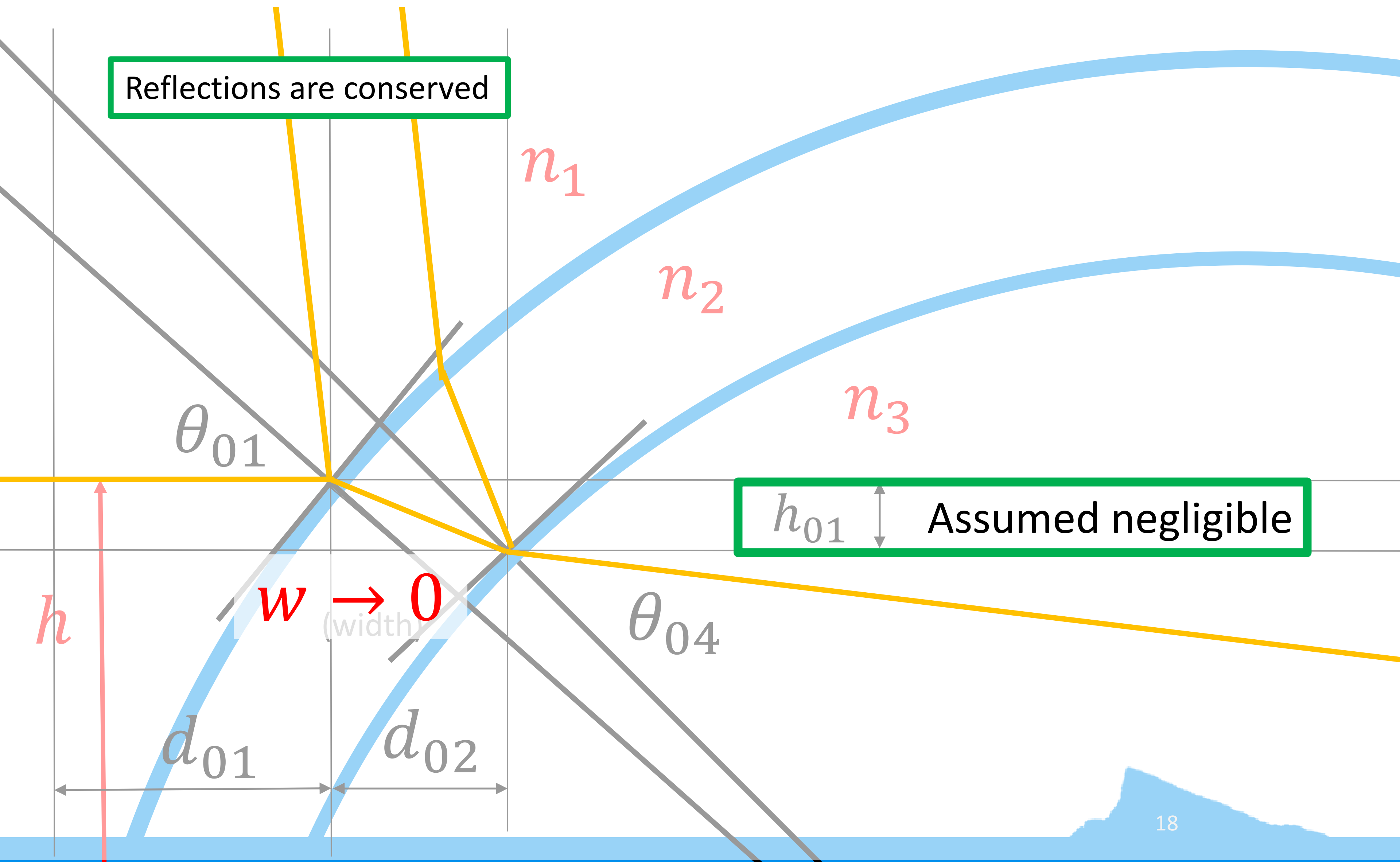
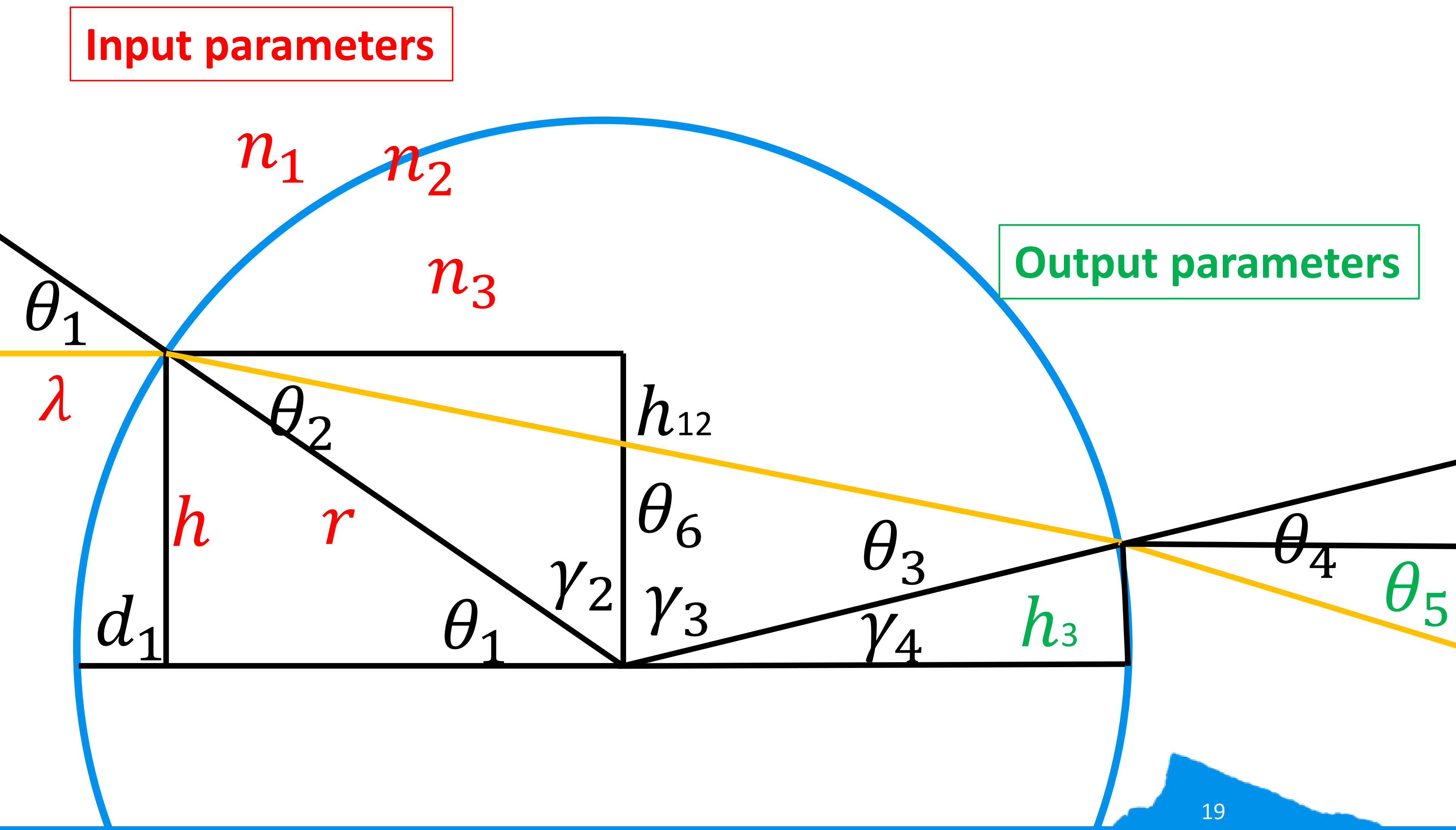


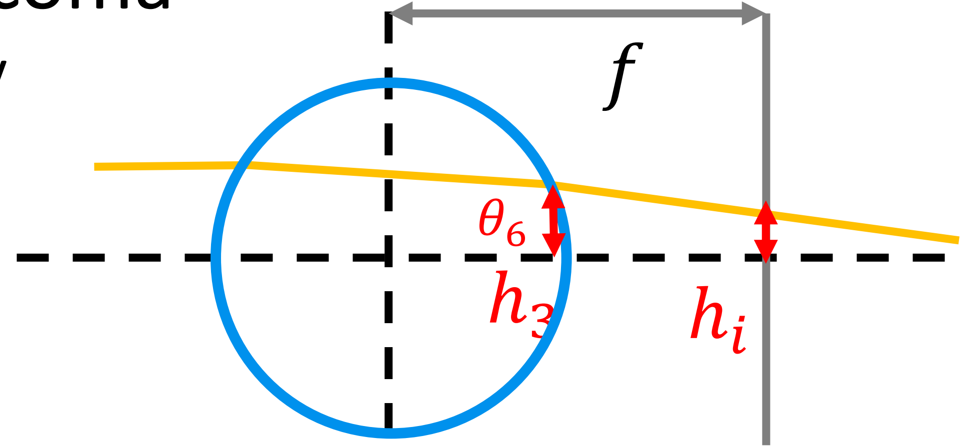
Ray tracing – ins and outs



Method: included effects

- Aberration and coma

  included by geometry



- Reflection – Fresnel equations *unpolarized light assumed

$$R = \frac{\left|\frac{n_1 cos\theta_i - n_2\, cos\theta_t}{n_1 cos\theta_i + n_2\, cos\theta_t}\right|^2 + \left|\frac{n_1 cos\theta_t - n_2\, cos\theta_i}{n_1 cos\theta_t + n_2\, cos\theta_i}\right|^2}{2}$$

Method: included effects

- Aberration and coma

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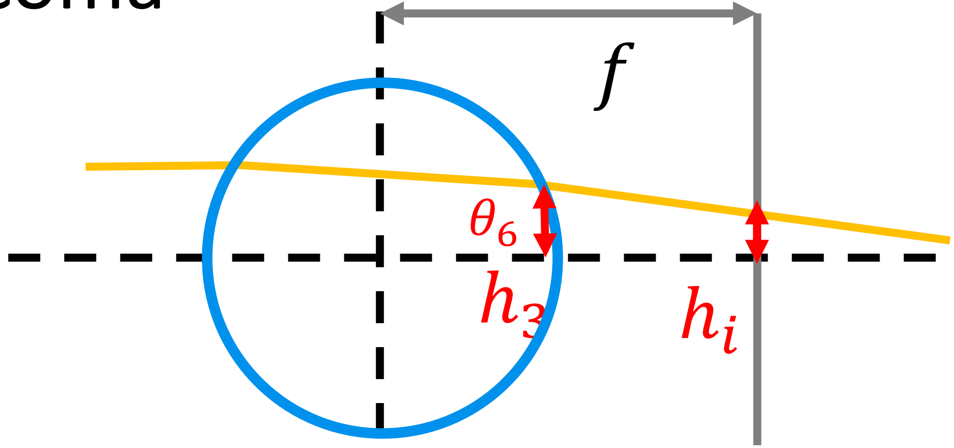

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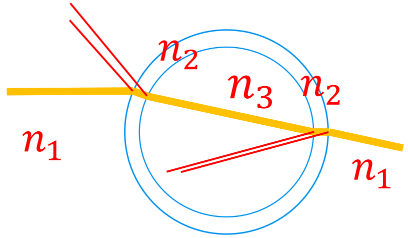

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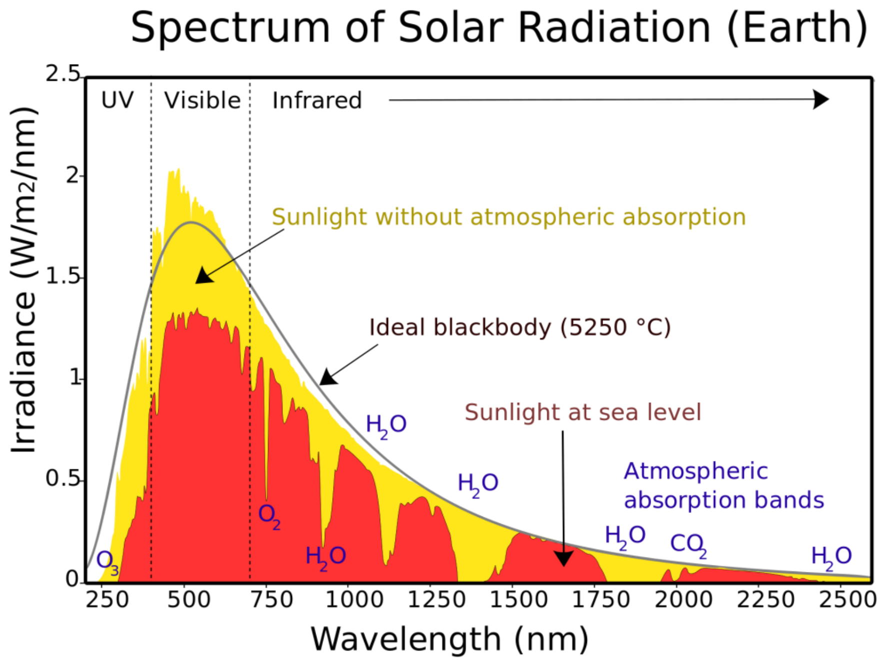
Method: included effects

- Sun's spectrum
  - black body radiation

$$I_{(v,T)} = \frac{2hv^3}{c^2}\frac{1}{e^{\frac{hv}{kT}}-1}\left[\frac{W}{m^2\ sr\ Hz}\right]$$



- Dispersion – Cauchy's equation *for water:

$$n(\lambda) = 1.13199 + \frac{6878}{\lambda^2} + \frac{1.132\ x\ 10^9}{\lambda^4} + \frac{1.11\ x\ 10^{14}}{\lambda^6} \ldots [1]$$

[1] Water Refractive Index in Dependence on Temperature and Wavelength, by Alexey N. Bashkatov, Elina A. Genina, Optics Department Saratov State University, Saratov, Russia

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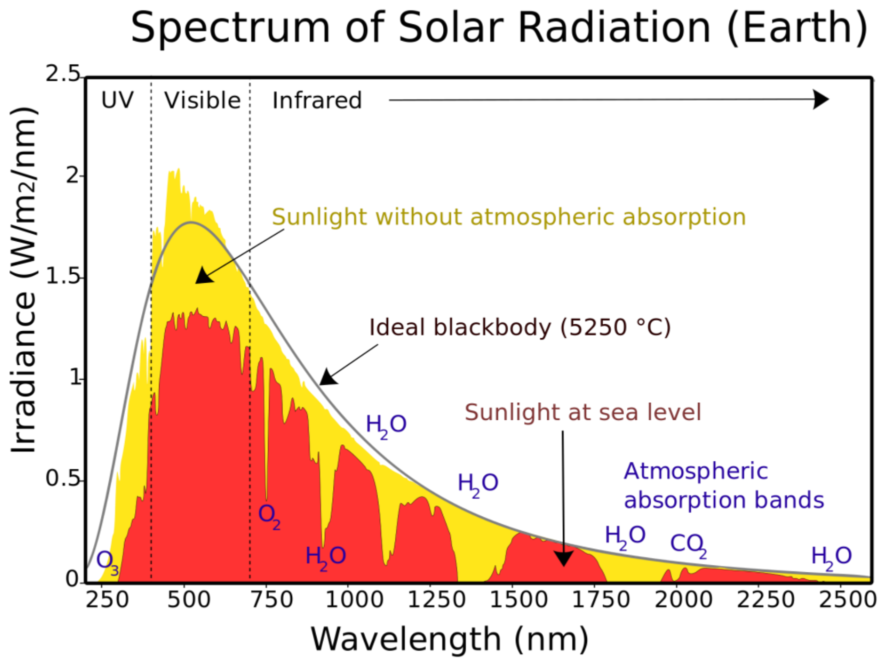

