HOW TO EMPLOY RANDOM PARTICULATE MEDIA TO DESIGN NEAR PERFECT ABSORPTION AND SPECTRAL SELECTIVITY?

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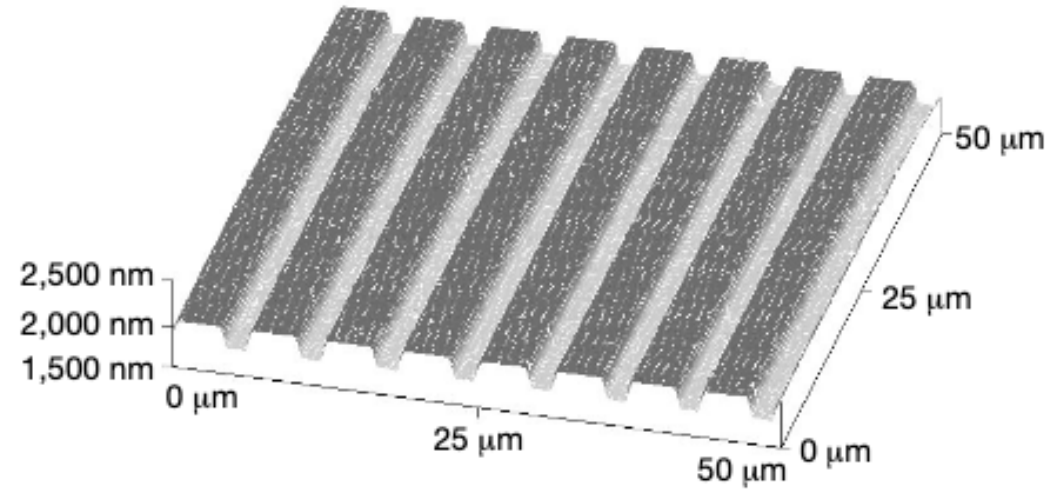
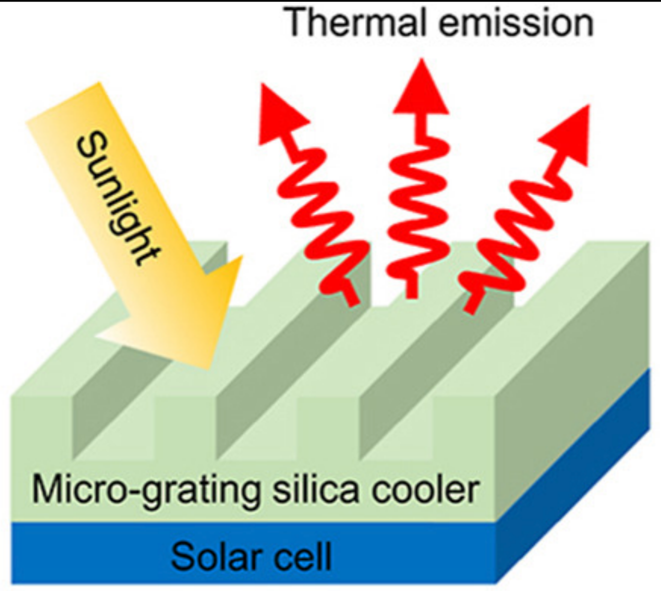
Context: applications requiring controlled spectral properties

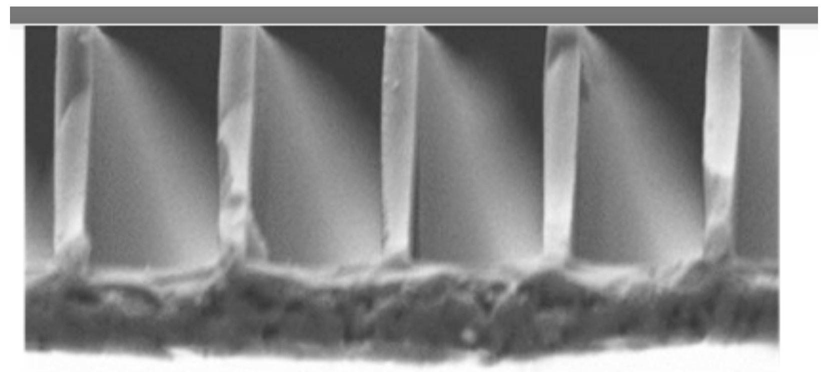
Control of emission/absorption properties has improved a number of applications:

- Infrared sources
- Radiative cooling
- Thermophotovoltaics (TPV)
- Perfect absorption devices
- ...

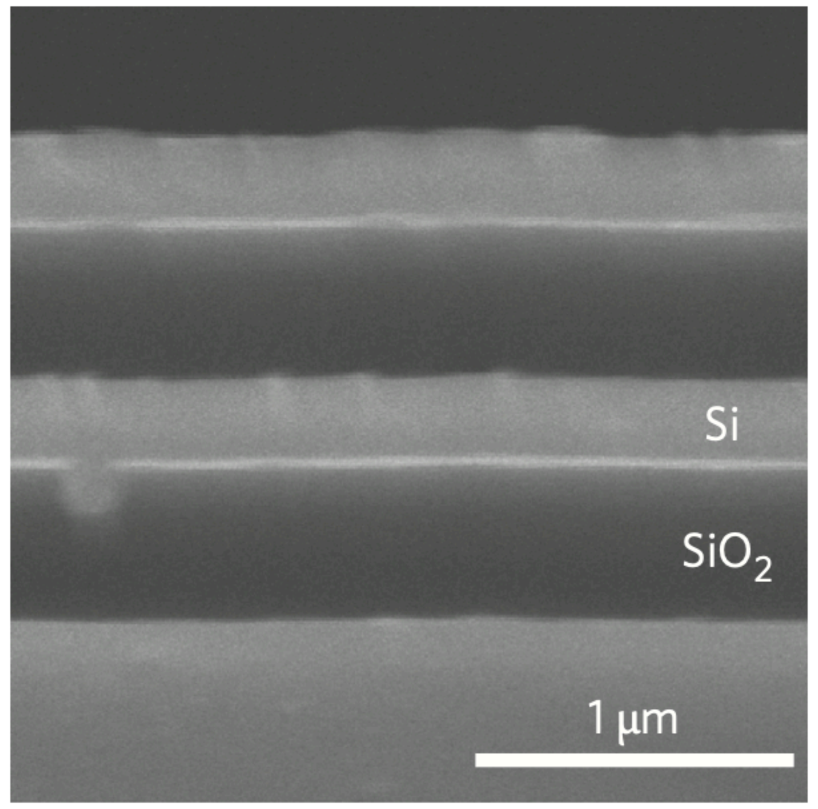


J. J. **Greffet** et al. Nature, 416(6876), 2002
Coherent emission of light by thermal sources

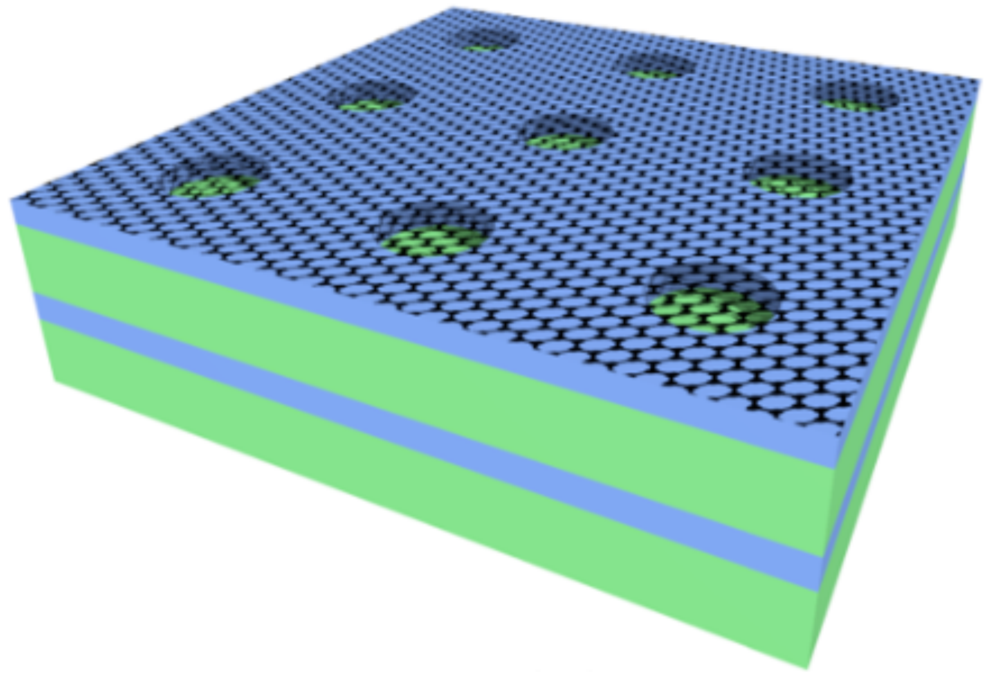




B. **Zhao** et al. Renewable Energy, 191, 2022
Radiative cooling of solar cells with micro-grating photonic cooler



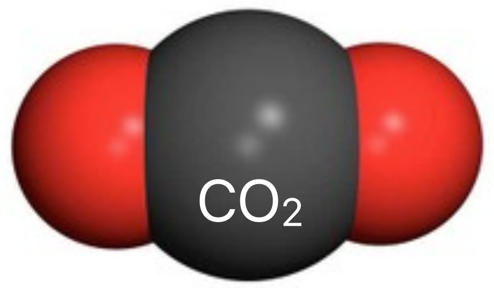
A. **Lenert** et al. Nature Nanotech, 9, 2014
A nanophotonic solar thermophotovoltaic device



J. R. **Piper**. ACS Photonics, 1(4), 2014
Total Absorption in a Graphene Monolayer [...] with a Photonic Crystal Guided Resonance

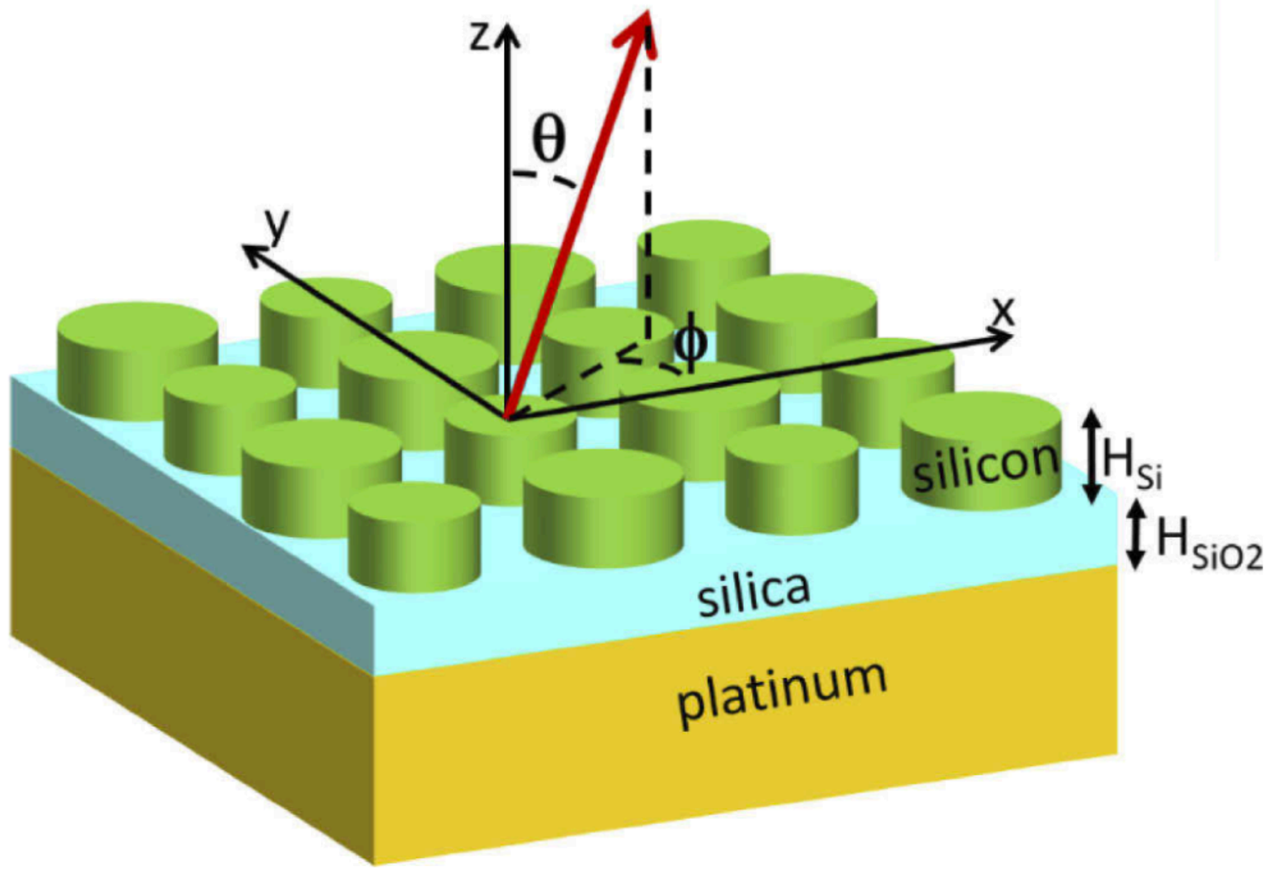
An example: CO_2 sensing

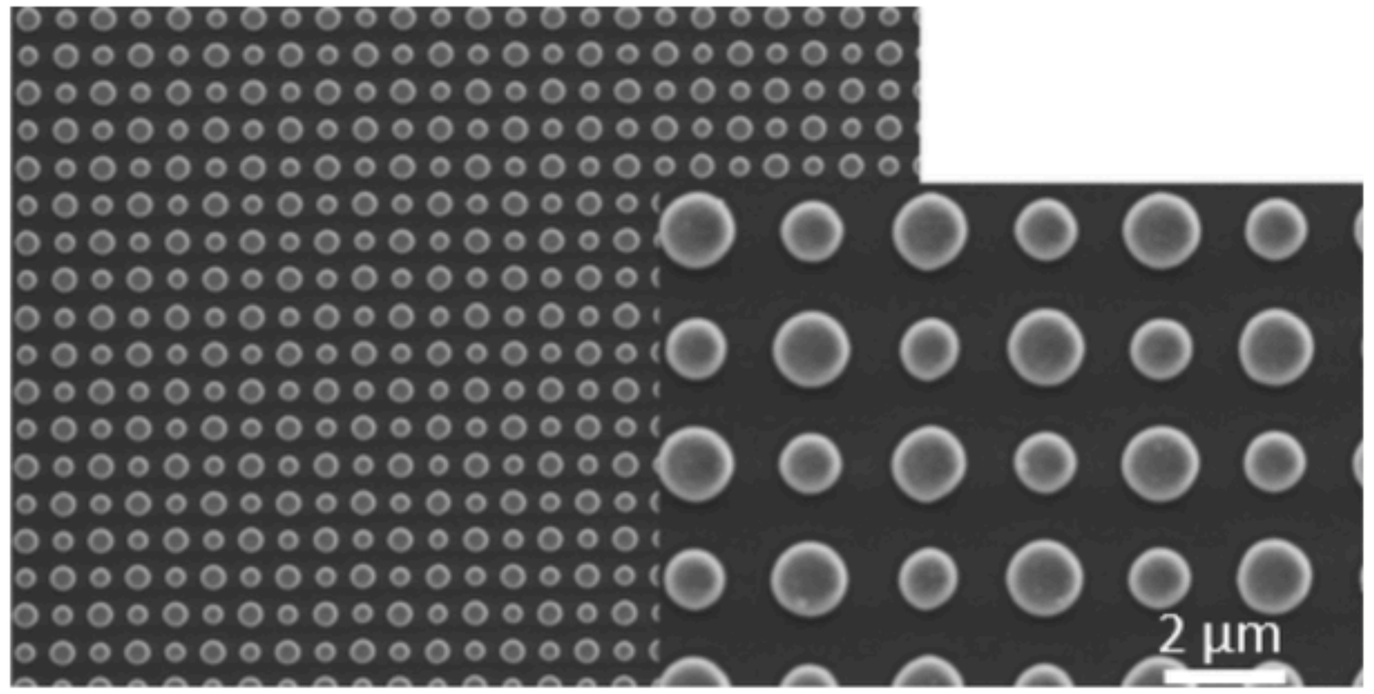
Incandescent source emitting a radiation which is:

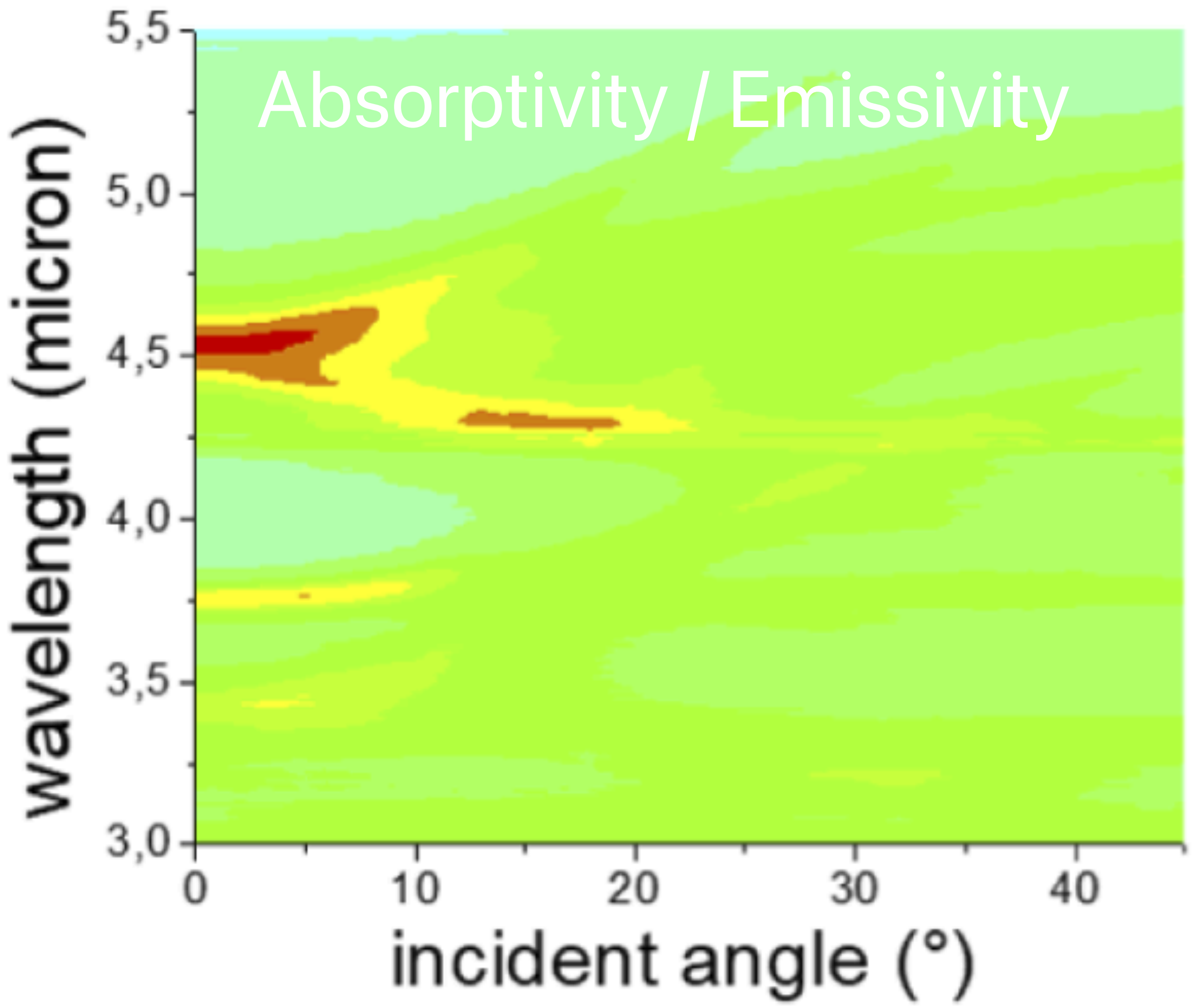


Vibrational frequency $\sim 4.5\ \mu m$

- **Spectrally broad**
- **Isotropic**







$\varepsilon_\lambda = \alpha_\lambda$
(Kirchhoff's law)

*C. **Blanchard** et al. Opt. Mat. Express (12), 2022.*
Metallo-dielectric metasurfaces for thermal emission with controlled spectral bandwidth and angular aperture

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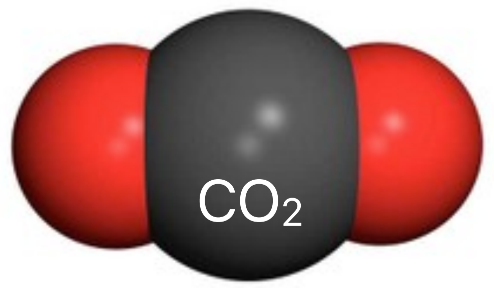

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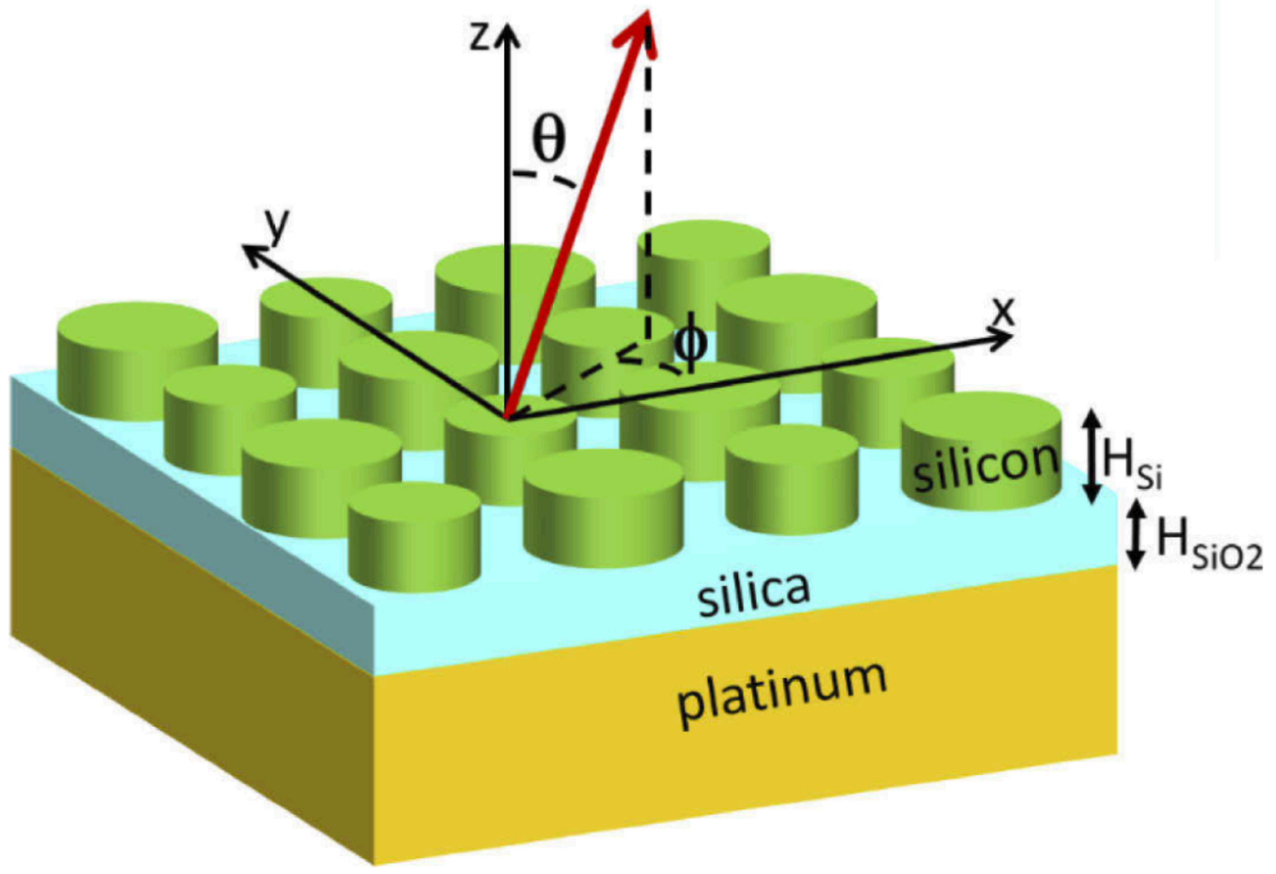

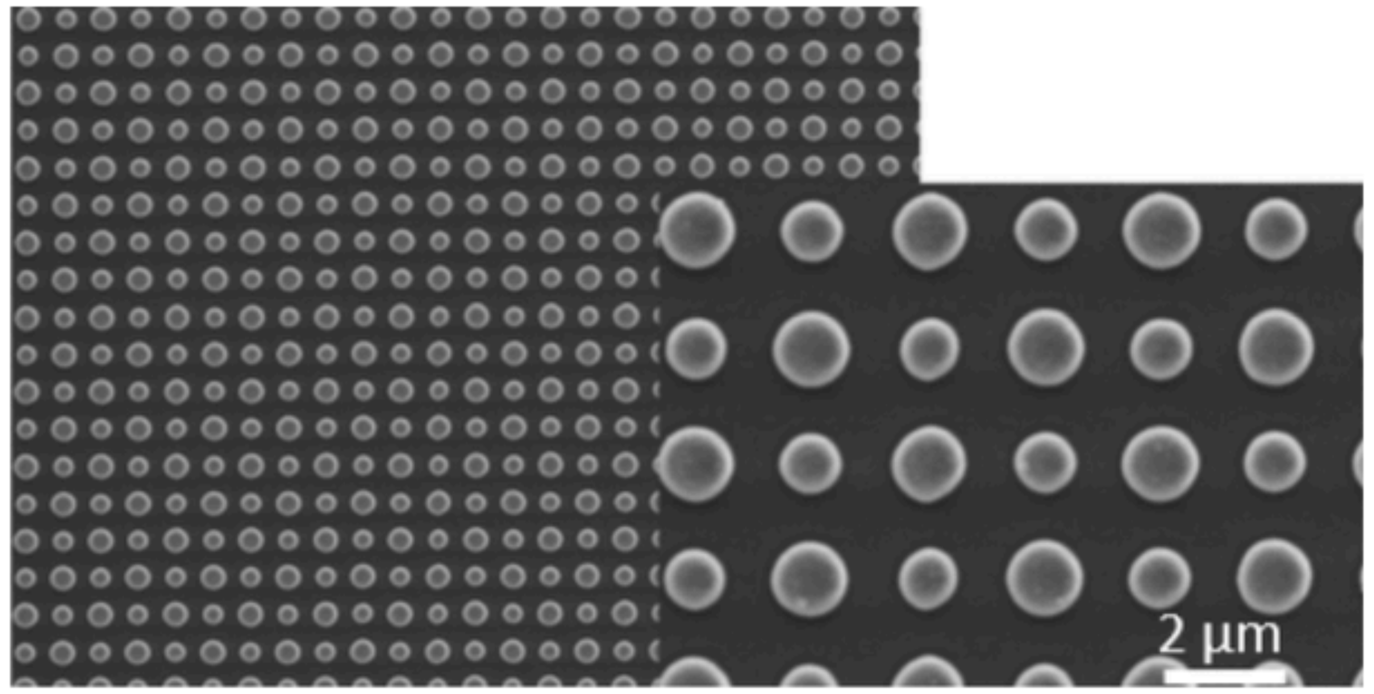

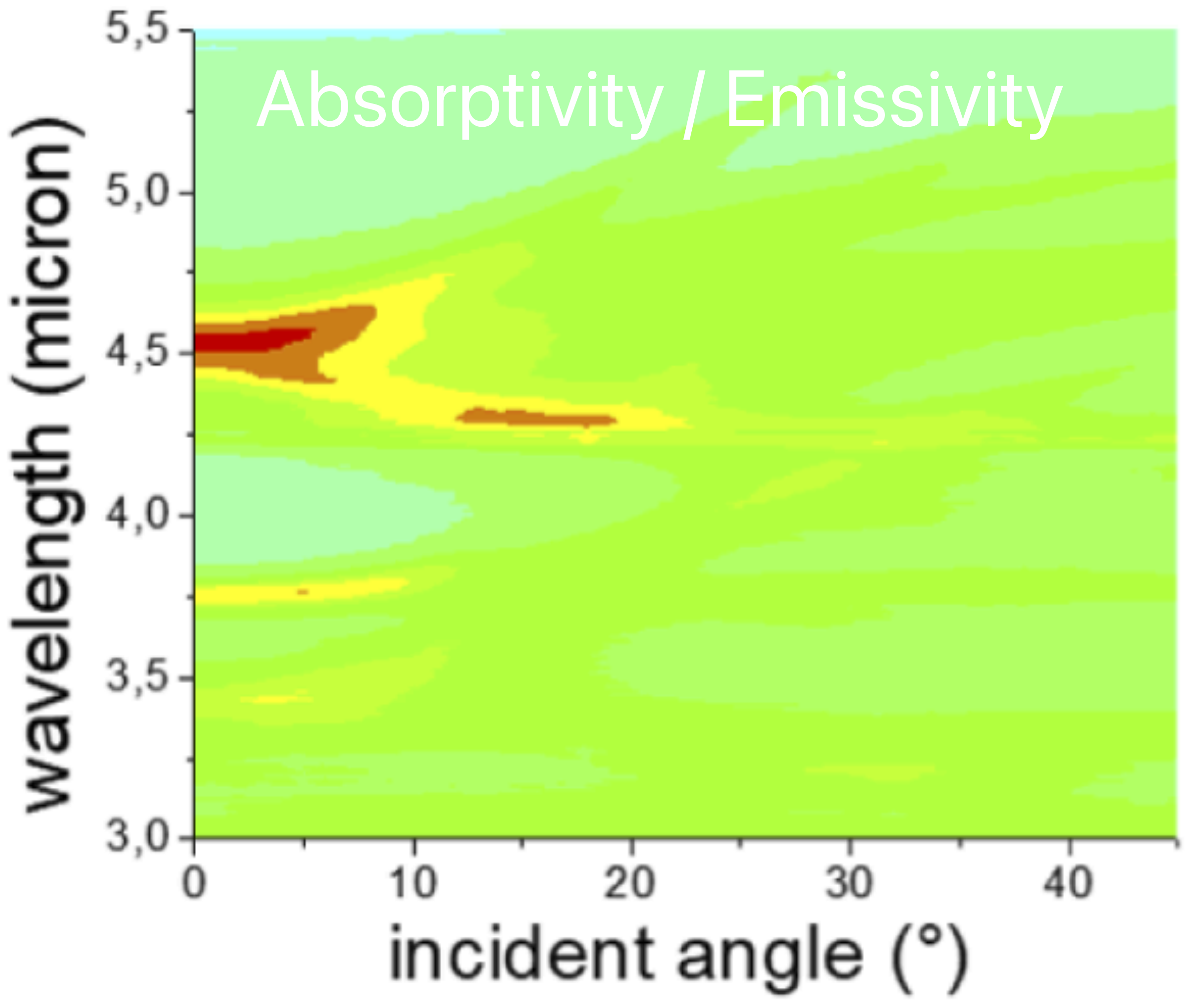

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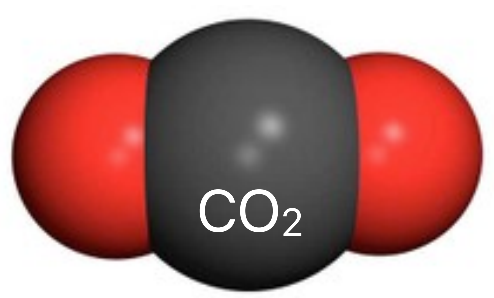

