Heat Transfer: Radiation

Example: Three-body problem

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HEATQUIZ

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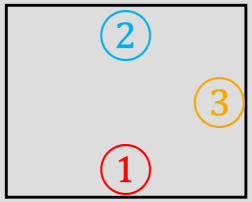
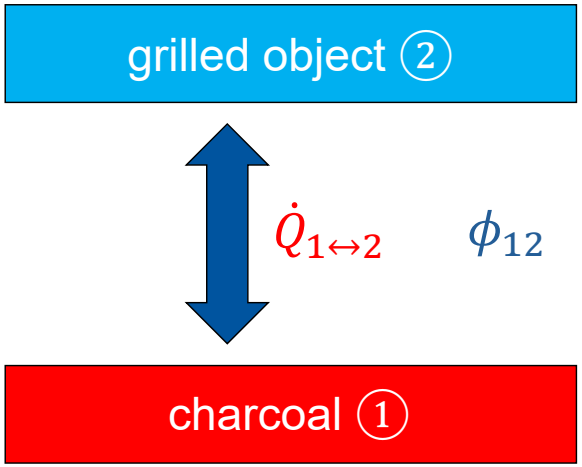
Learning goals

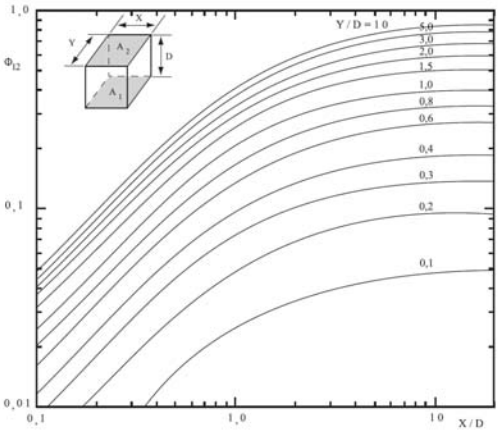
Three bodies:

- Expansion of the balances from two-body to multi-body problems
- Learning Approaches to solve Radiation tasks using the example of a three-body problem



Two-body problem





Question:

- Which heat flow goes from the charcoal ① by radiation to the grilled object ② ?

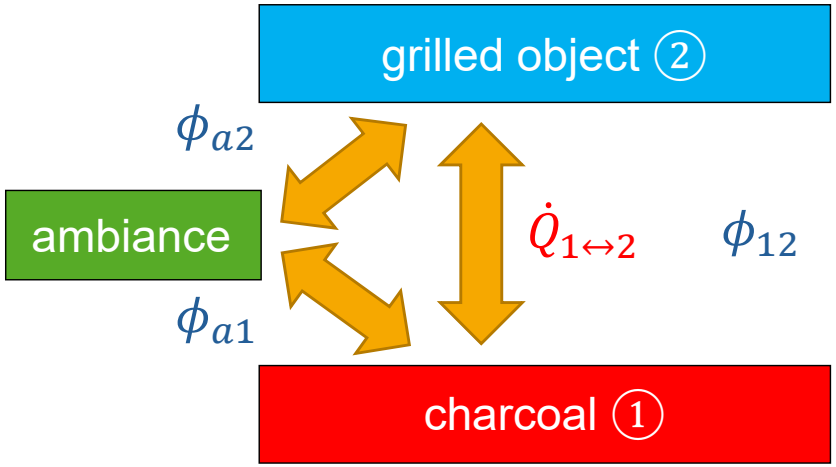
Initial situation:

- The charcoal has a higher temperature than the grilled object
- Charcoal and grilled object irradiate black

Approach:

- 1 energy balance
  (around charcoal or grilled object)
- 2 surface brightnesses
  (charcoal and grilled object)
- 1 relevant view factor (ϕ_{12})

Two-body problem



Question:

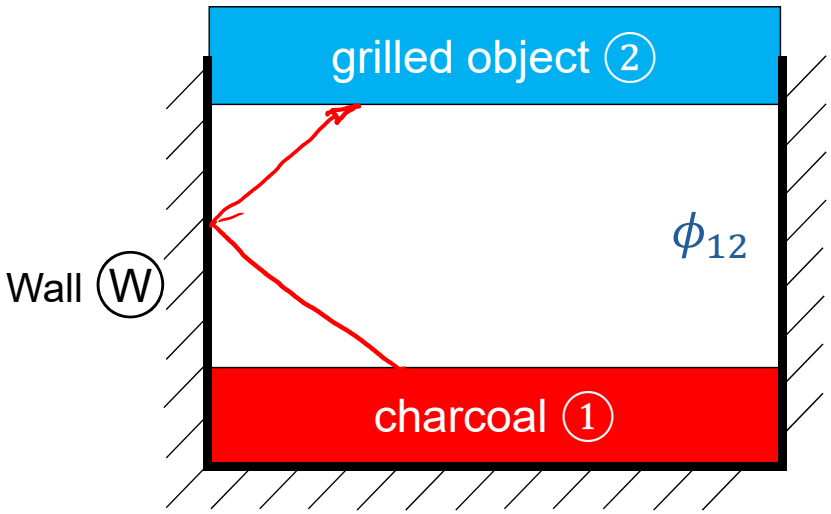
- Which heat flow goes from the charcoal ① by radiation to the grilled object ② ?

Initial situation:

- The heat transfer from the charcoal to the grilled object remains unchanged as long as the ambient radiation is not influenced by the radiation of objects ① and ②.

- https://www.amazon.de/dp/B00AC9B256/ref=asc_df_B00AC9B2561624469460000/?tag=lionshome-21&creative=22662&creativeASIN=B00AC9B256&linkCode=df0

Three-body problem



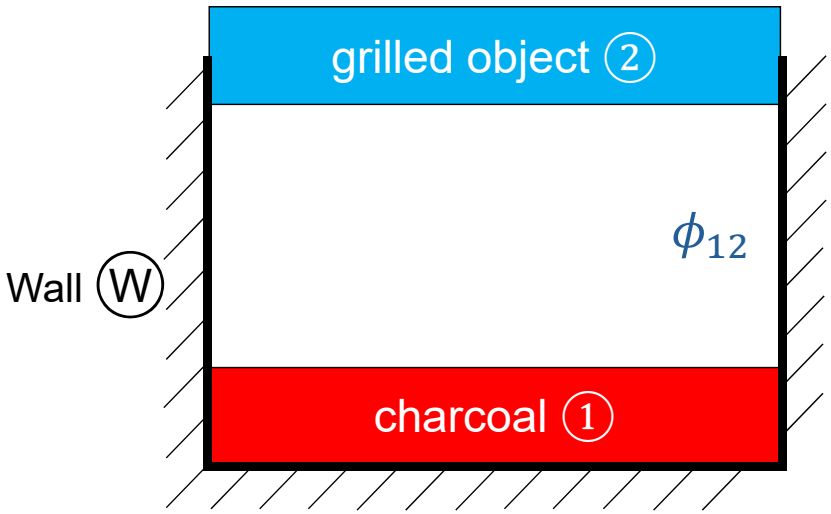
Question:

- Which heat flow goes from the charcoal ① by radiation to the grilled object ② ?

Considerations:

- Radiation transfer takes place between charcoal and wall as well as between grilled object and wall
- Charcoal, grilled object and wall irradiate black
- The wall is adiabatic towards the back, so all absorbed energy is released again by self-emission, this results in the wall temperature
- The radiant heat flow from the charcoal to the wall is larger than the one from the grilled object to the wall
- The wall irradiates evenly (symmetry) on charcoal and grilled object
- The wall causes a net radiant heat flow from the charcoal indirectly to the grilled object

Procedure to solve the task



Problem analysis:

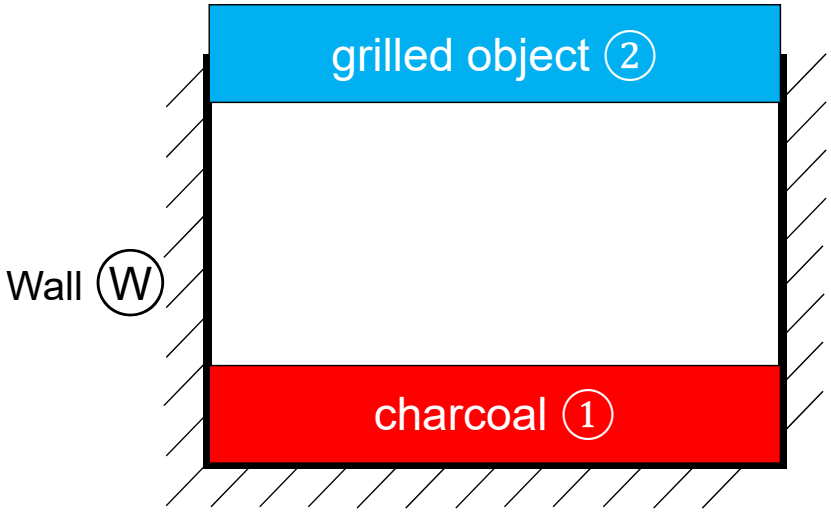
- Which heat flow goes from the charcoal ① by radiation to the grilled object ② ?