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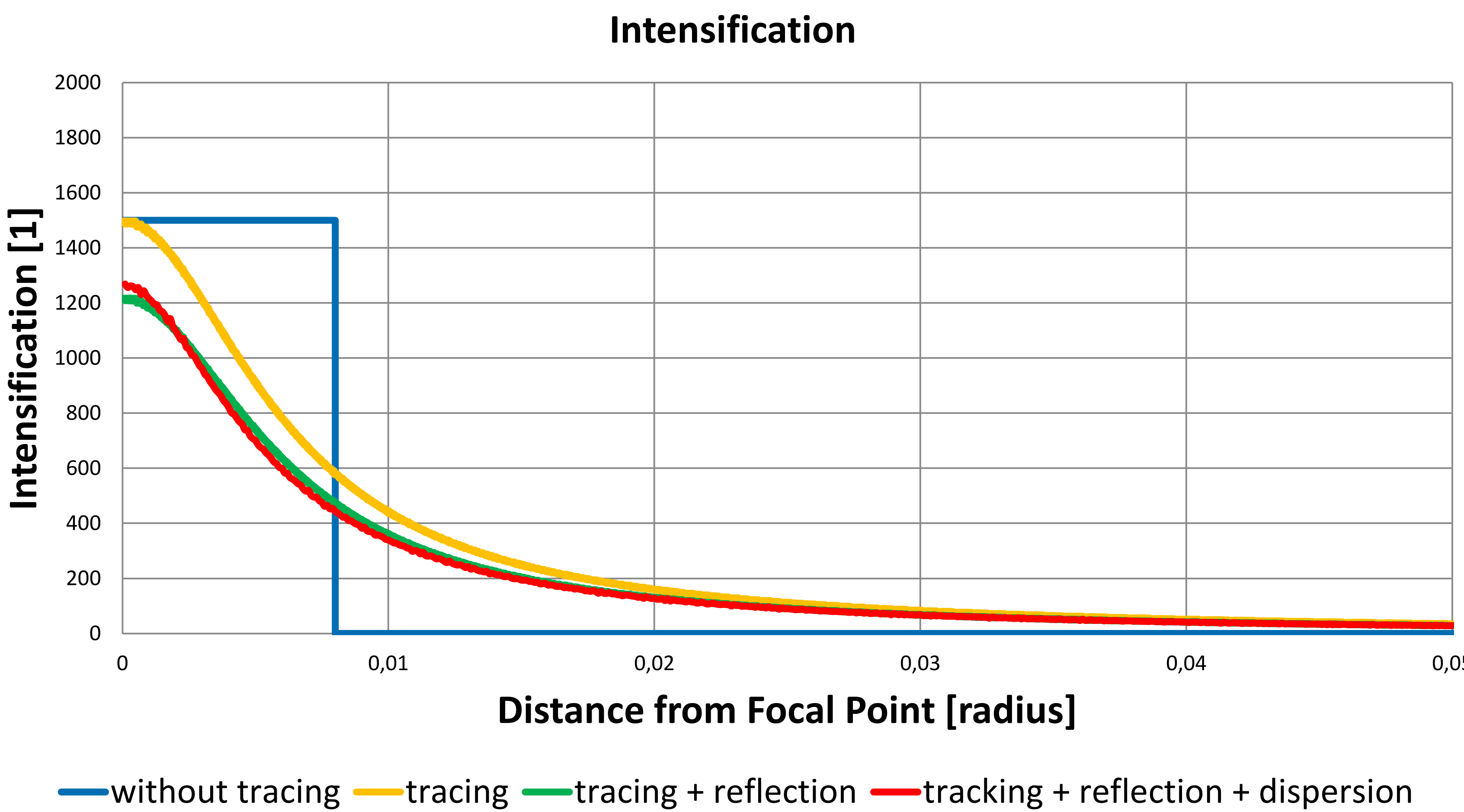
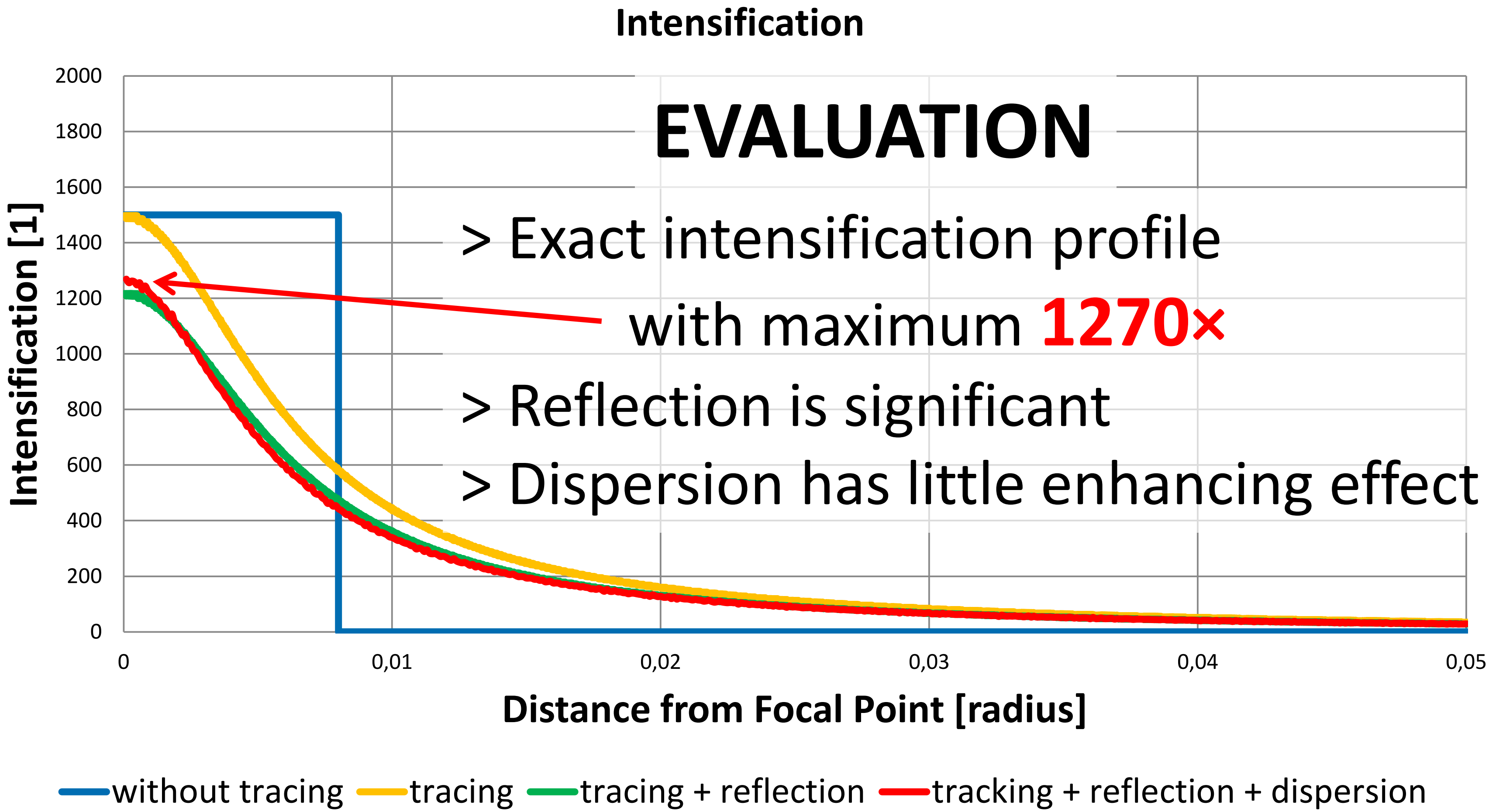
Ray tracing – processed output



Ray tracing – processed output



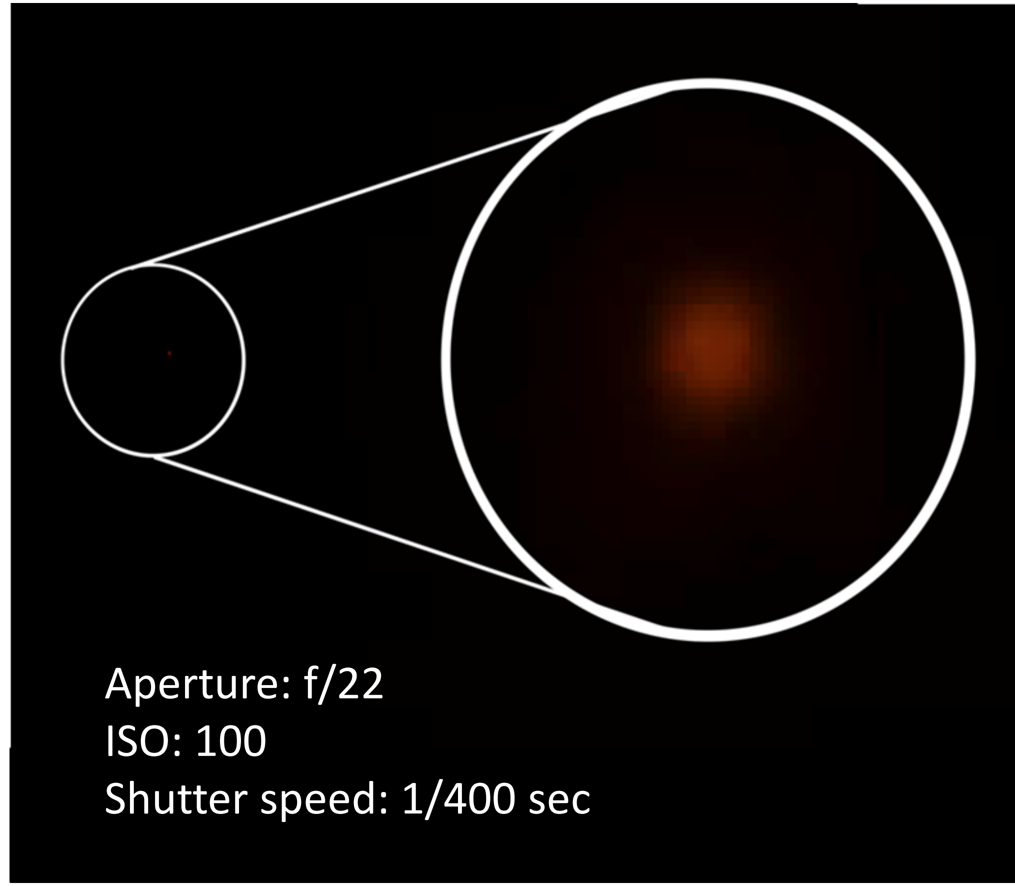
EVALUATION

> Exact intensification profile with maximum **1270×**

> Reflection is significant

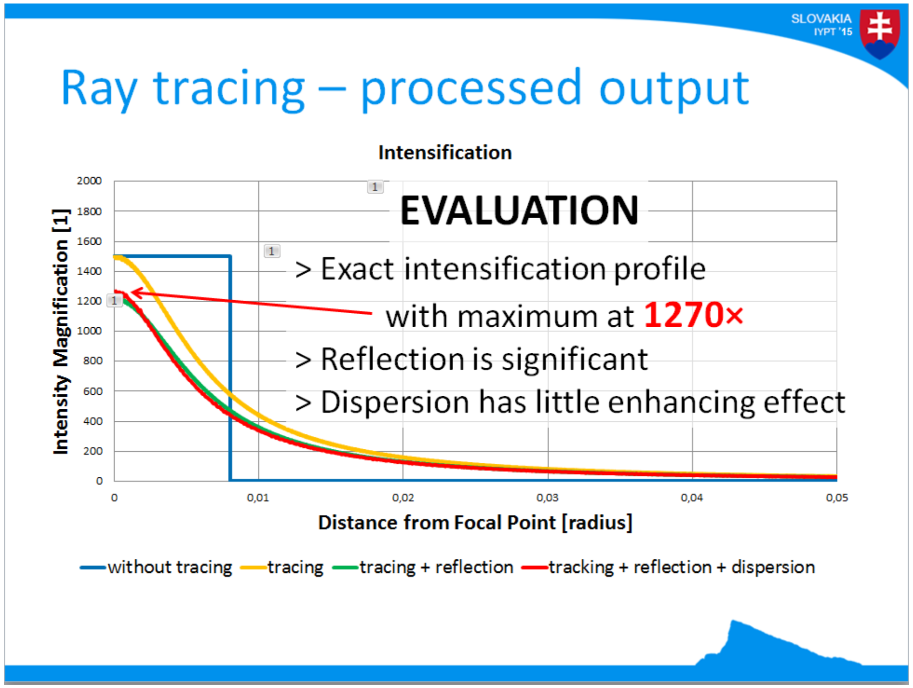
> Dispersion has little enhancing effect

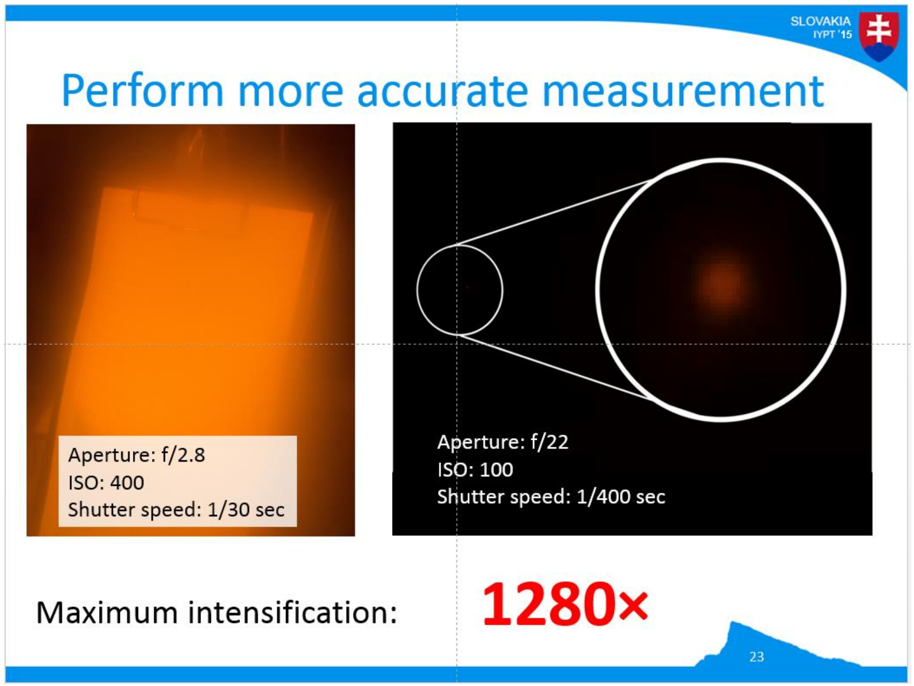
Perform more accurate measurement



Maximum intensification: **1280×**

Ray tracing vs. accurate measurement





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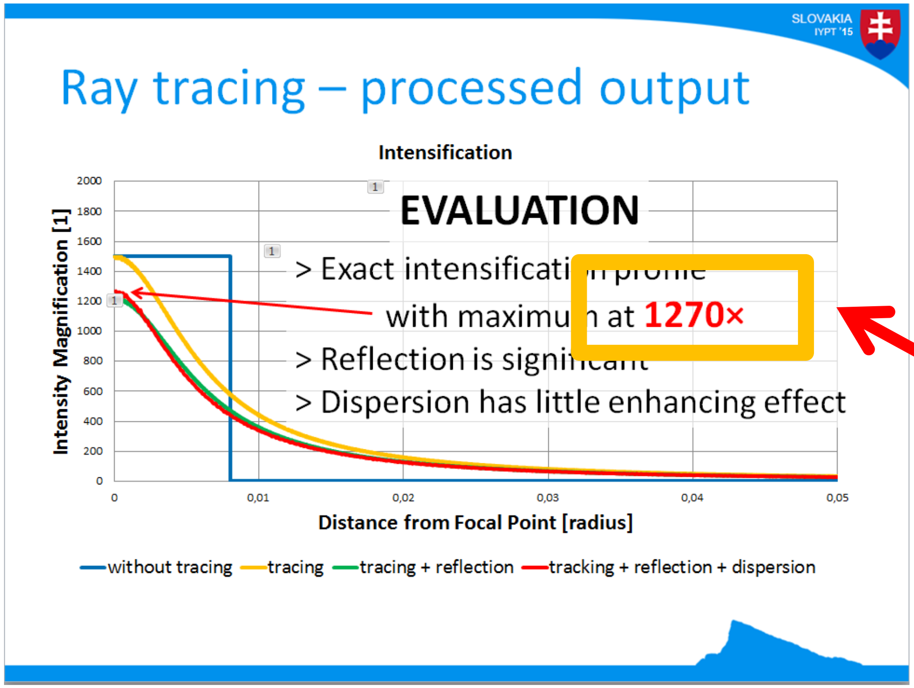
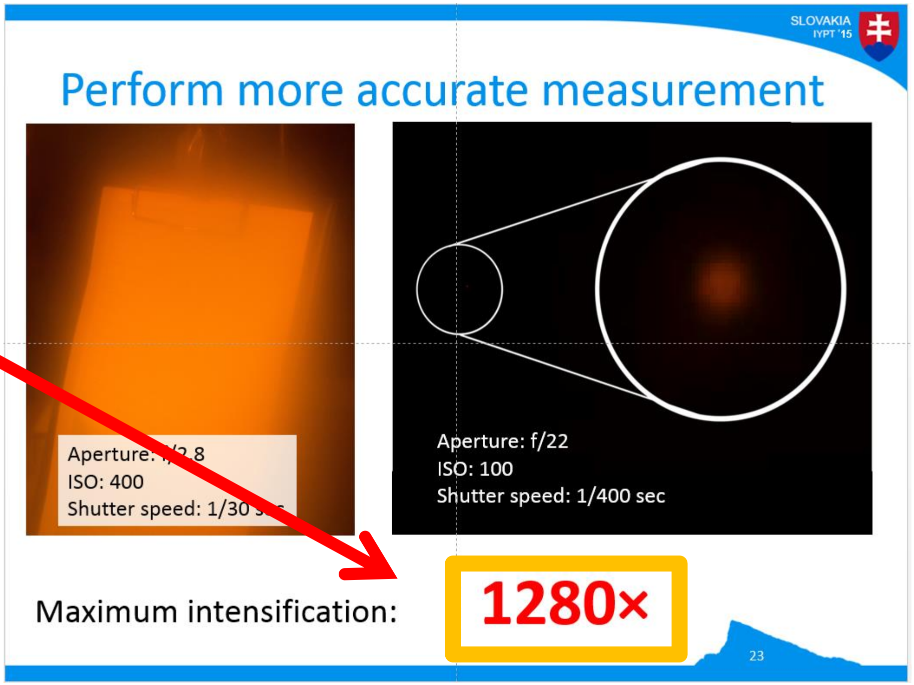


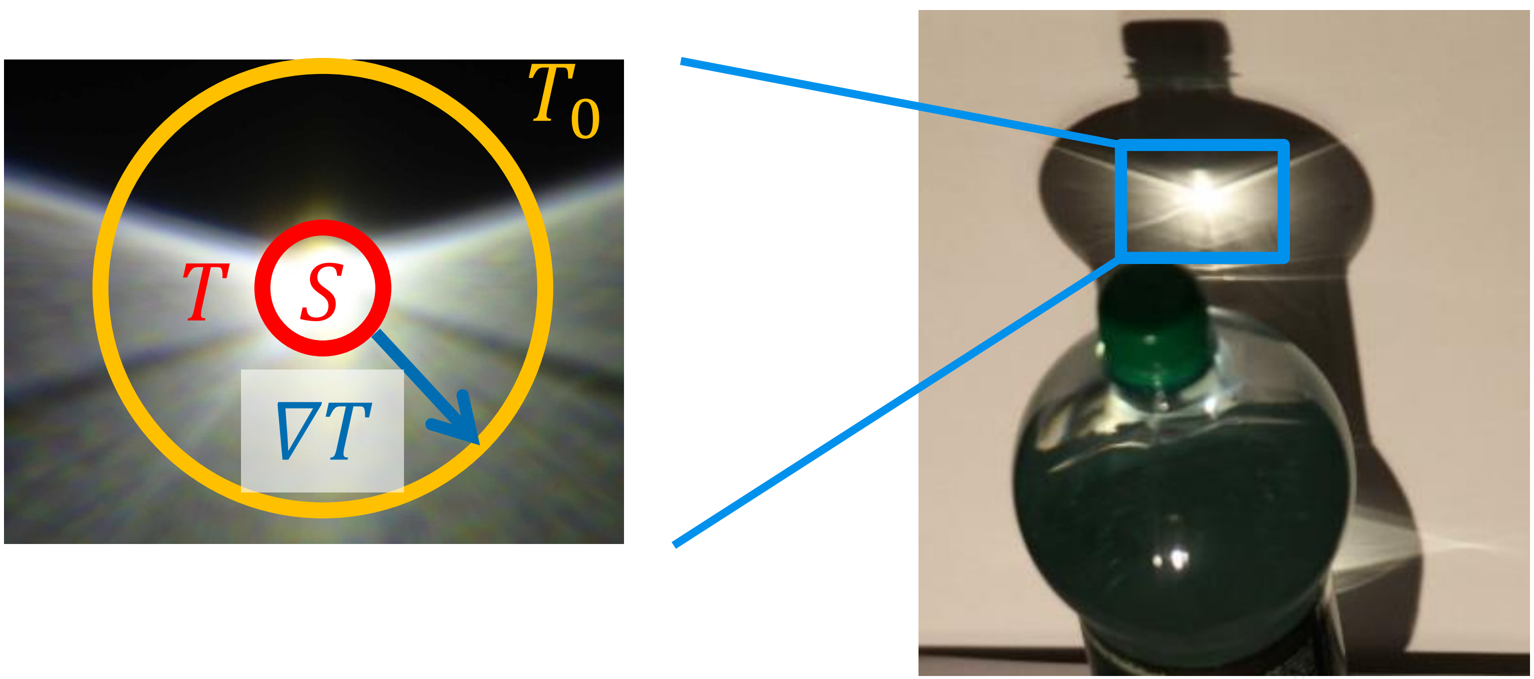


99% correlation!