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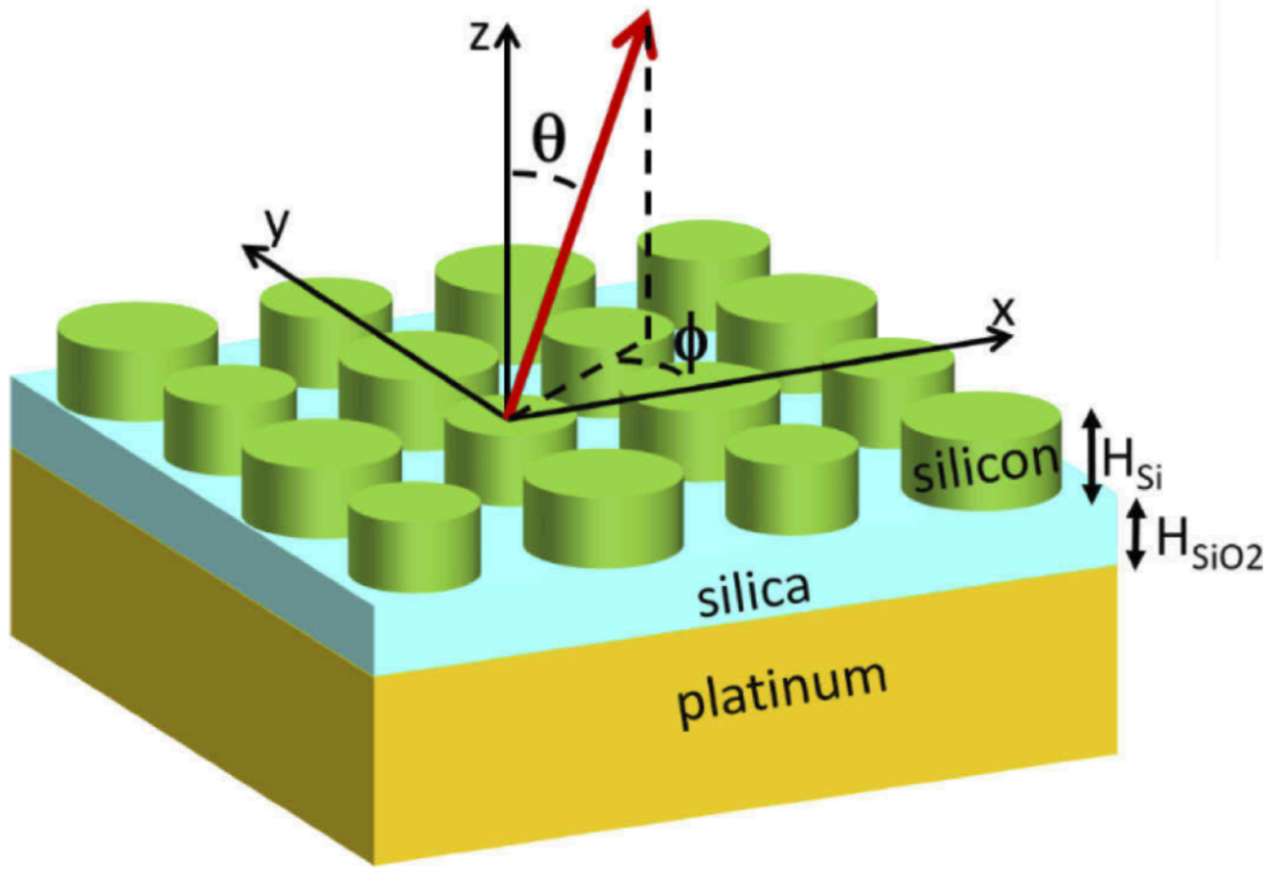

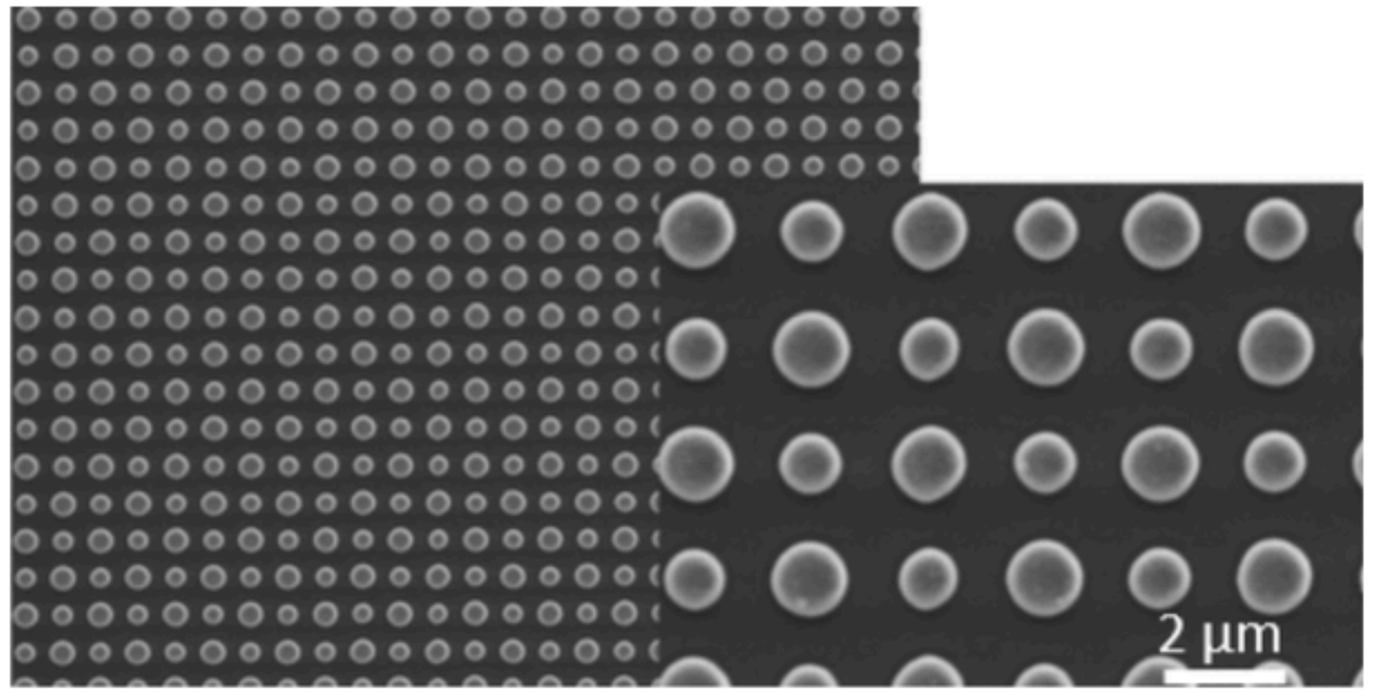

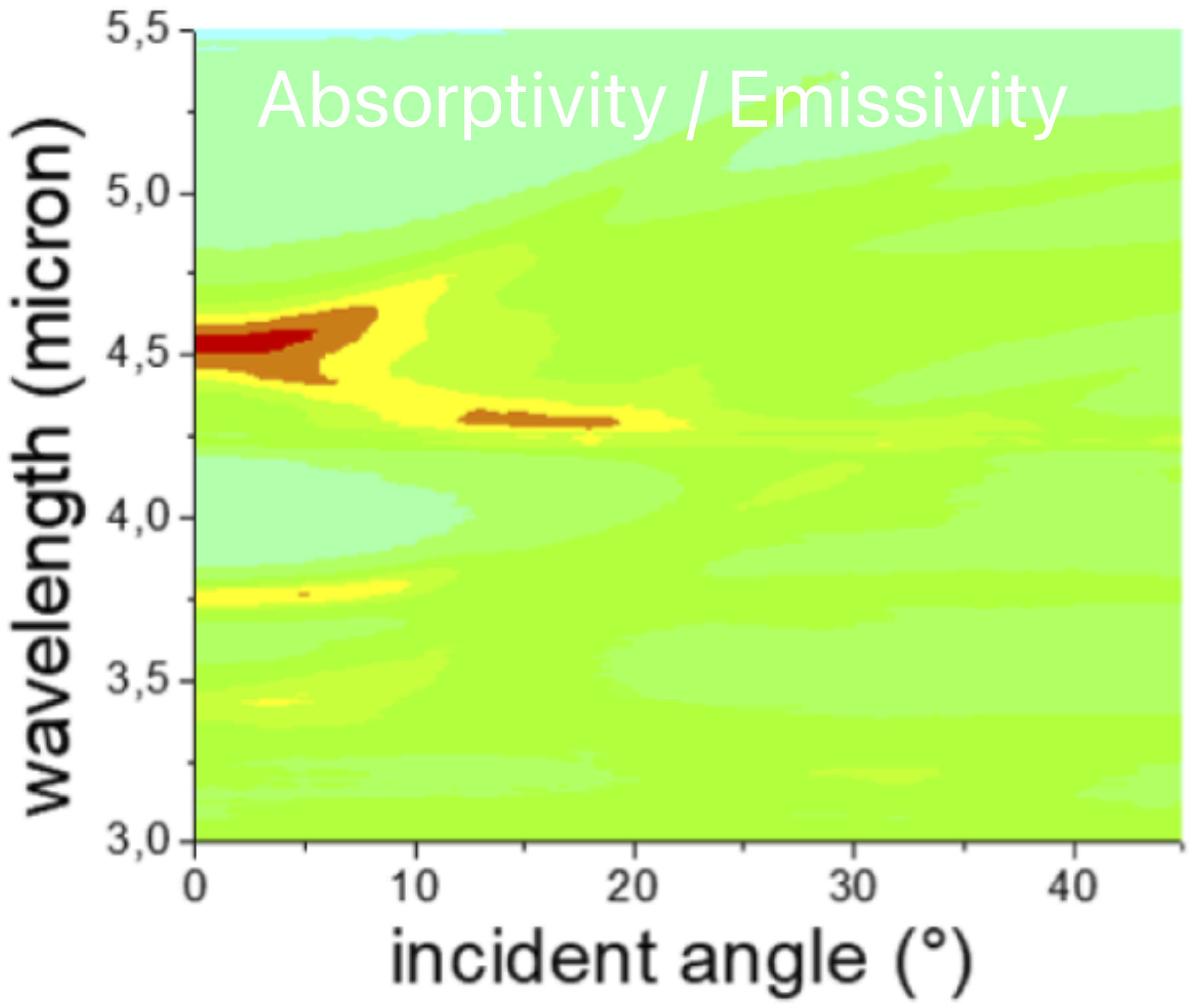

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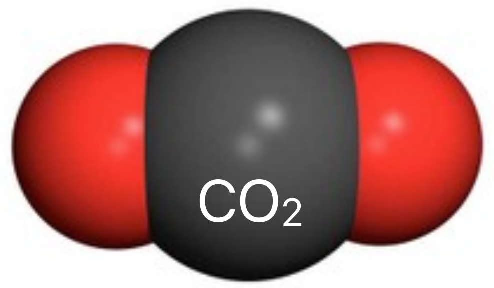

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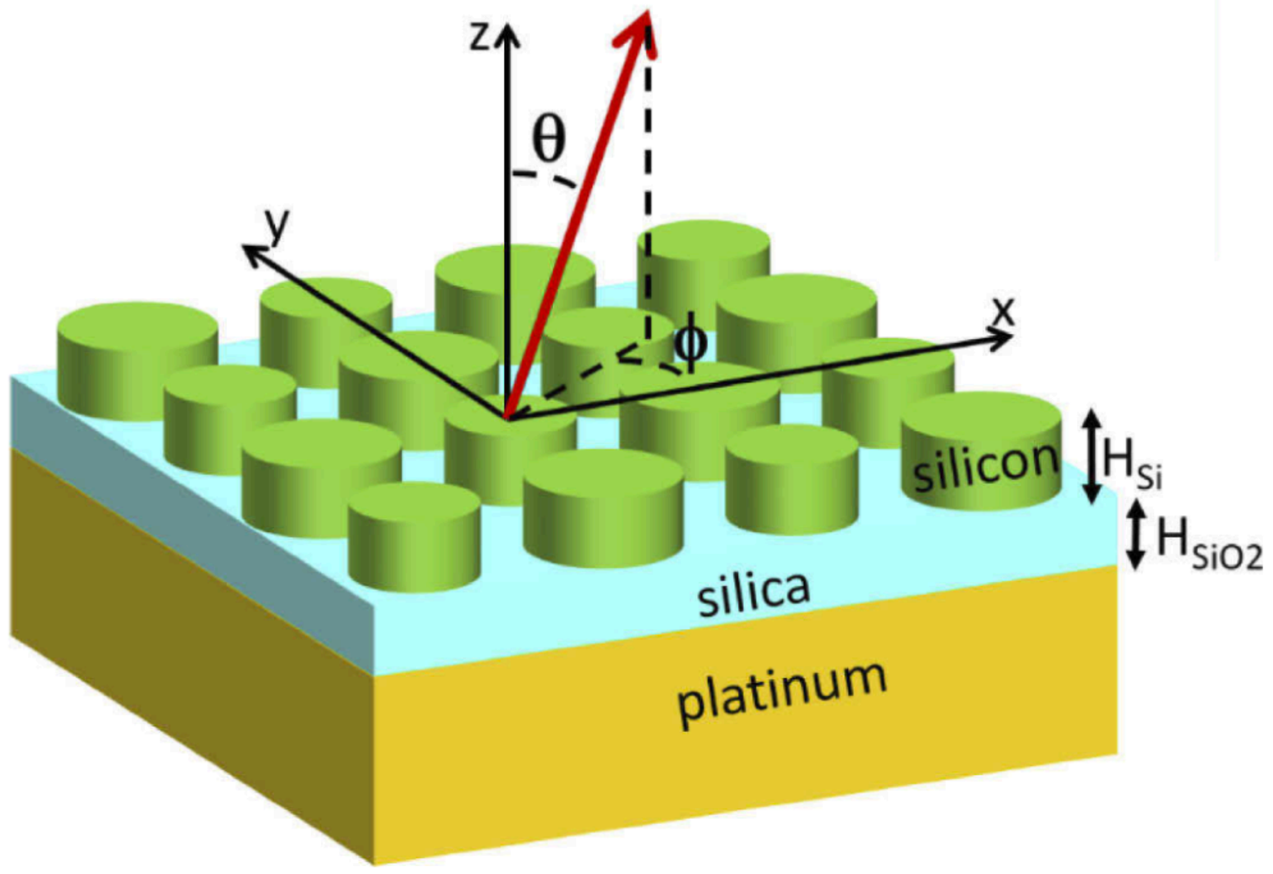
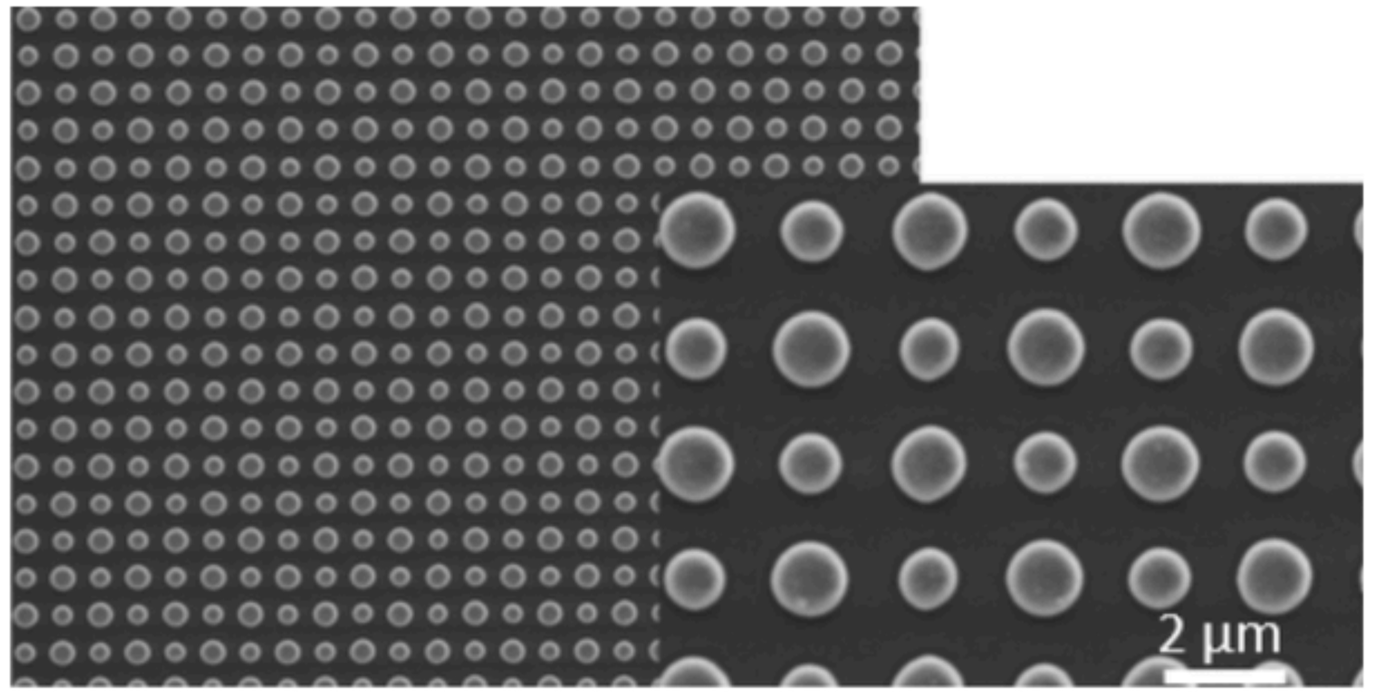
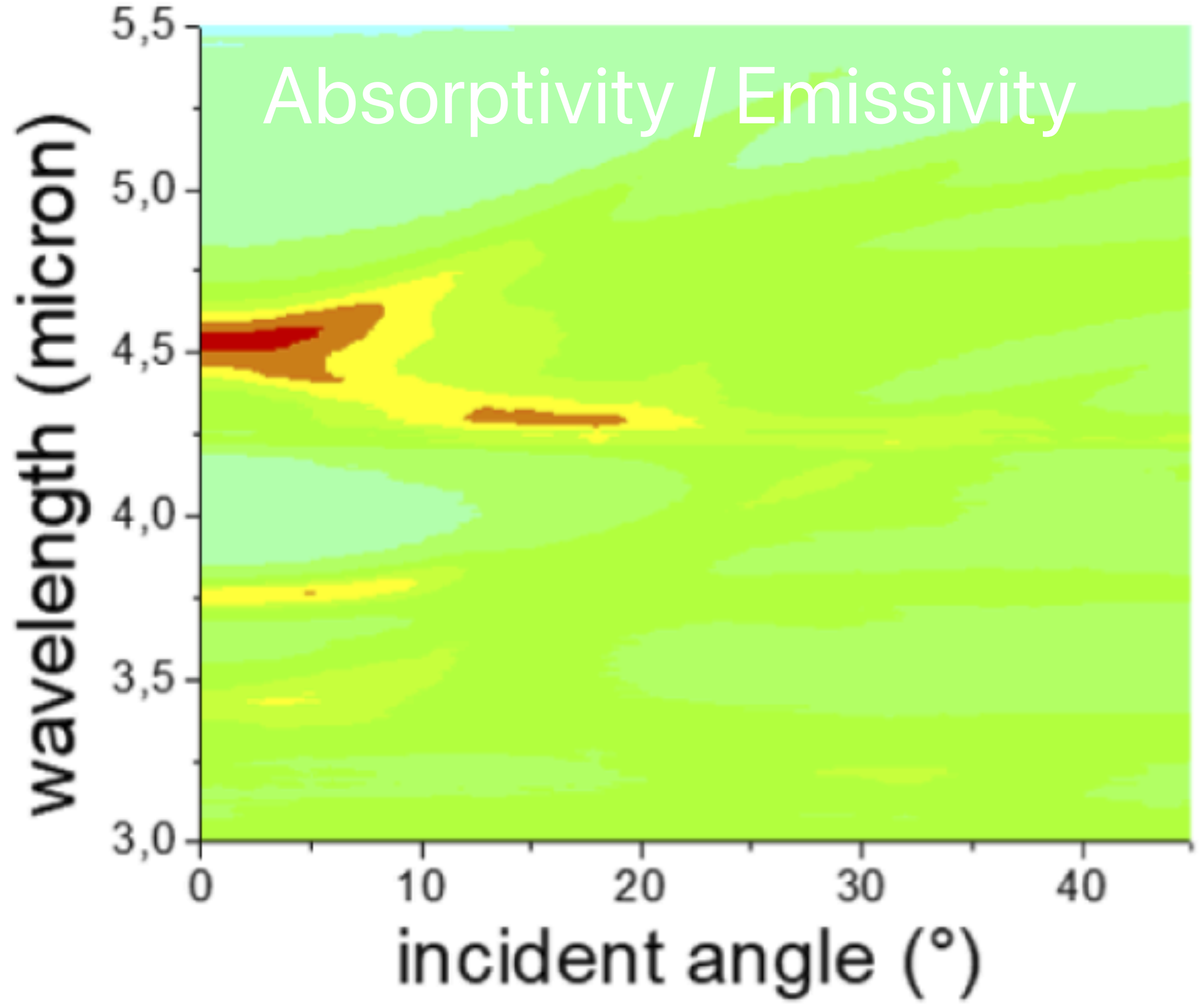




Objective: emit with spectral and angular selectivity



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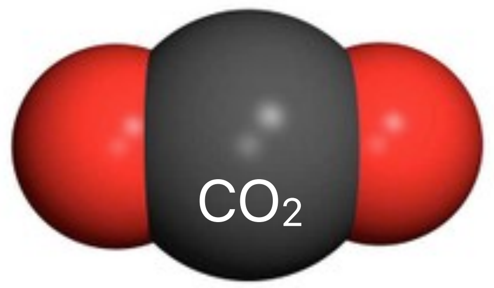

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absorption in the metal (associated with τ_{abs})

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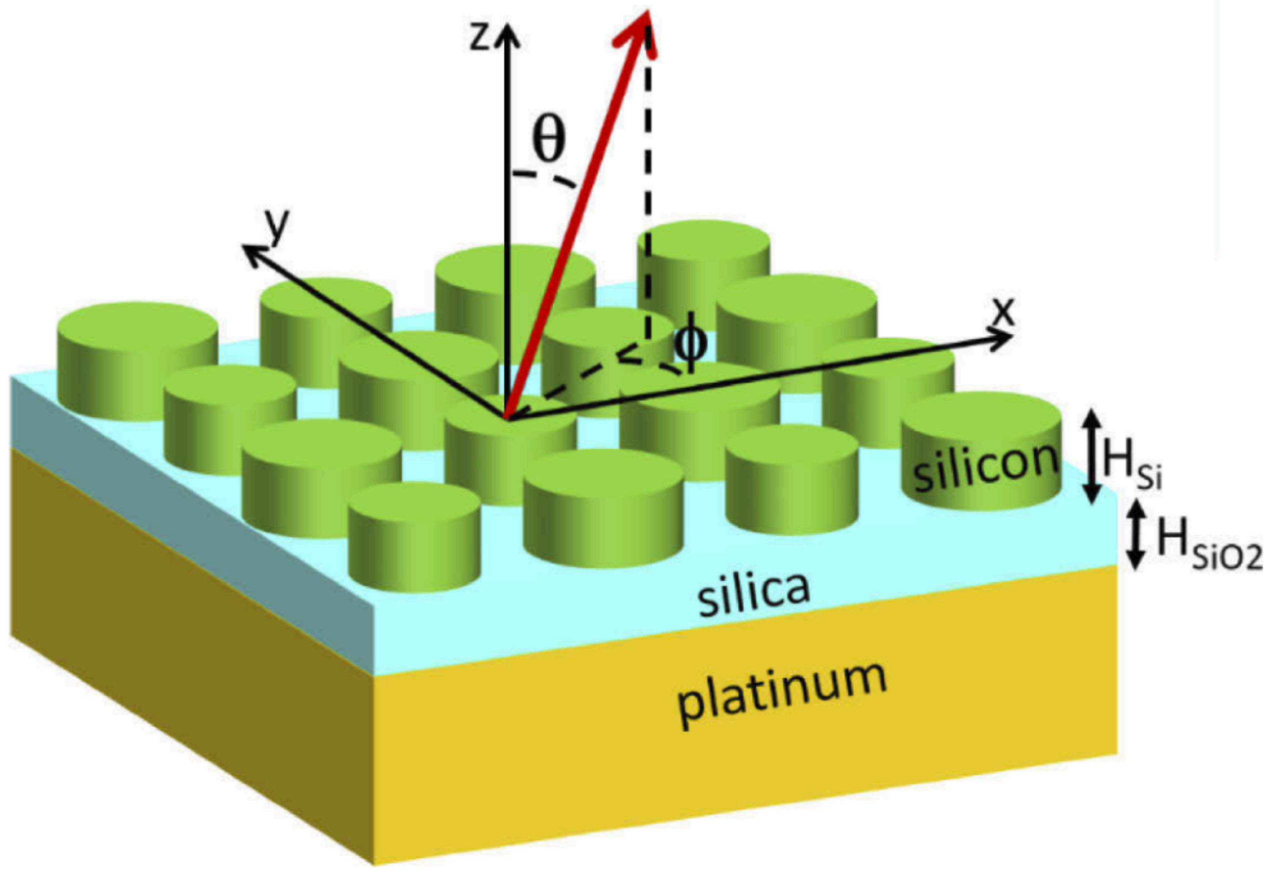