Procedure:

- Setting up the balances with **surface brightness** and **view factors**
  - Balance around grilled object
  - Balance around charcoal
  - Balance around wall

  } one of two balances is enough.
- Define all **surface brightnesses** (implicit)
  - Charcoal ⇨ f (T_1, $\dot{Q}_2$ and $\dot{Q}_W$)
  - Grilled body ⇨ f (T_2, $\dot{Q}_1$ and $\dot{Q}_W$)
  - Wall ⇨ f (T_W,$\dot{Q}_1$, $\dot{Q}_2$)
- Define all view factors
- **Solve it**

Solution of the Two-body problem



Assumptions:

- Walls remain unconsidered
- All bodies irradiate black
- T_1, T_2 are known

Reciprocal rule:

$$A_1\phi_{12} = A_2\phi_{21}$$

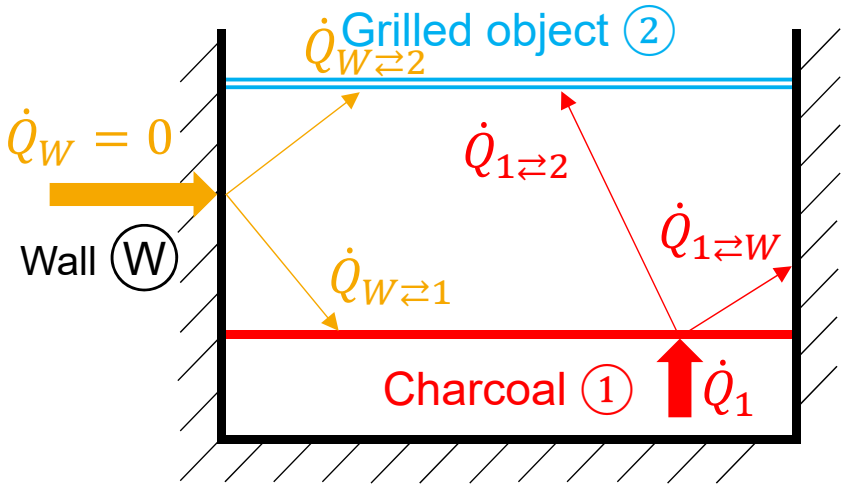
Procedure:

$$\dot{Q}_{1\rightleftarrows 2} = \dot{Q}_{1\rightarrow 2} - \dot{Q}_{2\rightarrow 1}$$

$$\dot{Q}_{1\rightleftarrows 2} = A_1\phi_{12}(\dot{q}_1'' - \dot{q}_2'')$$

$$\dot{Q}_{1\rightleftarrows 2} = A_1\phi_{12}\sigma(T_1^4 - T_2^4)$$

Three-body problem



Energy Balance 1 (Charcoal):

$$\dot{Q}_1 = \dot{Q}_{1\rightleftarrows 2} + \dot{Q}_{1\rightleftarrows W}$$

$$= A_1\phi_{12}\sigma(T_1^4 - T_2^4) + A_1\phi_{1W}\sigma(T_1^4 - T_W^4)$$

unknown

Energy balance 2 (Wall):

$$\dot{Q}_W = 0 = \dot{Q}_{W\rightleftarrows 1} + \dot{Q}_{W\rightleftarrows 2} + \cancel{\dot{Q}_{W\rightleftarrows W}}$$

$$= \underbrace{A_W\phi_{W1}}_{A_1\phi_{1W}}\sigma(T_W^4 - T_1^4) + \underbrace{A_W\phi_{W2}}_{A_2\phi_{2W}}\sigma(T_W^4 - T_2^4)$$

Wall Temperature:

$$T_W^4 = \frac{A_1\phi_{1W}T_1^4 + A_2\phi_{2W}T_2^4}{A_1\phi_{1W} + A_2\phi_{2W}}$$

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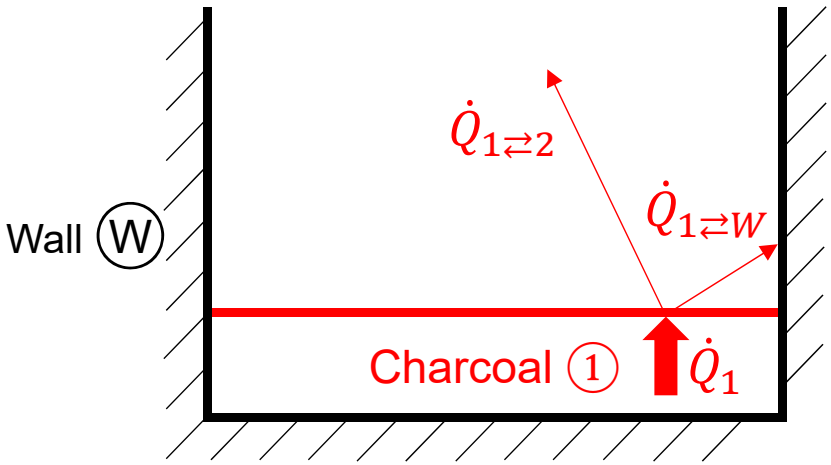
Three-body problem



Assumptions:

- Walls remain unconsidered (considered)
- All bodies irradiate black
- T_1, T_2 are known

Energy Balance 1 (Charcoal):

$$\dot{Q}_1 = \dot{Q}_{1\rightleftarrows 2} + \dot{Q}_{1\rightleftarrows W}$$

$$= A_1\phi_{12}\sigma(T_1^4 - T_2^4) + A_1\phi_{1W}\sigma(T_1^4 - T_W^4)$$

Energy Balance 1 (Charcoal):

$$\dot{Q}_1 = \dot{Q}_{1\rightleftarrows 2} + \dot{Q}_{1\rightleftarrows W}$$

$$= A_1\phi_{12}\sigma(T_1^4 - T_2^4) + A_1\phi_{1W}\sigma(T_1^4 - T_W^4)$$

$$= \sigma T_1^4 \left[A_1\phi_{12} + \frac{(A_1\phi_{1W})(A_2\phi_{2W})}{A_1\phi_{1W} + A_2\phi_{2W}}\right]$$

Wall Temperature:

$$= A_1\sigma(T_1^4 - T_W^4)\left[\phi_{12}T_1^4 + \frac{A_1\phi_{1W}\phi_{2W}}{A_1\phi_{1W} + A_2\phi_{2W}}\left(\frac{1}{A_2}\phi_{1W}T_1^4 + \frac{1}{A_2}\phi_{2W}T_2^4\right)\right]$$

$$T_W = \frac{}{A_1\phi_{1W} + A_2\phi_{2W}}$$

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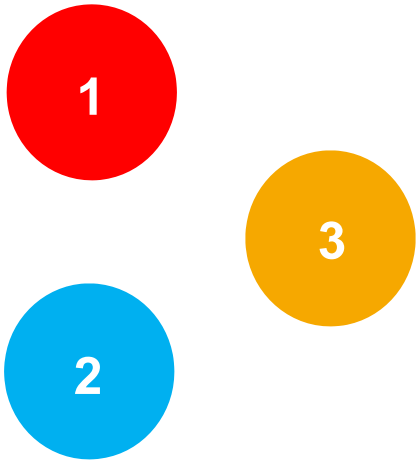
Three-body problem: summery of the assumptions

Assumptions:

- All bodies irradiate black
- The radiation transfer takes place exclusively between the bodies
  (sum of the View Factors is 1)
- The temperature of Body ① and Body ② is given
- Body ③ emits all received Radiation energy (adiabatic)