SECTION 2: DISSIPATION FROM MATERIAL

Heating equation

$$mk\frac{\mathrm{d}T}{\mathrm{d}t} = \epsilon\, I_{in}\boldsymbol{S} - \left(c\frac{\boldsymbol{S}}{\boldsymbol{l}} + h\boldsymbol{S}\right)\Delta T - \sigma\epsilon\boldsymbol{S}T^4$$



Heating equation

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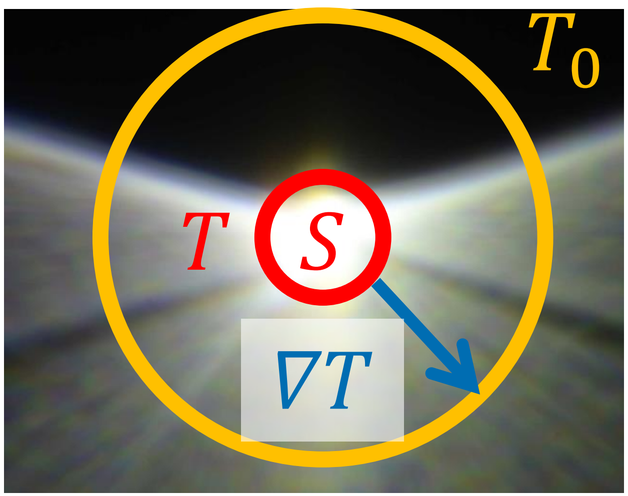
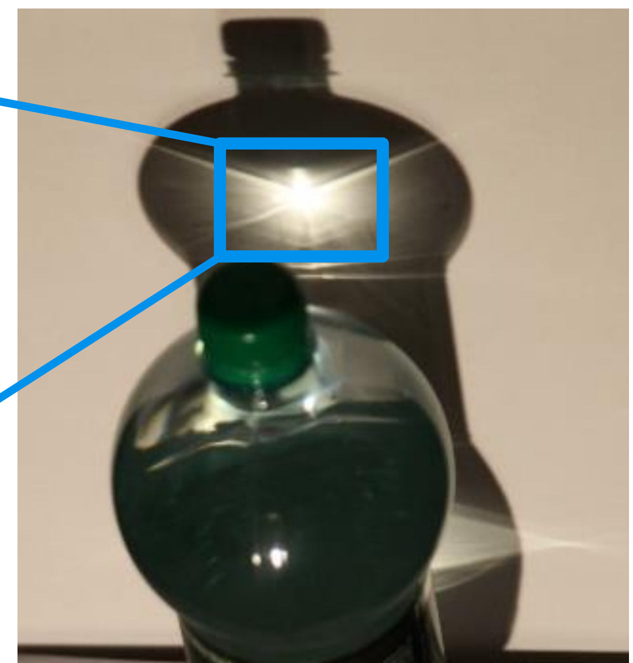
Change in internal energy



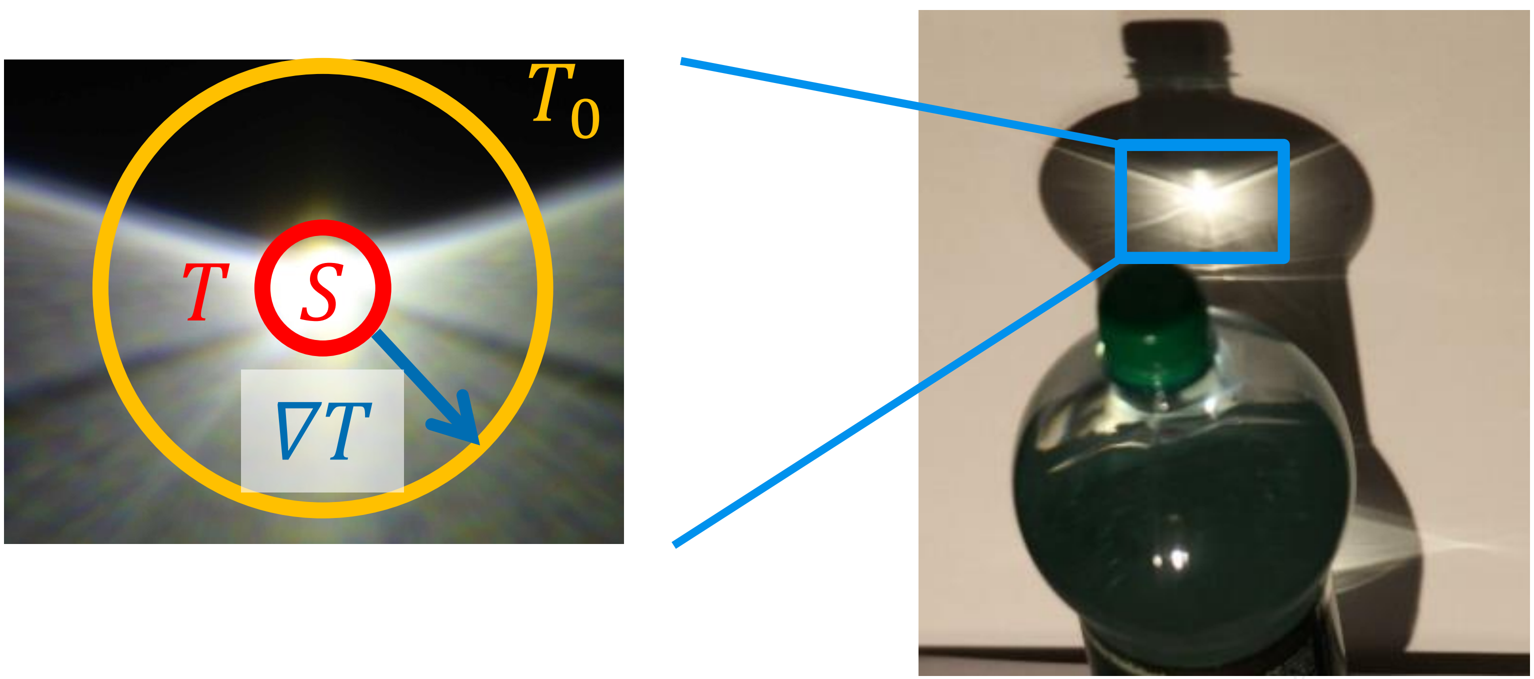


Heating equation

$$\boxed{mk\frac{\mathrm{d}T}{\mathrm{d}t}} = \boxed{\epsilon I_{in}\boldsymbol{S}} - \left(c\frac{\boldsymbol{S}}{\boldsymbol{l}} + h\boldsymbol{S}\right)\Delta T - \sigma\epsilon \boldsymbol{S}T^4$$

Change in internal energy

Net power input



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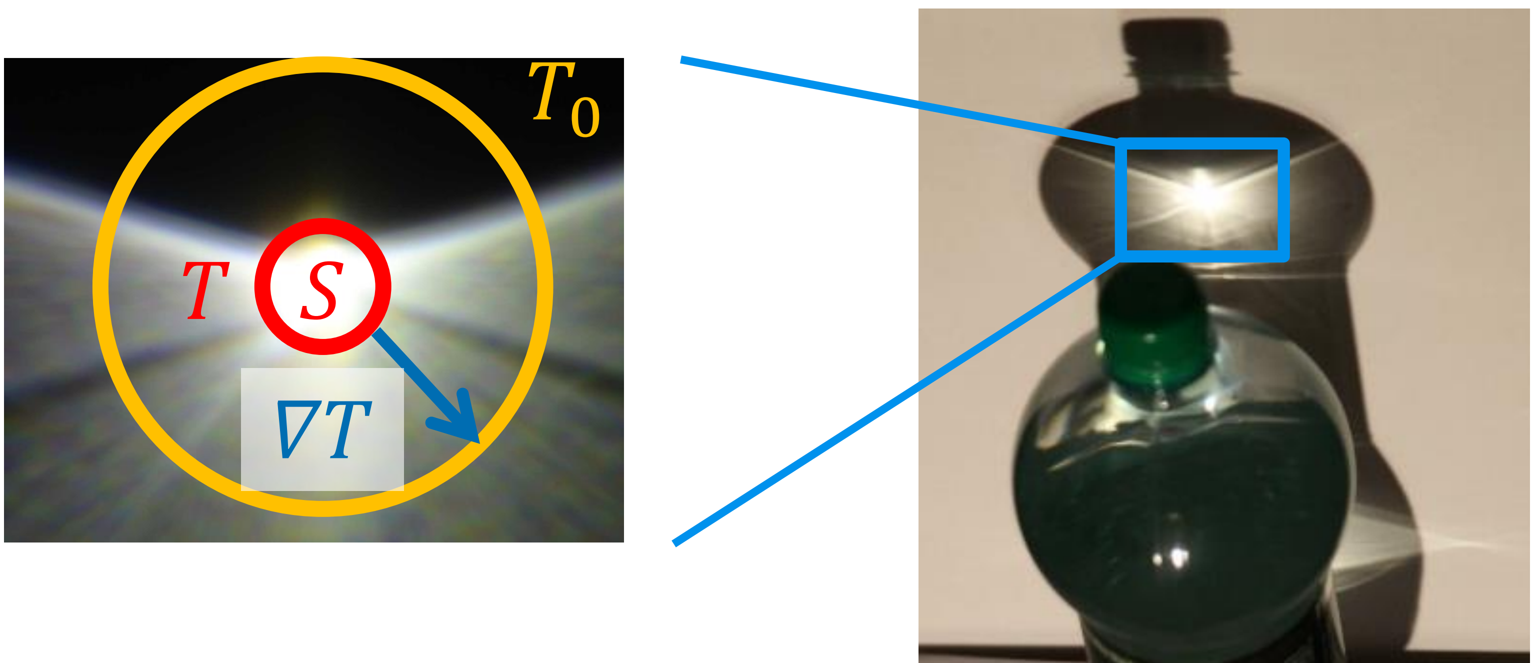
$$mk\frac{\mathrm{d}T}{\mathrm{d}t} = \epsilon I_{in}S - \left(c\frac{S}{l} + hS\right)\Delta T - \sigma\epsilon S T^4$$

Change in internal energy

Heat dissipated to surroundings by…

Net power input



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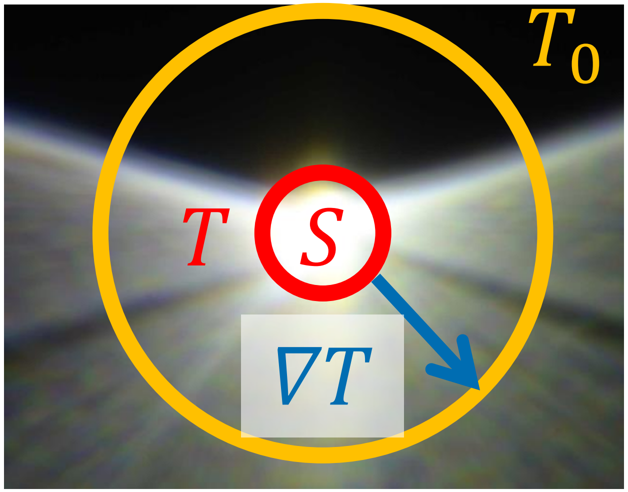
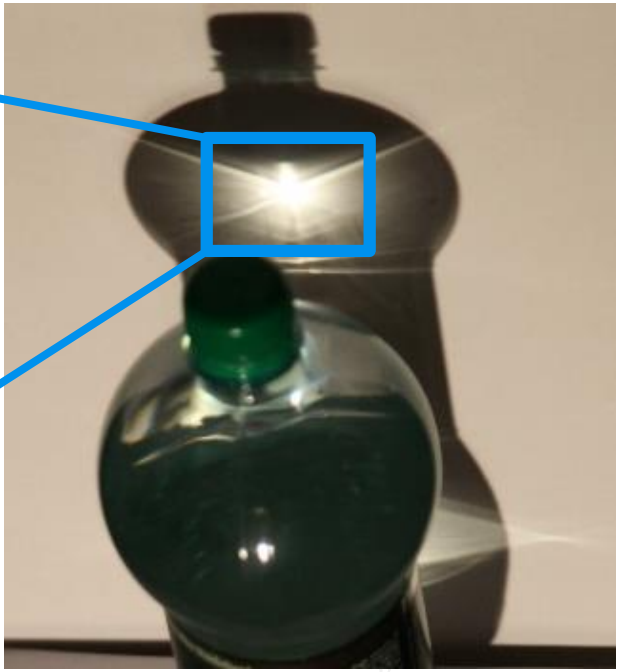
Change in internal energy

Heat dissipated to surroundings by…

Net power input

conduction





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Heat dissipated to surroundings by…

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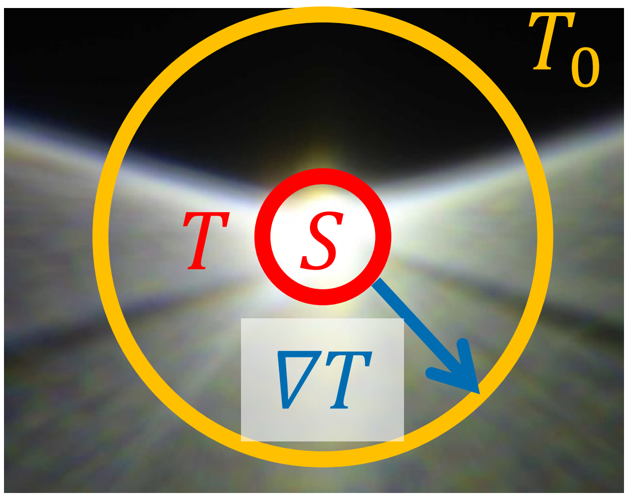