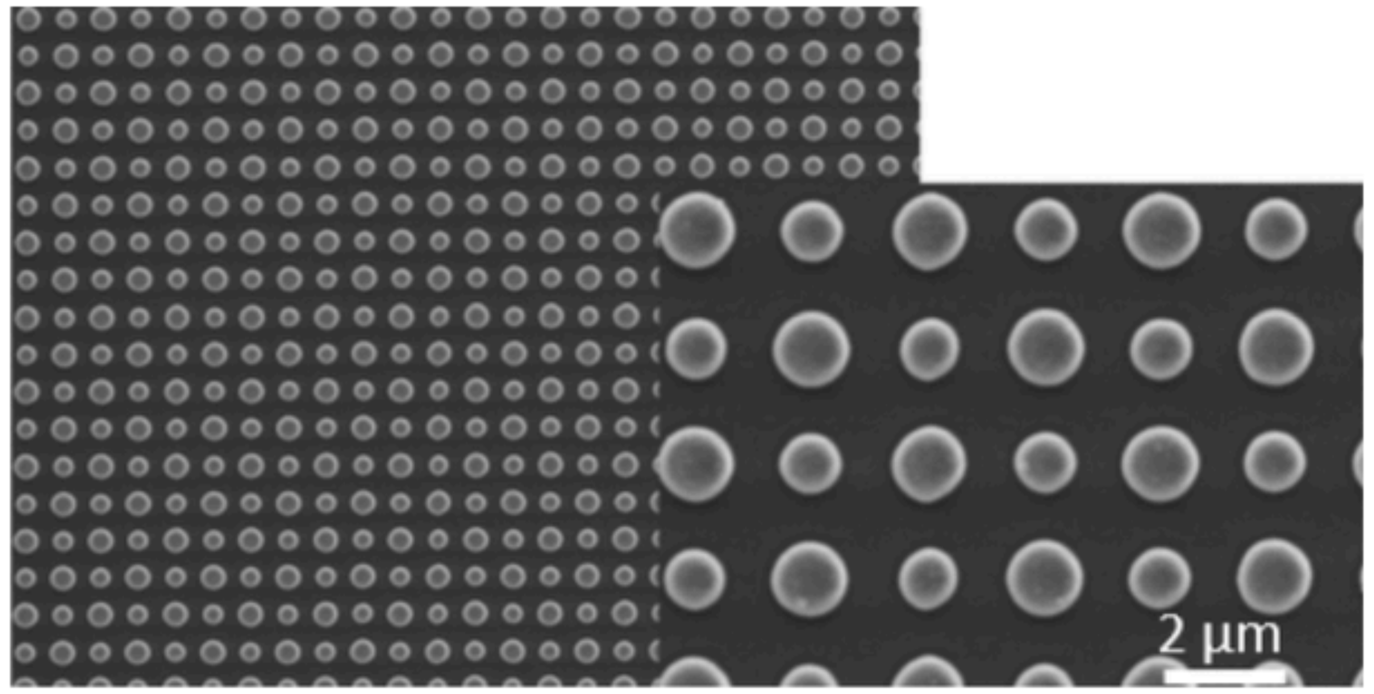

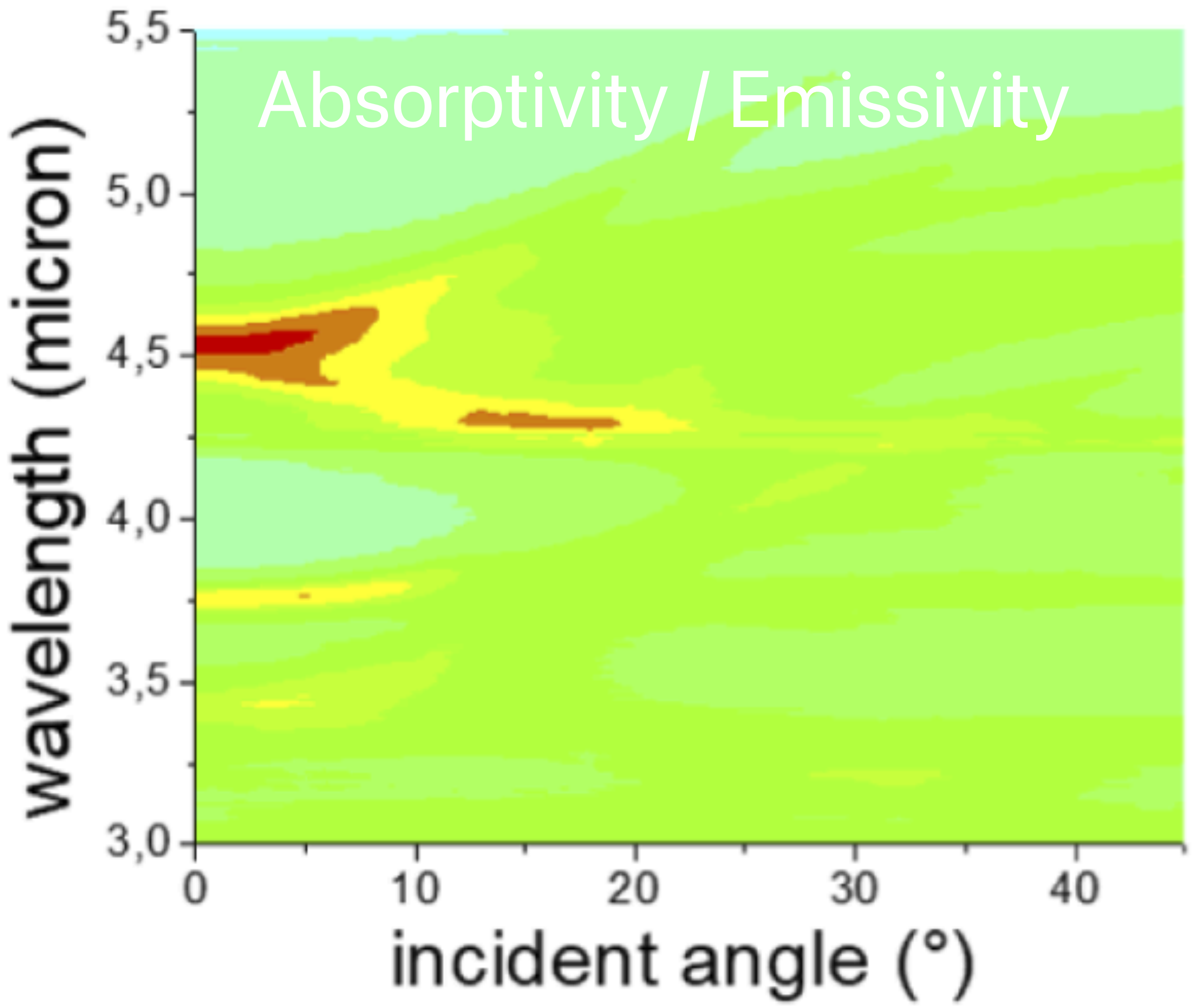

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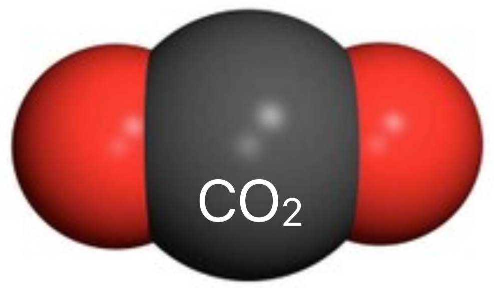

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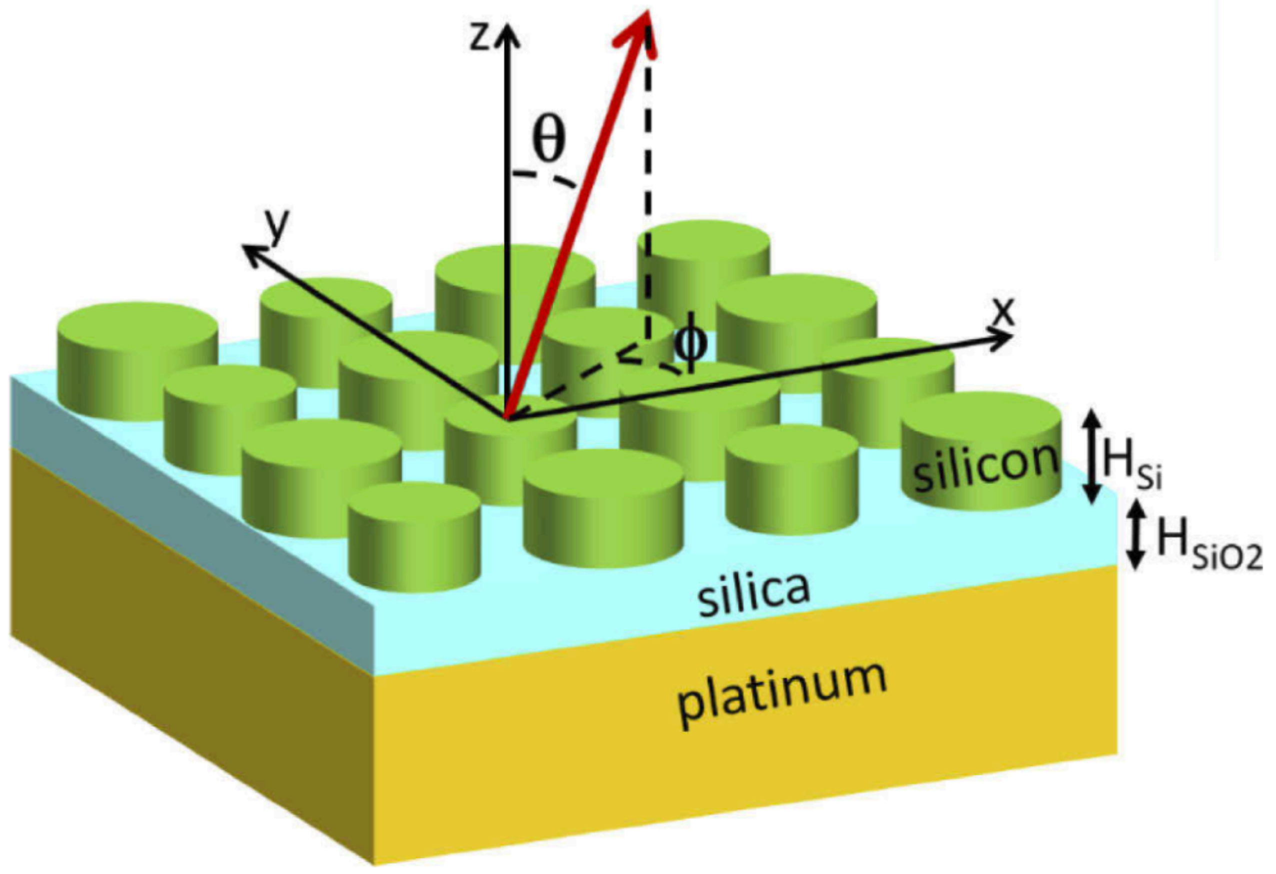
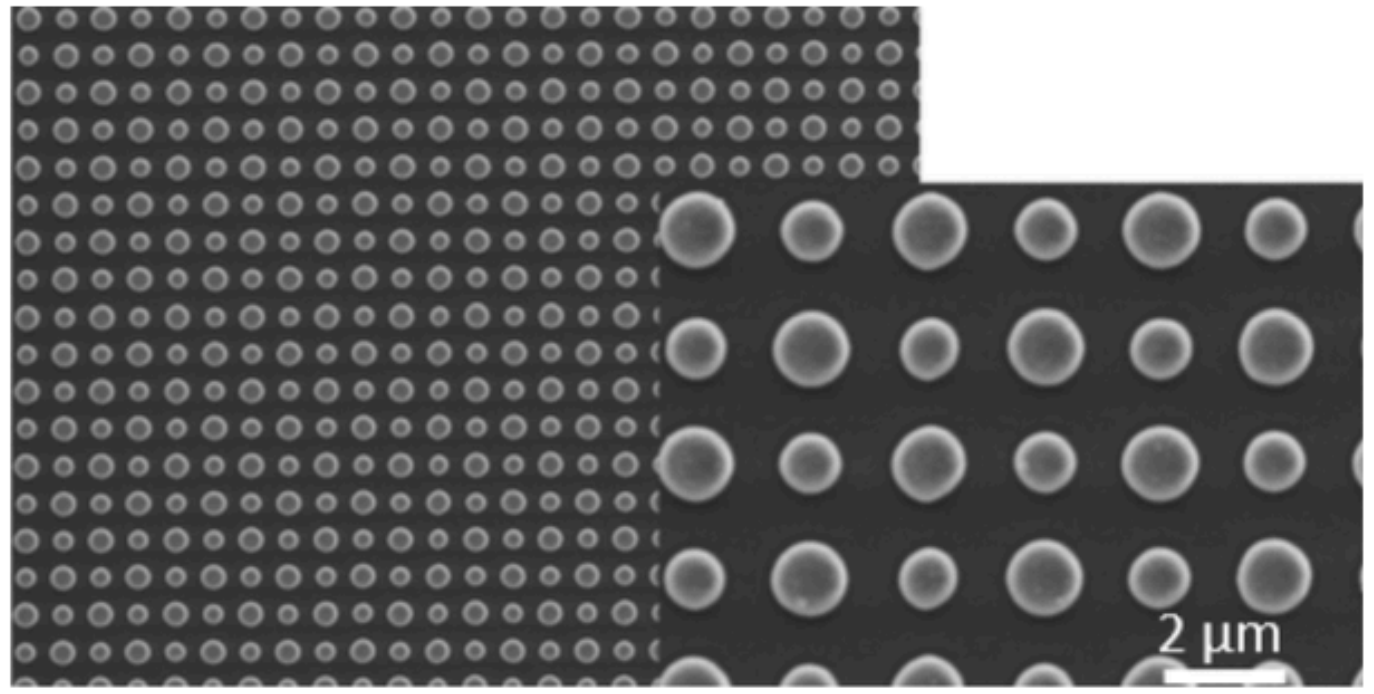
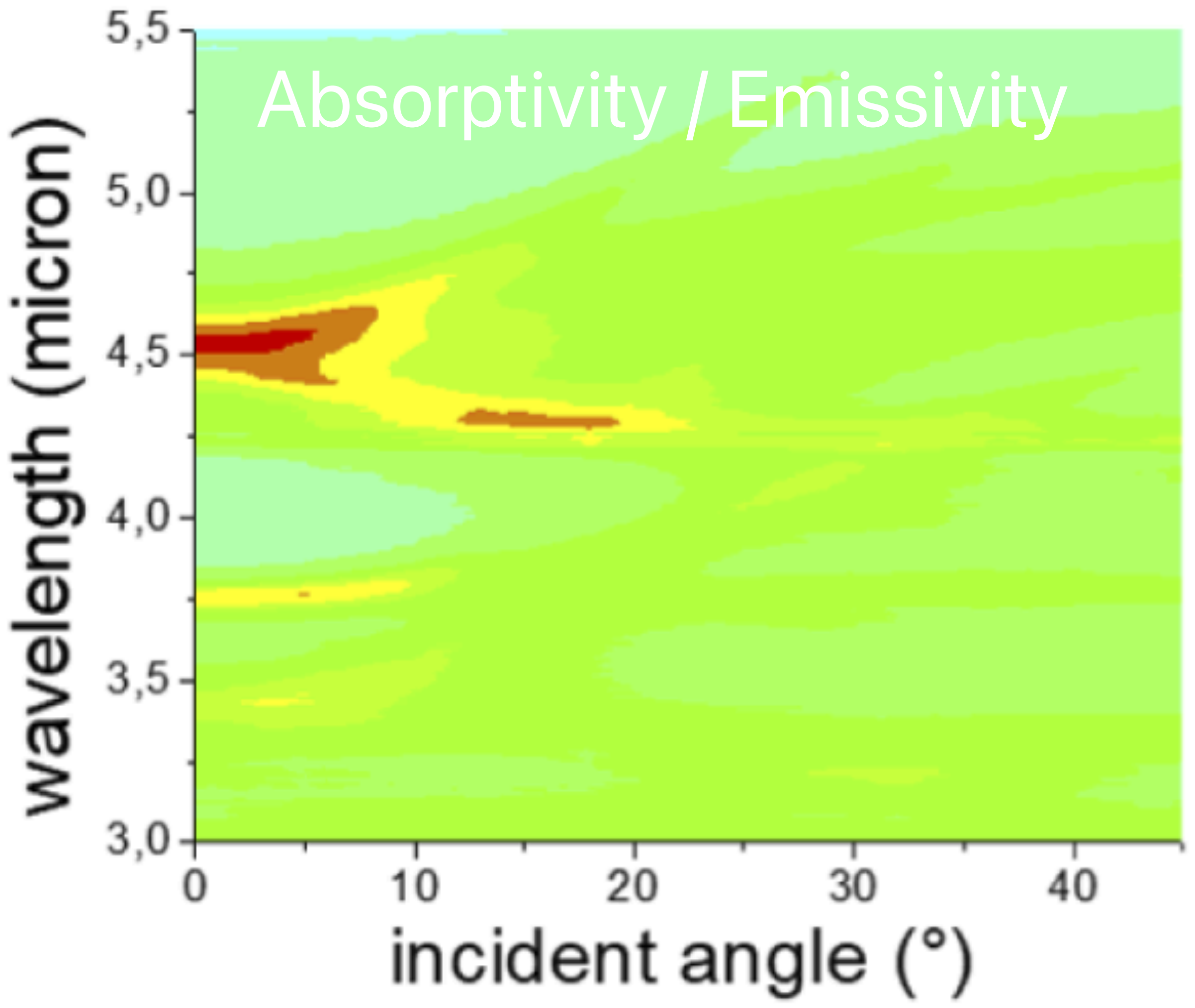
$\tau_{abs} = \tau_{sca}$ **Critical coupling condition**







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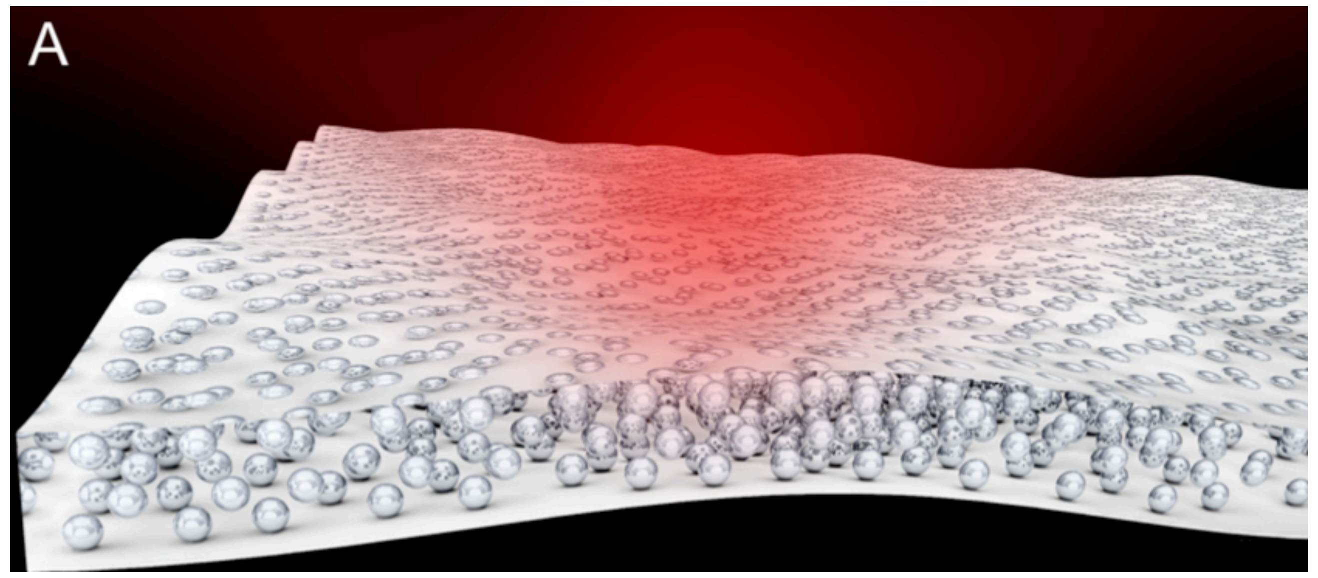
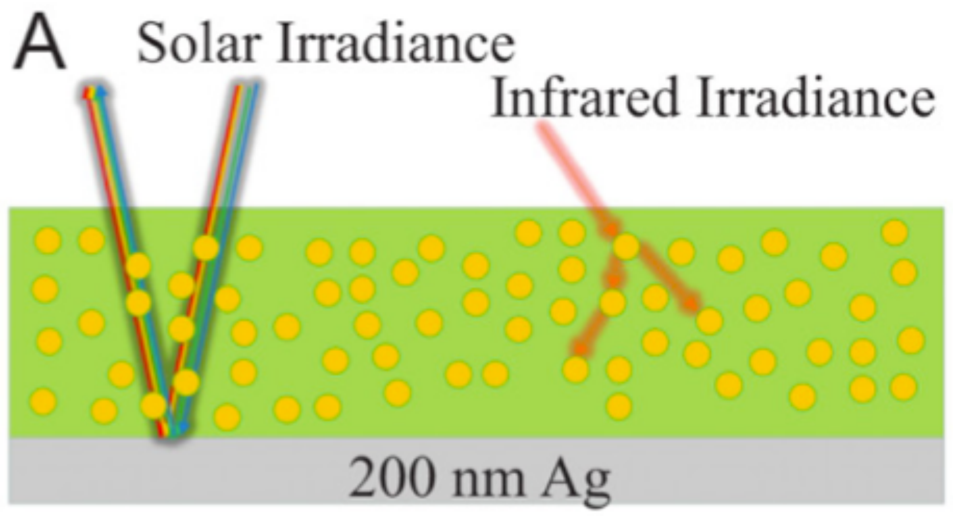
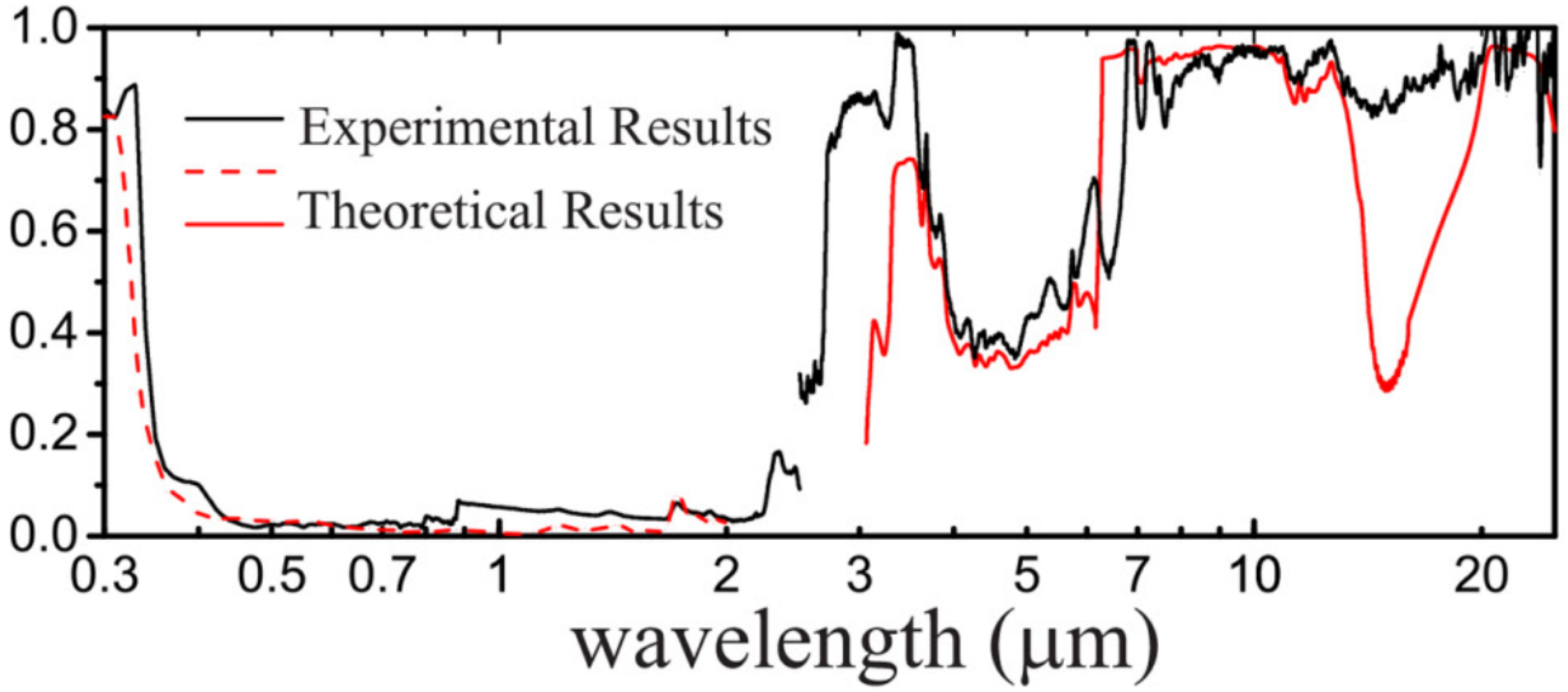
Previous realizations have an **ordered textural structure**

High standard **cleaning rooms**: lithography process, reactive ion etching, etc.







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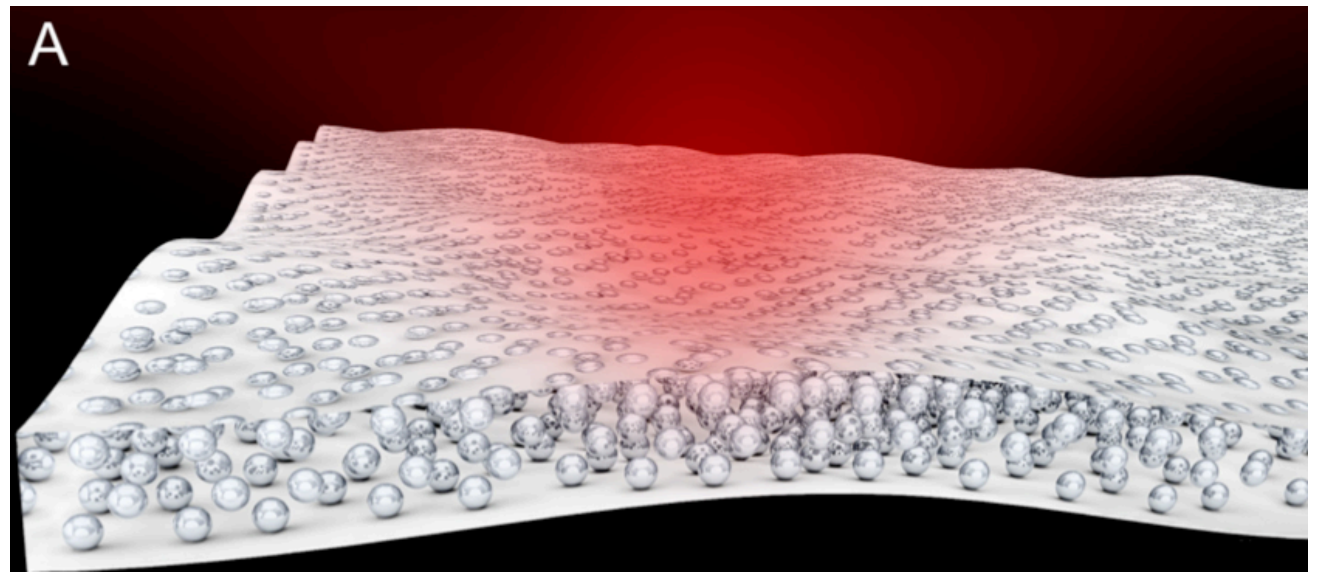

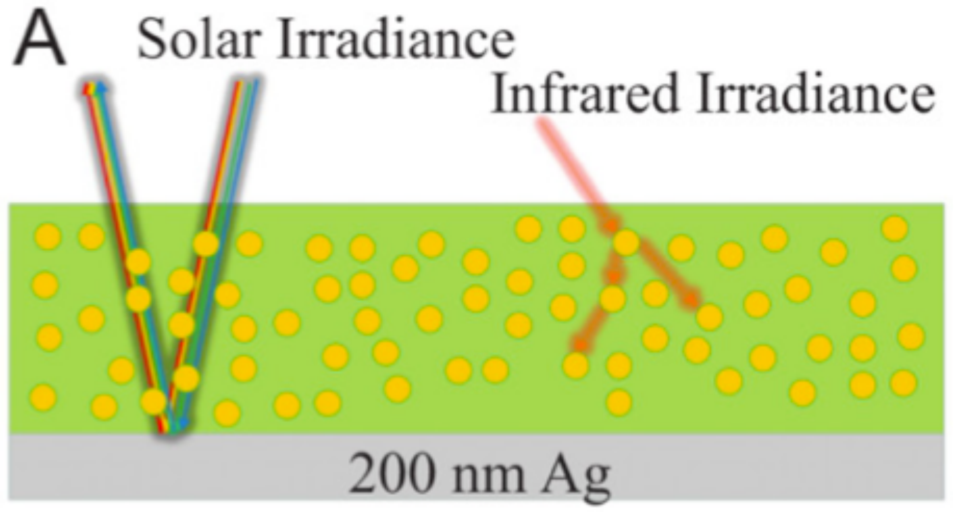

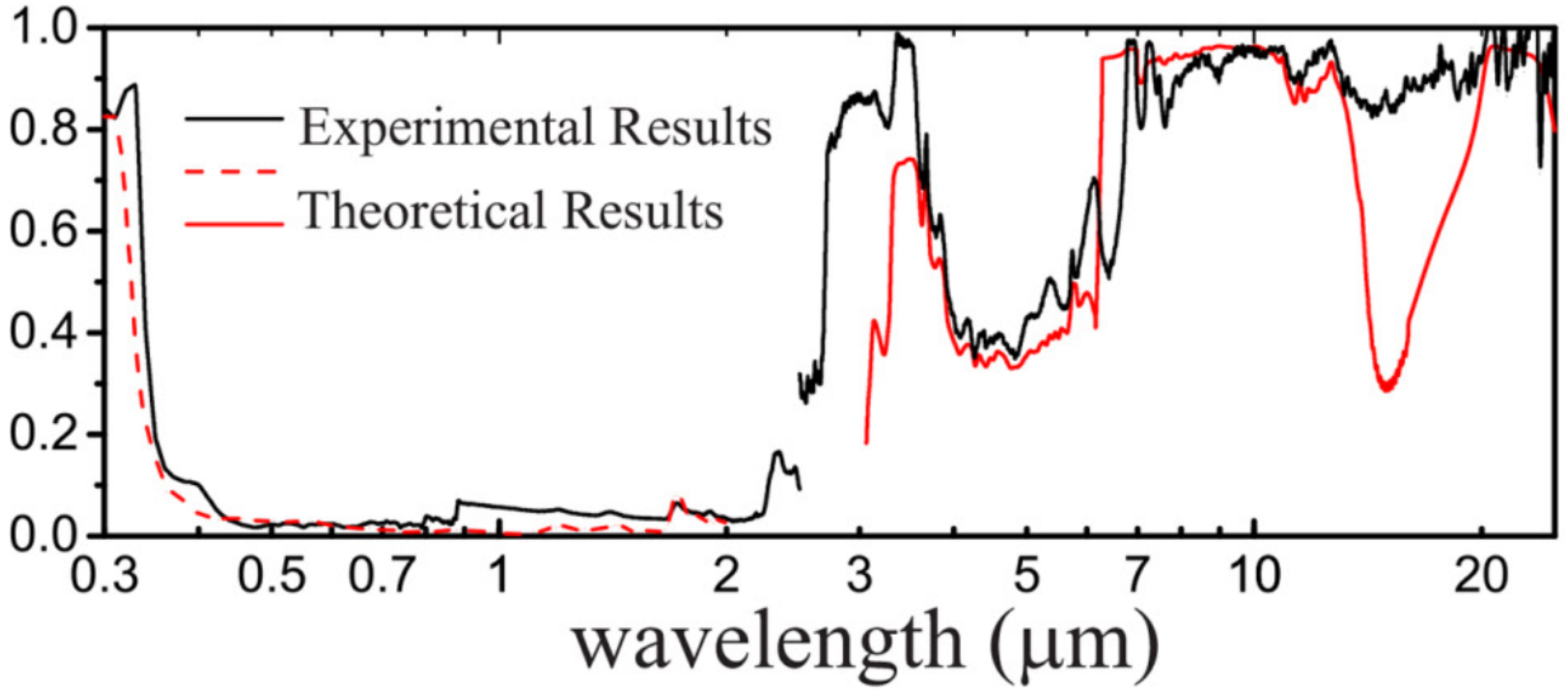

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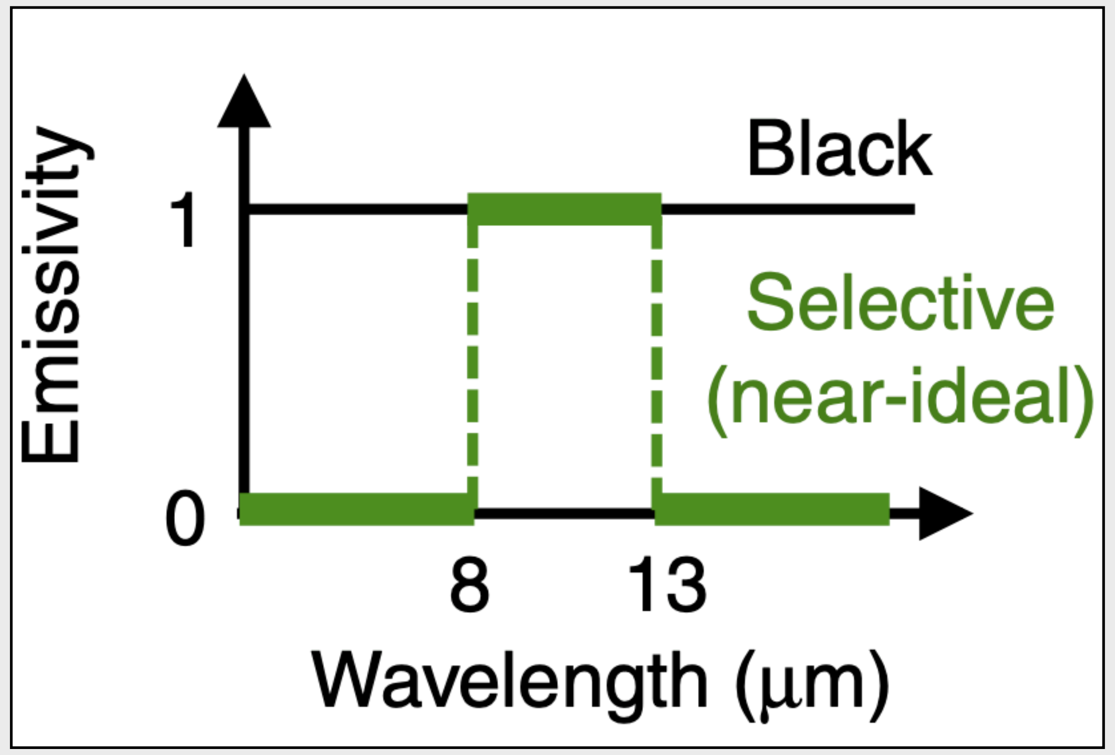