Solution:

$$\dot{Q}_1 = \dot{Q}_{1\rightleftarrows 2} + \dot{Q}_{1\rightleftarrows 3}$$

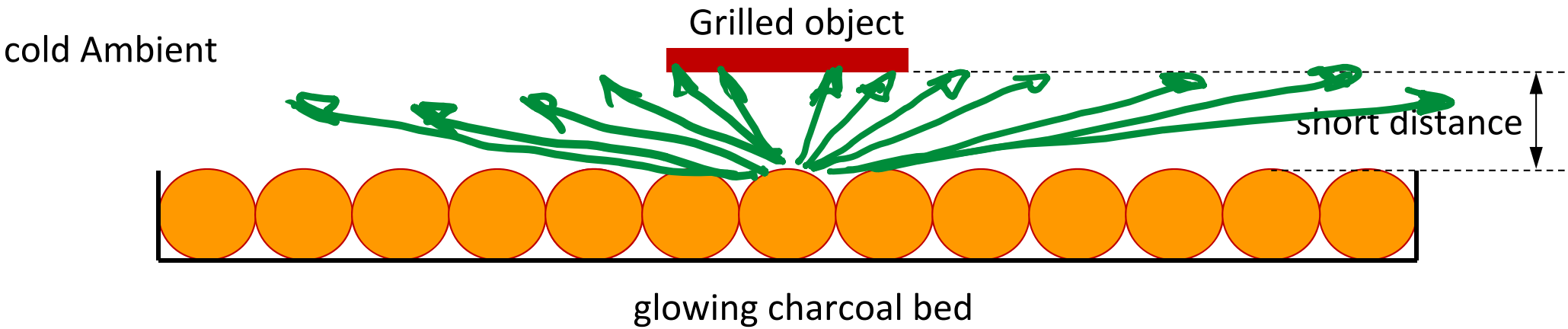
$$= A_1 \sigma (T_1^4 - T_2^4) \left[\Phi_{12} + \frac{1}{\frac{A_1}{A_2 \Phi_{23}} + \frac{1}{\Phi_{13}}} \right]$$

Grilling on a kettle grill

Tips for the next Barbecue:

- Lifting the grill hardly slows down the cooking process
- Black as color and spherical as a shape are extremely unfavorable

Lifting the grill grate during grilling



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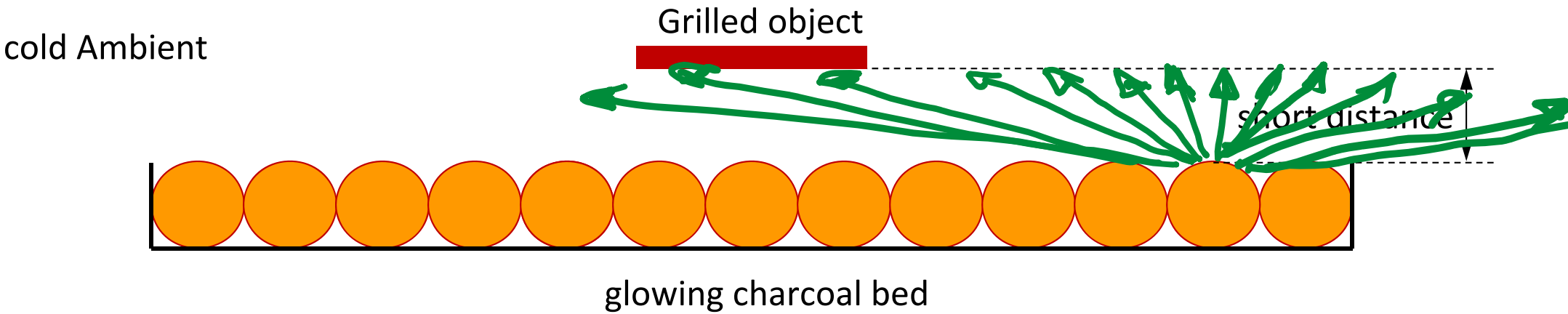

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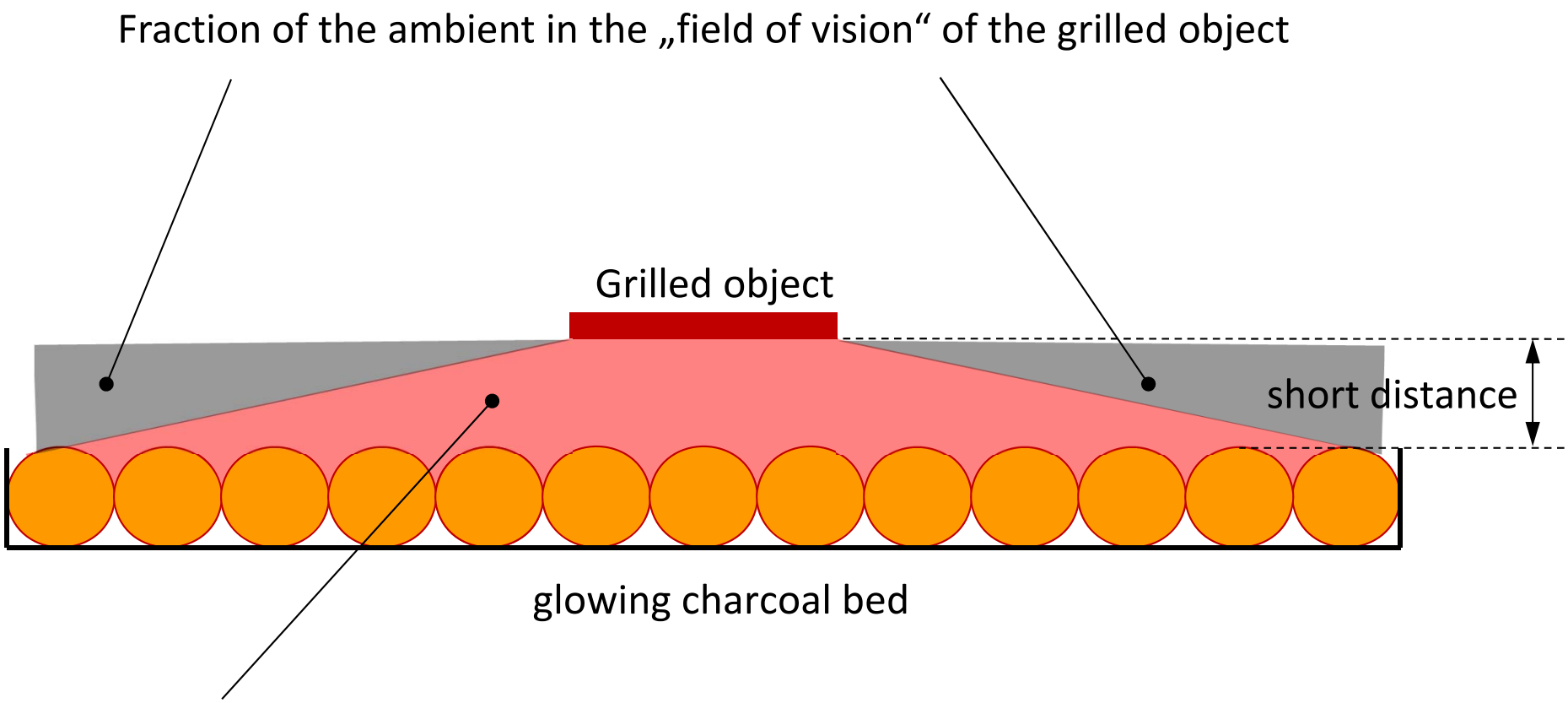