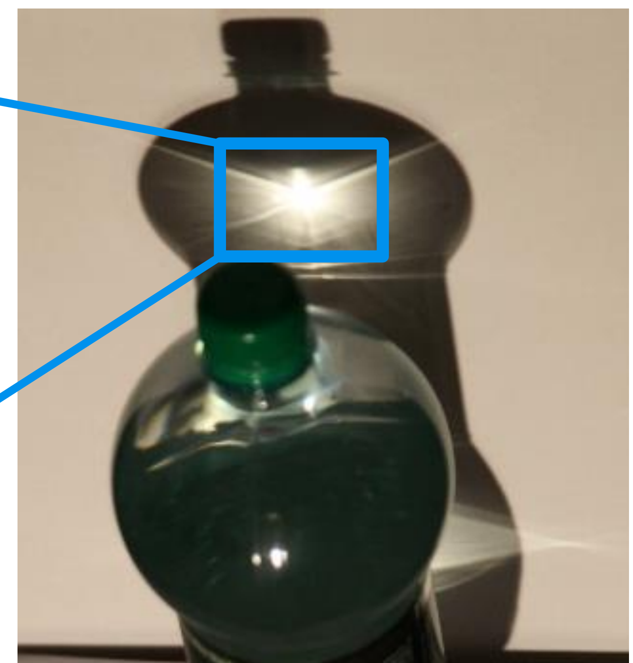

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Change in internal energy

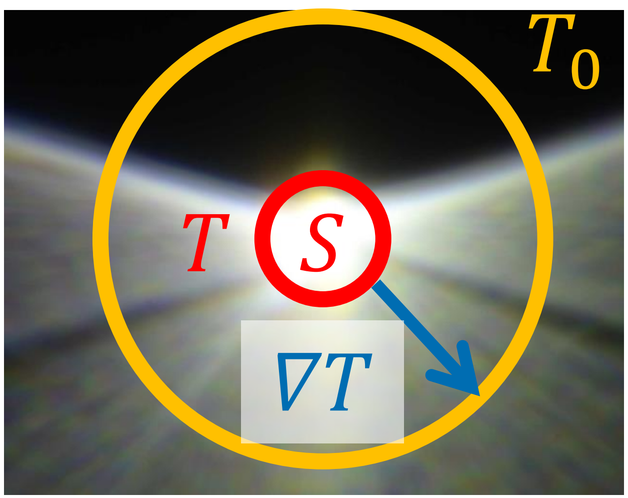
Net power input

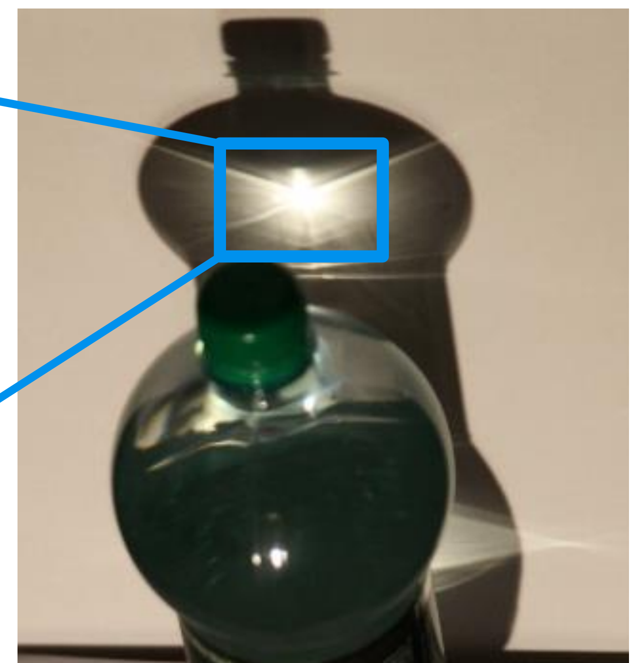
Heat dissipated to surroundings by…

conduction

convection

Power dissipated by radiation





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Change in internal energy

Net power input

Heat dissipated to surroundings by...

conduction

convection

Power dissipated by radiation

Typical times of ignition (without considering losses)

$$t = \frac{mk\left(T_{scorching} - T_0\right)}{\epsilon\, I_{in} S} = 1.76\ \mathrm{s}$$

$$m = 7 \times 10^{-7}\ kg$$

$$k = 2000\,\frac{J}{kg\ K}$$

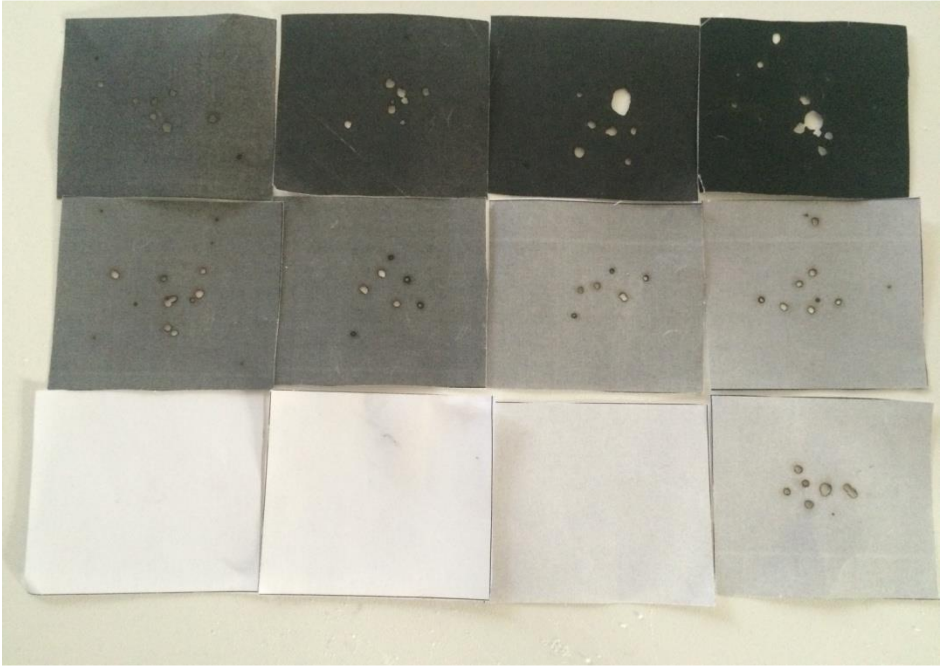
$$T_{scorching} = 670\ K$$

$$I_{in} = 320\,\frac{kW}{m^2}$$

$$S = 10^{-6} m^2$$

$$\epsilon = 0.92$$

Significance of **albedo**



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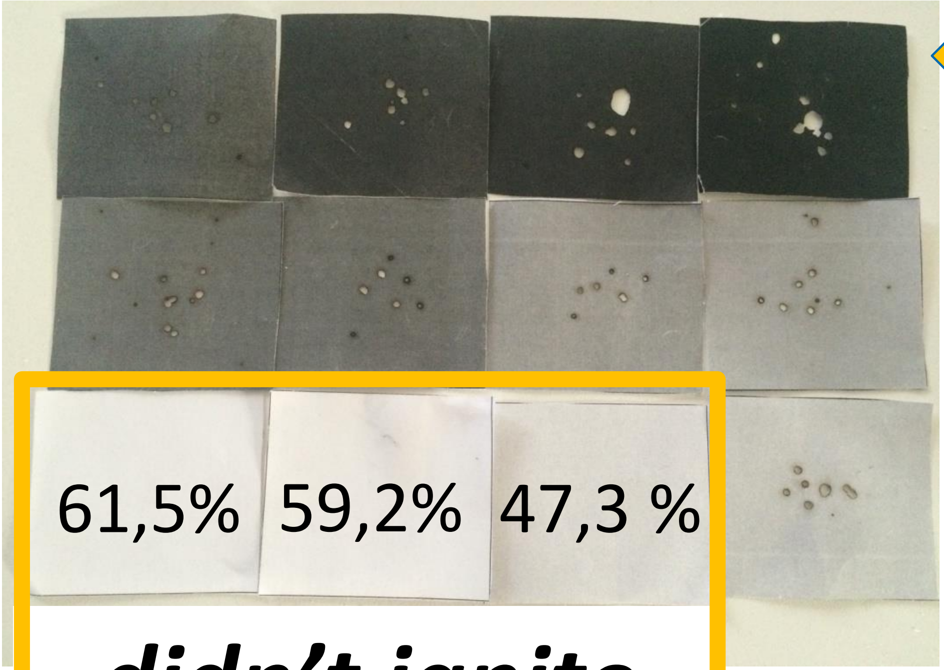
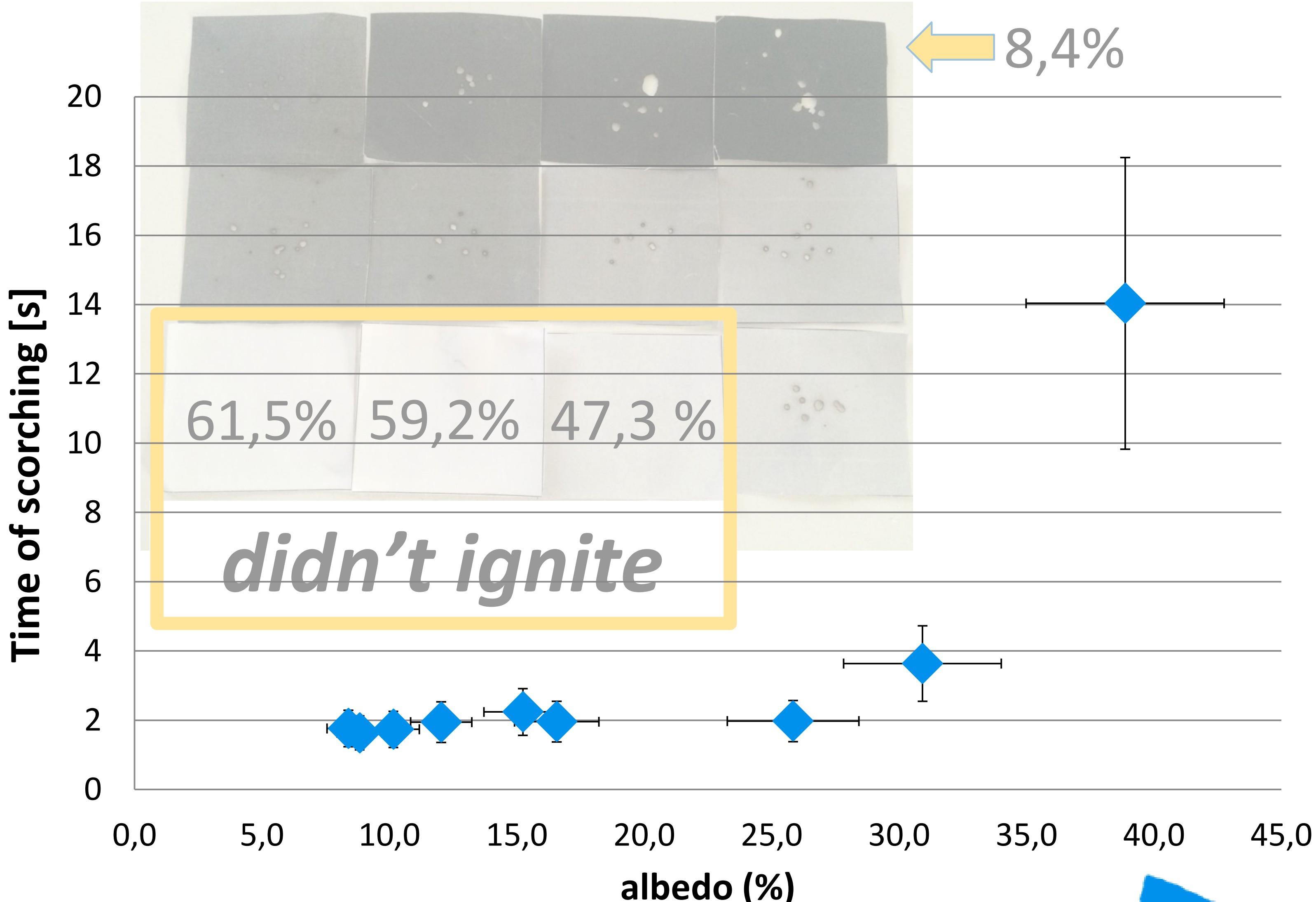


8,4%

61,5% 59,2% 47,3 %

didn't ignite

Significance of **albedo**



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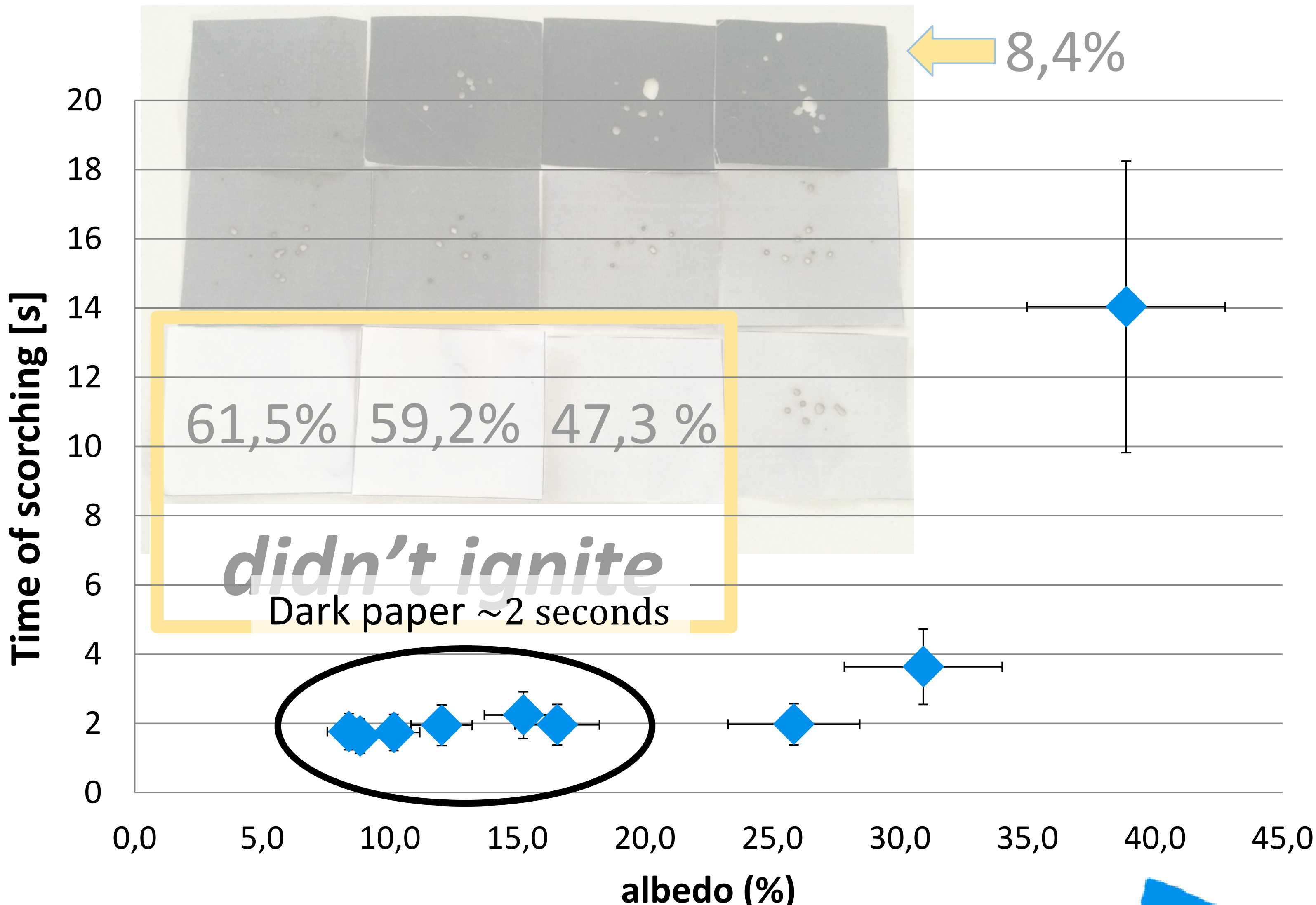

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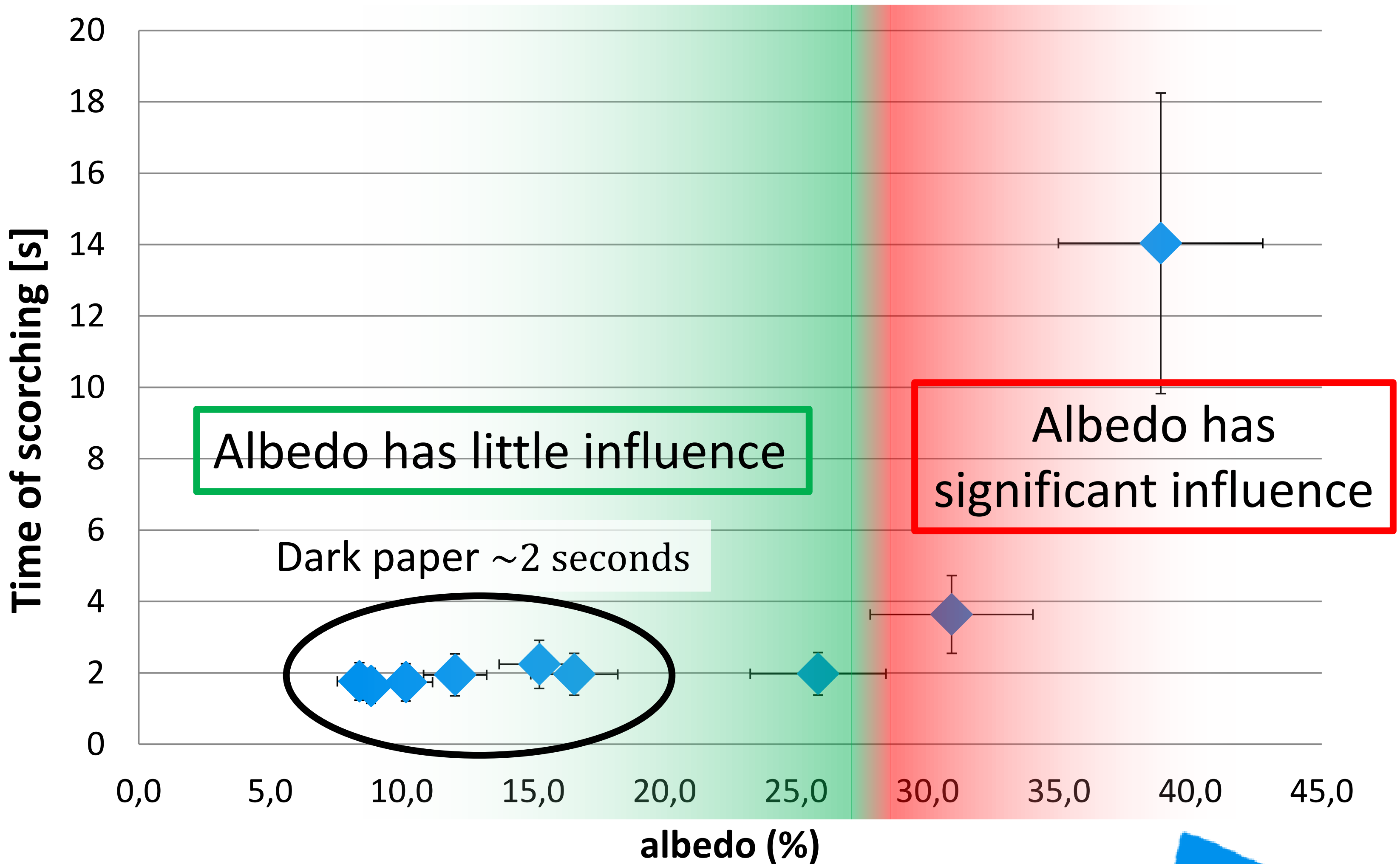