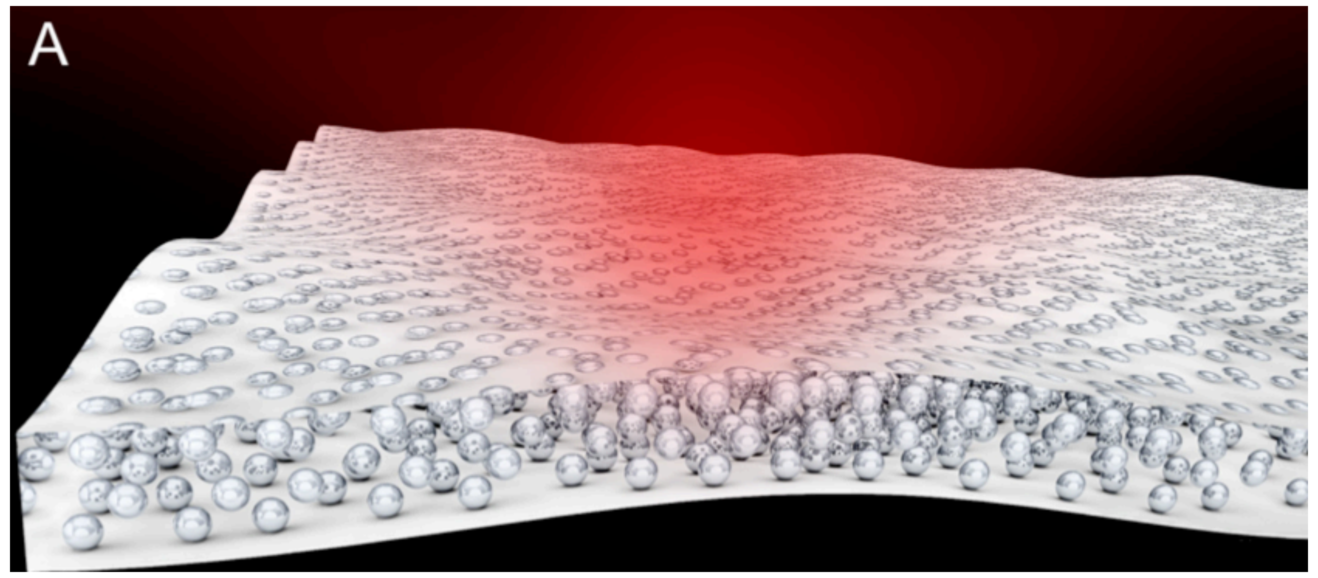

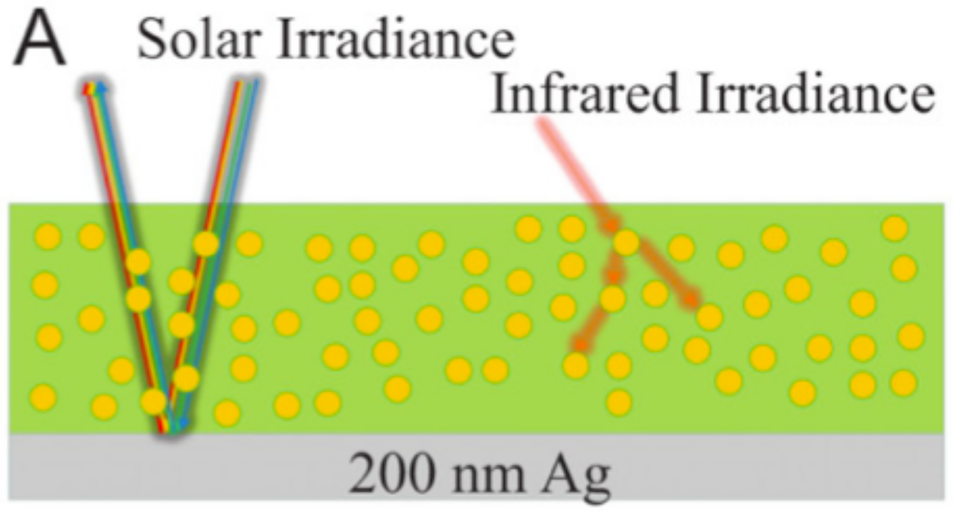

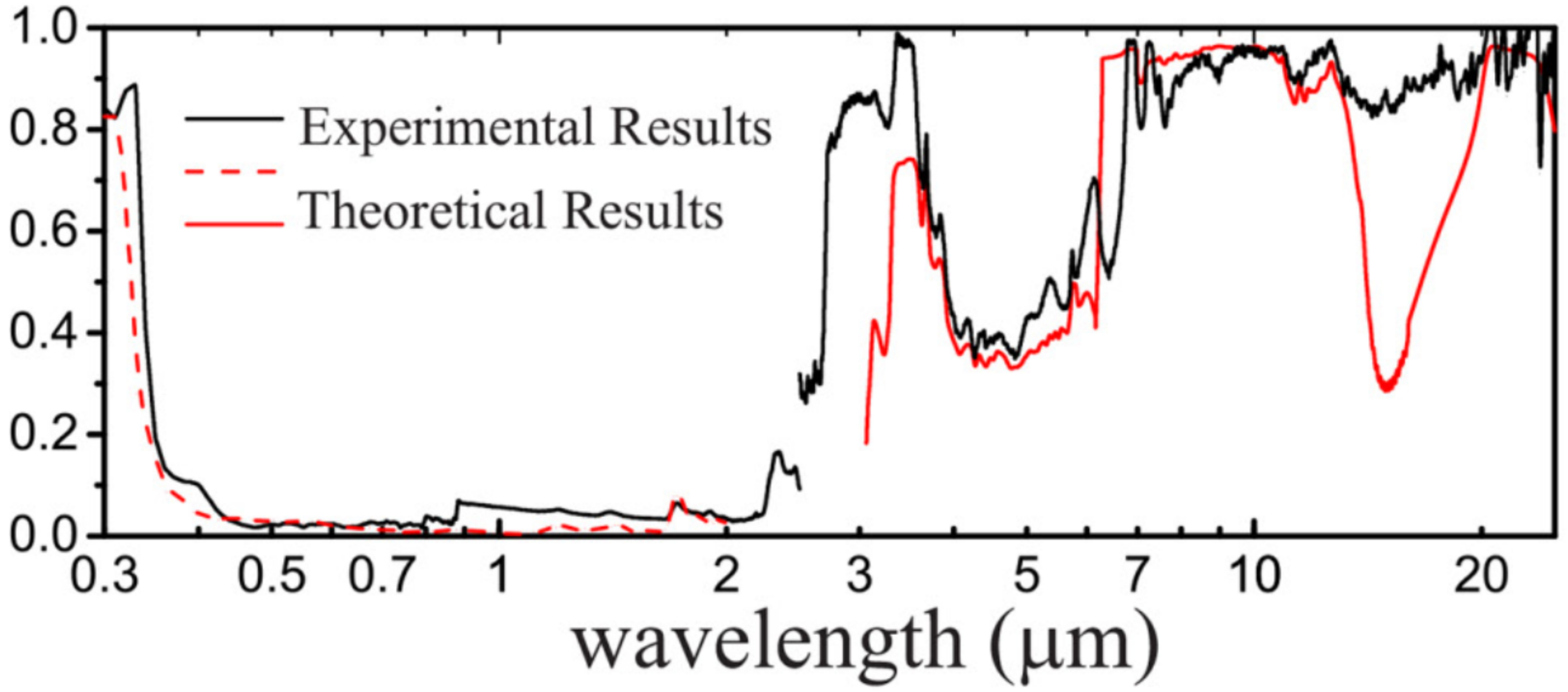

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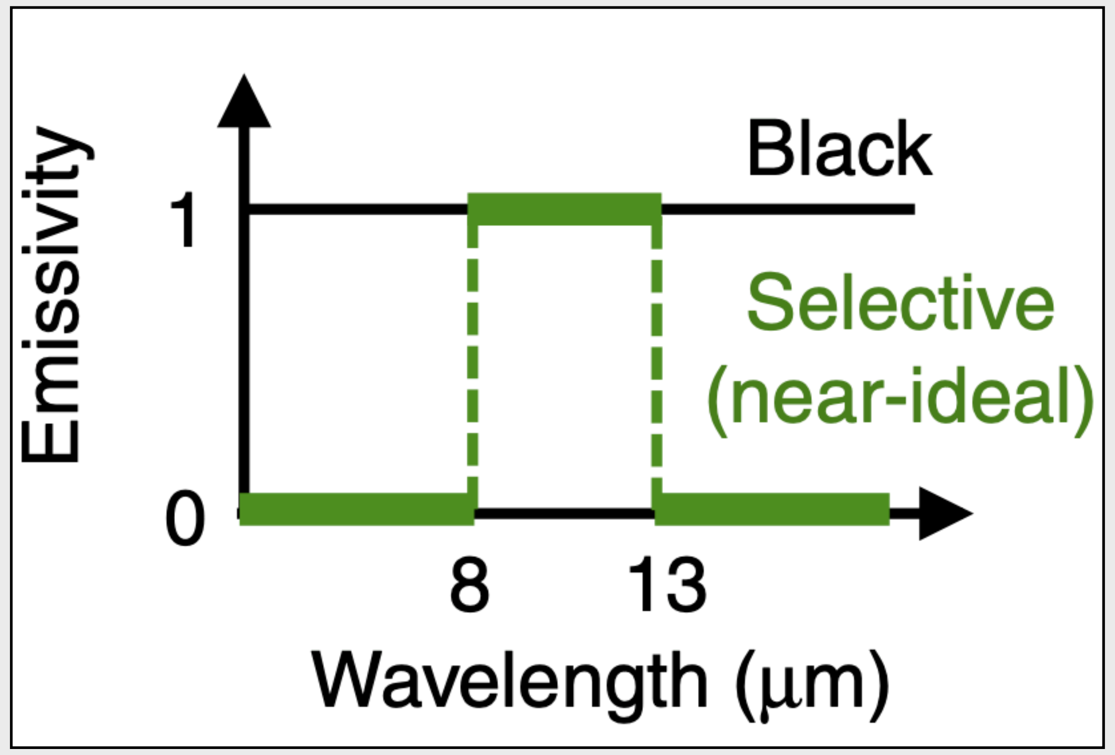

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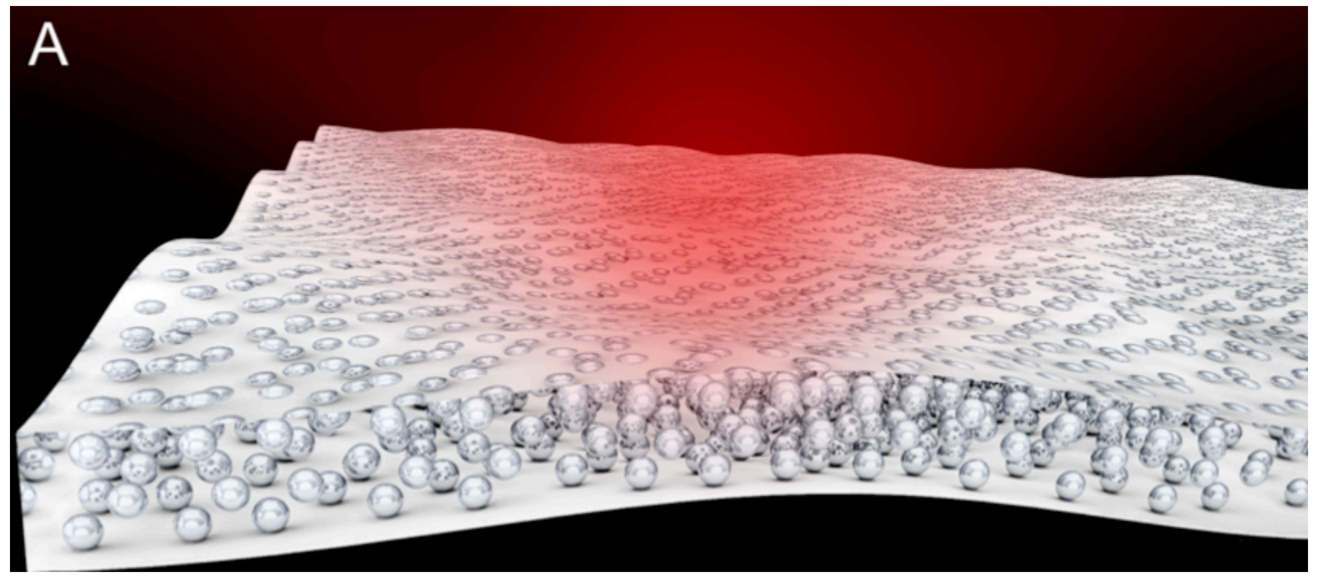

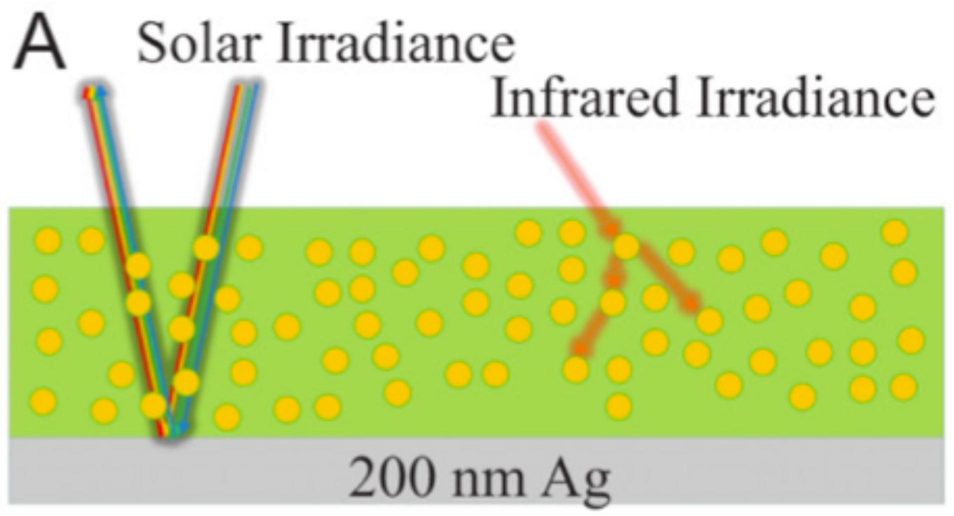

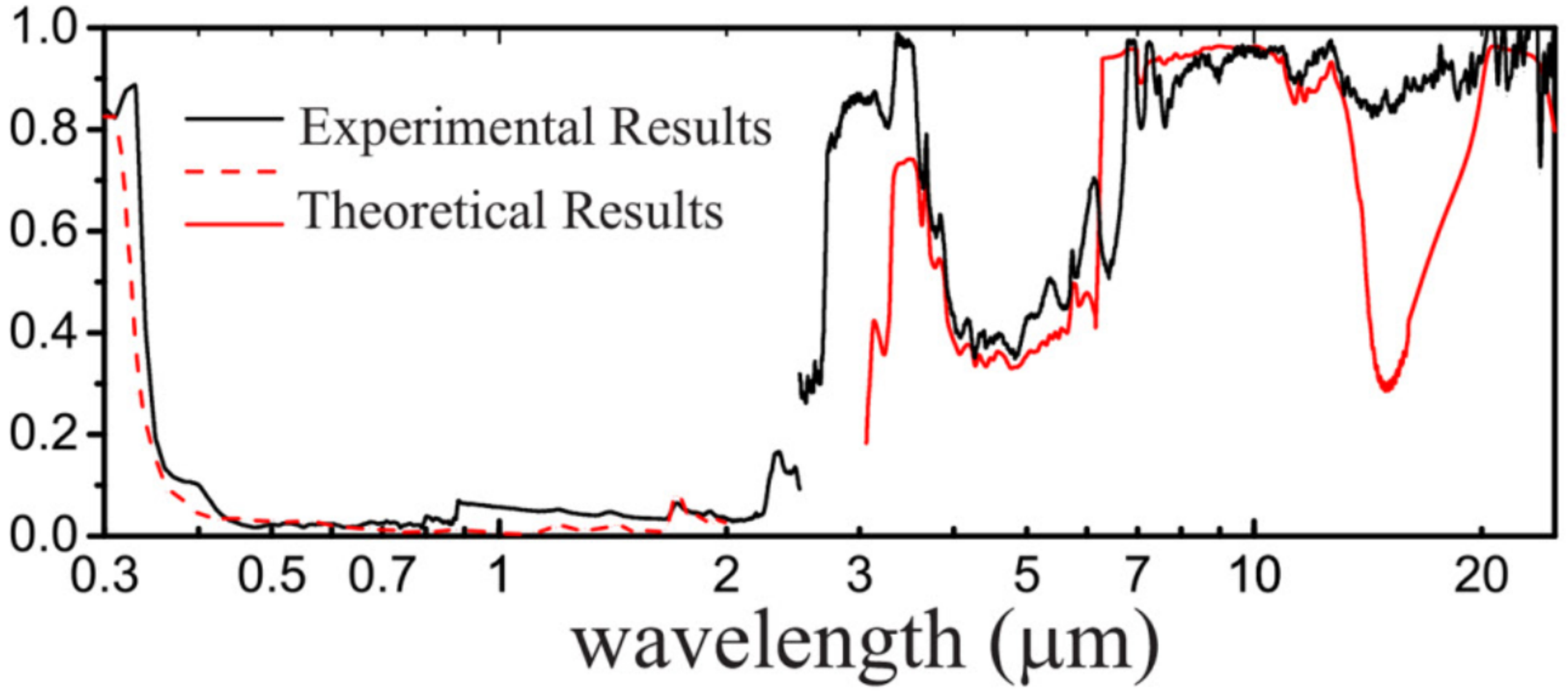

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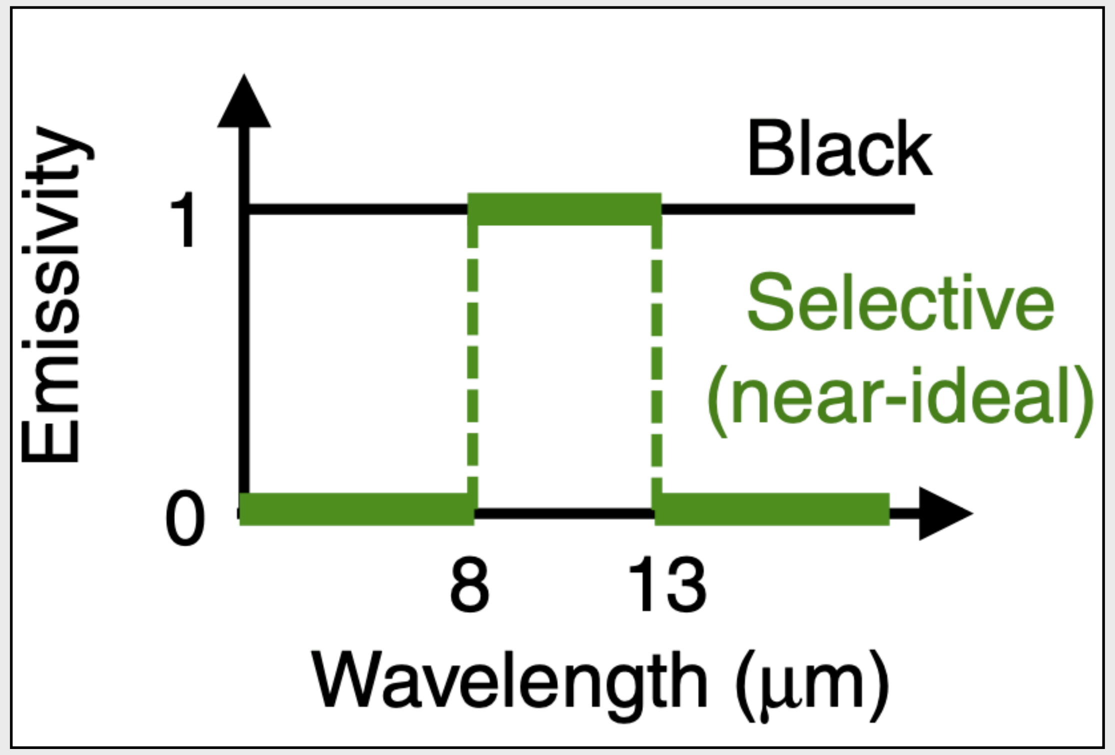

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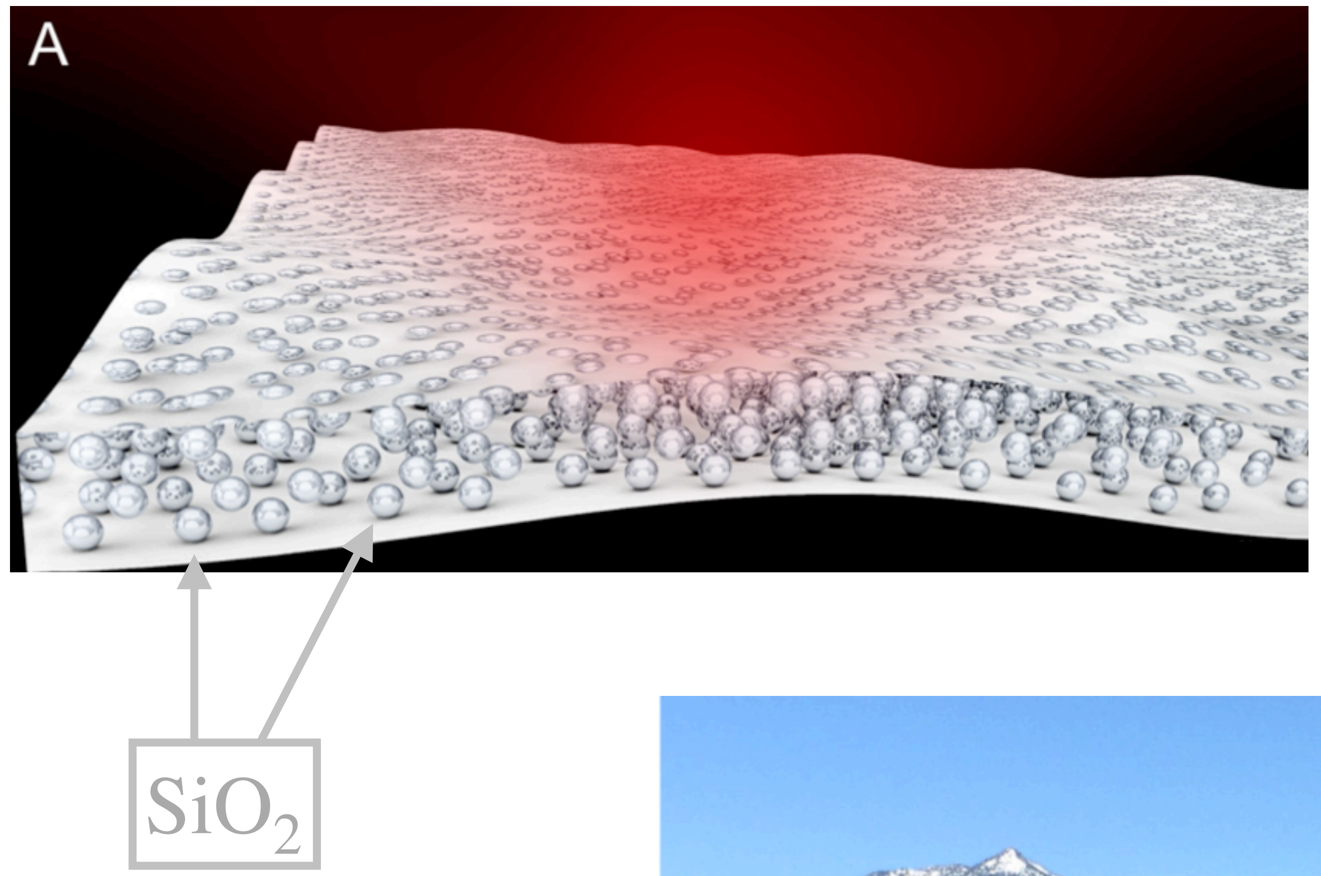

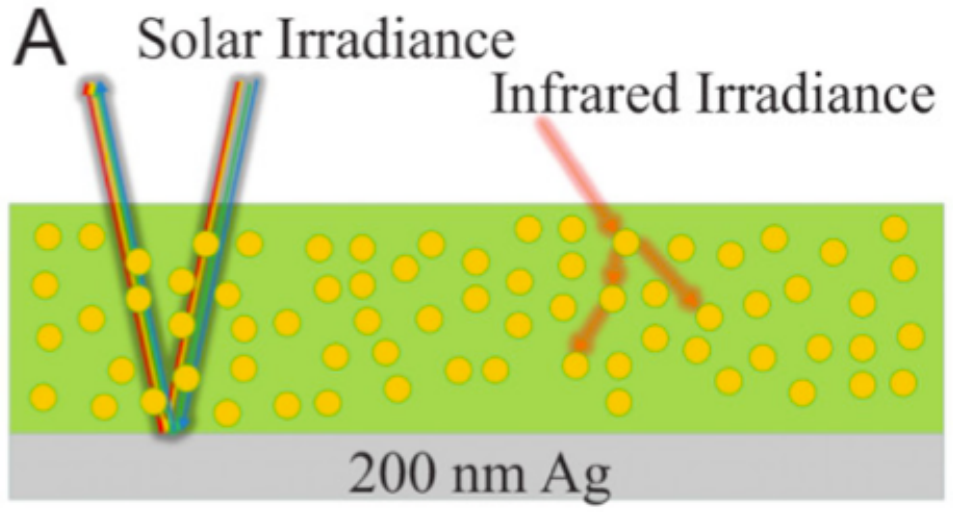

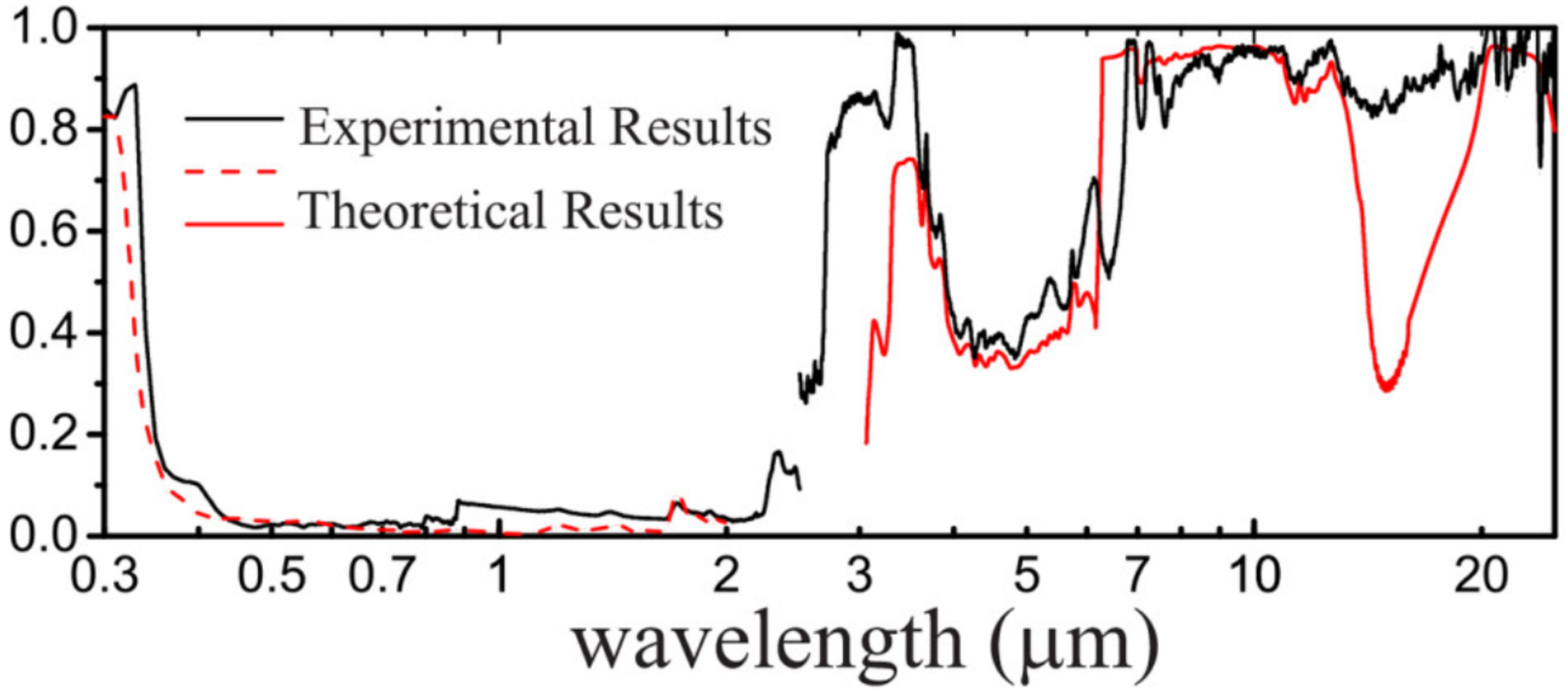

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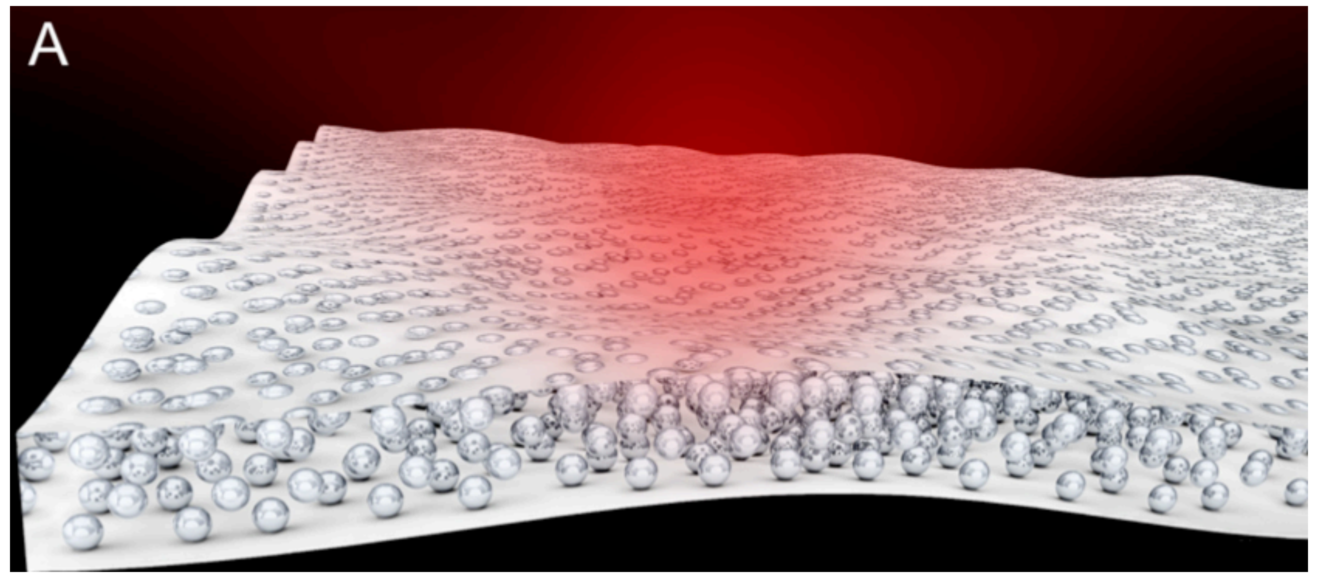
Random particulate media: collective effects