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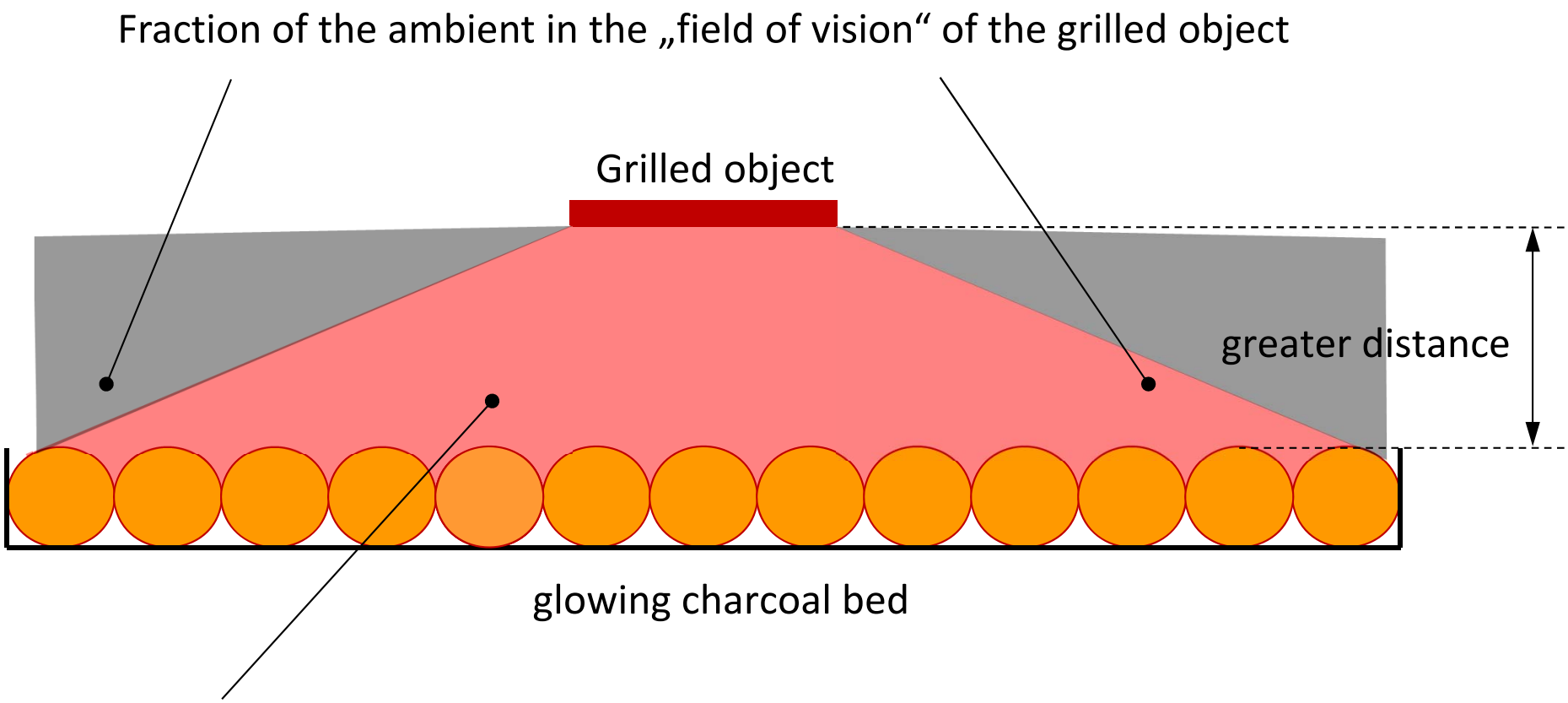
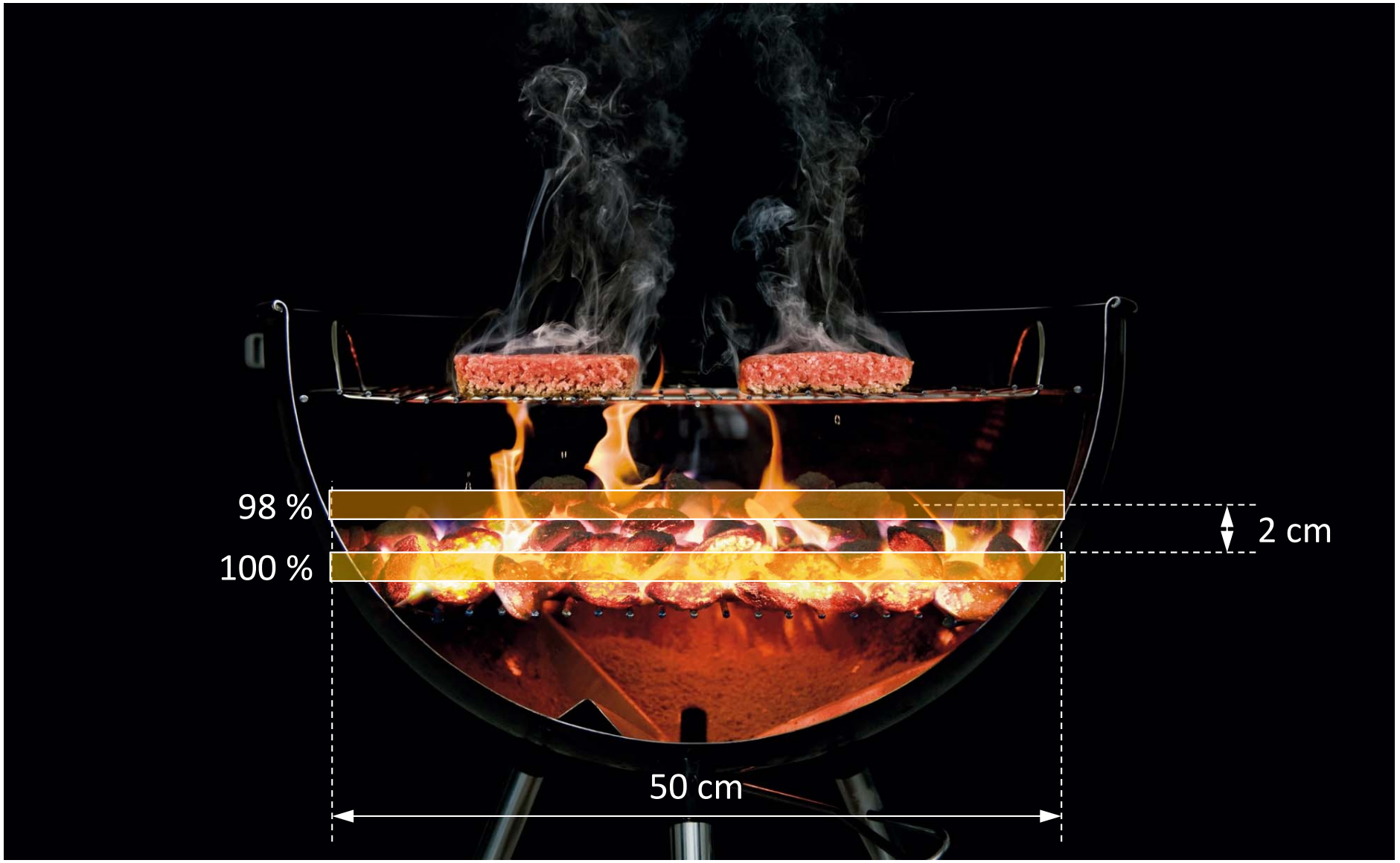