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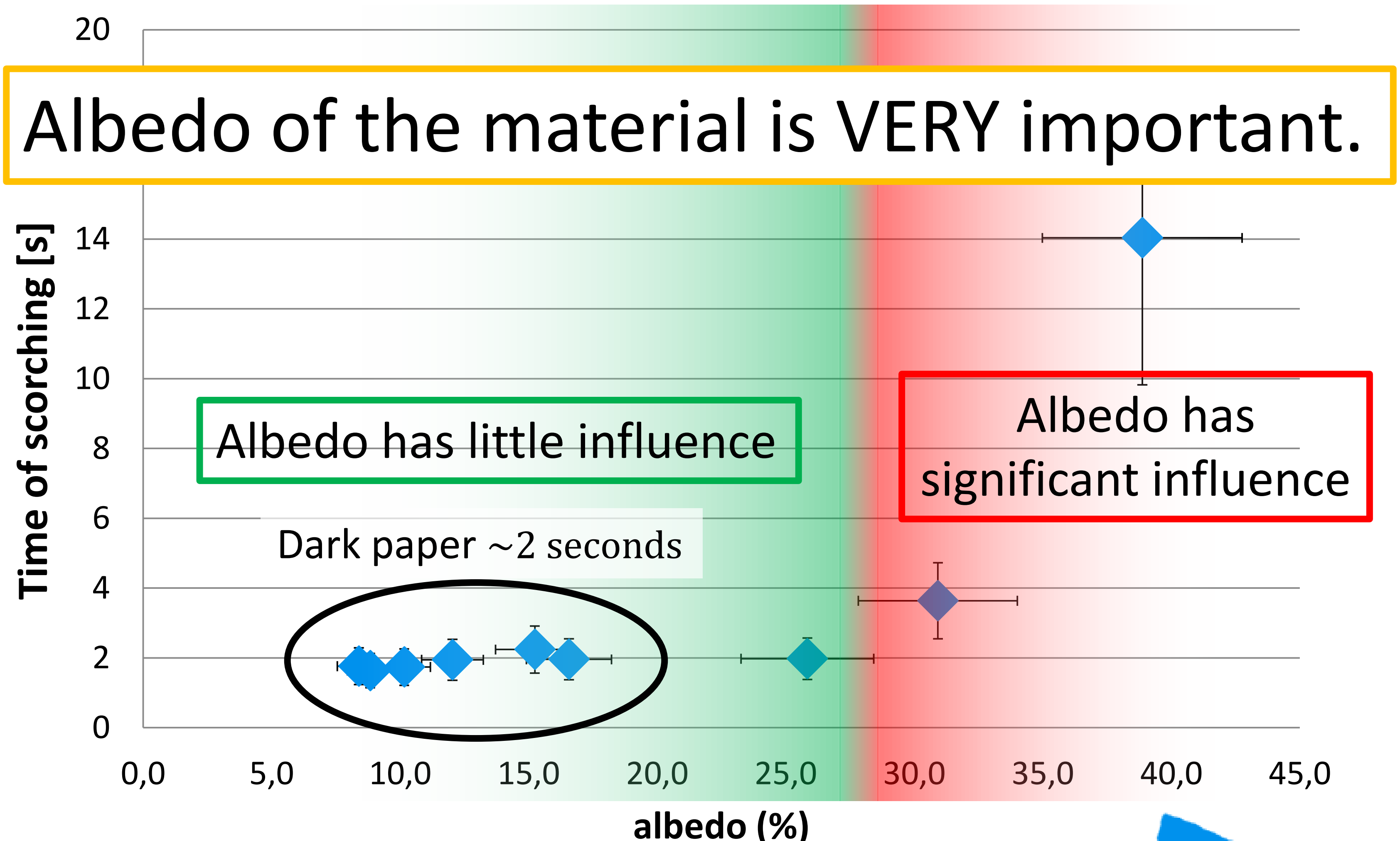

Basic condition for ignition

To heat the material further, this condition must be satisfied:

$$\boxed{P_{incoming} \geq \underbrace{P_{losses}(T_{ignition})}_{}}$$

Reflection **Conduction** **Convection** **Radiation**

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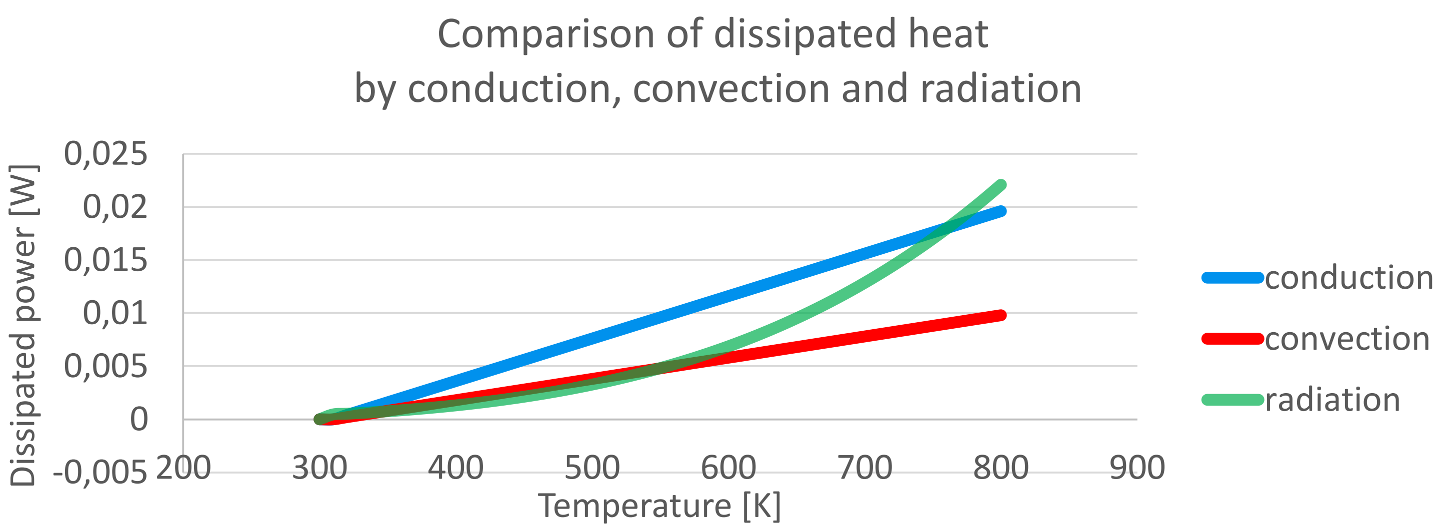

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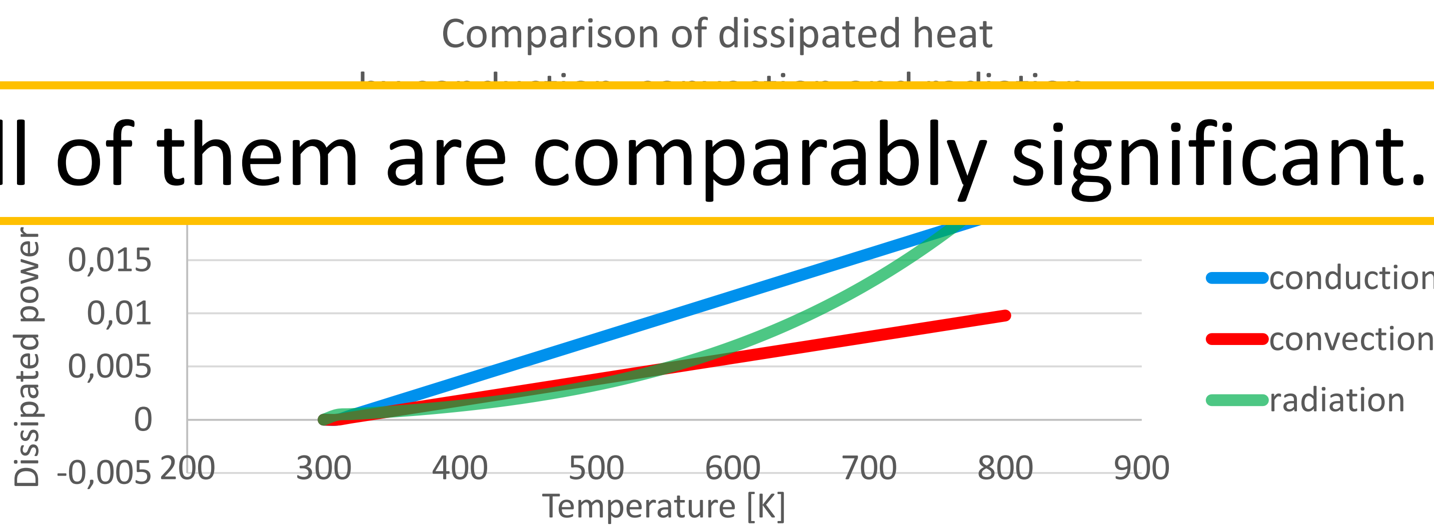
Reflection | **Conduction** | **Convection** | **Radiation**

All of them are comparably significant.



Condition for ignition

$$P_{in}(T) \geq \epsilon P_{in} + \left(c\frac{S}{l} + h\,S\right)\Delta T + \sigma\epsilon S\,T^4$$

If incoming intensity is sufficiently large,

$\Downarrow$

temperature rises until ignition

Condition for ignition

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<u>If incoming intensity is sufficiently large,</u>

What is sufficient?

temperature rises until ignition

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$$P_{in}(T) \geq \epsilon P_{in} + \left(c\frac{S}{l} + h\,S\right)\Delta T + \sigma\epsilon S\,T^4$$

Critical intensity *(peak) intensity of incoming radiation that ignites the surface*

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Critical intensity

(peak) intensity of incoming radiation that ignites the surface

Calculation

$$P_{dissipated} = \boxed{c\frac{S}{l}\Delta T} + \boxed{h\,S\,\Delta T} + \boxed{\sigma\epsilon S\,T^4}$$

$$0.015\ \mathrm{W} + 0.0074\ \mathrm{W} + 0.0114\ \mathrm{W} = 0.033\ \mathrm{W}$$

At ignition temperature for wood: $T = 670\ \mathrm{K}$

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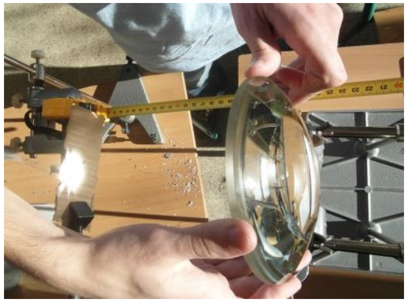
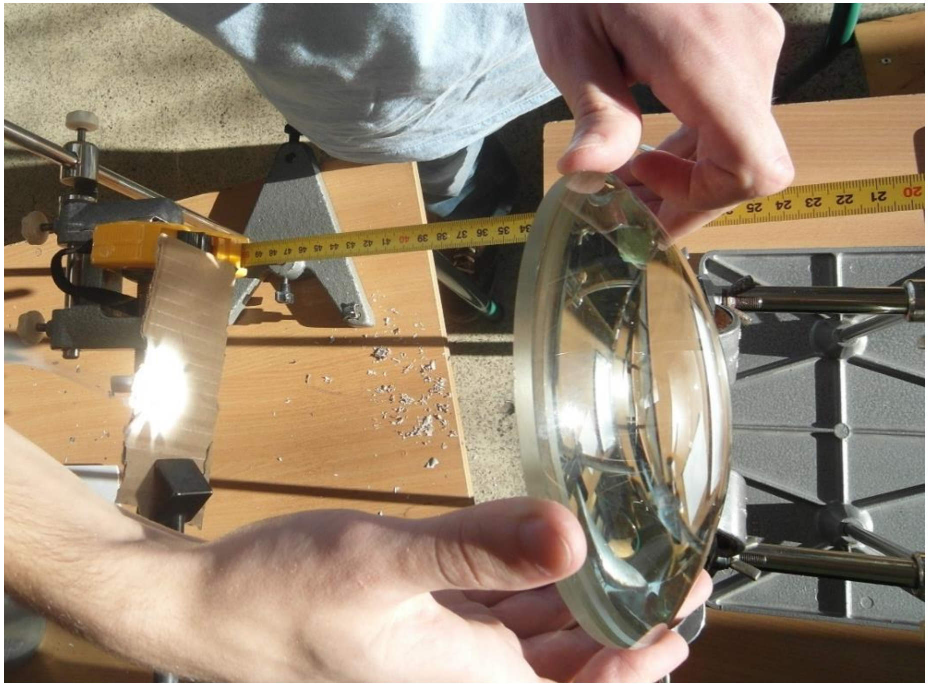
Measurement…



Critical intensities (the measurement)

- We change distance between the lens and the target
- What is the range of distances in which the material scorch?
- Conditions of the experiment
  - Sunlight intensity $380\ W/m^2$
  - Typical shifts: $1 - 5\ cm$



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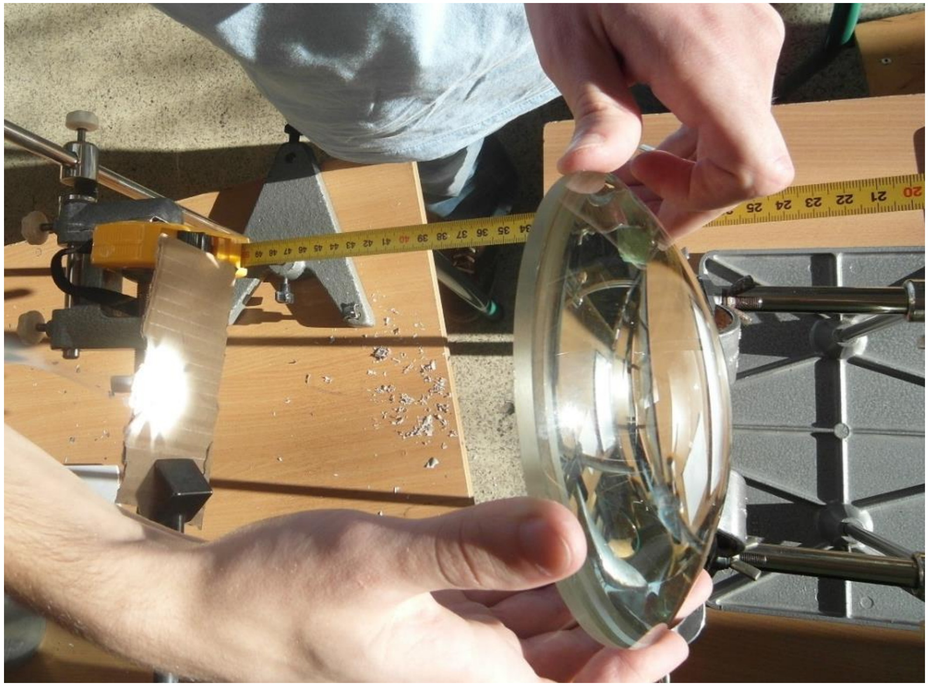

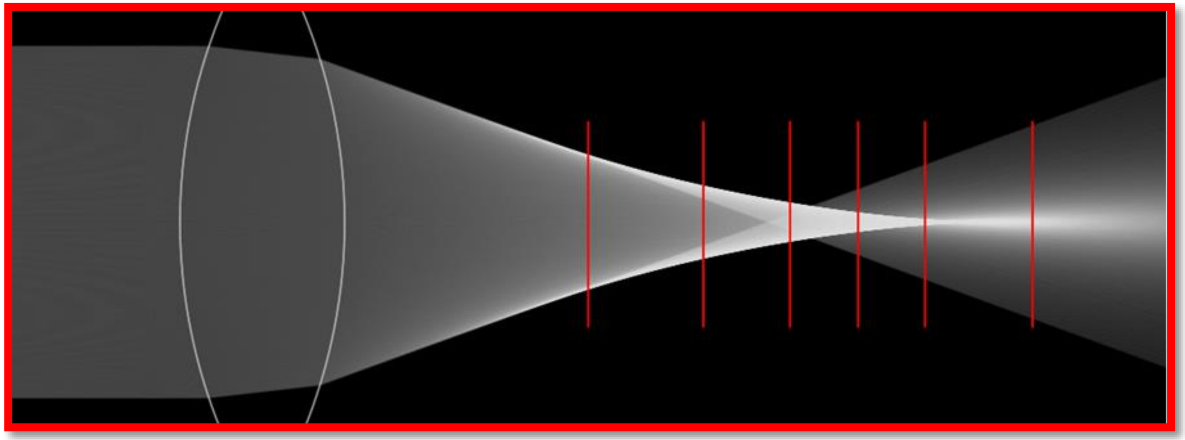

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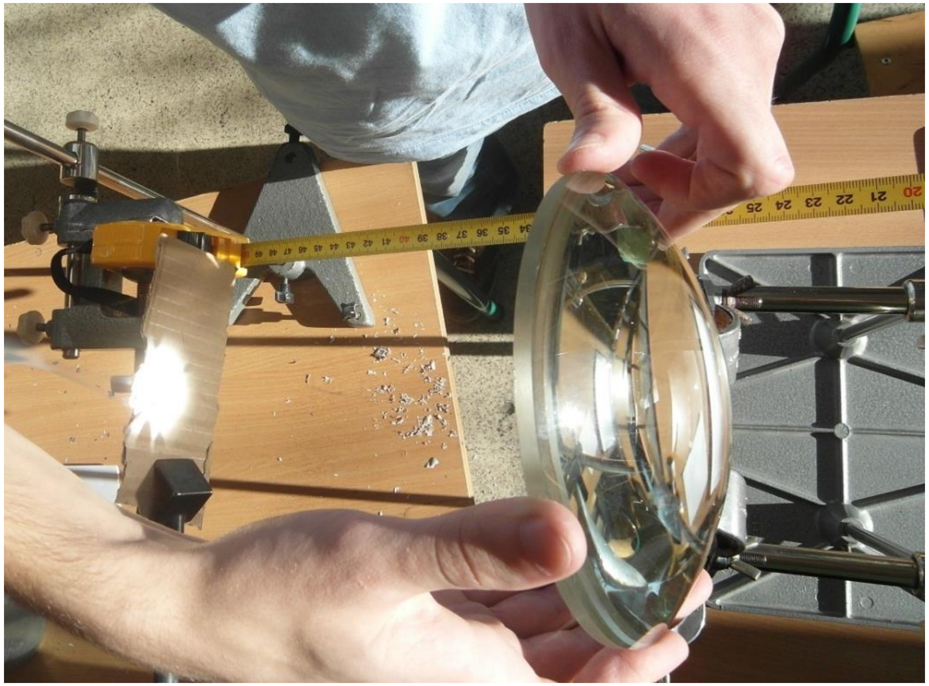