Spectral selectivity of the previous slide relied on **pure material effects**

Convenient absorption of silica



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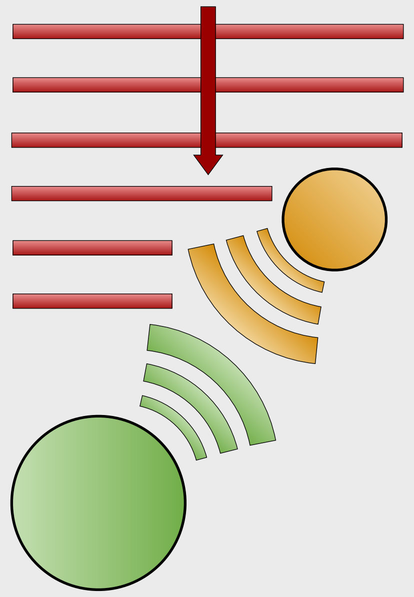

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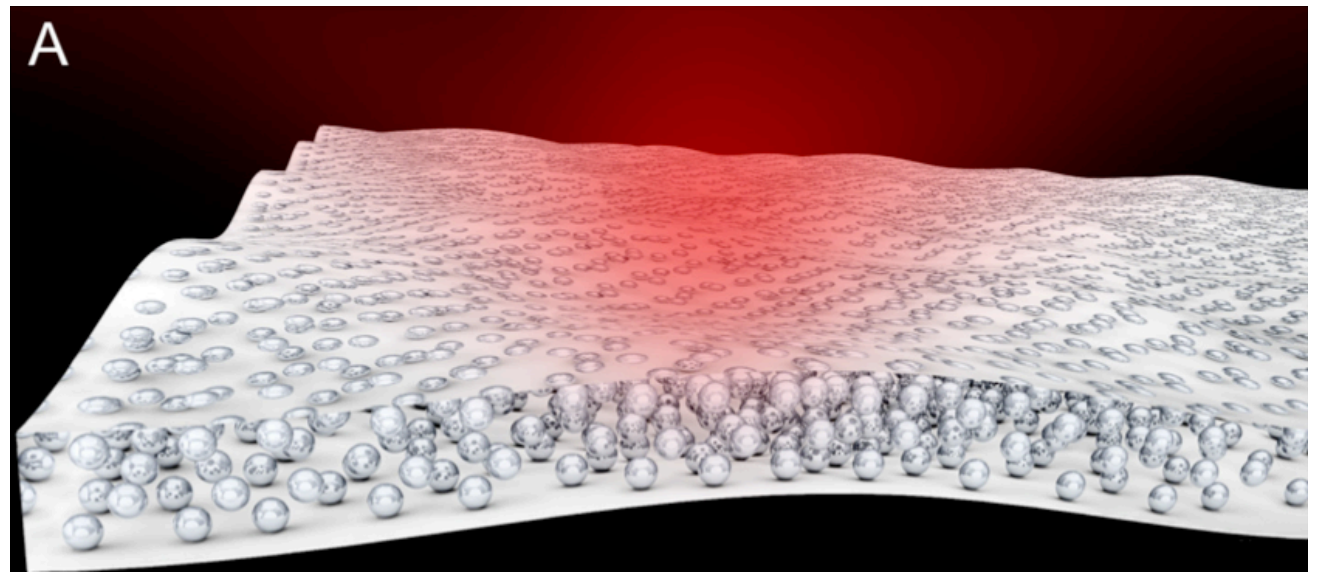

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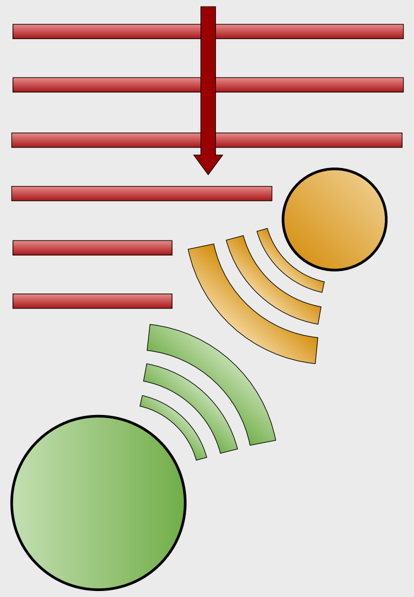

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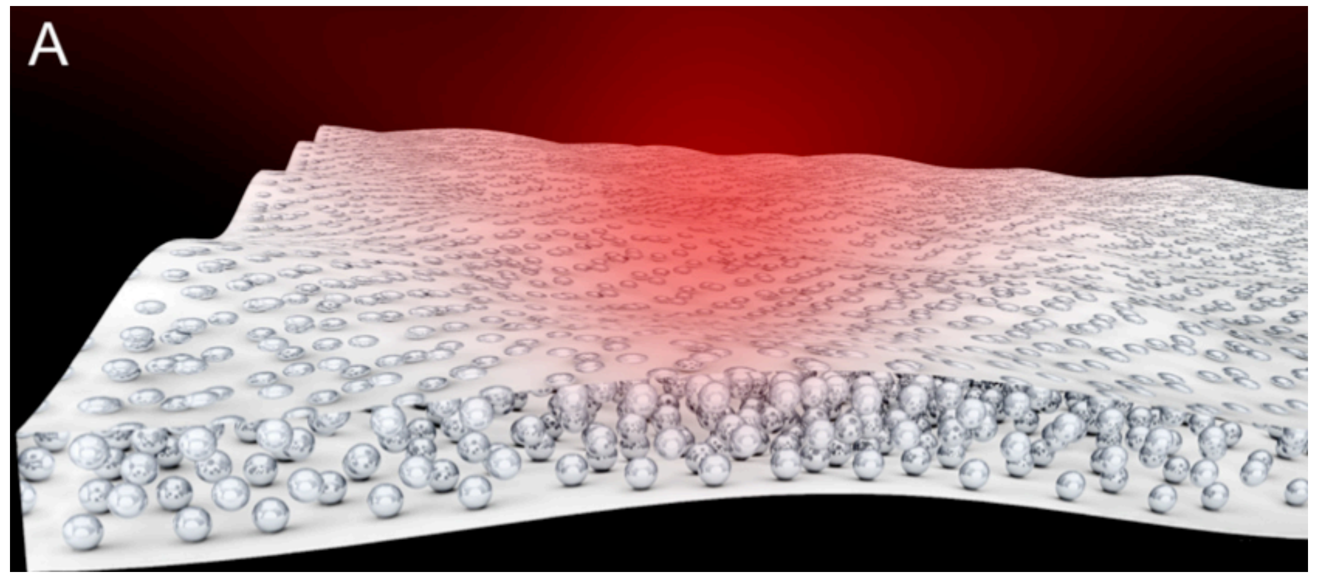

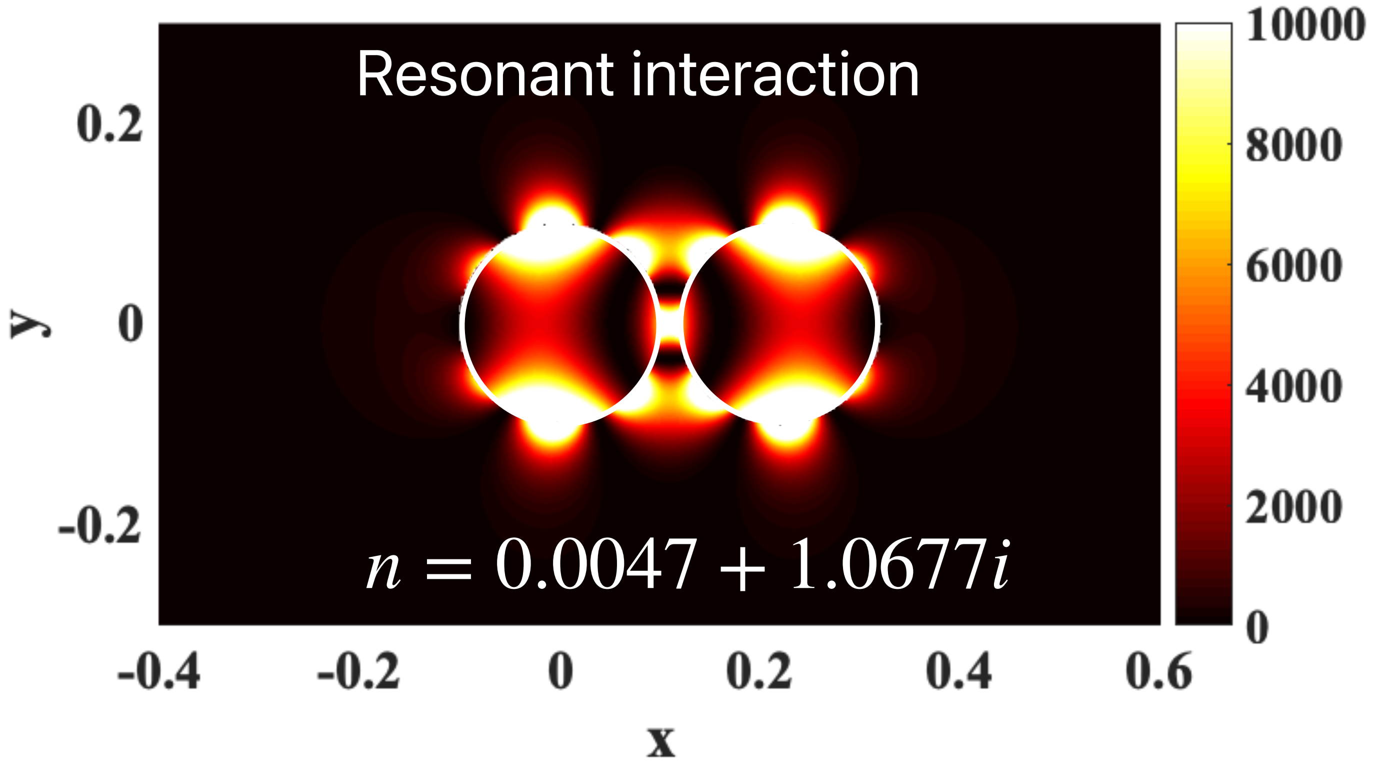

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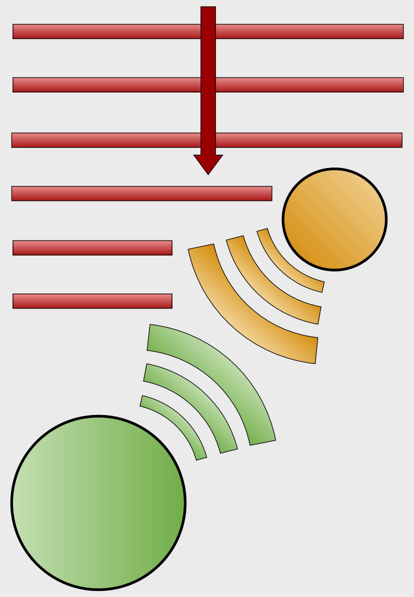

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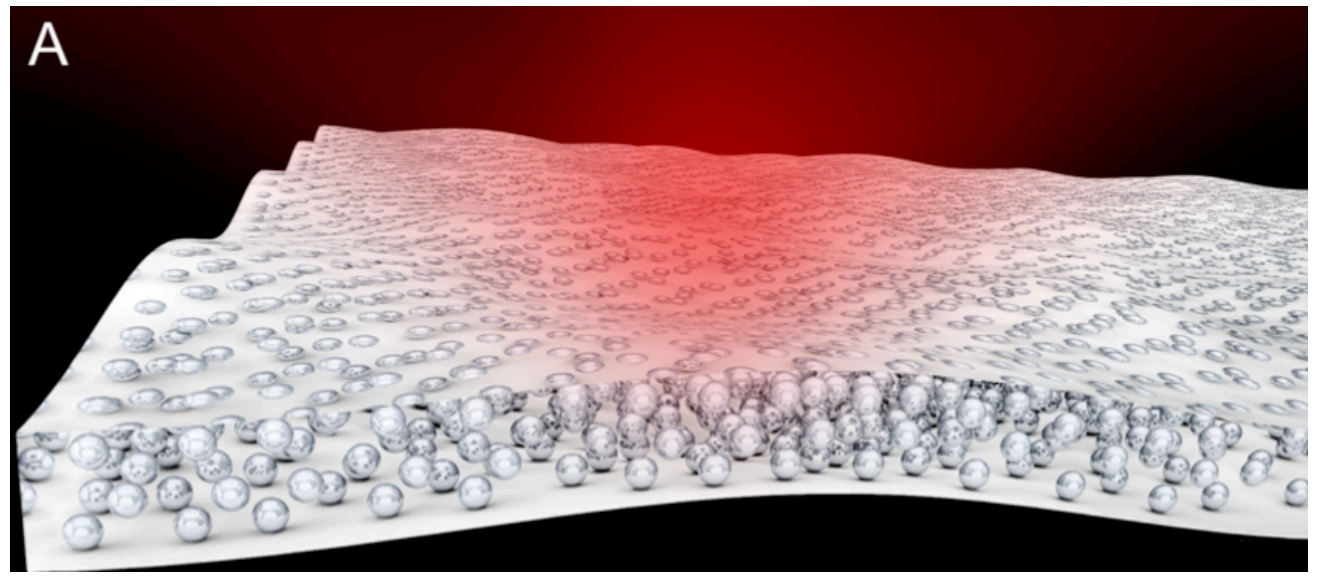
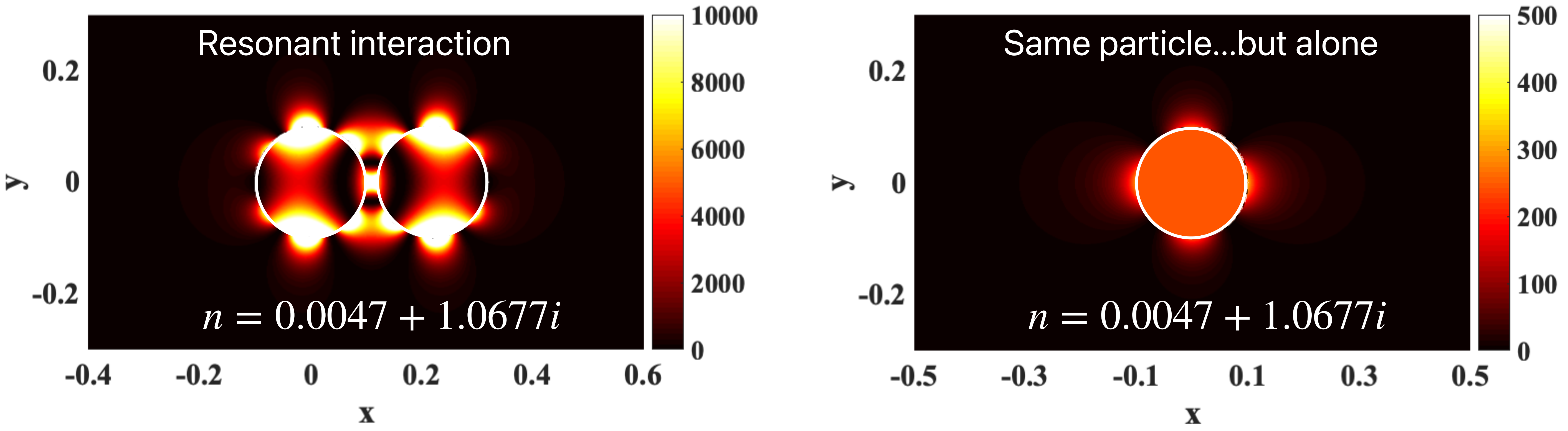
Collective effects

Behavior due to electromagnetic interferences between the particles, which would not be observed for a single particle

T. **Guerra**, D. **De Sousa Meneses**, J. P. **Hugonin**, C. **Blanchard**. Part. Syst. Charac., 2100245, 2022





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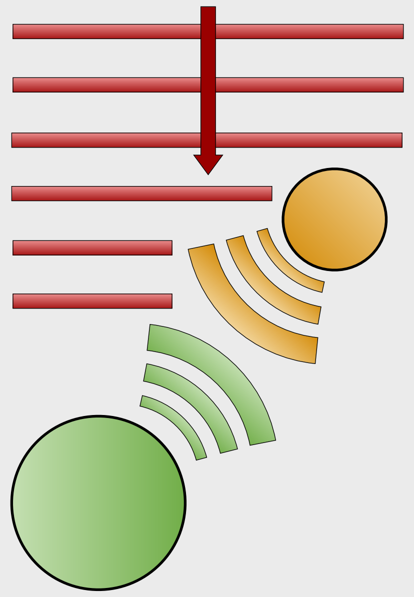
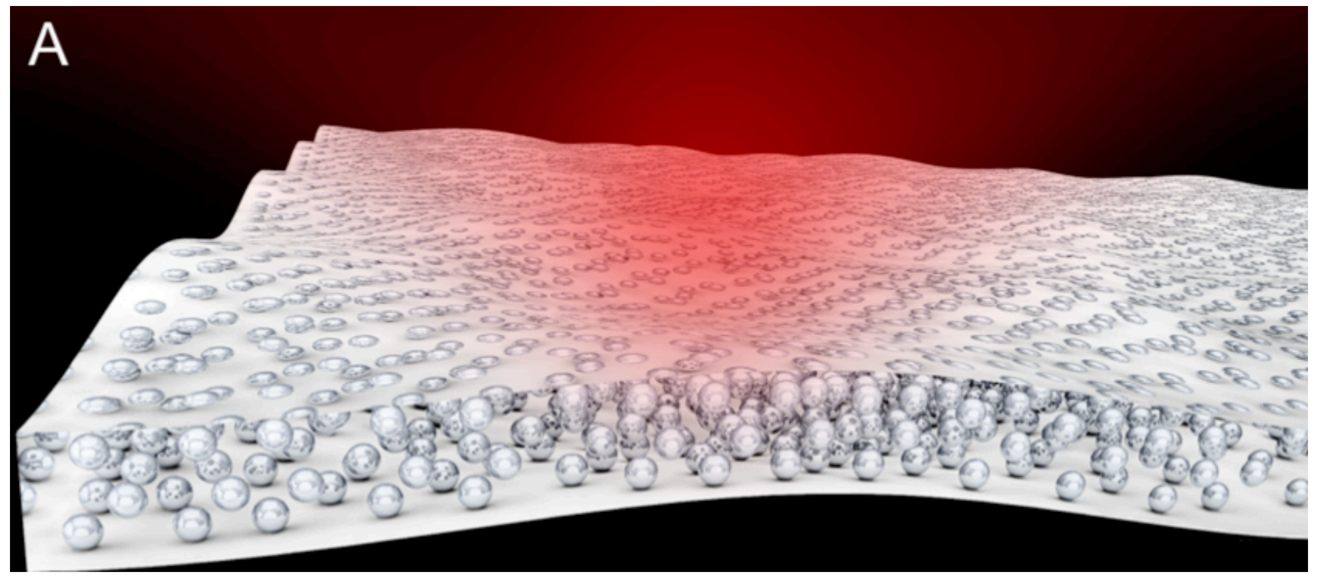


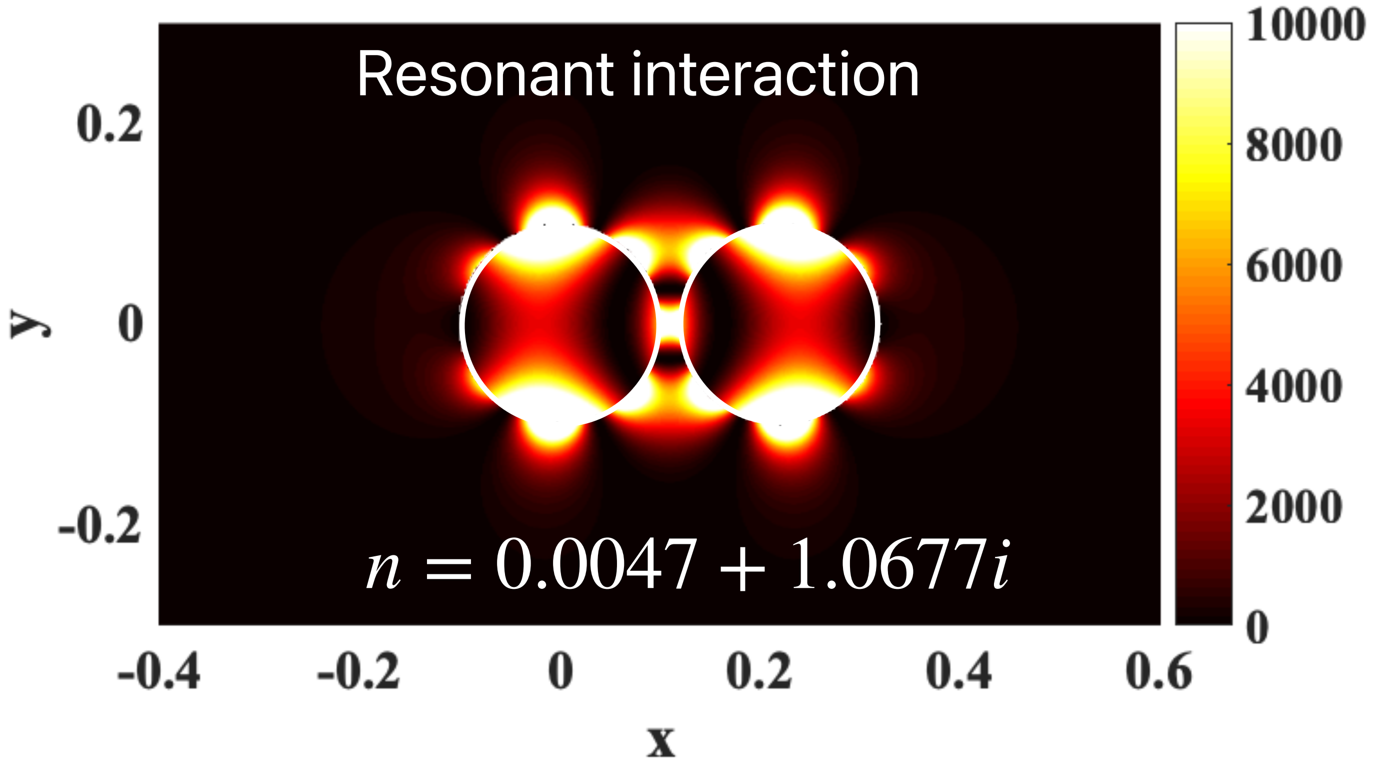
Is it possible to generate functional properties by relying on **collective effects** ?

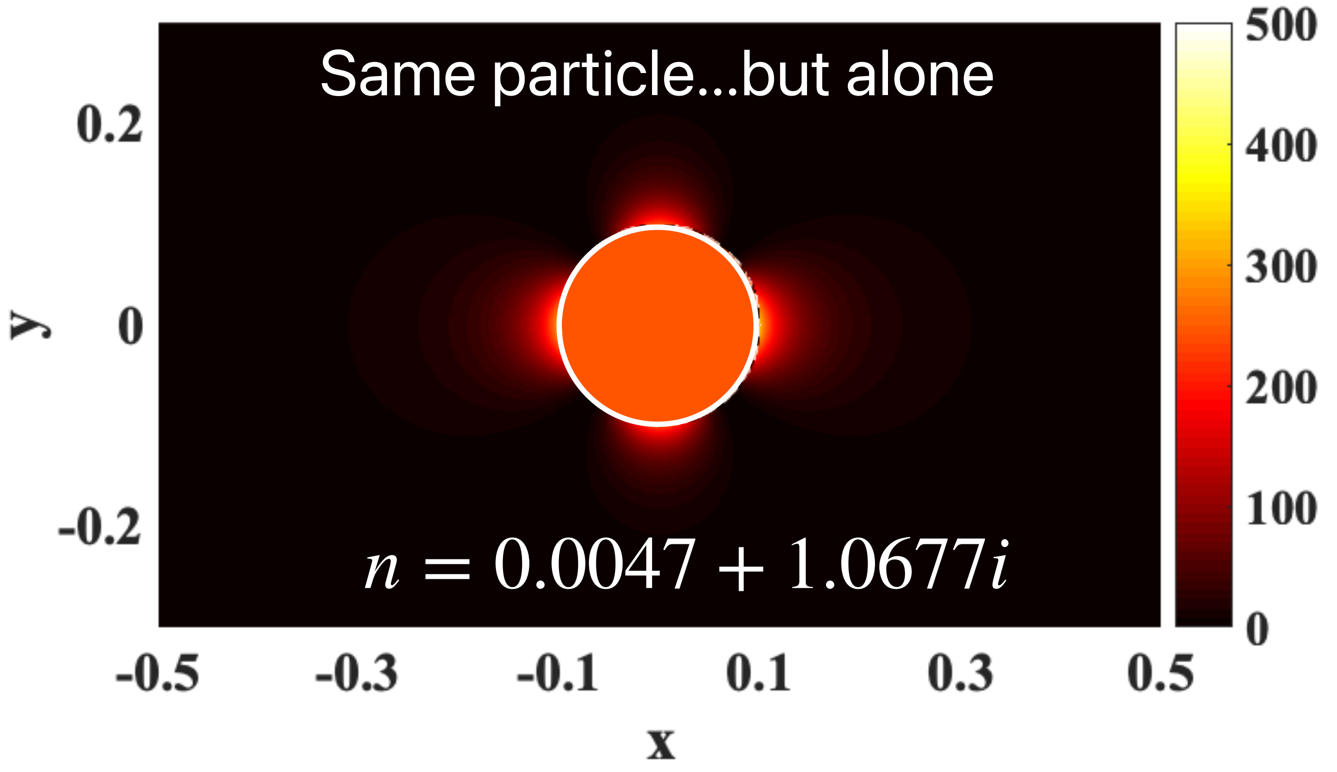
Collective effects

Behavior due to electromagnetic interferences between the particles, which would not be observed for a single particle

*T. **Guerra**, D. **De Sousa Meneses**, J. P. **Hugonin**, C. **Blanchard**. Part. Syst. Charac., 2100245, 2022*







Particles **much smaller** than λ

T-matrix method

What are the expected features of a suspension of small particles in the IR domain?