Lifting the grill grate during grilling



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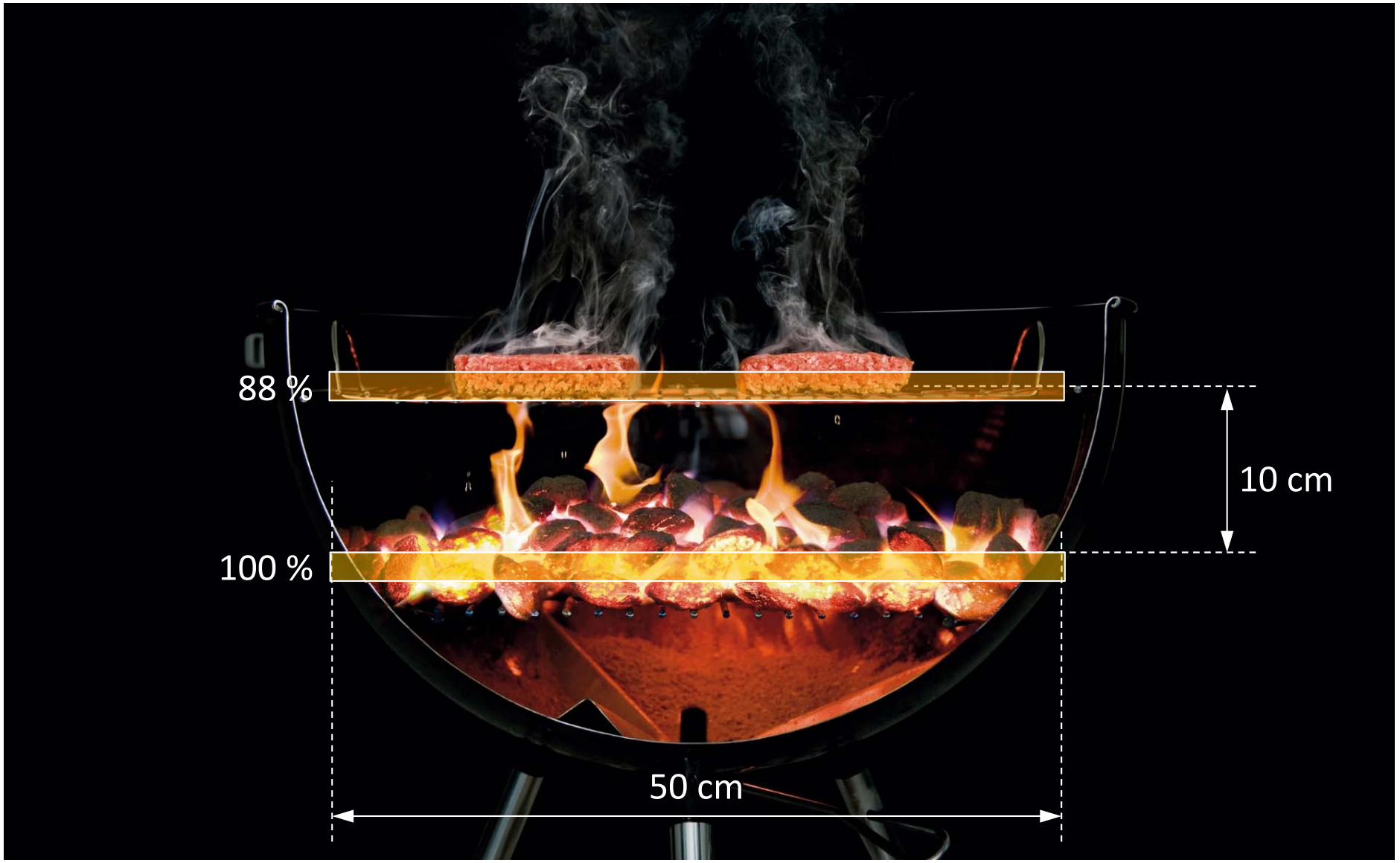
Lifting the grill grate during grilling



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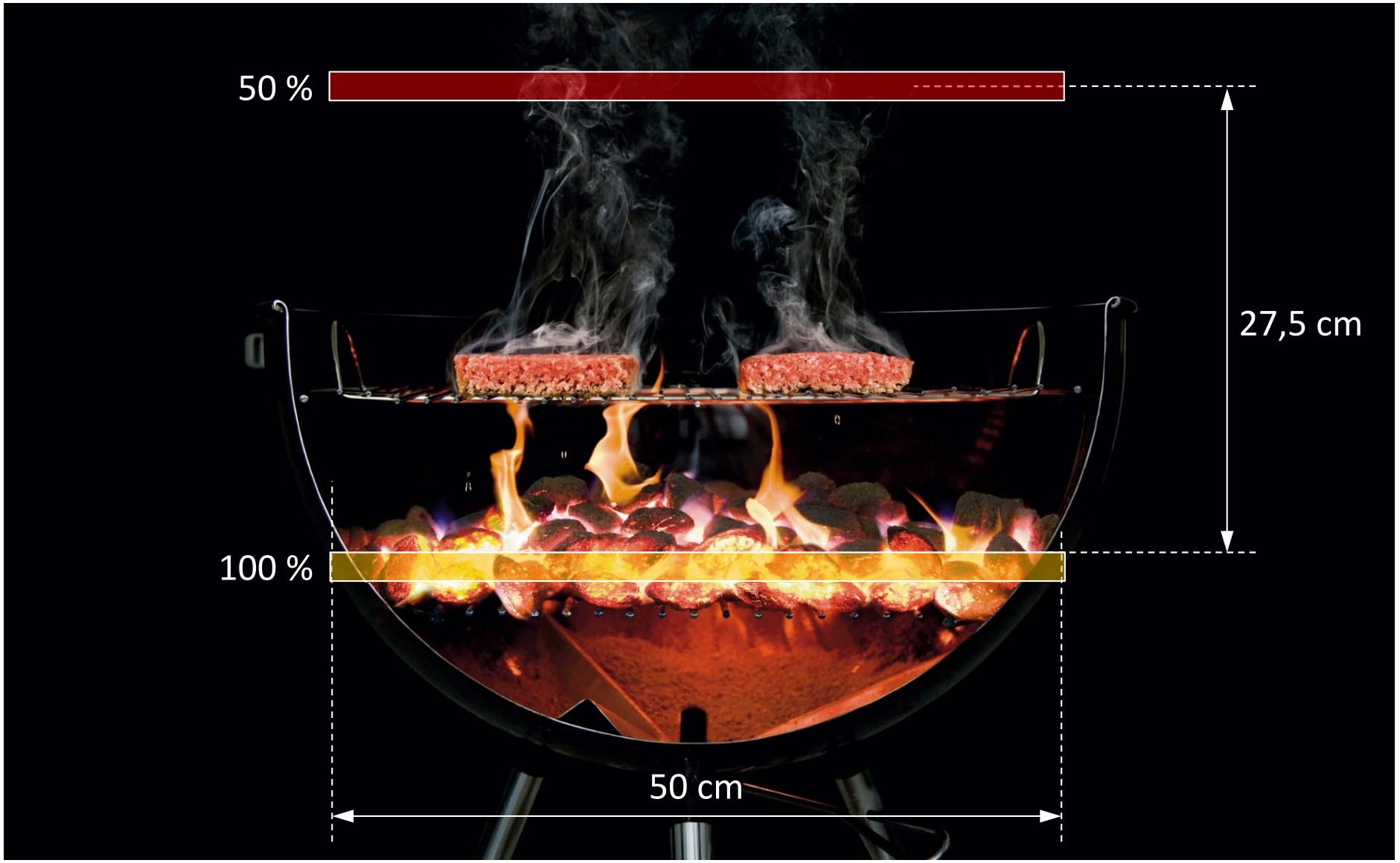

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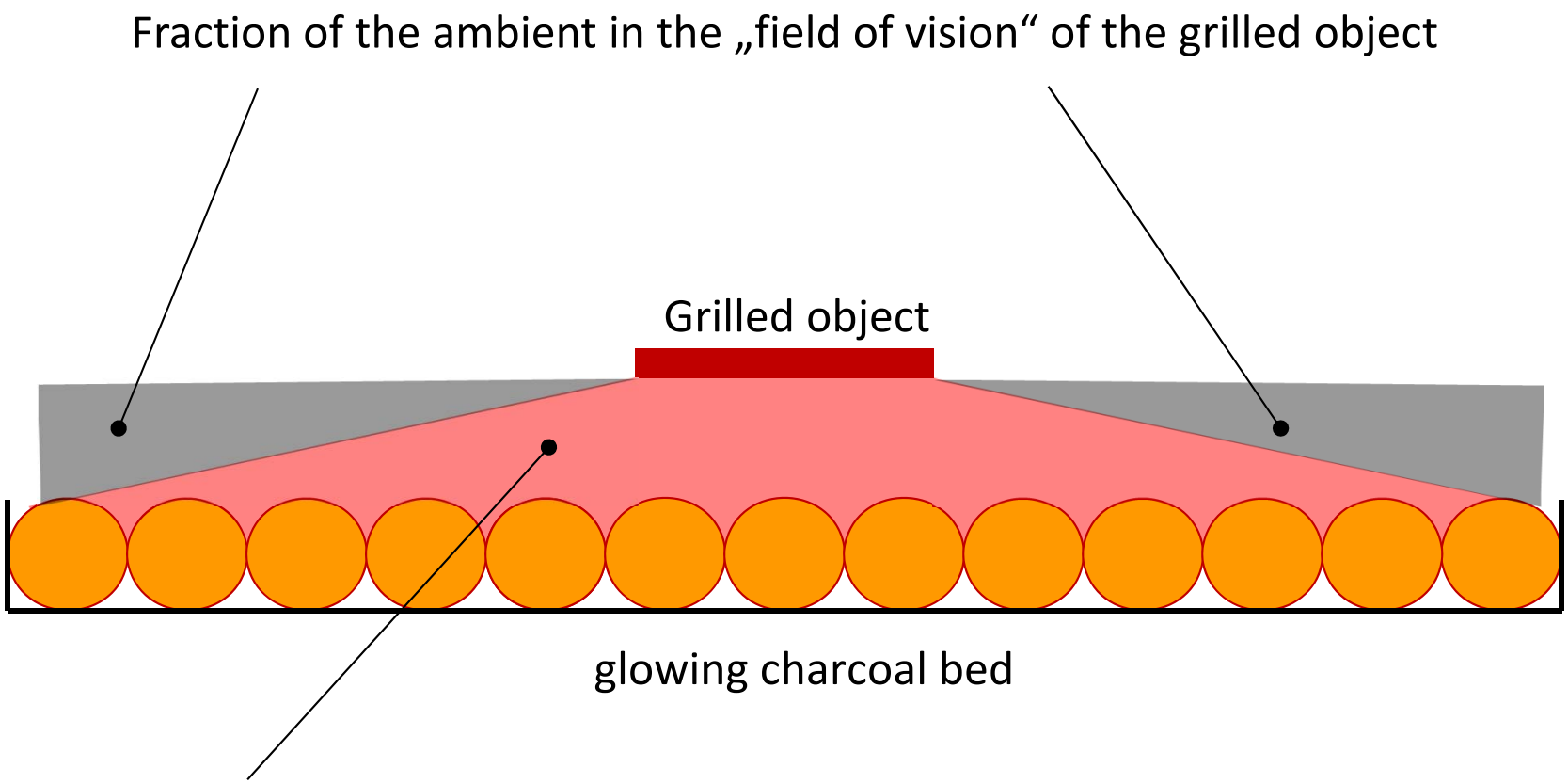
Influence of shape and optical properties of the grill