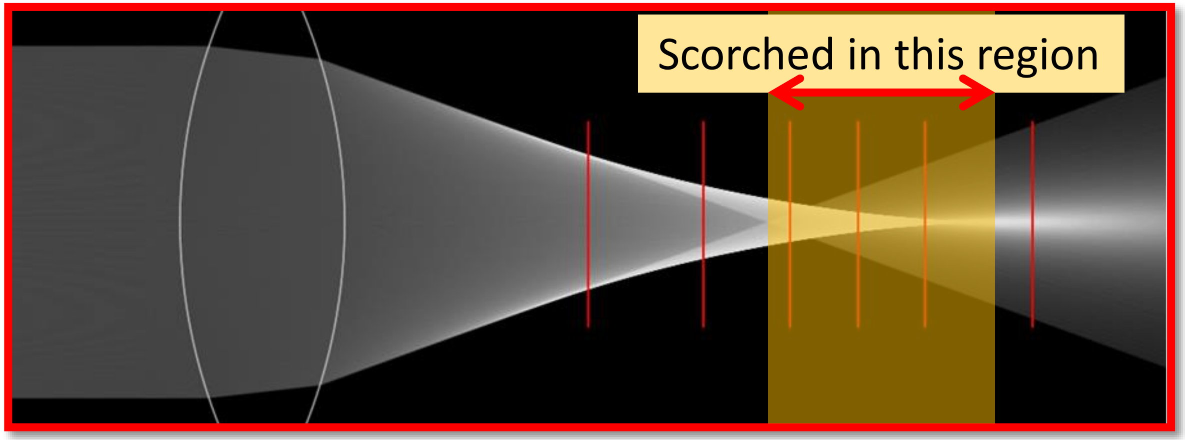

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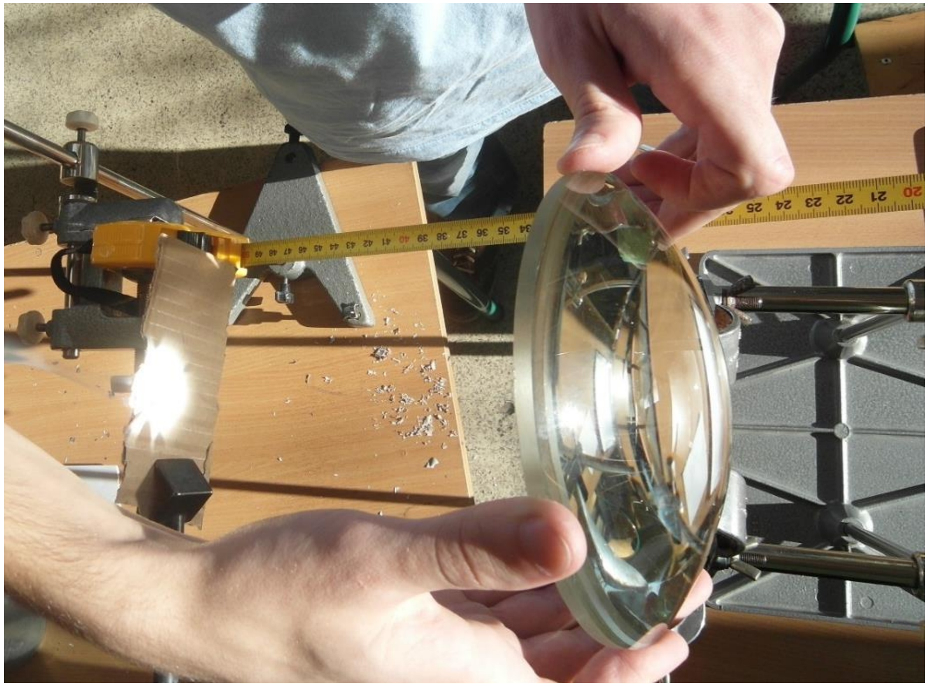

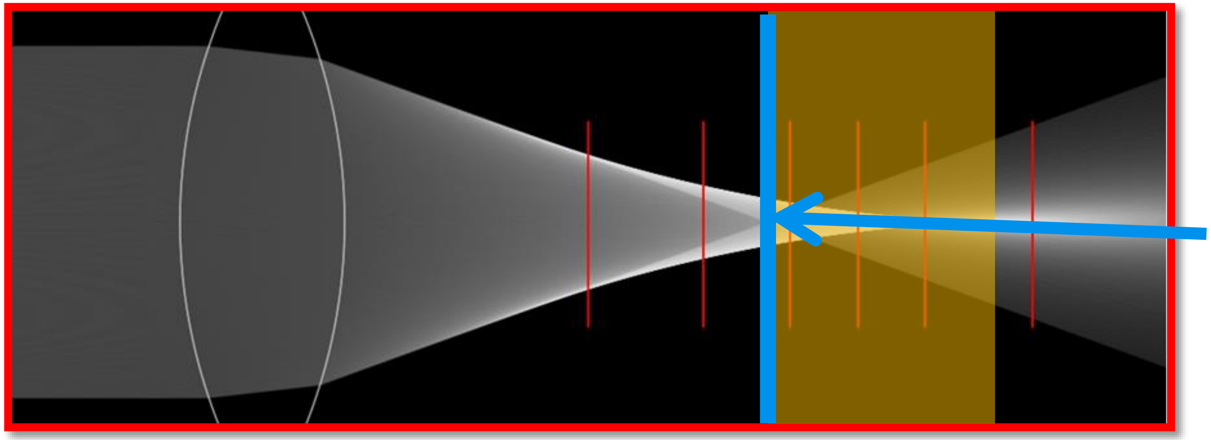

Critical intensity
value calculated
from geometry

Comparison

Comparison

Light intensity achieved by lens in the **experiment**
to scorch the wooden sample

$$I_{charring} = 14 \pm 1.4 \frac{kW}{m^2}$$

Comparison

Calculated light intensity from the condition of ignition

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Light intensity achieved by lens in the **experiment**
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Heat flux used to ignite a wooden sample in the article*

$$\phi_{heat} = 15 - 30 \frac{kW}{m^2}$$

Li, Yudong and Drysdale, D.D., 1992. Measurement Of The Ignition Temperature Of Wood. *AOFST* 1

Measurements

Material	Critical Intensity* ($\pm 10\%$) [W/m^2]
Bond paper (white)	500 000
Dot matrix printing paper	175 000
Cardboard	10 000
Wood	14 000
Black scarf (100% polyacryl)	4 000
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*to damage the surface

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scorched or burned

melted

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Measurements

Theoretical maximum
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(depends on Sunlight intensity)

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CONFIRMED BY AN EXPERIMENT

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Albedo > 60%
¼ energy absorbed by water in IR region

scorched
burned
melted

CONFIRMED BY AN EXPERIMENT

Conclusion

Section 1

Ray tracing vs. accurate measurement

99% correlation!

Section 2

Lost power

$$P_{losses}(T) = (1-\epsilon)P_{incoming} + c\nabla T\, A + h\,\Delta T\, S + \sigma\epsilon S\, T^4$$

Reflection term | Conduction and convection term | Radiation term

Time evolution of temperature

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Change in internal energy
Net power input
Heat dissipated to surroundings by...
conduction
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CONFIRMED BY AN EXPERIMENT

Conclusion

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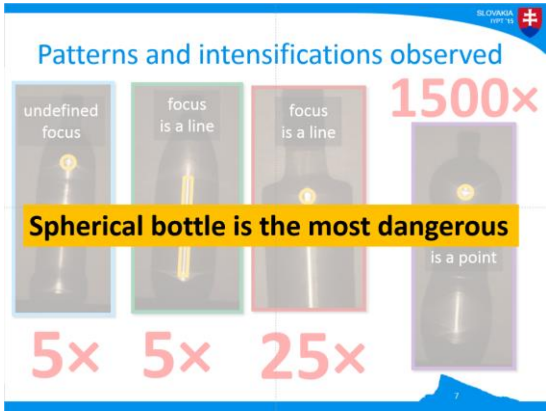

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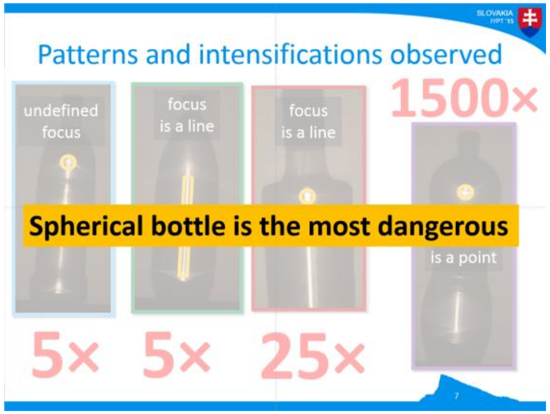

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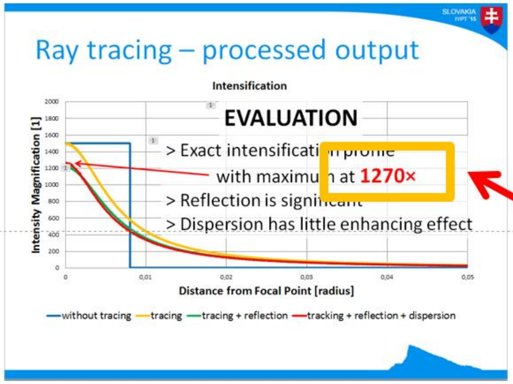

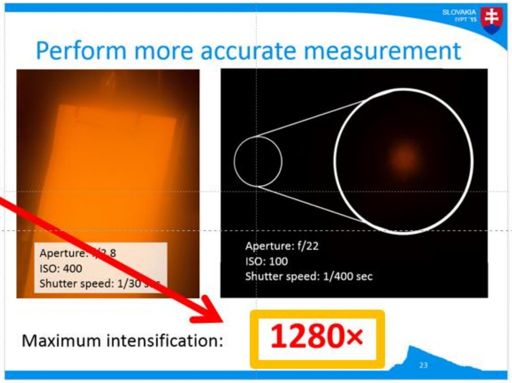

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CONFIRMED BY AN EXPERIMENT

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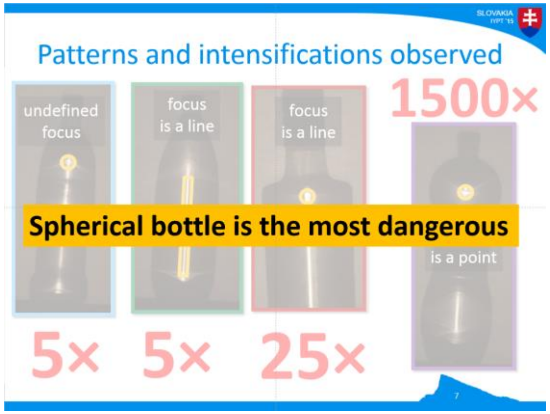

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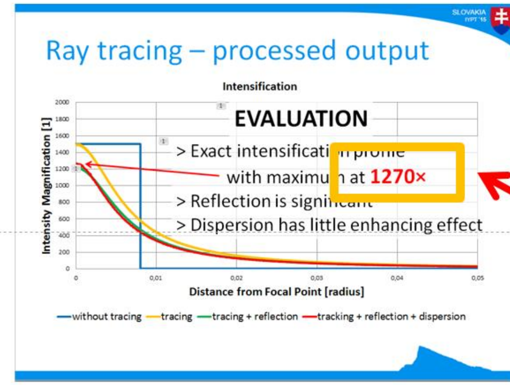

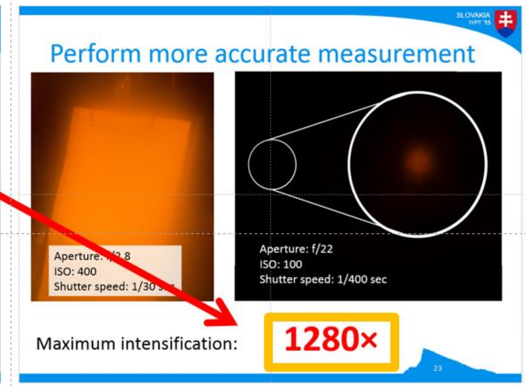

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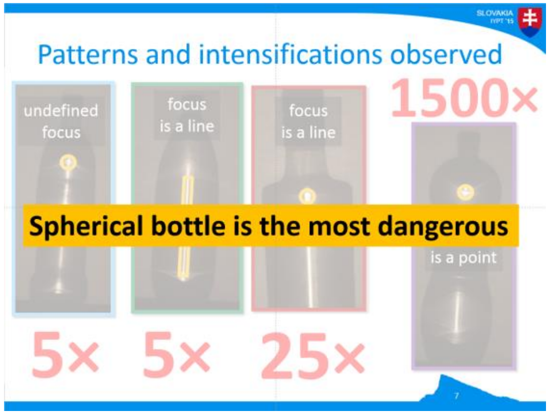
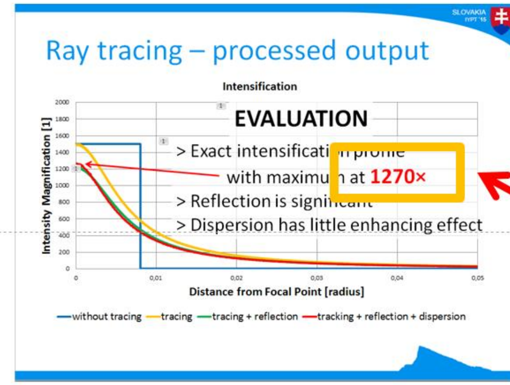
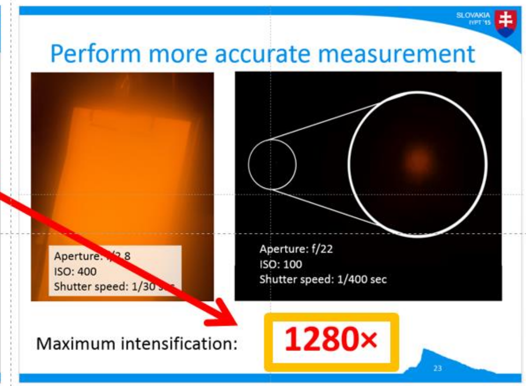


Ray tracing vs. accurate measurement





99% correlation!

Section 2

Lost power

$$P_{losses}(T) = \boxed{(1-\epsilon)P_{incoming}} + \boxed{c\nabla T\, A + h\,\Delta T\, S} + \boxed{\sigma\epsilon S\, T^4}$$

Reflection term | Conduction and convection term | Radiation term

Time evolution of temperature

$$\boxed{mk\frac{dT}{dt}} = \boxed{(1-\epsilon)I_{in}S} + \boxed{T_0\left(c\frac{A}{l}+hS\right) - \left(c\frac{A}{l}+hS\right)T} - \boxed{\sigma\epsilon S T^4}$$

Change in internal energy

Net power input

Heat dissipated to surroundings by...

conduction

convection

Power dissipated by radiation

Measurements

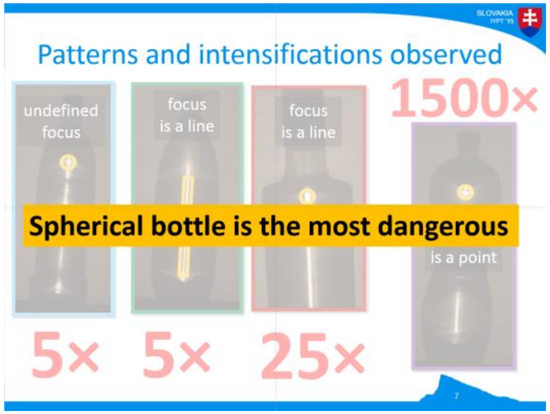
Maximum for Brusnianka is $\sim 1\,280\,000\ W/m^2$
(depends on Sunlight intensity)

Bond paper (white)	1 500 000	
Dot matrix printing paper	175 000	scorched or burned
Cardboard	10 000	
Wood	14 000	
Black scarf (100% polyacryl)	4 000	melted
Thin blue plastic bag (polyethylen)	3 000	

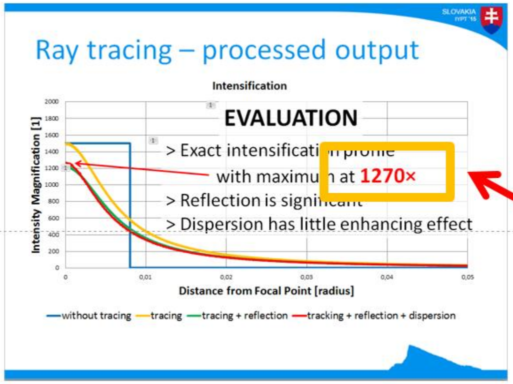
CONFIRMED BY AN EXPERIMENT

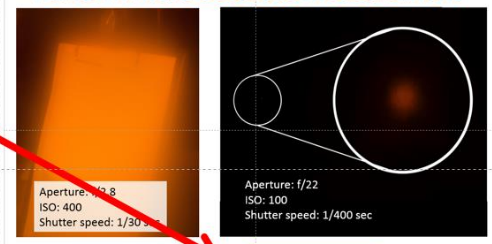
Conclusion

Section 1



Ray tracing vs. accurate measurement





99% correlation!