Random particulate media: light/matter interaction with small particles

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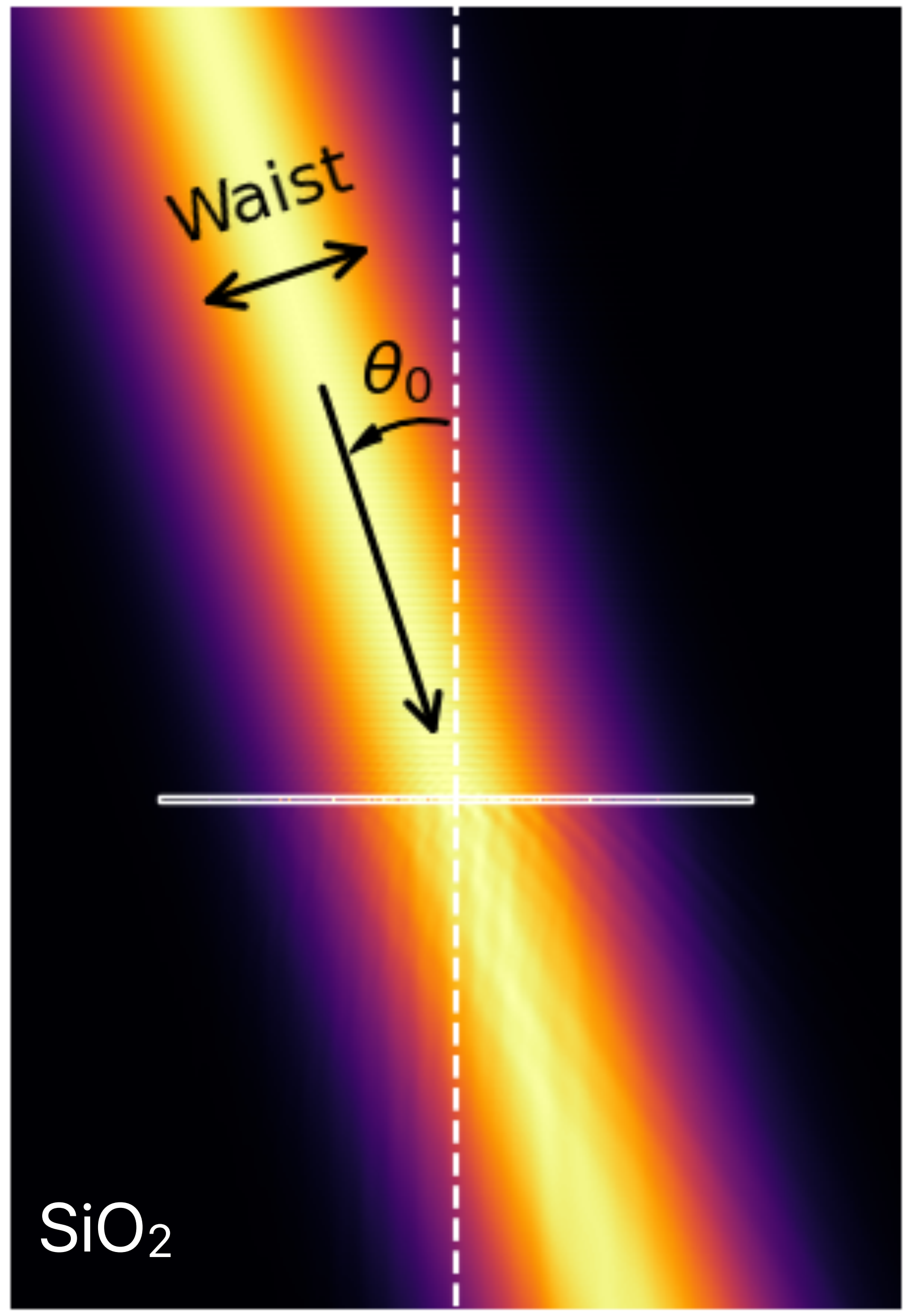
Rigorous **T-Matrix calculation** of the electromagnetic fields



Cédric Blanchard: cedric.blanchard@cnrs-orleans.fr

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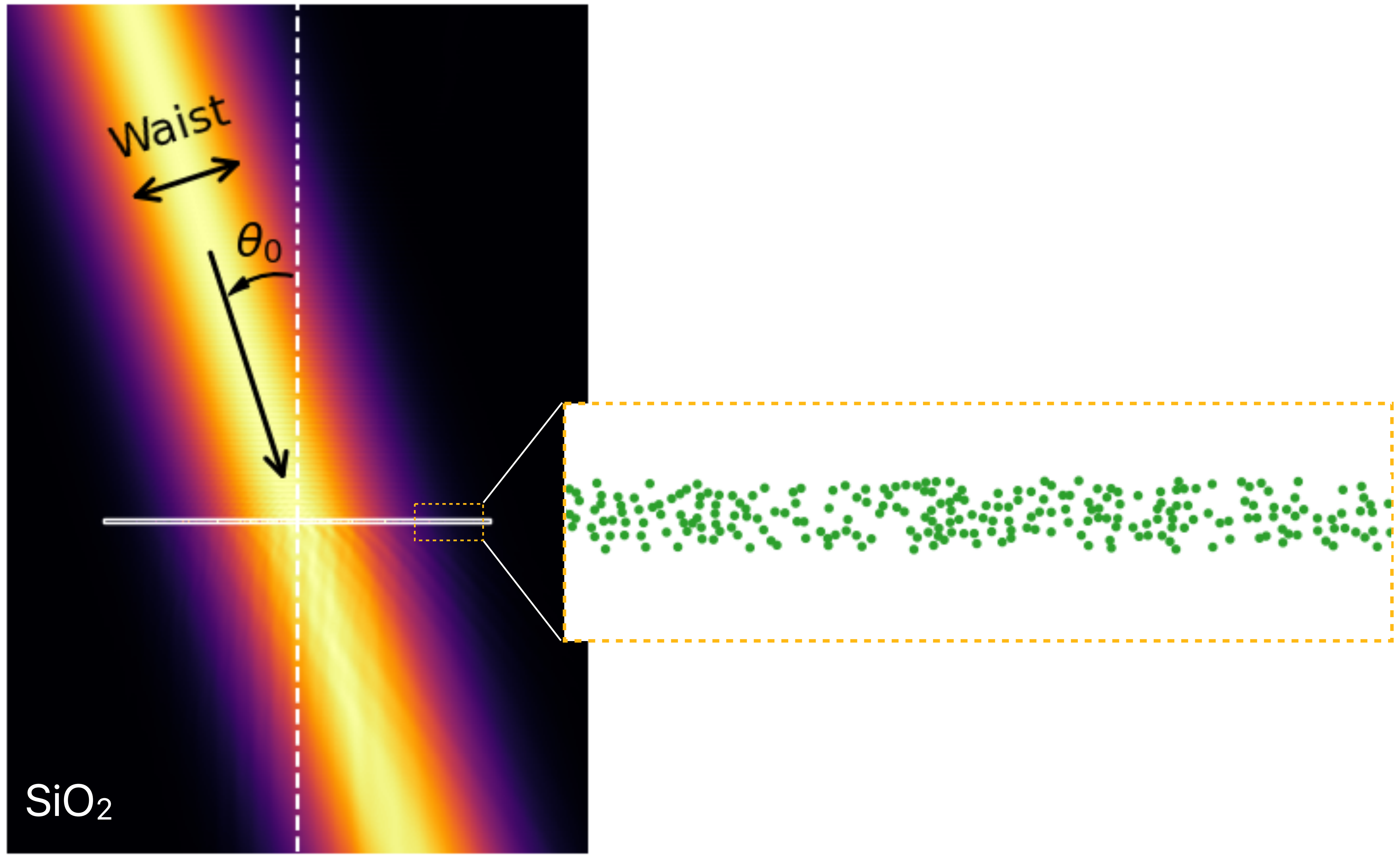

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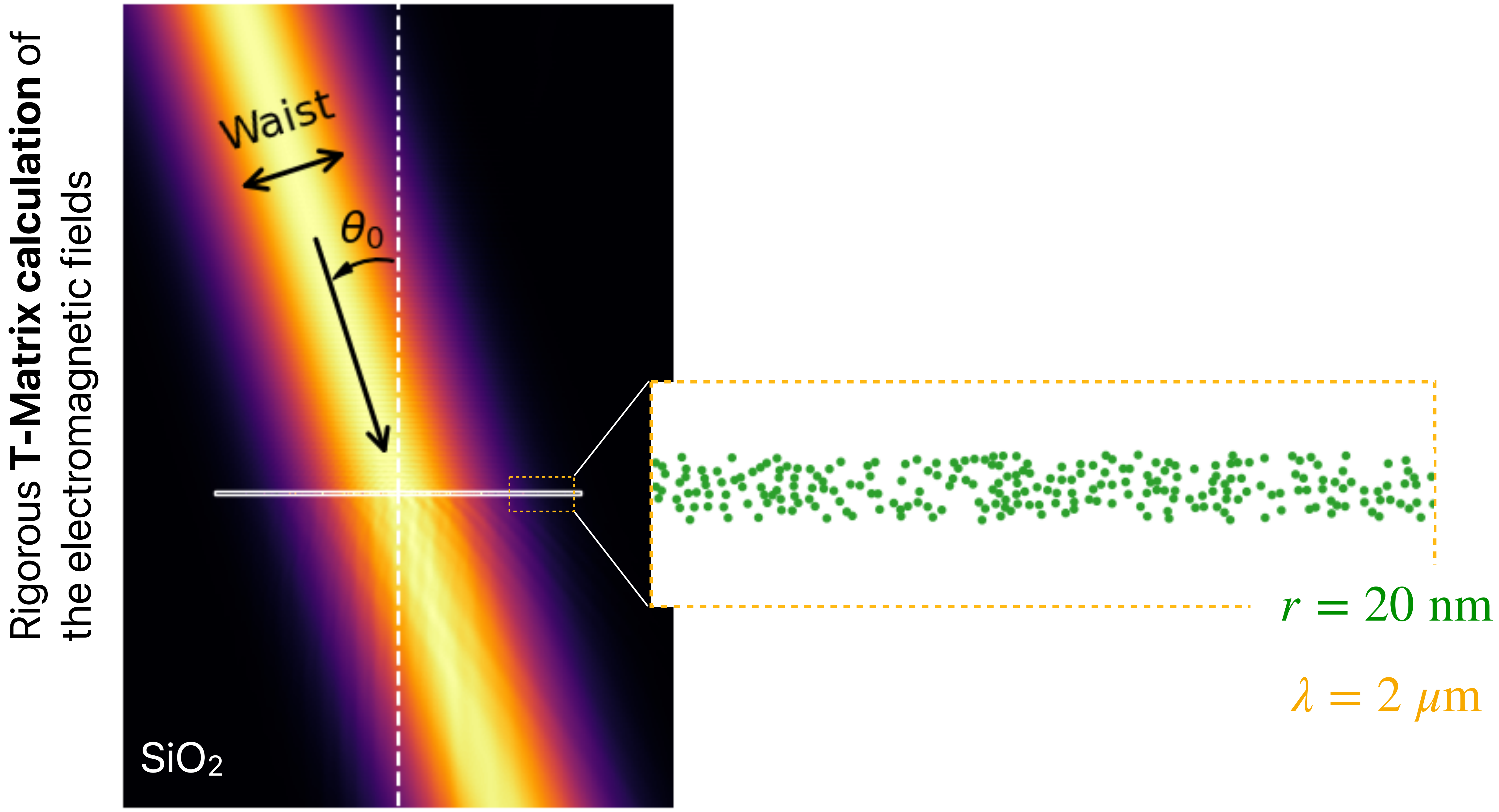

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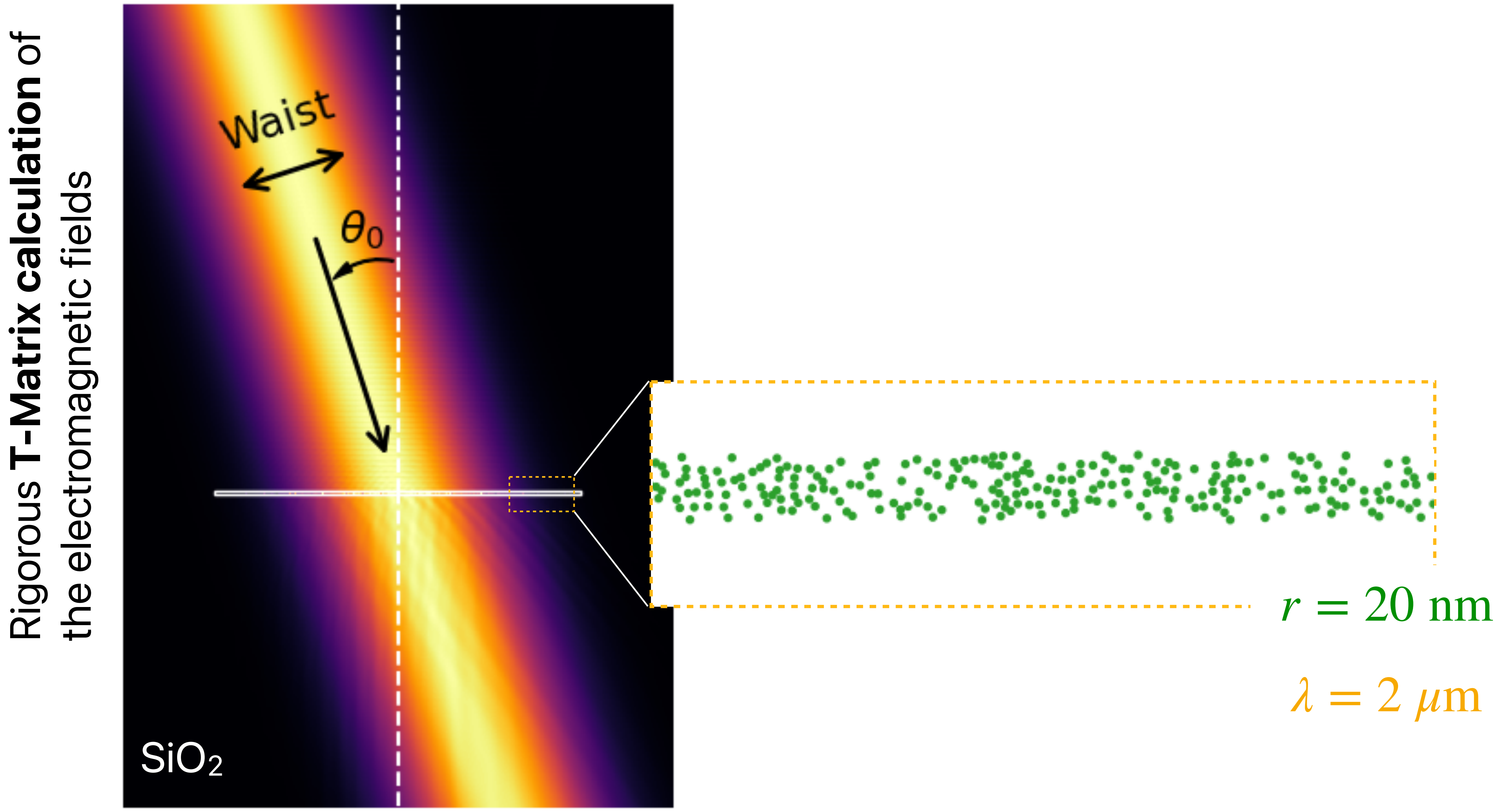

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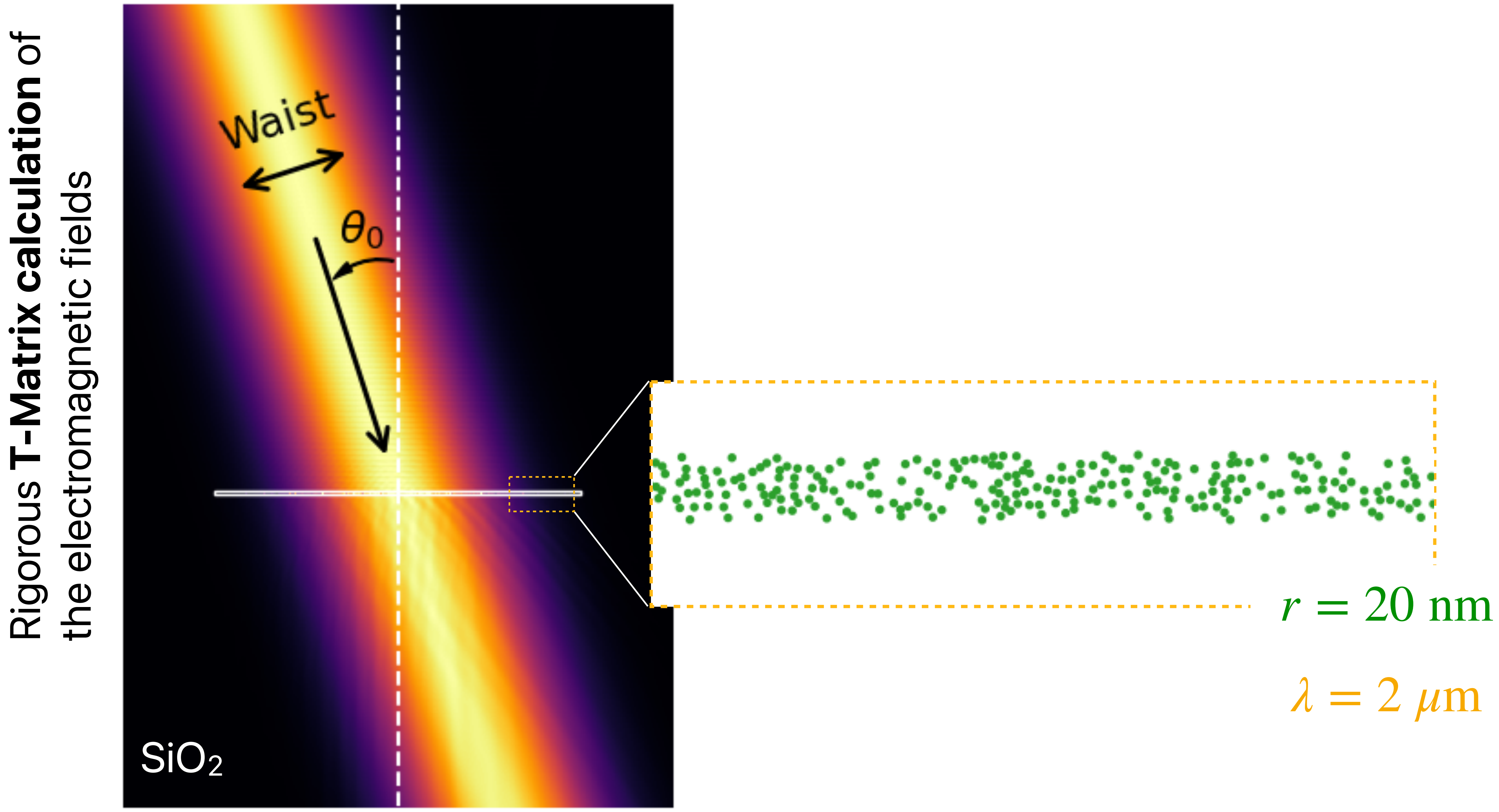

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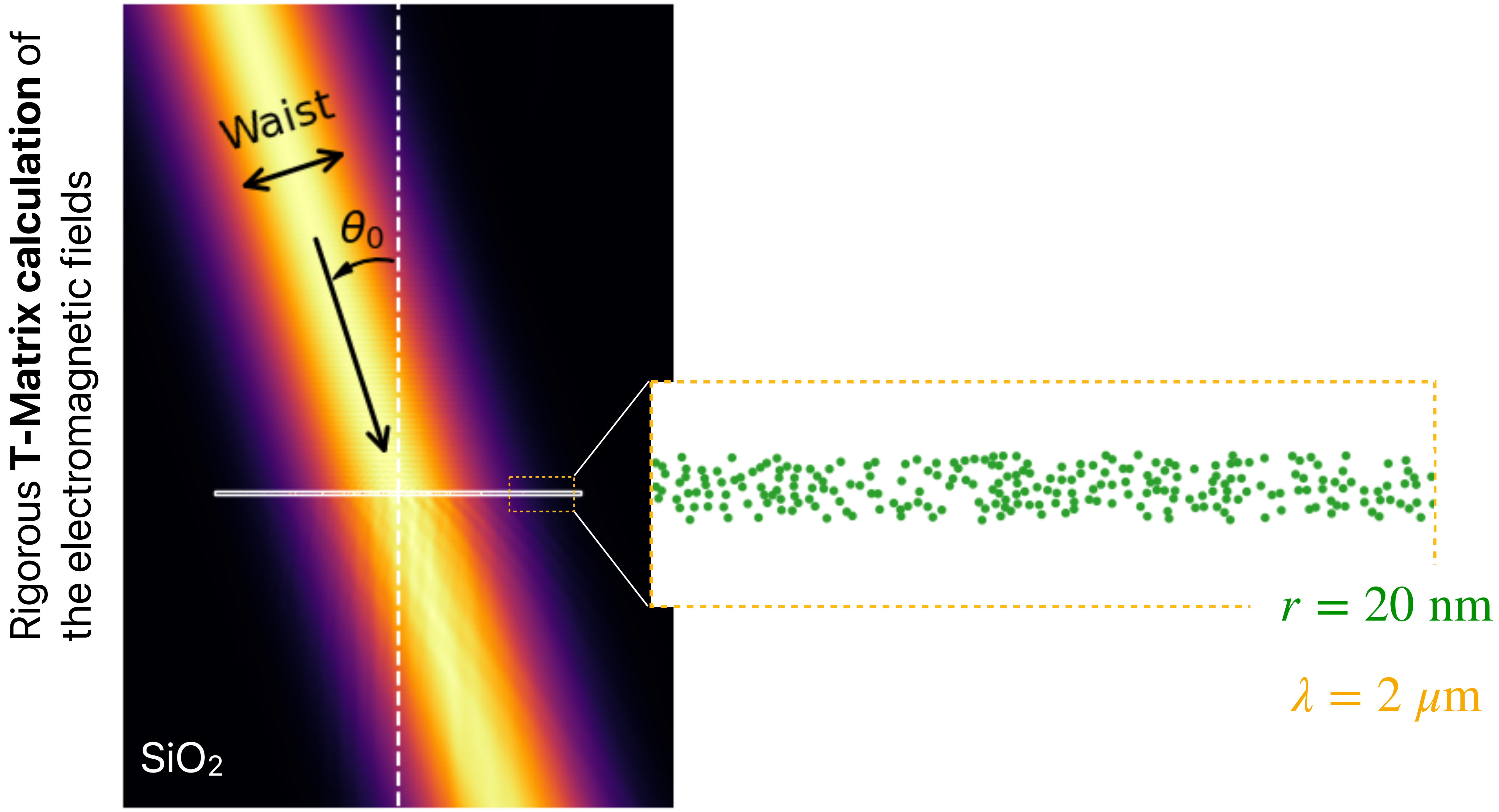

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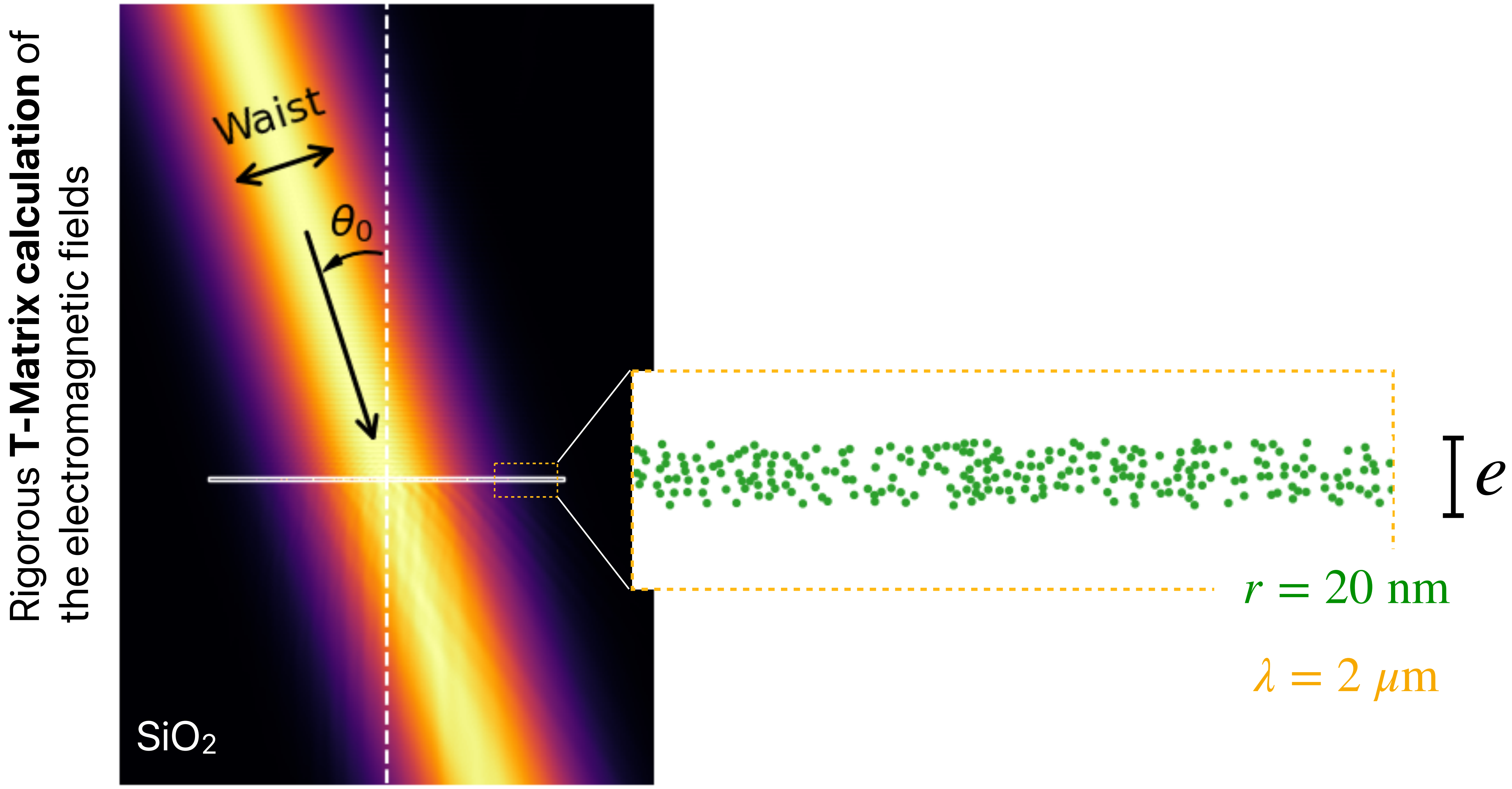

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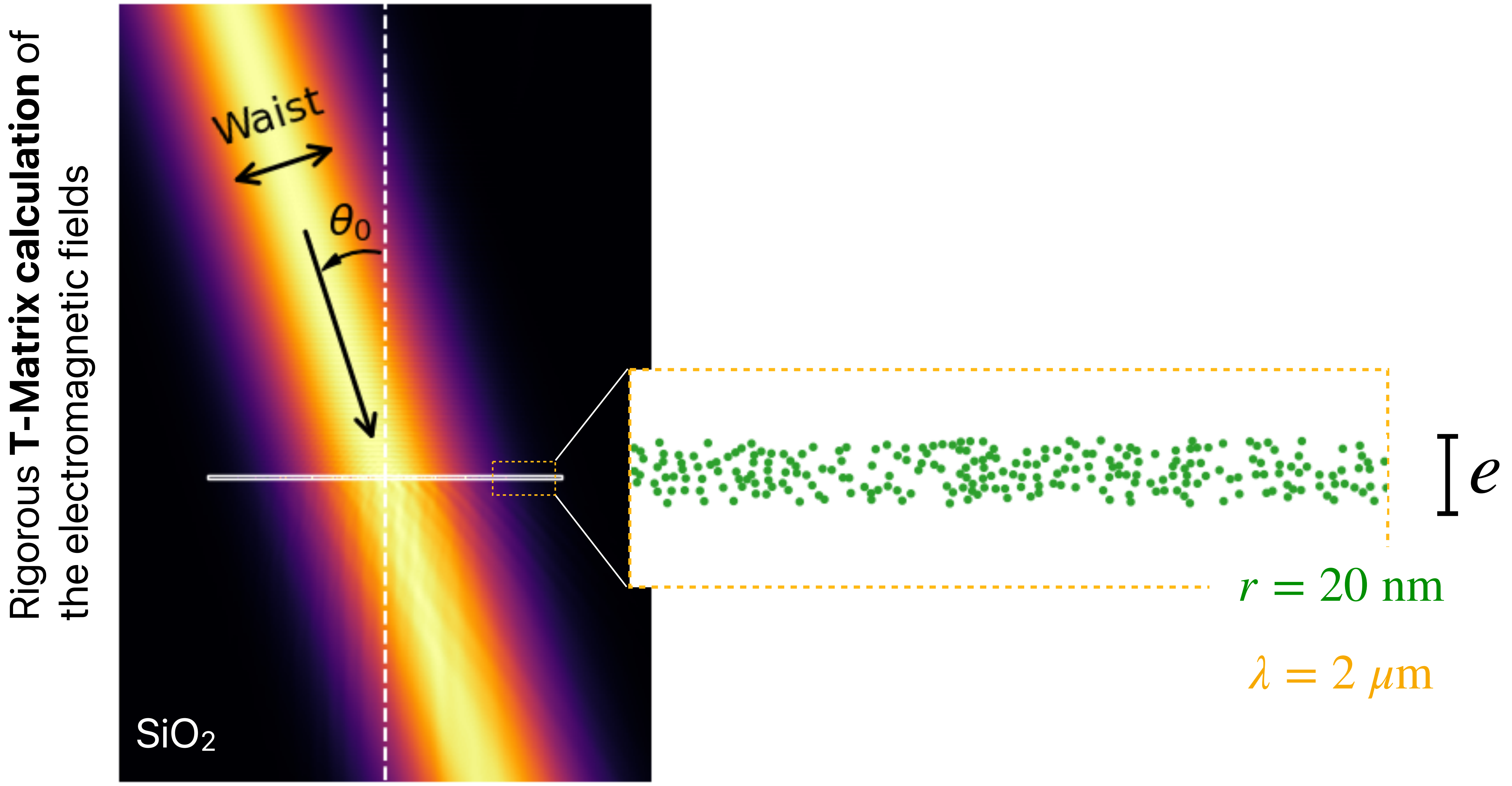
Difficult to compete with the devices of nanophotonics, and disorder has often been viewed as a constraint.