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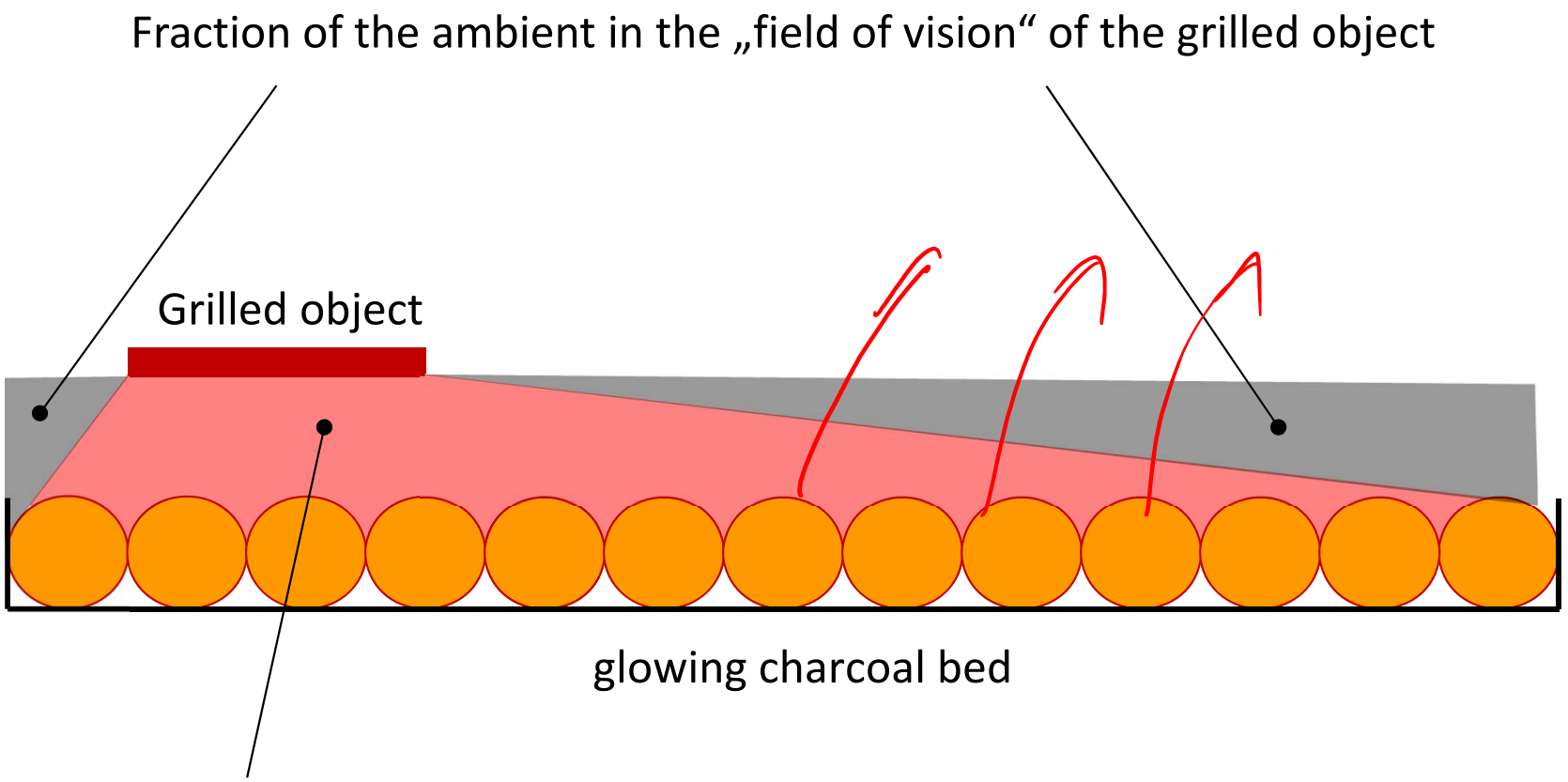

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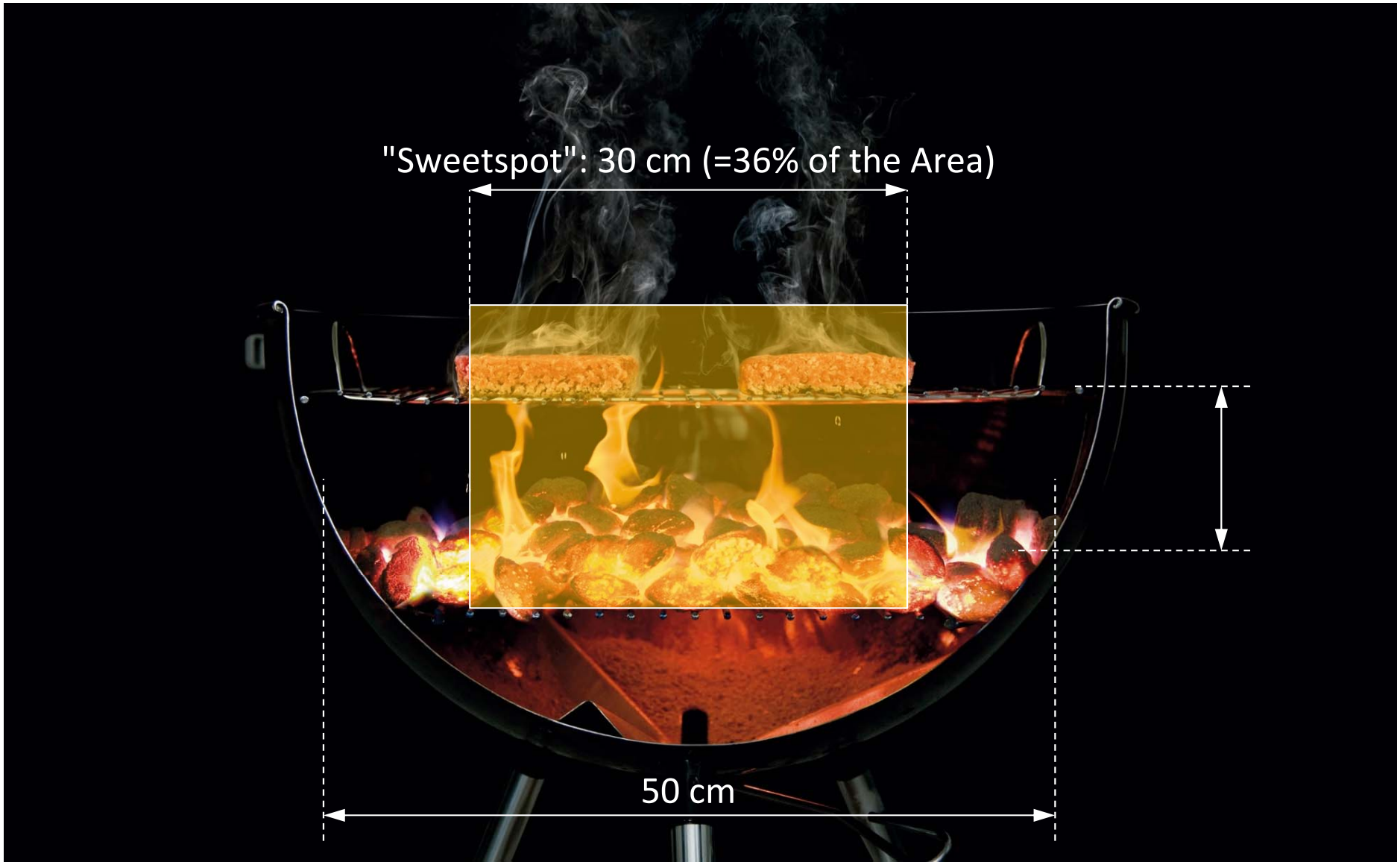