Section 2

Lost power

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CONFIRMED BY AN EXPERIMENT

Thank you for your attention!

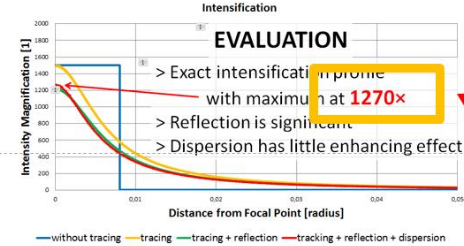
surement

Section 1

Patterns and intensifications observed

Spherical bottle is the most dangerous

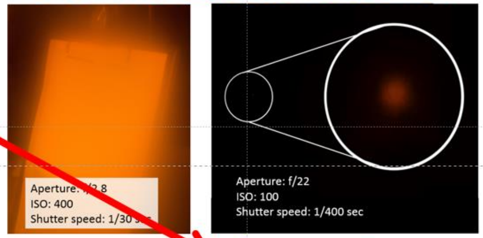
Ray tracing – processed output



EVALUATION

> Exact intensification profile
with maximum at **1270×**
> Reflection is significant
> Dispersion has little enhancing effect

Perform more accurate measurement



Maximum intensification: **1280×**

99% correlation!

Section 2

Lost power

$$P_{losses}(T) = \boxed{(1-\epsilon)P_{incoming}} + \boxed{c\nabla T\, A + h\,\Delta T\, S} + \boxed{\sigma\epsilon S\, T^4}$$

Reflection term **Conduction and convection term** **Radiation term**

Time evolution of temperature

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Change in internal energy
Net power input
Heat dissipated to surroundings by…
conduction
convection
Power dissipated by radiation

Measurements

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CONFIRMED BY AN EXPERIMENT

THANK YOU FOR YOUR ATTENTION!

Martin Murin

APPENDICES

Appendix A: Derivation of intensification

Power is conserved

$$I \times S_{image} = k\, I_0 \times S_{lens}$$

$$I = k\, I_0 \frac{S_{lens}}{S_{image}}$$

$$S_{image} = S_{sol} \times magnification^2$$

$$I = k\, I_0 \frac{S_{lens}}{S_{sol} M^2}$$

$$S_{sol} = 1.52 \times 10^{18}\, m^2 \qquad magnification = \left(\frac{h'}{h} = \frac{a'}{a} = \frac{\frac{fa}{f-a}}{a} = \frac{f}{f-a} \right) = \frac{f}{f - d_{sol}}$$

$$I = k\, I_0 \frac{S_{lens}}{S_{sol} \left(\frac{f}{f - d_{sol}} \right)^2} \Rightarrow I = k\, I_0 \frac{S_{lens}}{S_{sol}} \frac{d_{sol}^2}{f^2}$$

Appendix B: Different liquids in bottle

- The only relevant optical property of liquid is the <u>index of refraction</u>

"Lensmaker's equation"

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right]$$

(for sphere)

- The smaller the focal length, the smaller the magnification

$$image\ area = Solar\ area \times magnification^2$$

$$magnification = \frac{f}{f - d_{sol}}$$

- The smaller the magnification, the higher the intensity

$$I = k\ I_0 \frac{S_{lens}}{S_{sol}} \frac{d_{sol}^2}{f^2}$$

Appendix B: Different liquids in bottle

- The only relevant optical property of liquid is the index of refraction

"Lensmaker's equation"

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right] \xrightarrow[\text{(for sphere)}]{} f = \frac{nR}{2n-2}$$

- The smaller the focal length, the smaller the magnification

$$image\ area = Solar\ area \times magnification^2$$

$$magnification = \frac{f}{f - d_{sol}}$$

- The smaller the magnification, the higher the intensity

$$I = k\, I_0 \frac{S_{lens}}{S_{sol}} \frac{d_{sol}^2}{f^2}$$

Appendix C: Time evolution of temperature

$$\boxed{mk\frac{\mathrm{d}T}{\mathrm{d}t}} = \boxed{(1-\epsilon)I_{in}S} + \boxed{\left(\boxed{c\frac{S}{l}} + \boxed{hS}\right)\Delta T} - \boxed{\sigma\epsilon S T^4}$$

Using constants for ignition of wood

$\epsilon = 0.5$

$\sigma = 5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{K}^4}$

$m = 7 \times 10^{-7} \mathrm{kg}$

$I_{in} = 1000 \frac{\mathrm{W}}{\mathrm{m}^2}$

$k = 2000 \frac{\mathrm{J}}{\mathrm{kg\ K}}$

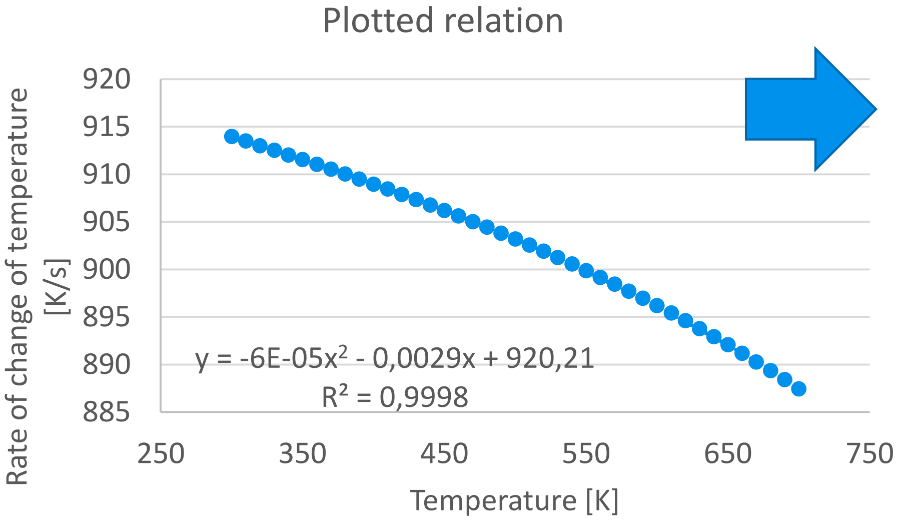
$T_0 = 300\ \mathrm{K}$

$S = 10^{-6} \mathrm{m}^2$

$l = 5 \times 10^{-4}\ \mathrm{m}$

$c = 0.05 \frac{\mathrm{W}}{\mathrm{m\ K}}$

$h = 20 \frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{K}}$



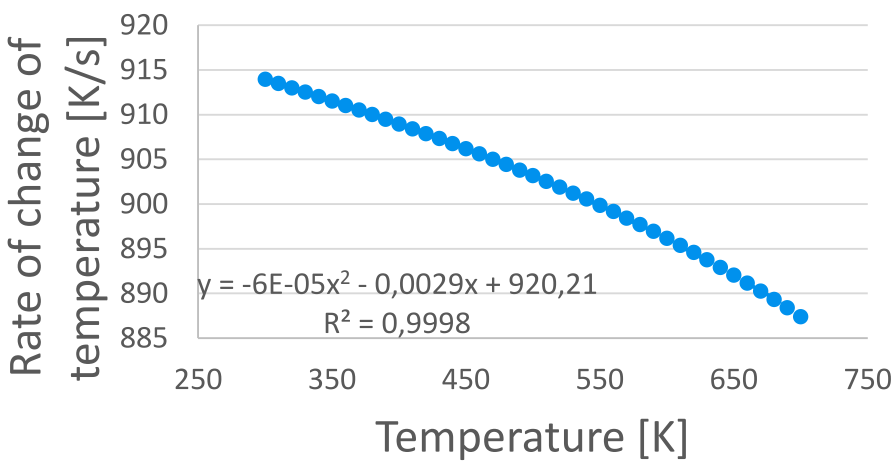
$$\frac{\mathrm{d}T}{\mathrm{d}t} = -6 \times 10^{-5}\ T^2 - 2.9 \times 10^{-3}\ T + 920.21$$

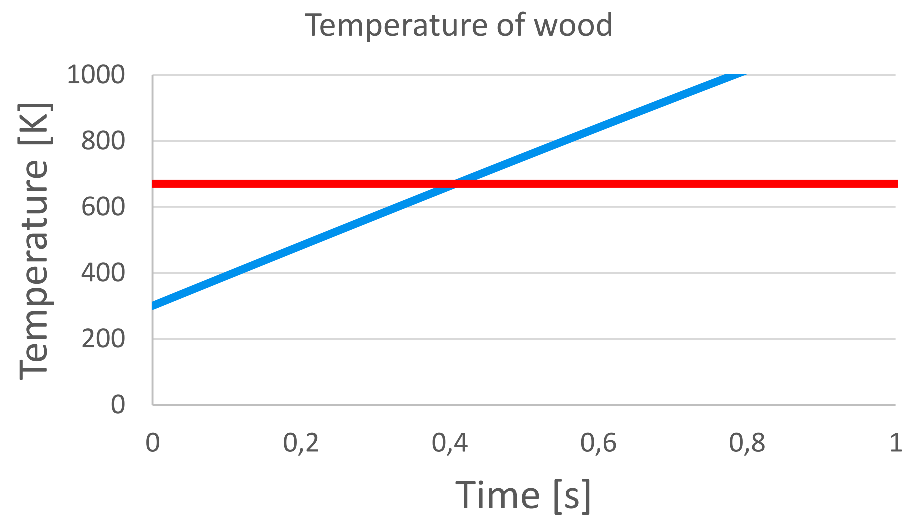
$$T = \frac{-3379.95 + 3940.47\ e^{0.47\ t}}{0.868404 + e^{0.47\ t}}$$

Appendix C: Time evolution of temperature

$$mk\frac{\mathrm{d}T}{\mathrm{d}t} = (1-\epsilon)I_{in}S + T_0\left(c\frac{A}{l}+hS\right) - \left(c\frac{A}{l}+hS\right)T - \sigma\epsilon S T^4$$

Plotted relation





$$\frac{\mathrm{d}T}{\mathrm{d}t} = -6\times 10^{-5}\ T^2 - 2.9\times 10^{-3}\ T + 920.21$$

$$T = \frac{-3379.95 + 3940.47\ e^{0.47\ t}}{0.868404 + e^{0.47\ t}}$$

Appendix D: Used materials – dot matrix paper

Appendix E: Experiments – conditions during critical intensity measurement

Lens parameters:

focal length	0.216 ± 0.004 m
radius of curvature	0.137 m
lens radius	0.073 m
index of refraction*	1.517

* crown glass, 589 nm, encyclopedia Britannica

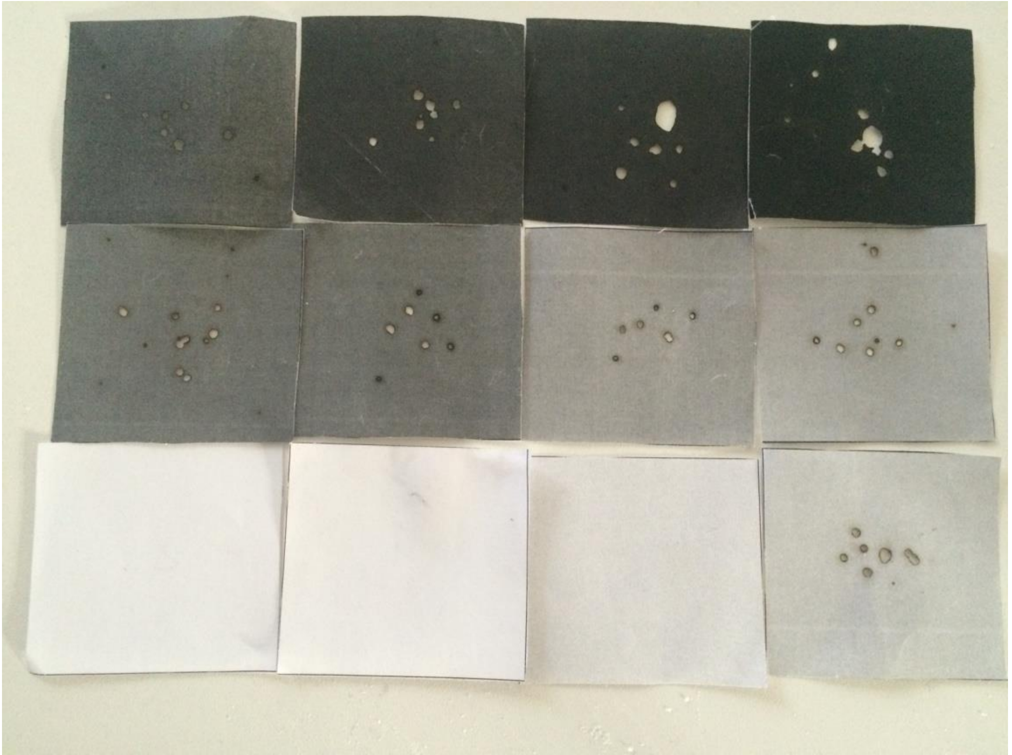
Measurement data:

date and time	6th January 2015 at 12:00 - 13:00
weather	sunny, no clouds
sunlight intensity [W/m²]	380 (Bratislava airport), 330 (Koliba)

Position of the Sun

altitude	12:10	19° 16´ 37´´
	12:30	18° 59´ 57´´
	13:00	17° 59´ 47´´
apparent diameter		00° 32' 32''
Solar diameter		1.391×10^9 m
distance from Earth		0.98328 AU $= 1.47097 \times 10^{11}$ m