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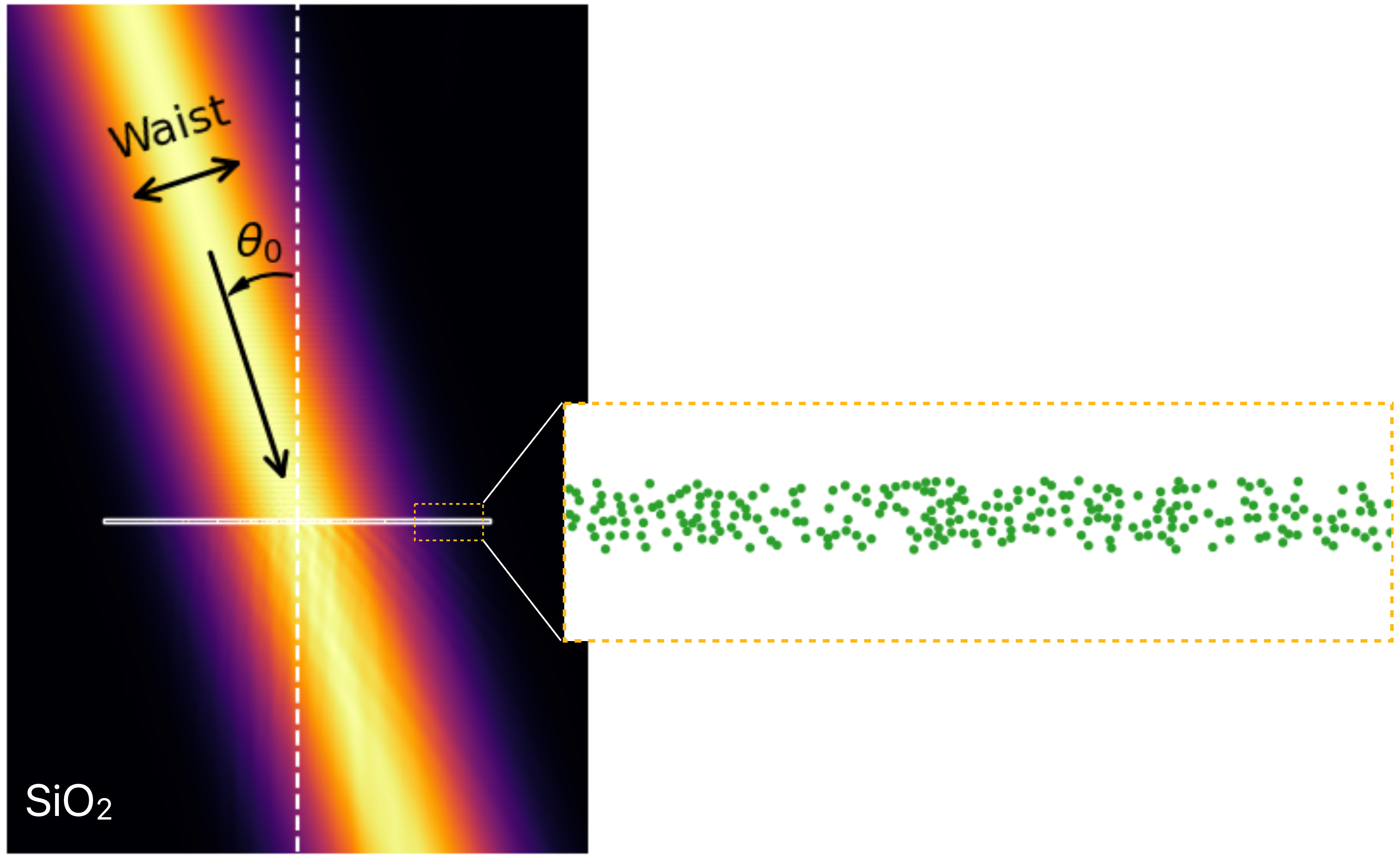

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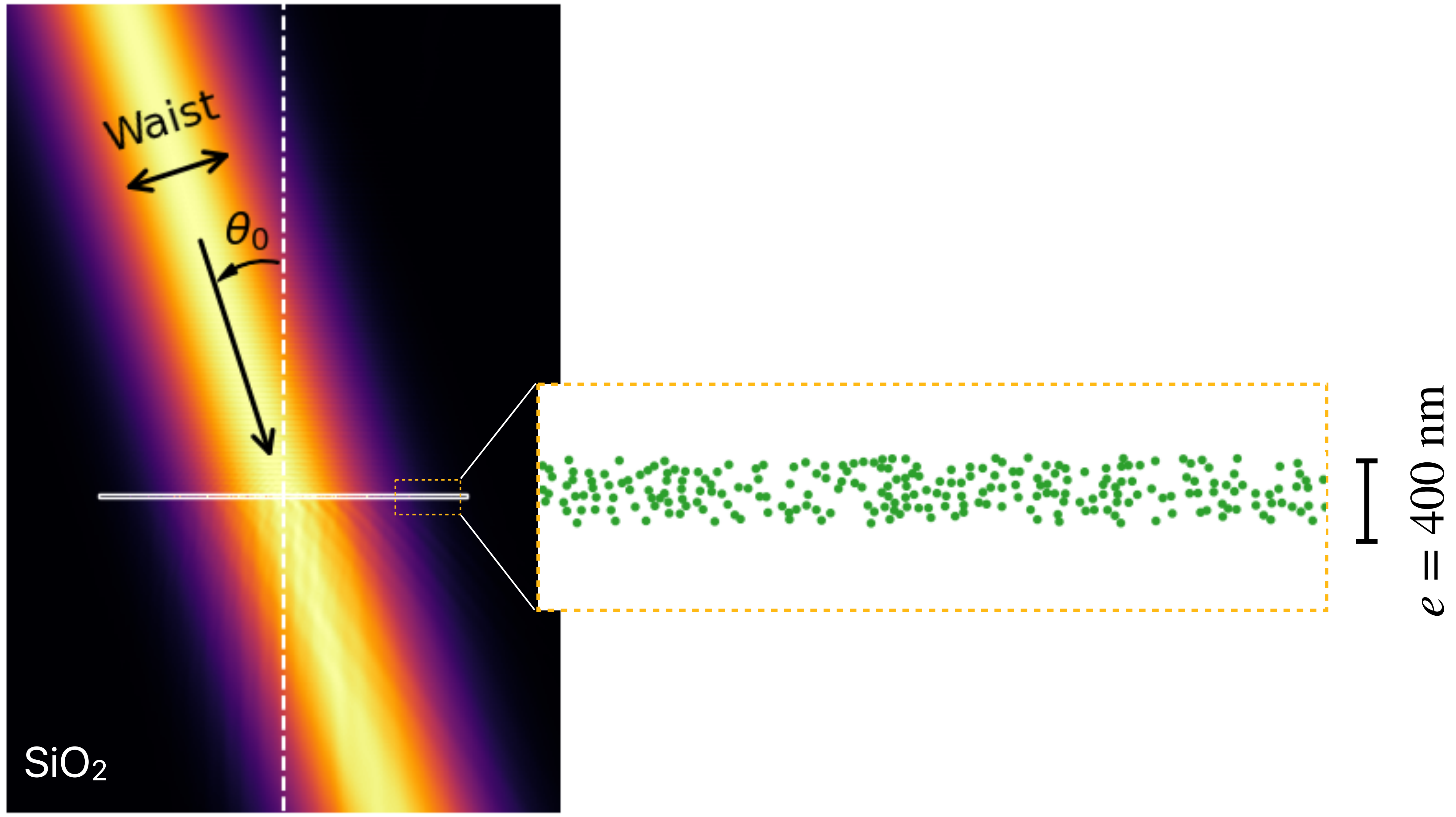

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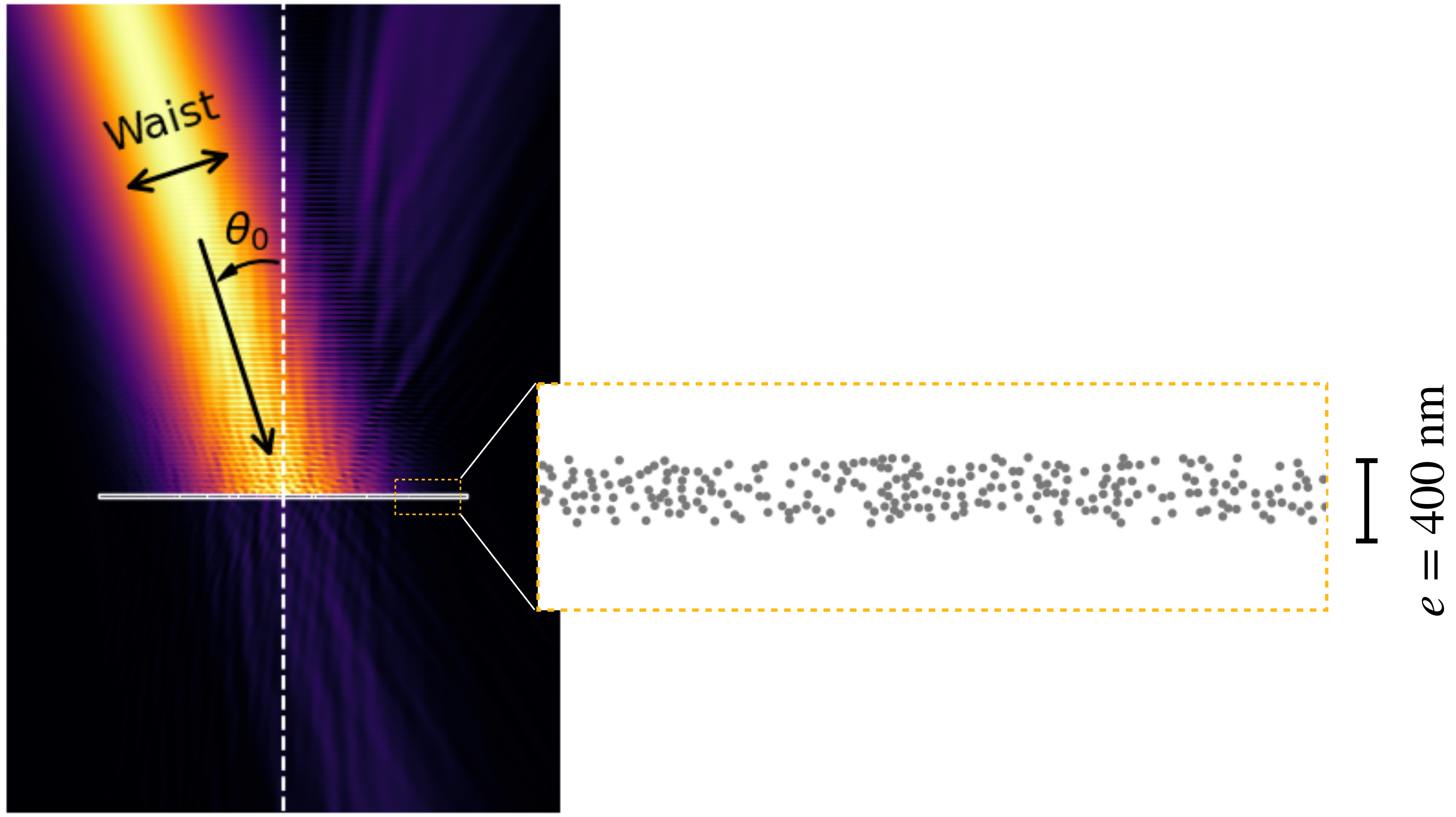

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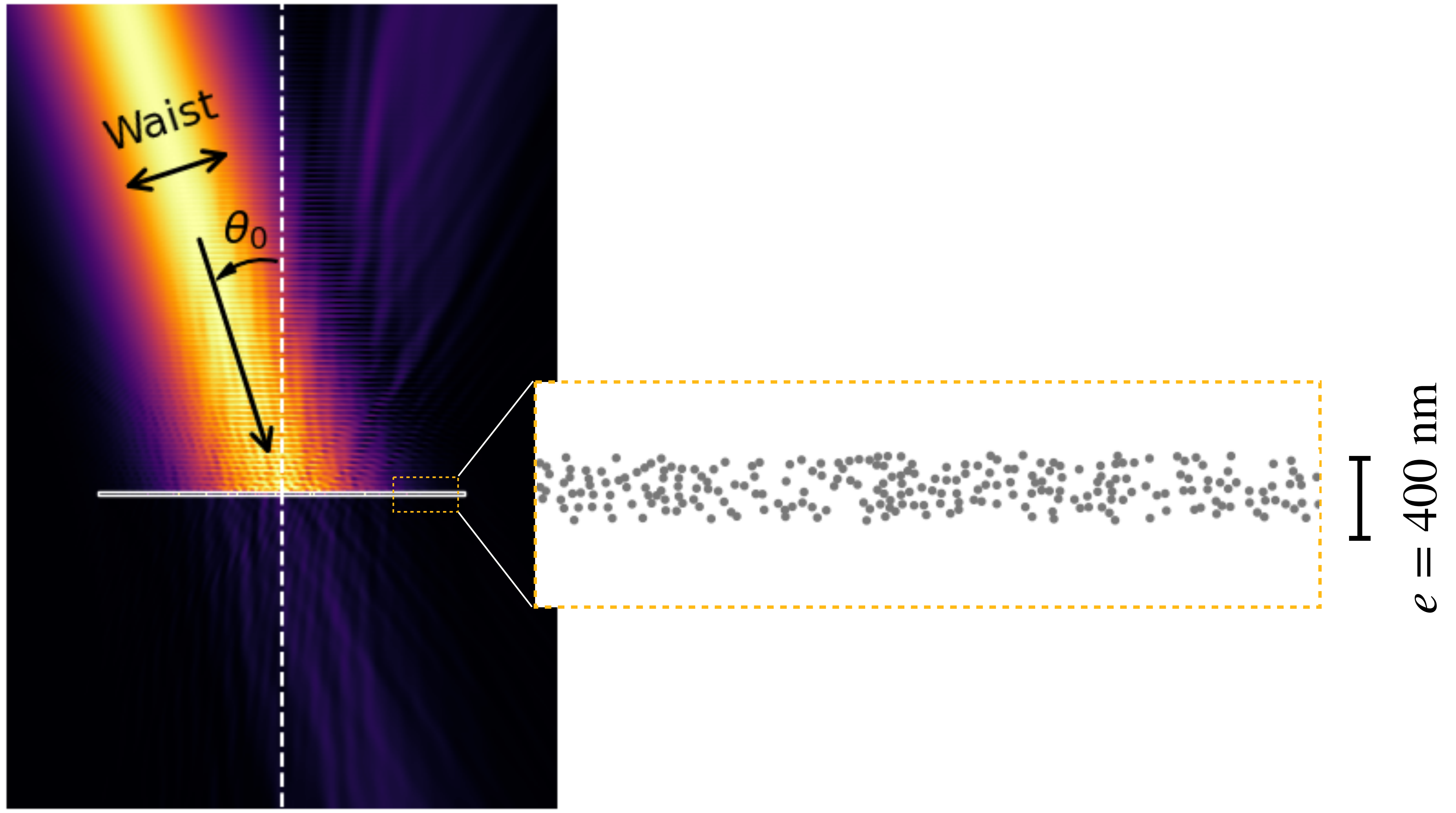

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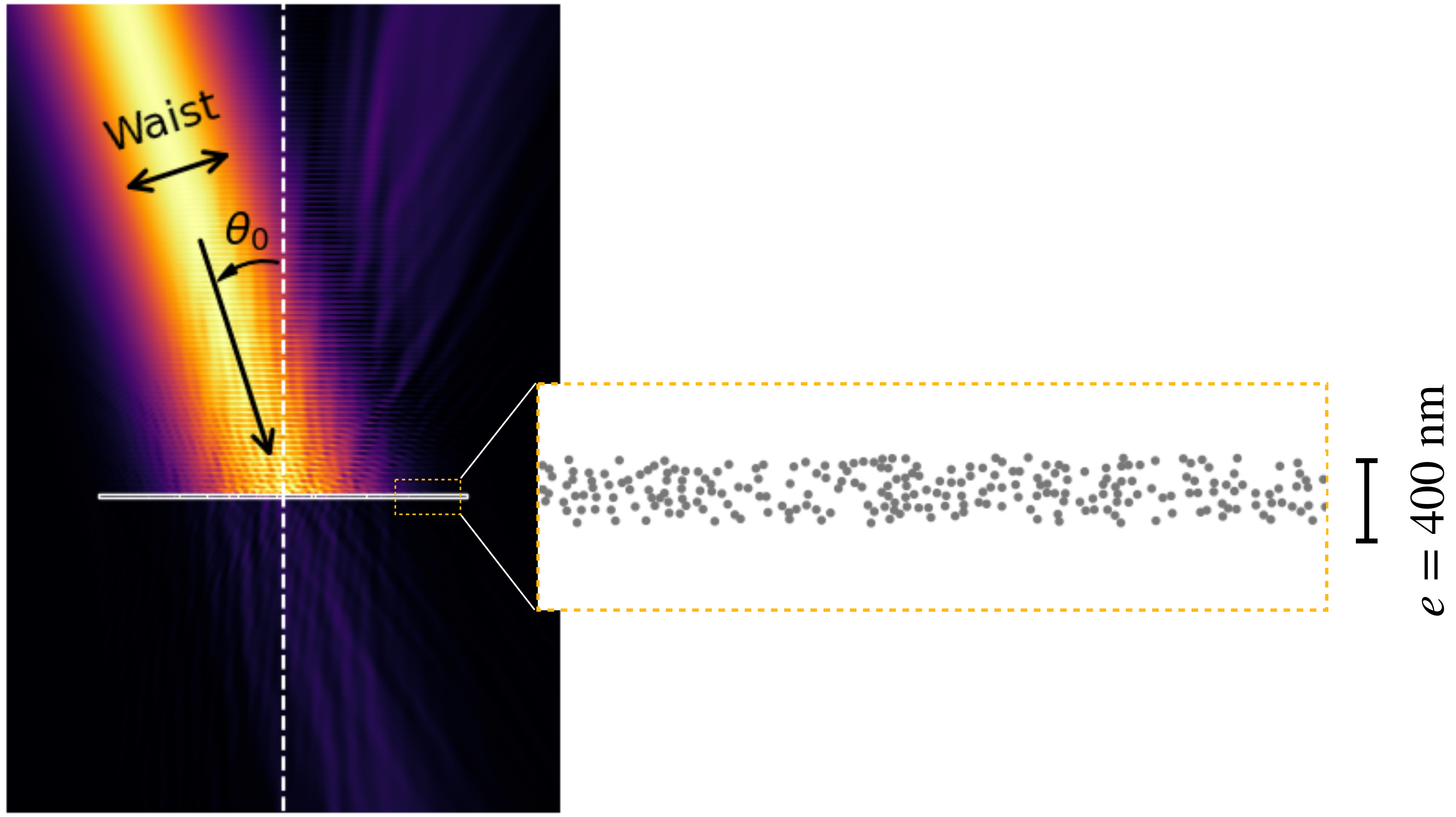

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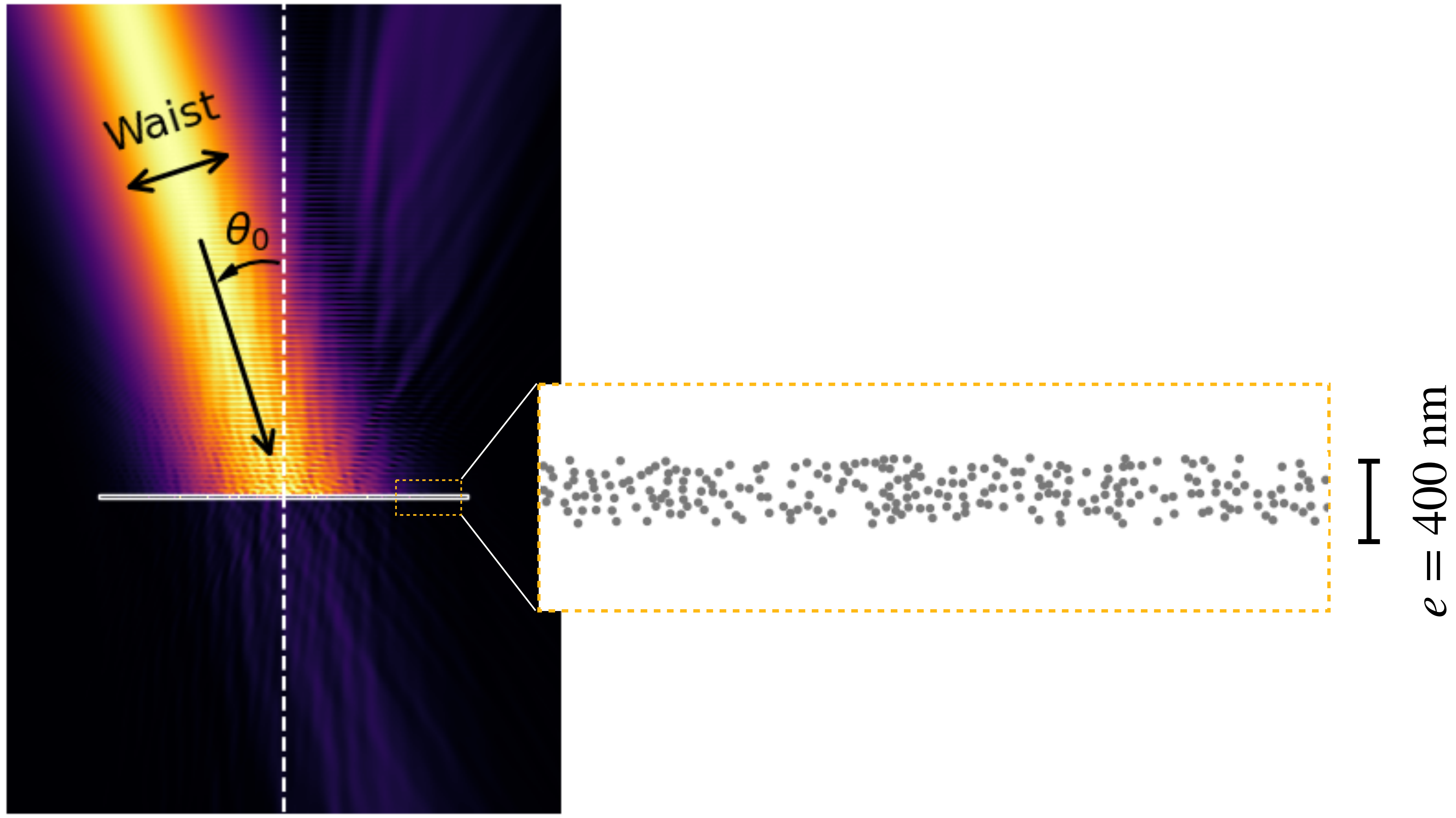

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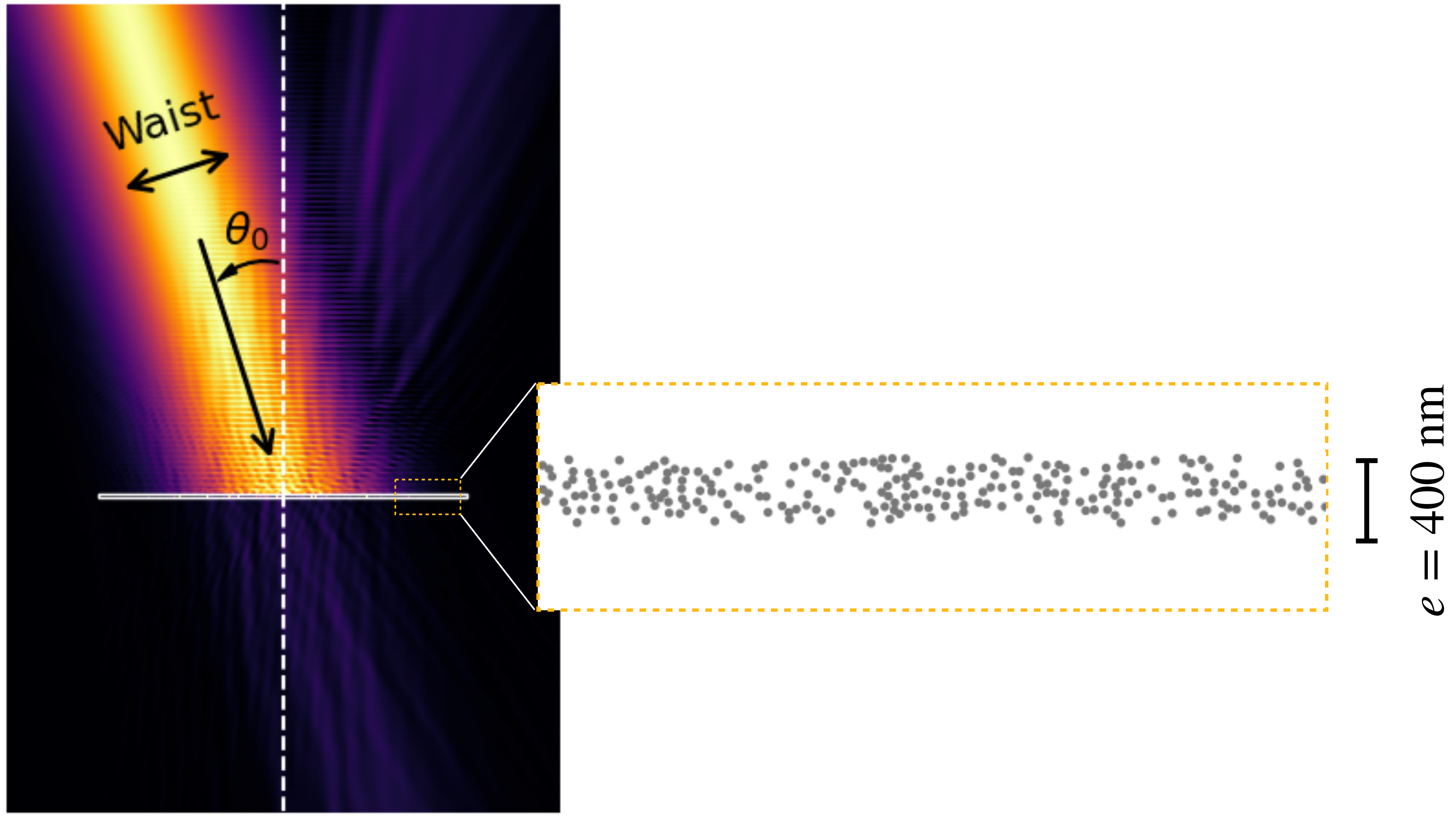

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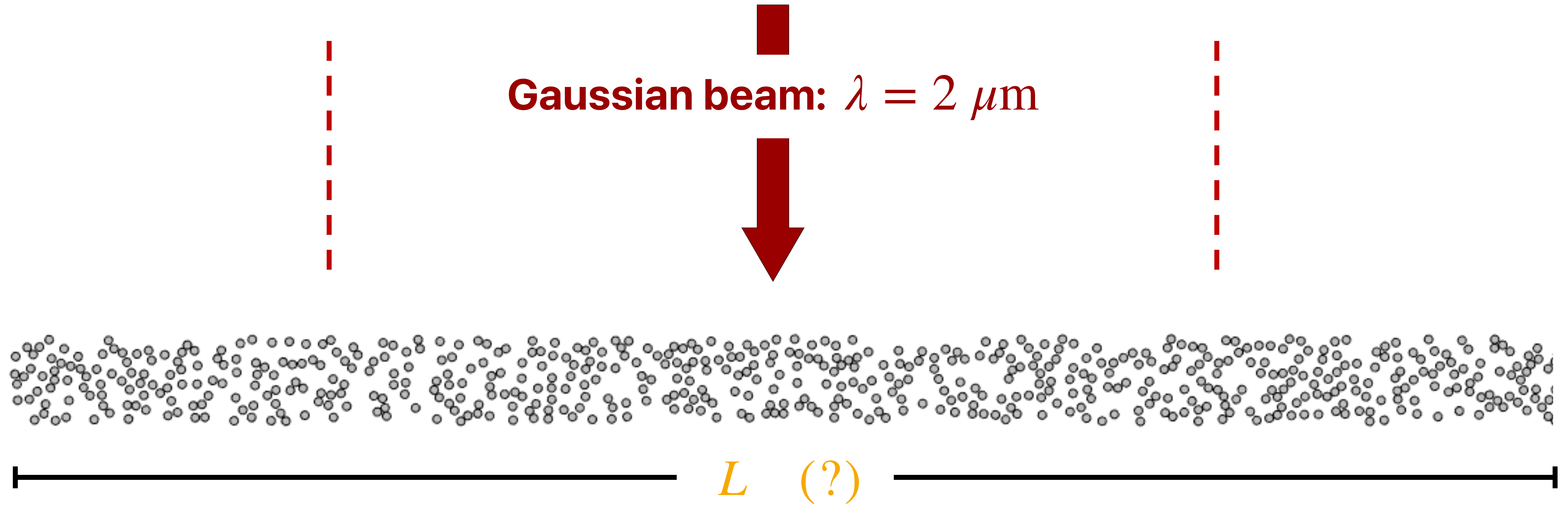
Impedance mismatch

Near perfect absorption: absorption metric

How absorption is calculated?