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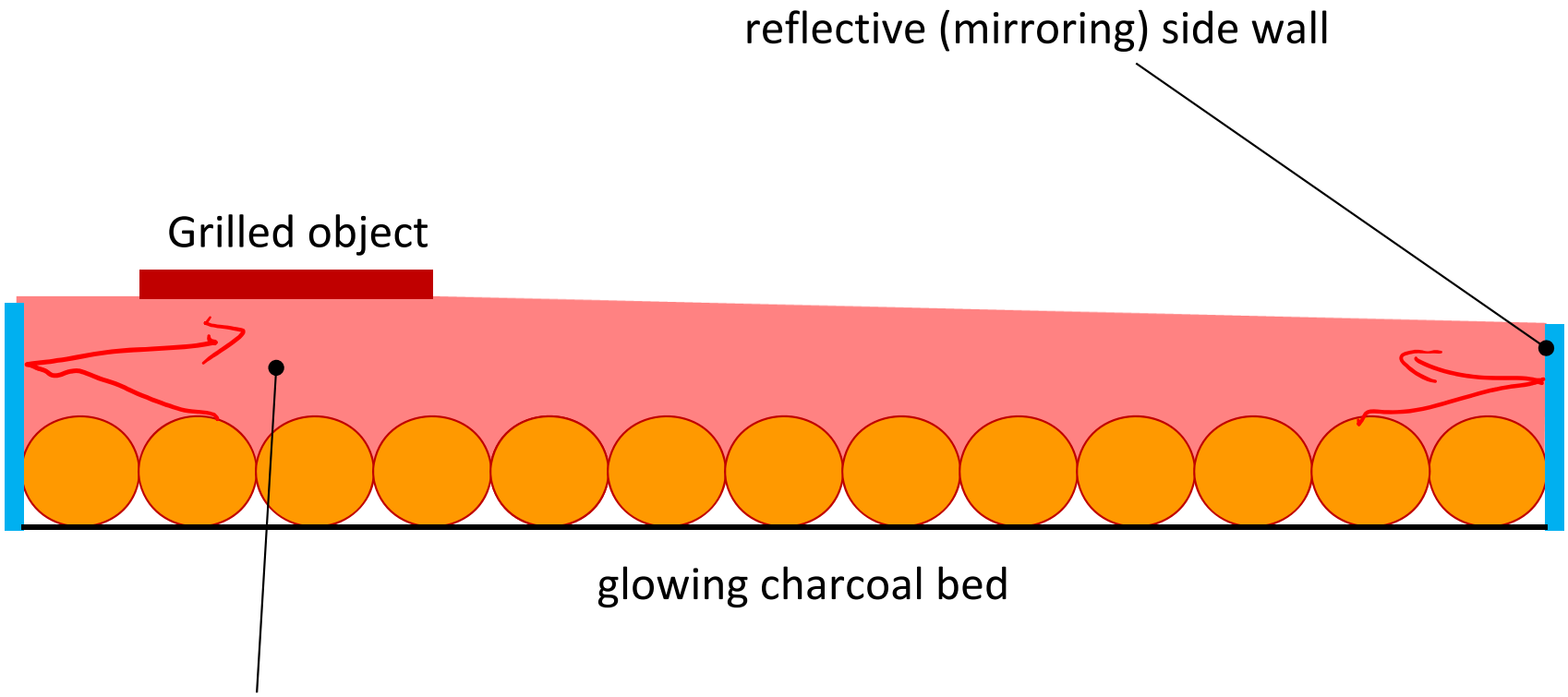
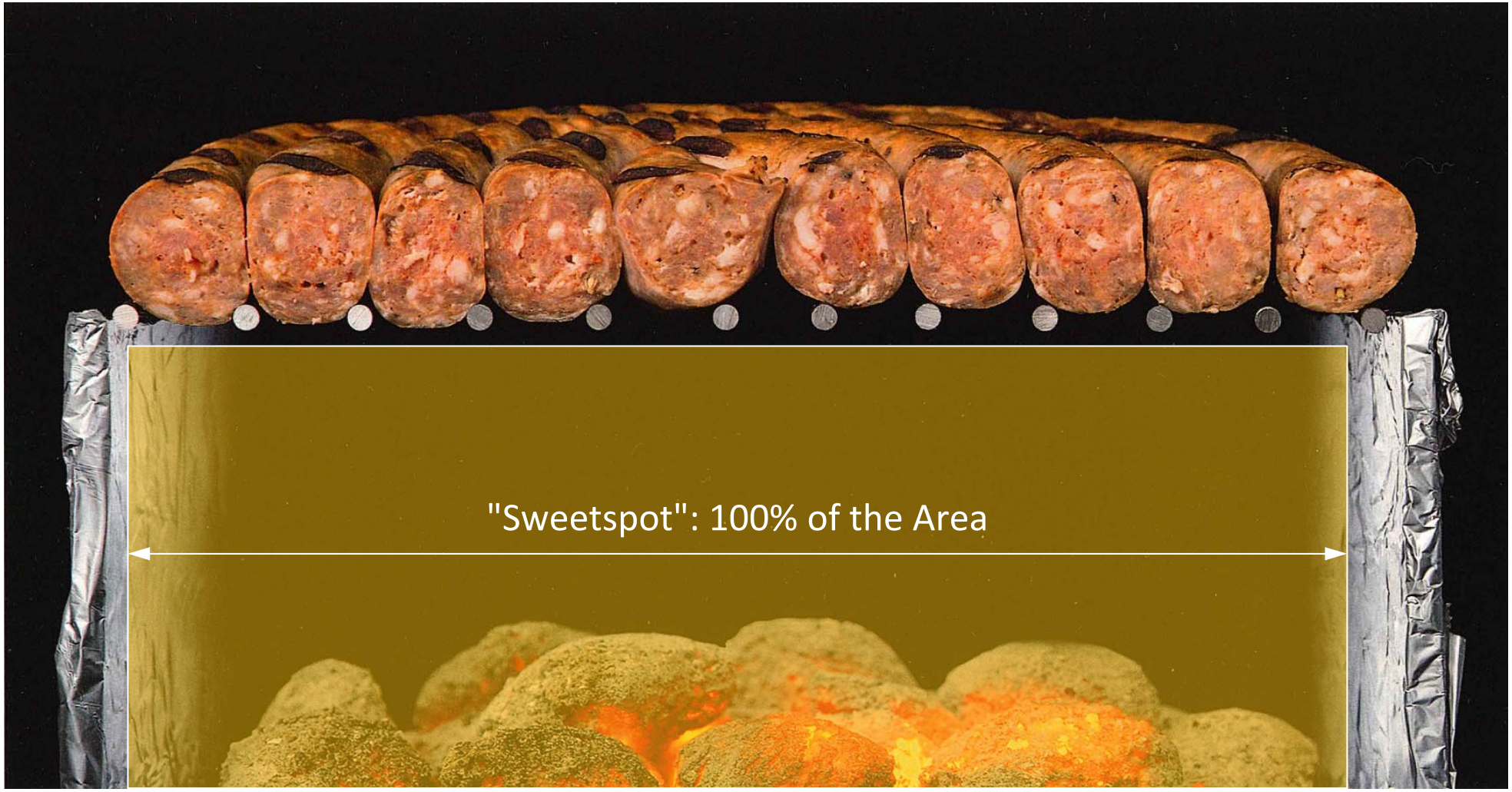