Appendix E: Experiments – time vs albedo



Round bottom boiling flask

$r = 4.2\ \mathrm{cm}$

Paper with different color (albedo) measured by albedometer

Appendix F: Light intensity ratio from a photo

1. Capture in RAW format

2. Convert to TIFF using *dcraw** program
   - *No color interpolations, compression, white balance…*

3. Set linear colorspace in Photoshop

4. Open linear TIFF in PS canceling any suggestions for “improvements”

5. Read RGB values and compare them within one image

6. Try different exposition times and verify that
   2x longer exposition gives 2x grater RGB values

http://www.cybercom.net/~dcoffin/dcraw/

Appendix G: Visual data – caustic curve

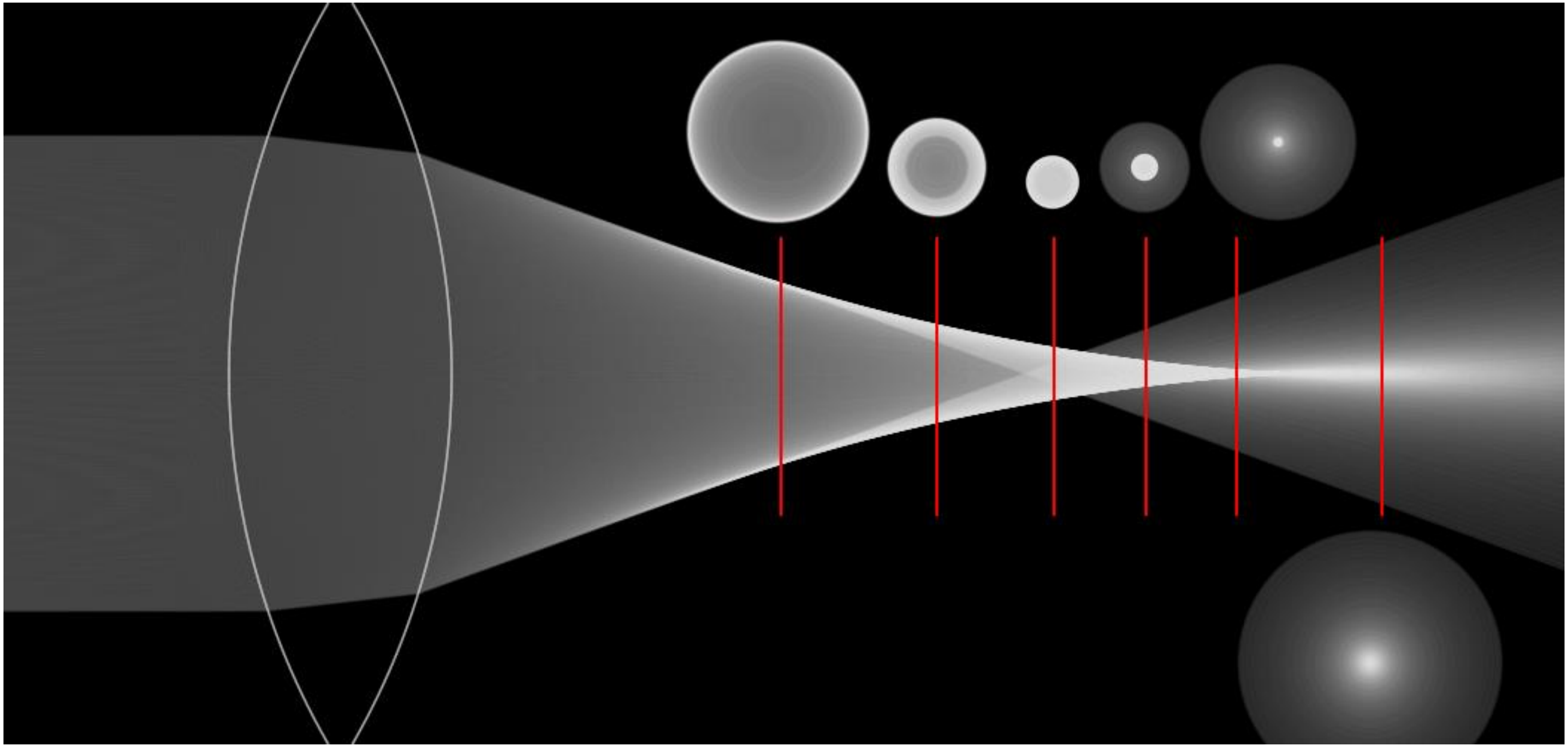
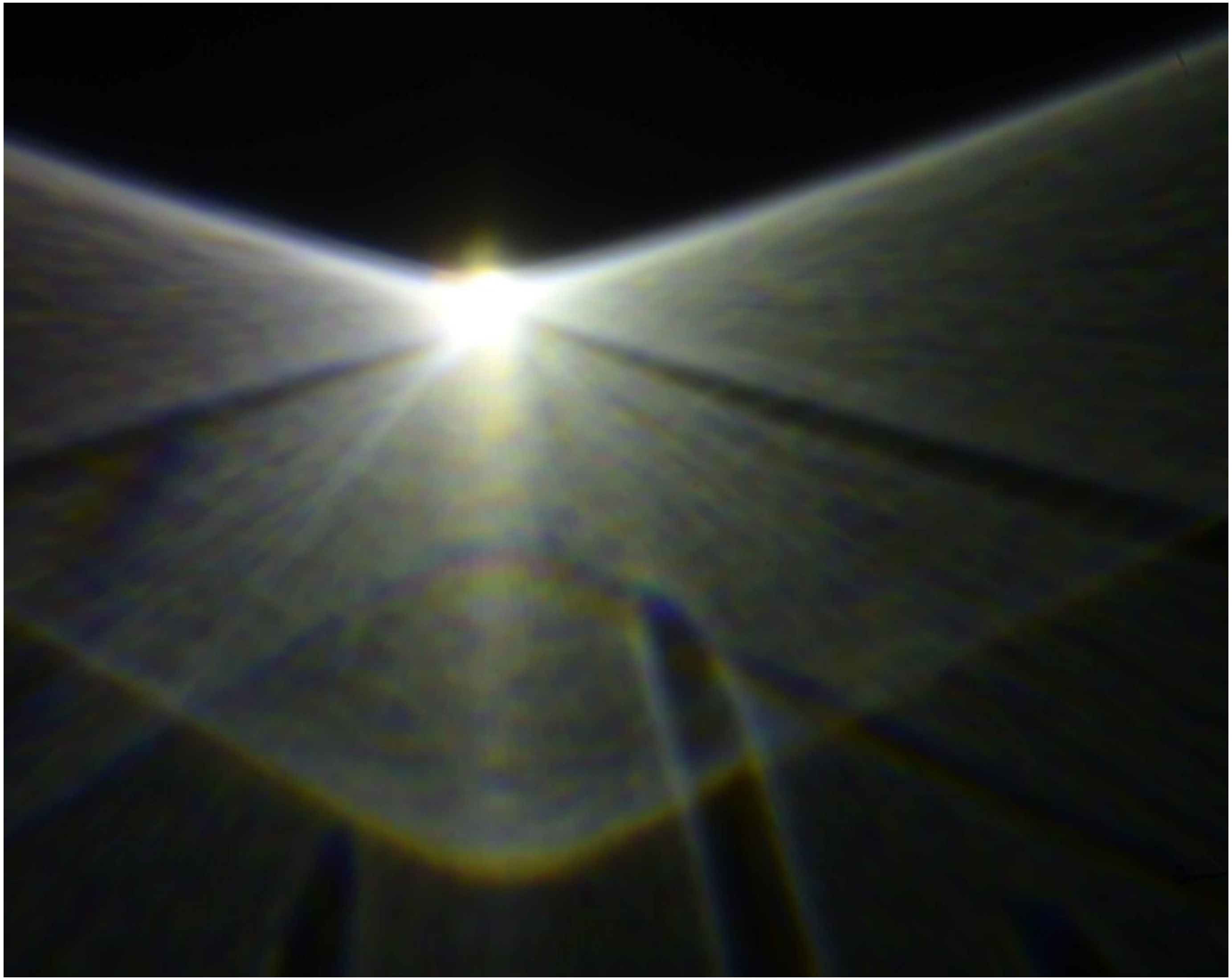
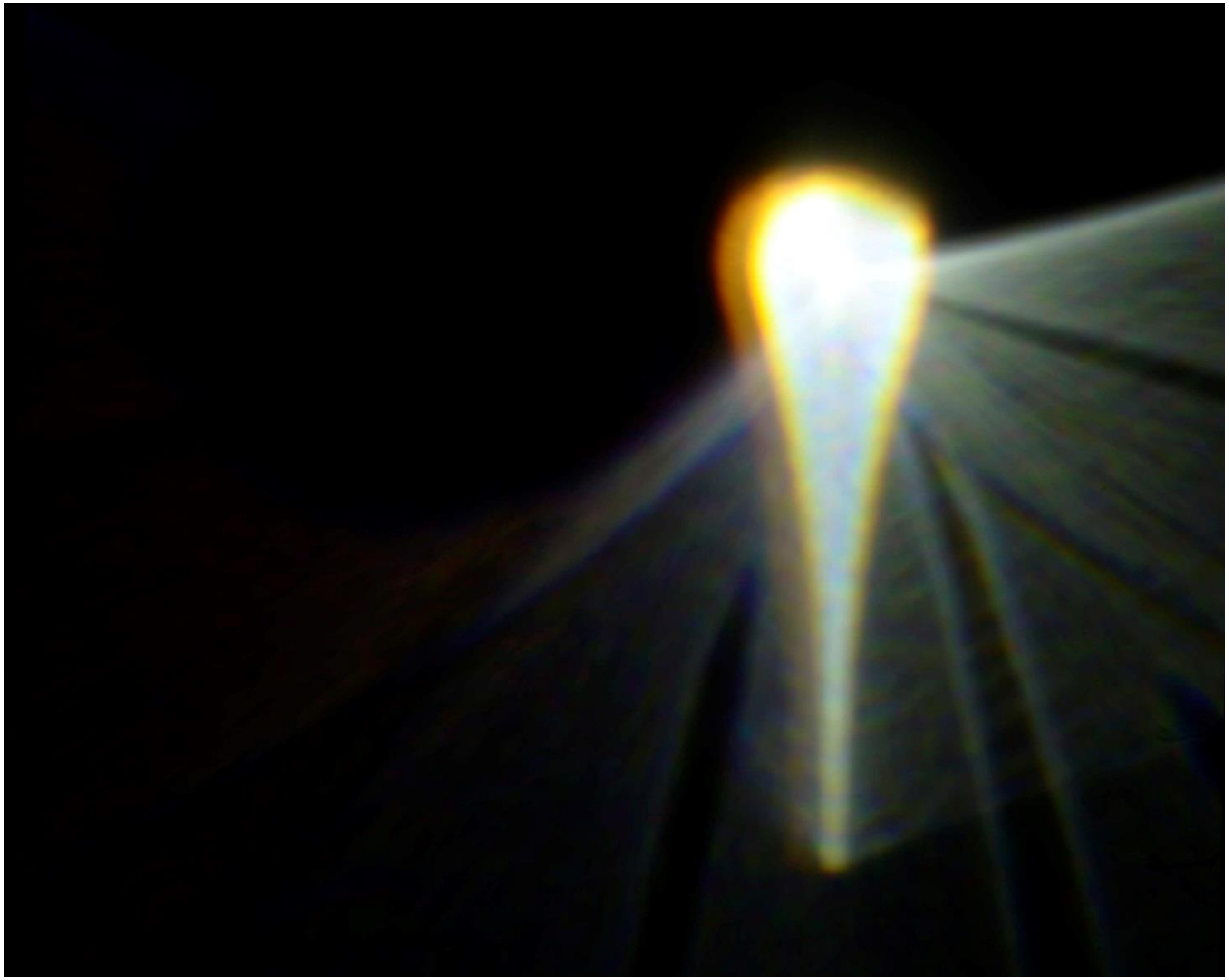


Image courtesy of *Jakub Trávník* *at http://jtra.cz*

Appendix G: Visual data – focused light on CMOS

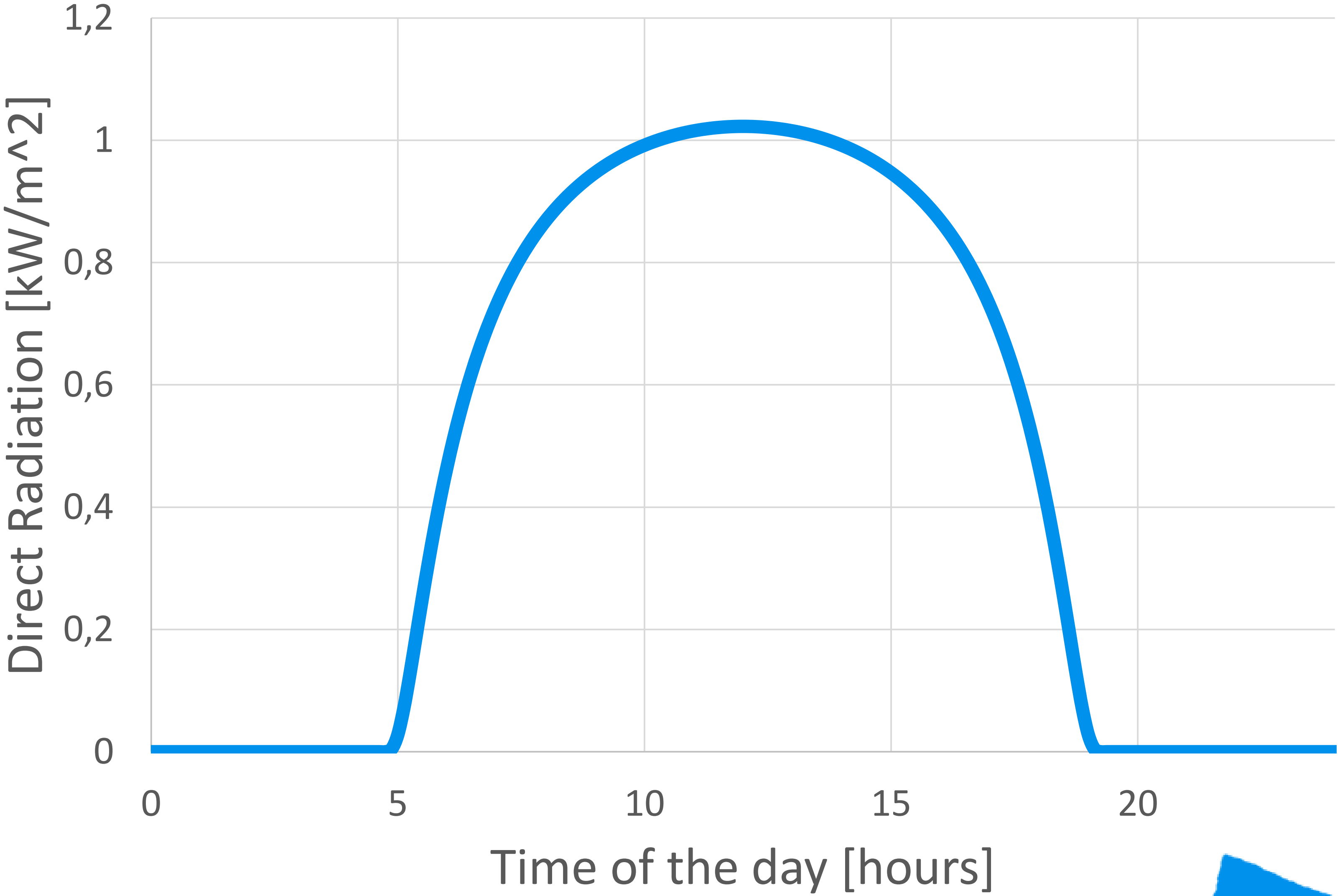


Appendix G: Visual data – focused light on CMOS (comma aberration)



Appendix H: Additional data – electromagnetic absorption by water

Appendix H: Additional data – intensity of solar irradiance during the day



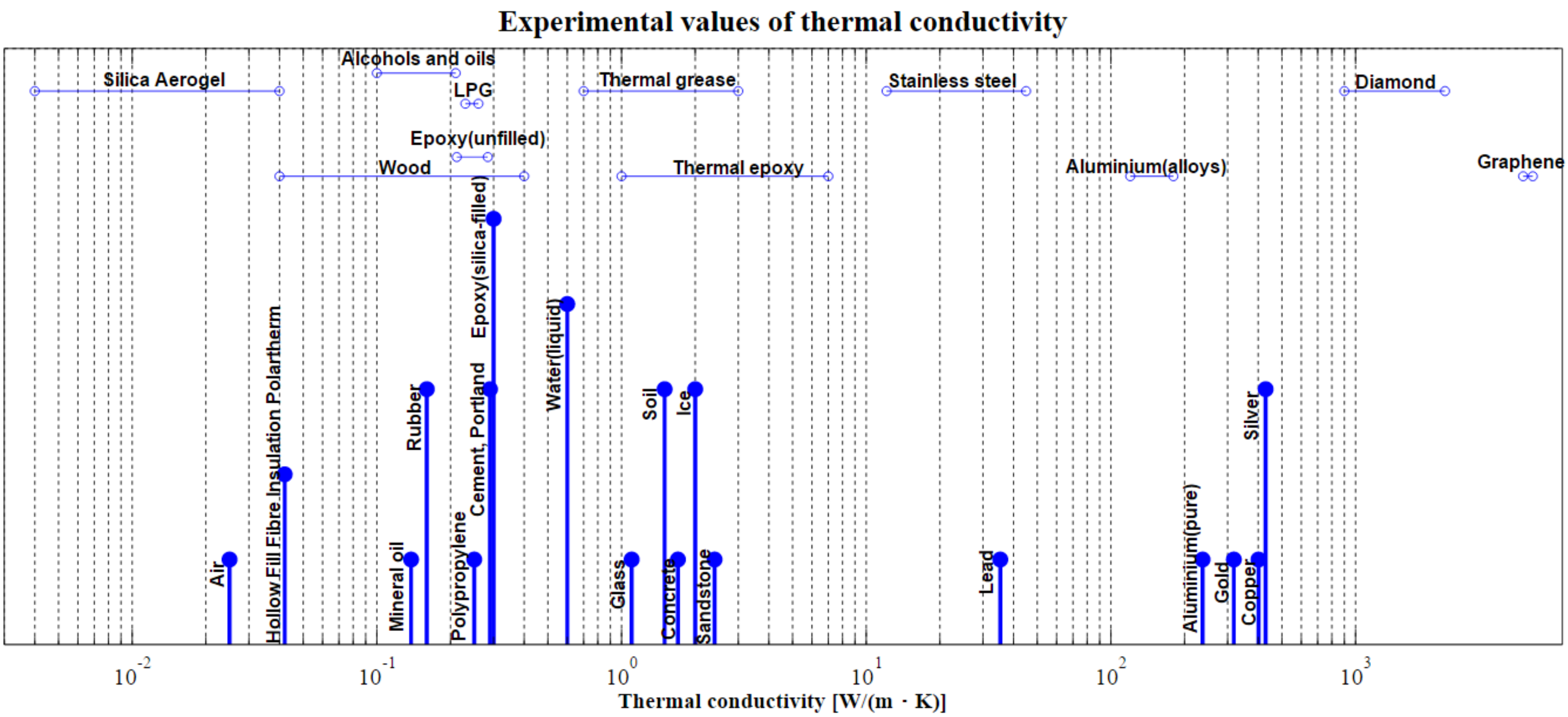
Appendix H: Additional data – ignition data

Table 2 Ignition data (present study).

Species (Density, g/cm^3)	Heat flux (kW/m^2)	Average T_{ig} (^oC)	Standard deviation	Plateau Temp. (^oC)	Standard deviation	Average t_{ig} (s)	Standard deviation	No. of Samples Tested
Mahogany (0.54)	15.4	465	21	365	3	850	80	7
	19.7	427	14	385	3	324	39	7
	24.0	364	8	-	-	90	7	8
	28.7	360	6	-	-	60	7	7
	31.7	353	10	-	-	38	4	9
Western Red Cedar (0.28)	15.4	450	19	366	1	583	95	6
	19.7	431	12	379	8	216	29	8
	24.0	365	4	-	-	57	8	7
	28.7	346	6	-	-	30	3	9
	31.7	354	7	-	-	23	1	8
Obeche (0.35)	15.4	497	74	359	7	684	121	9
	19.7	442	30	361	18	176	39	7
	24.0	364	8	-	-	60	5	6
	28.7	344	14	-	-	39	4	8
	31.7	340	12	-	-	29	3	8
White Pine (0.36)	15.4	446	13	354	4	1094	162	8
	19.7	411	25	380	11	257	69	11
	24.0	397	3	-	-	95	18	7
	28.7	387	4	-	-	48	4	7
	31.7	375	17	-	-	32	3	9

Li, Yudong and Drysdale, D.D., 1992. Measurement Of The Ignition Temperature Of Wood. *AOFST* 1

Appendix H: Additional data – thermal conductivities



Appendix H: Additional data – Fresnel equations

$$t_p = \frac{2n_1 \cos(\theta_i)}{n_1 \cos(\theta_t) + n_2 \cos(\theta_i)} \qquad r_s = \frac{n_1 \cos(\theta_i) - n_2 \cos(\theta_t)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)}$$

$$t_s = \frac{2n_1 \cos(\theta_i)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)} \qquad r_p = \frac{n_2 \cos(\theta_i) - n_1 \cos(\theta_t)}{n_1 \cos(\theta_t) + n_2 \cos(\theta_i)}$$