Fraction of the radiant charcoal bed in the „field of vision“ of the grilled object:
almost 100%

Influence of shape and optical properties of the grill



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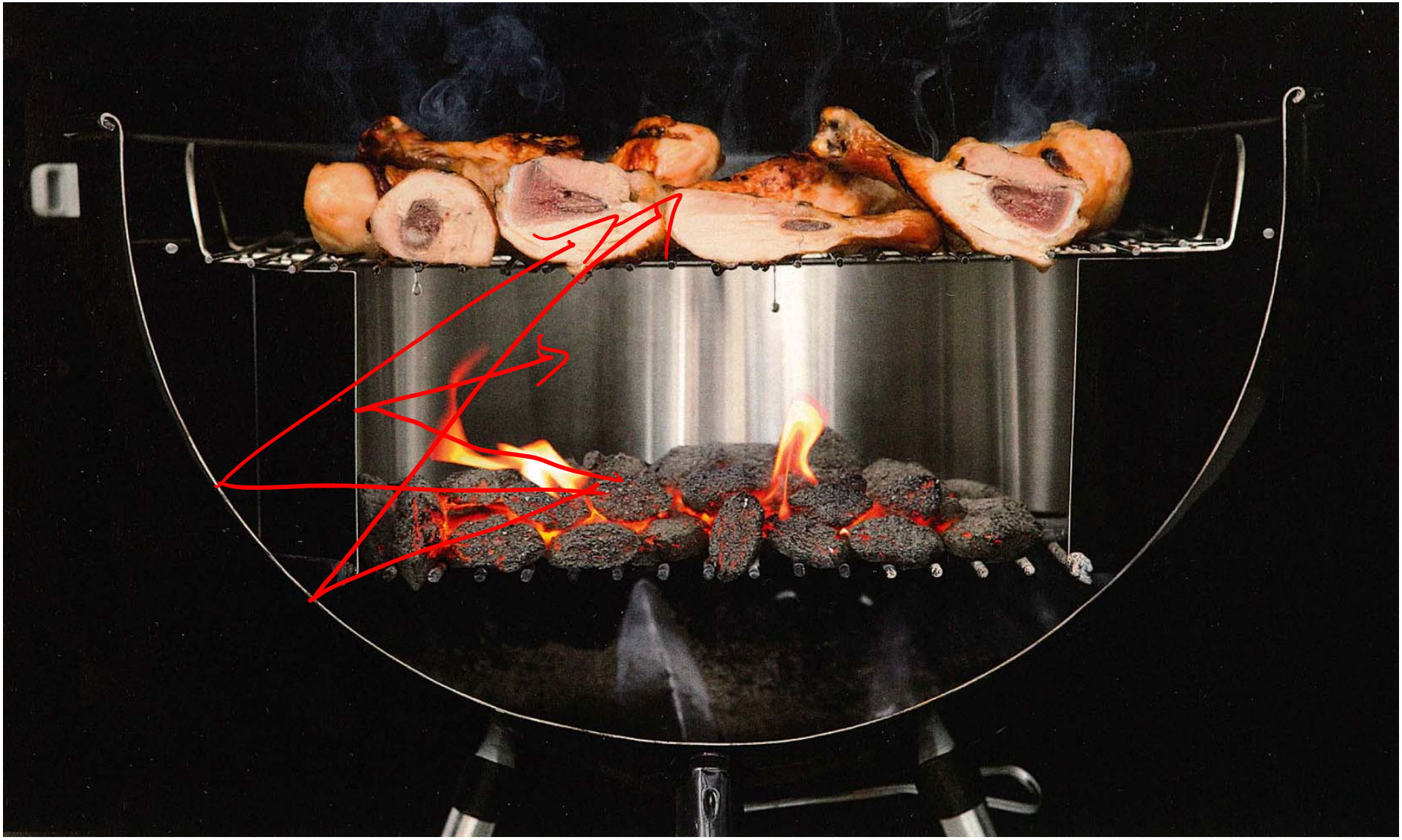
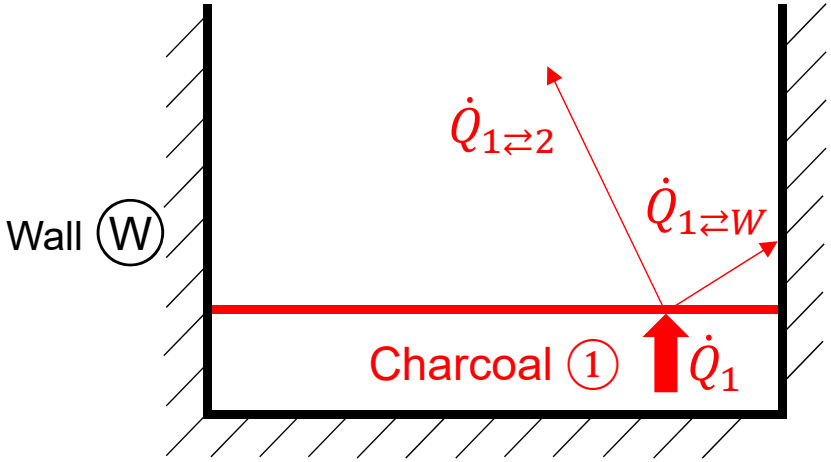
Influence of shape and optical properties of the grill



Discussion of assumptions and material properties



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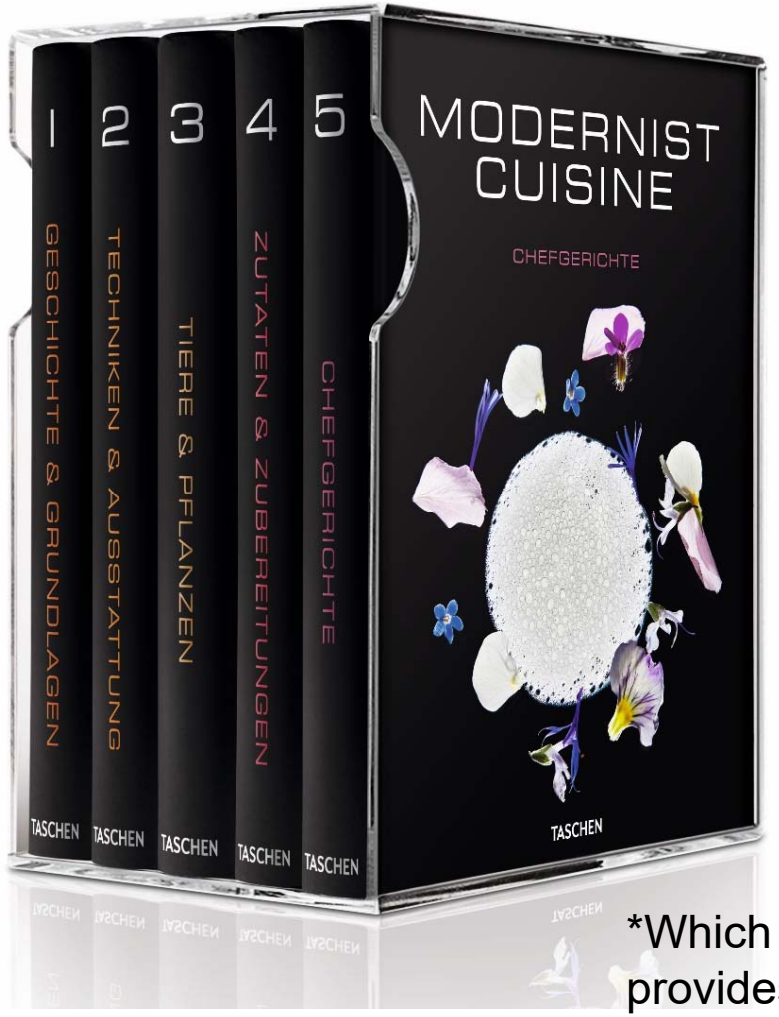
Comprehension Questions

Why is calculation of radiation transfer much more complicated when a third object is added?

If several bodies are involved in the radiation transfer, can certain bodies be combined?
In which case can bodies be combined?

Literature: Modernist Cuisine published by TASCHEN

All non-referenced images have been taken from this book*
Modernist Cuisine by Nathan Myhrvold et al.



*Which I acquired some years ago and, which provides a wealth of information

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