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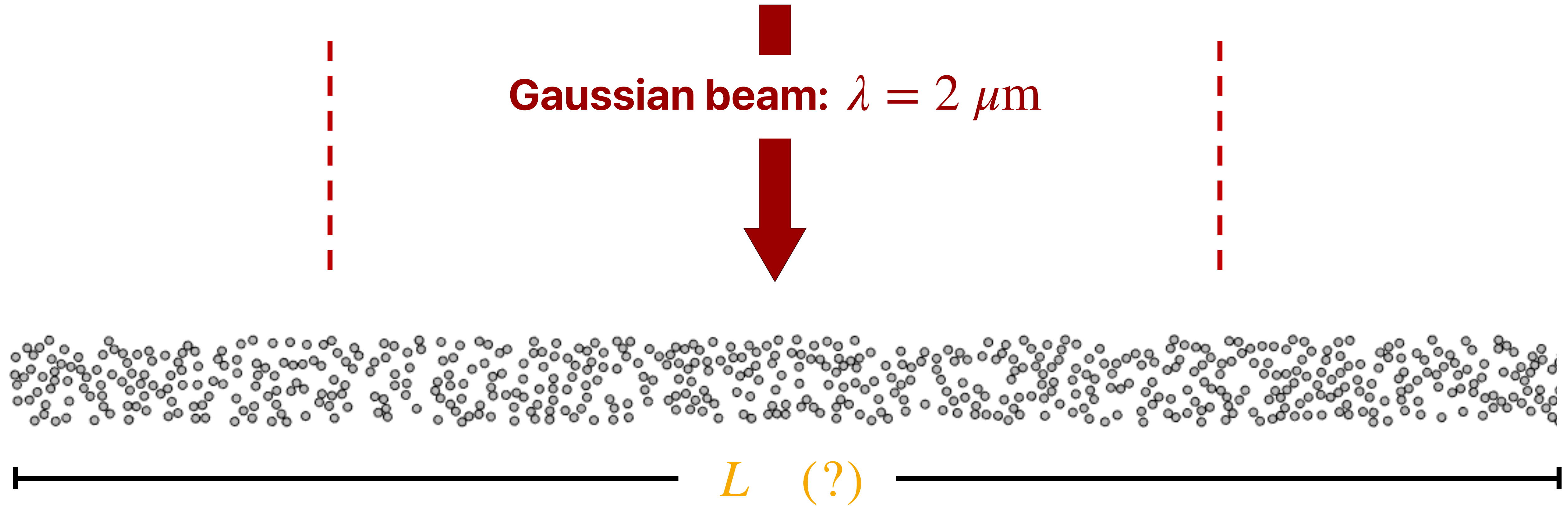

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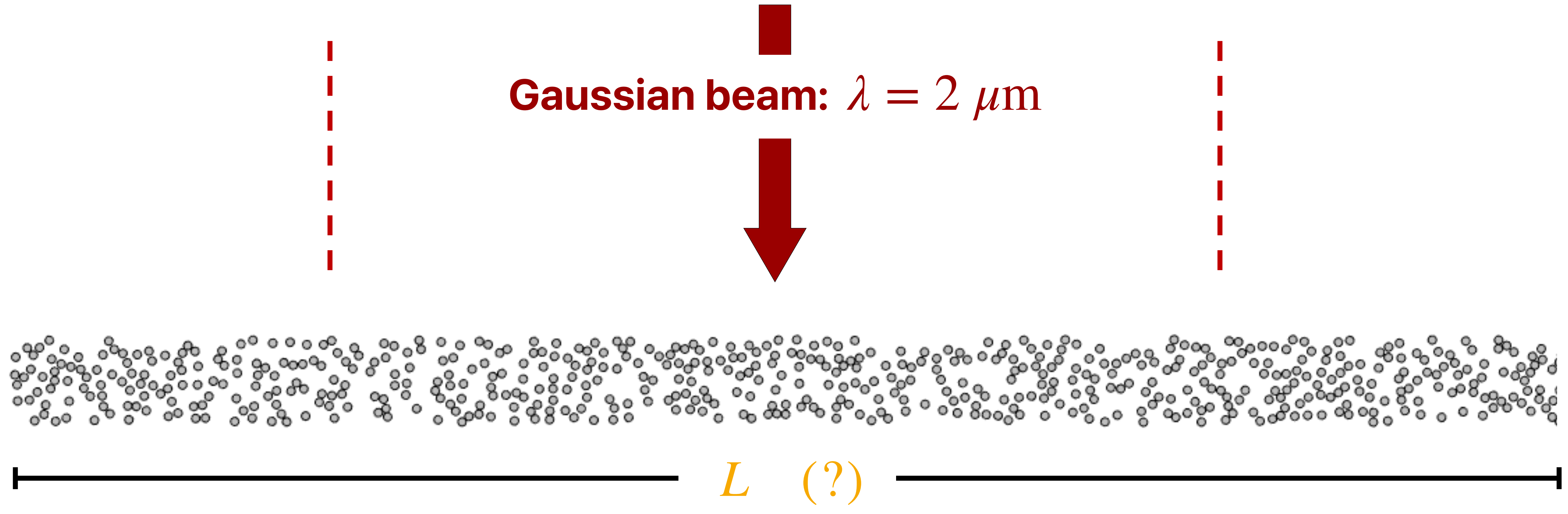

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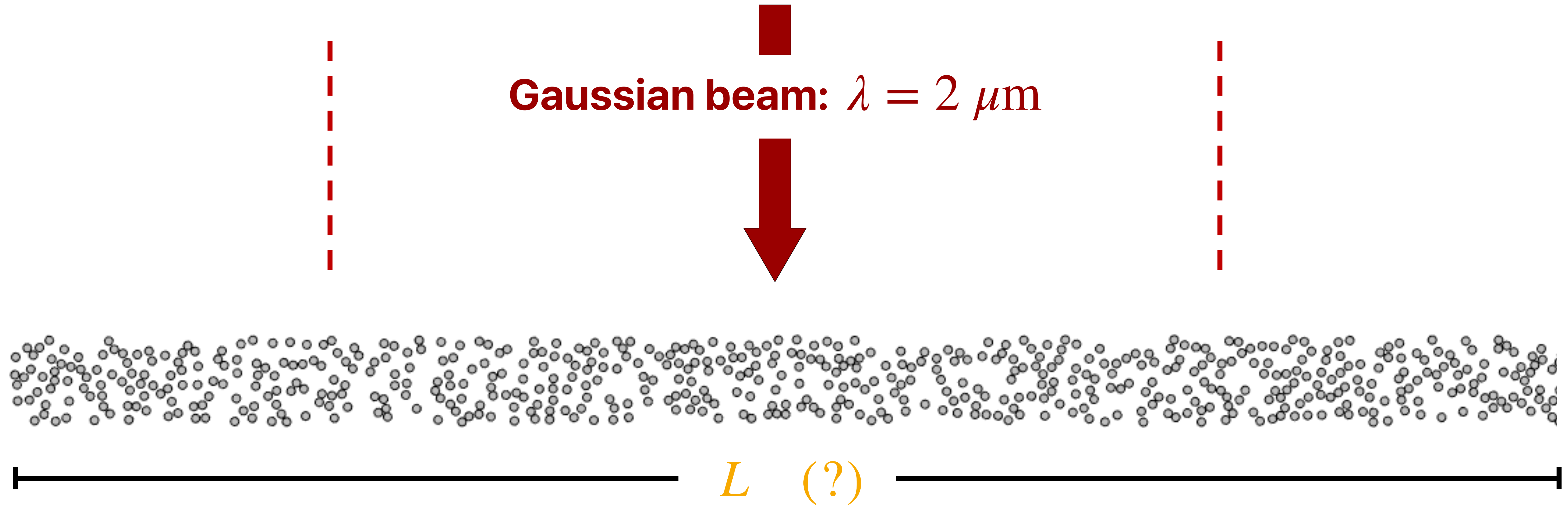

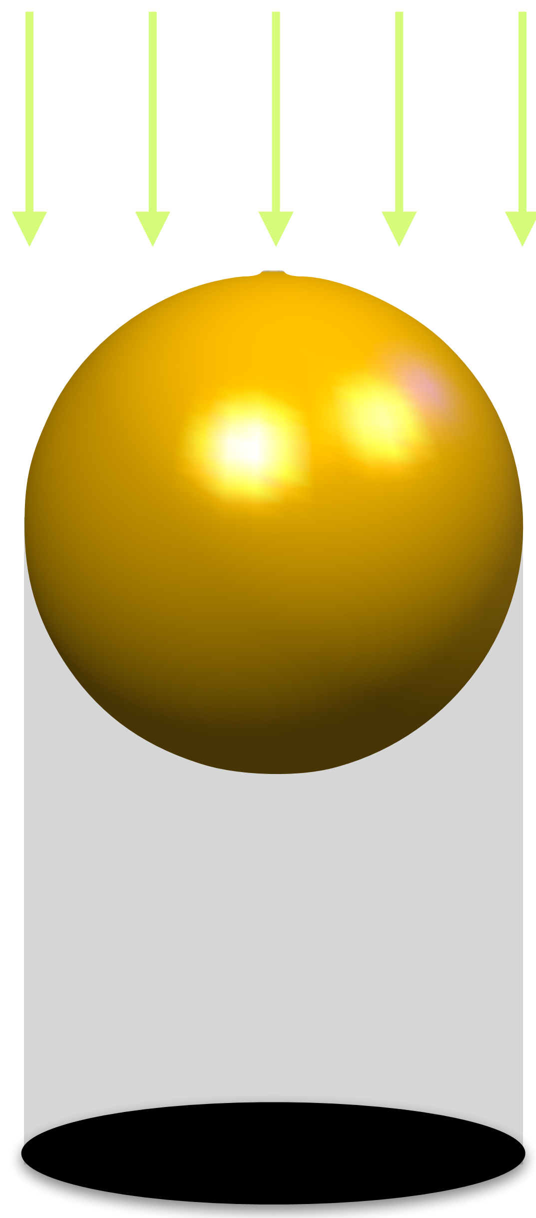

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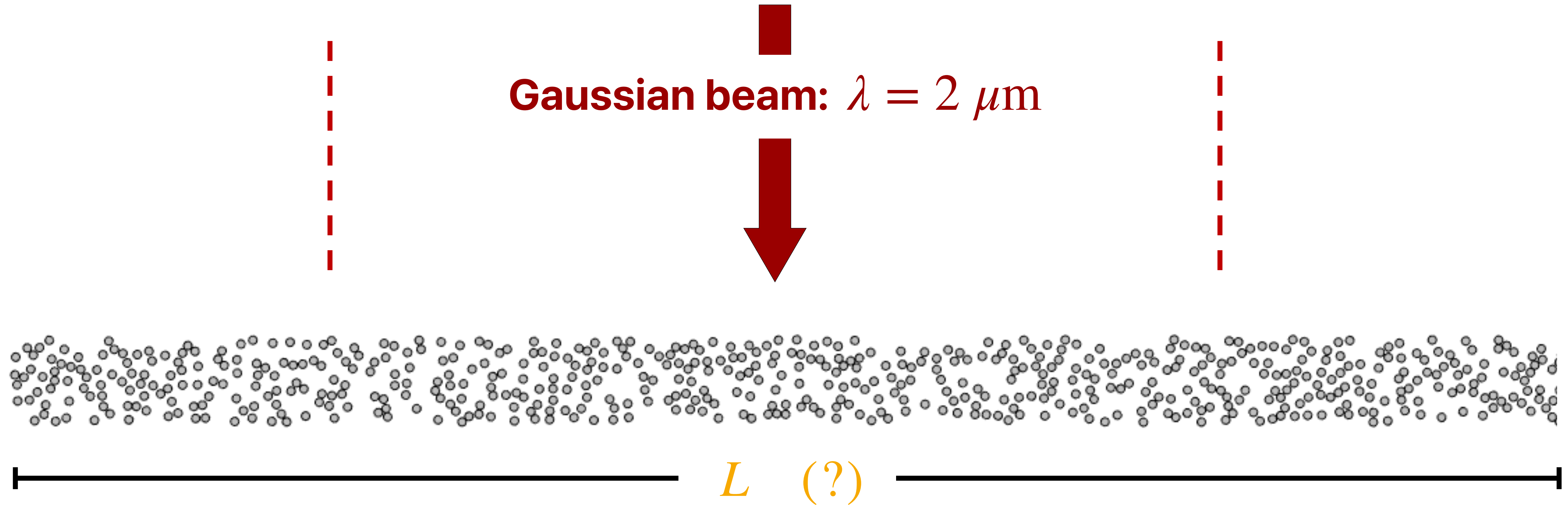

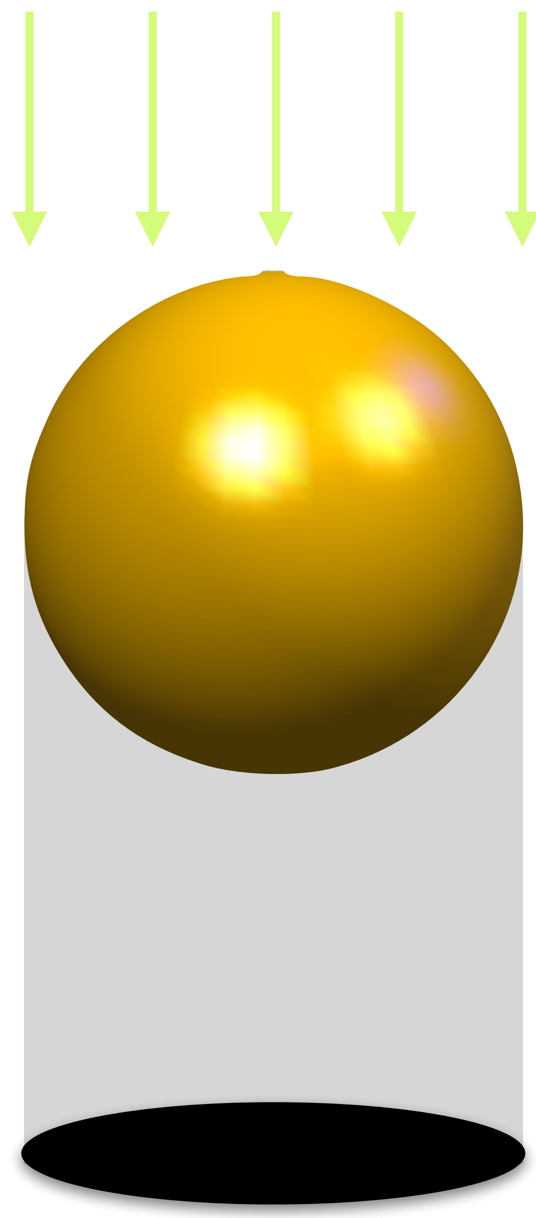

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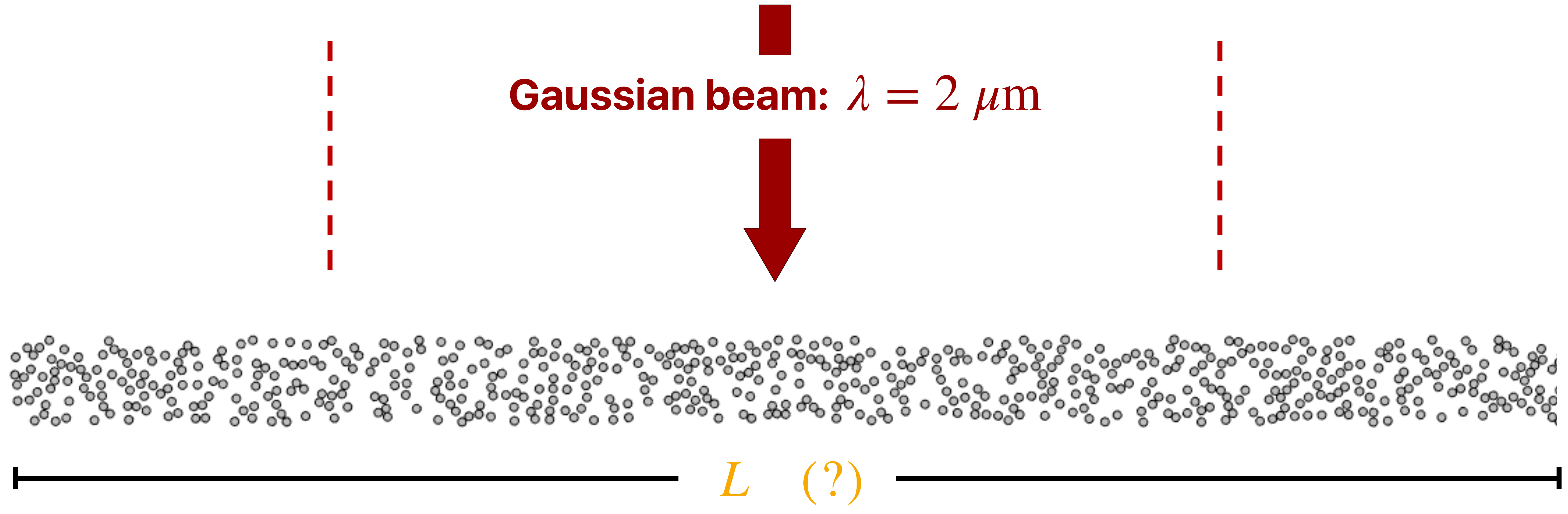

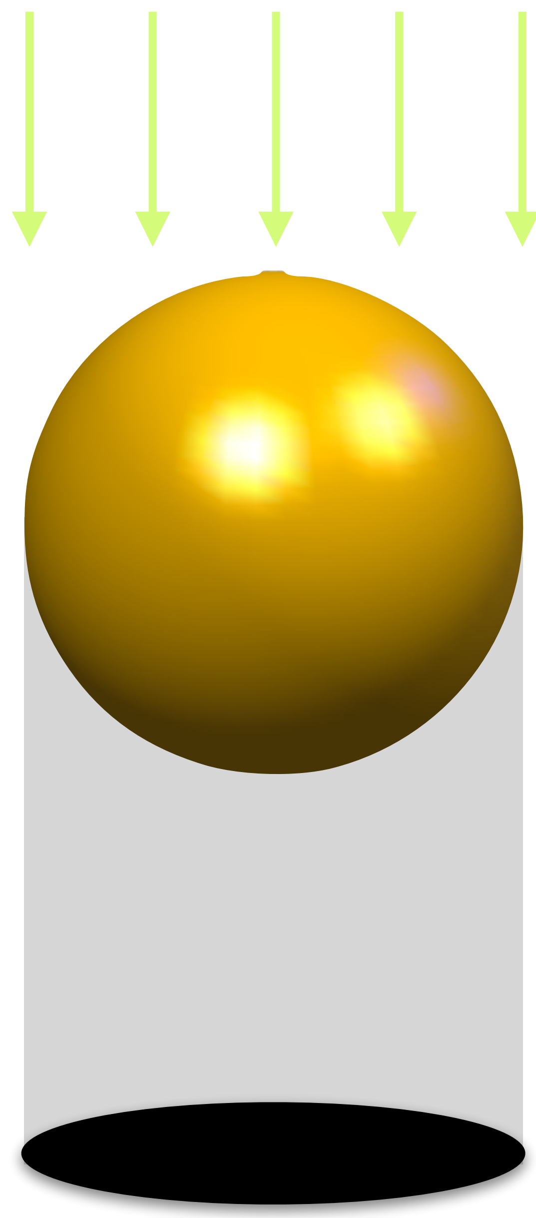

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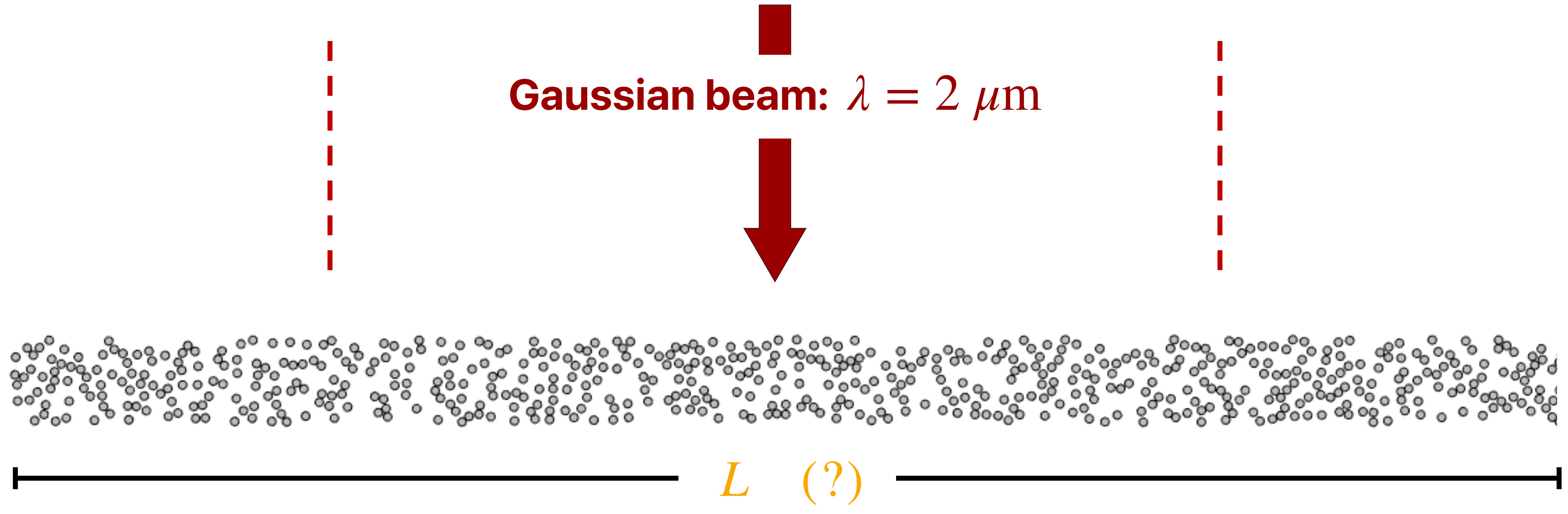

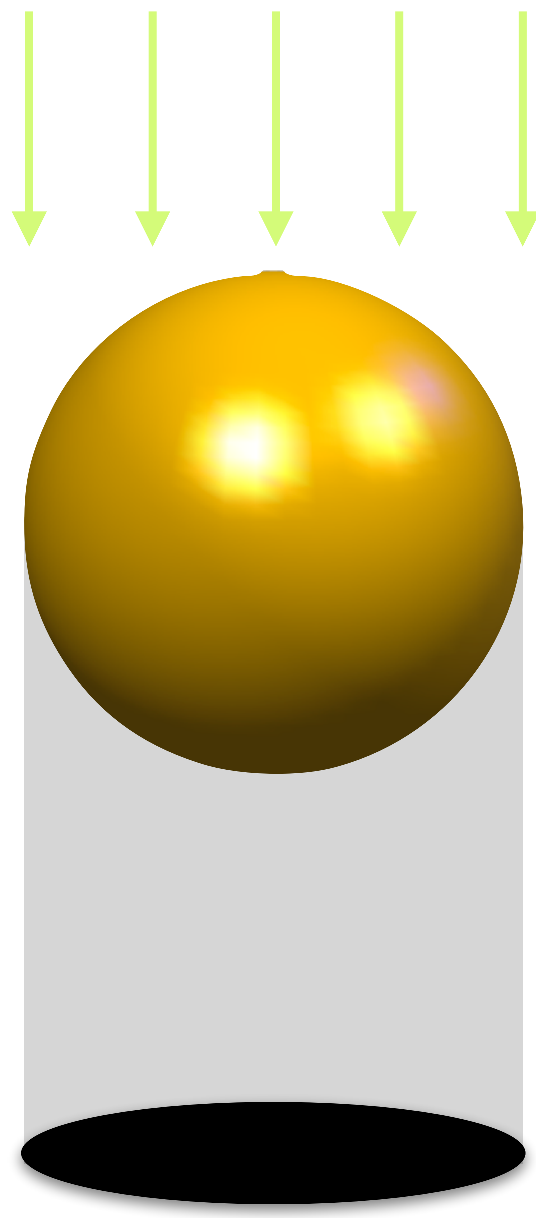

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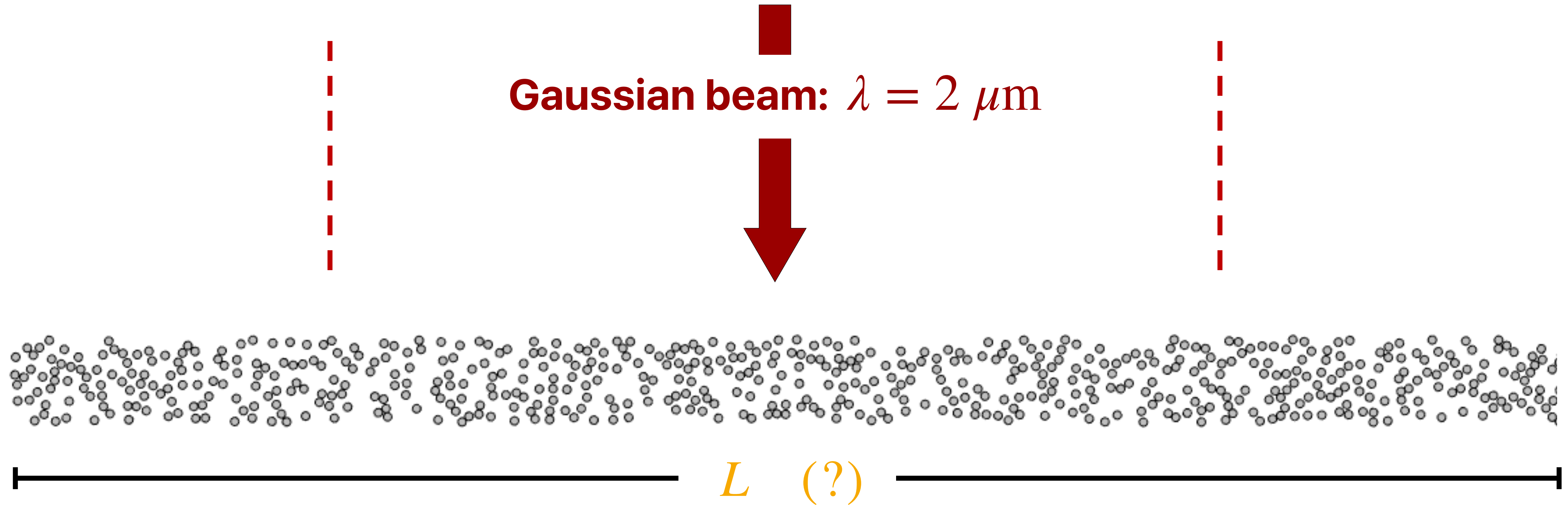

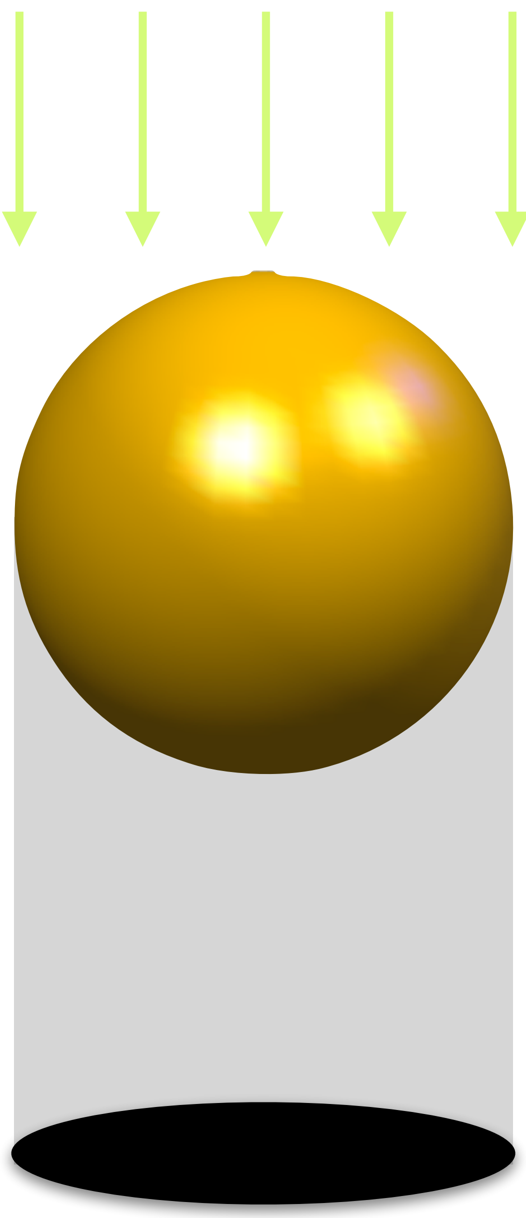

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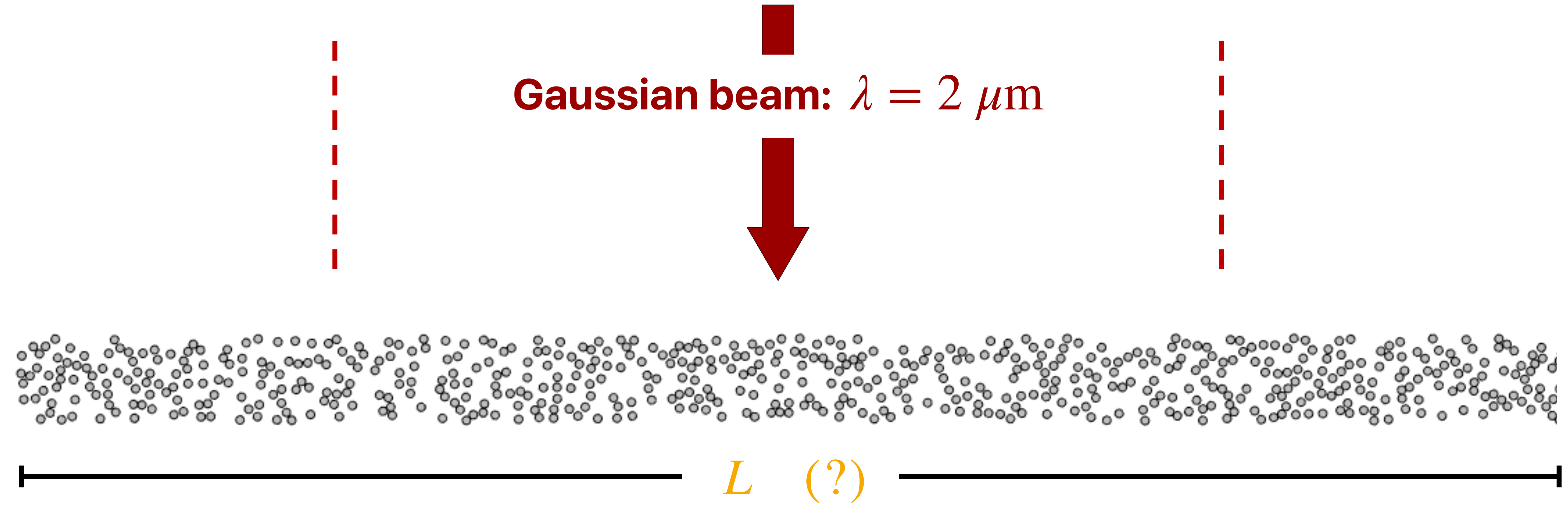

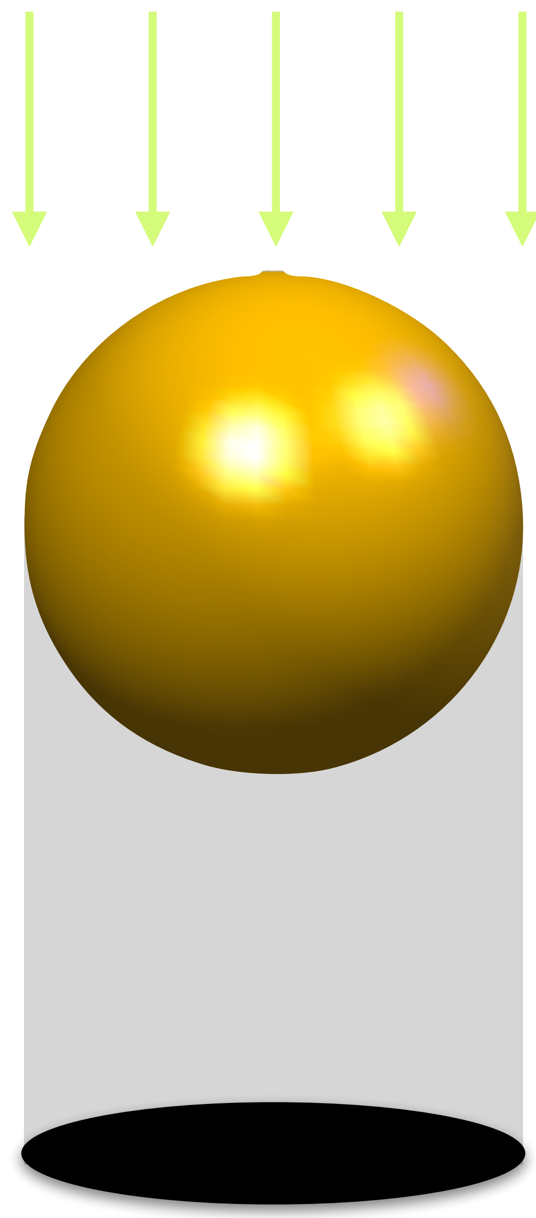

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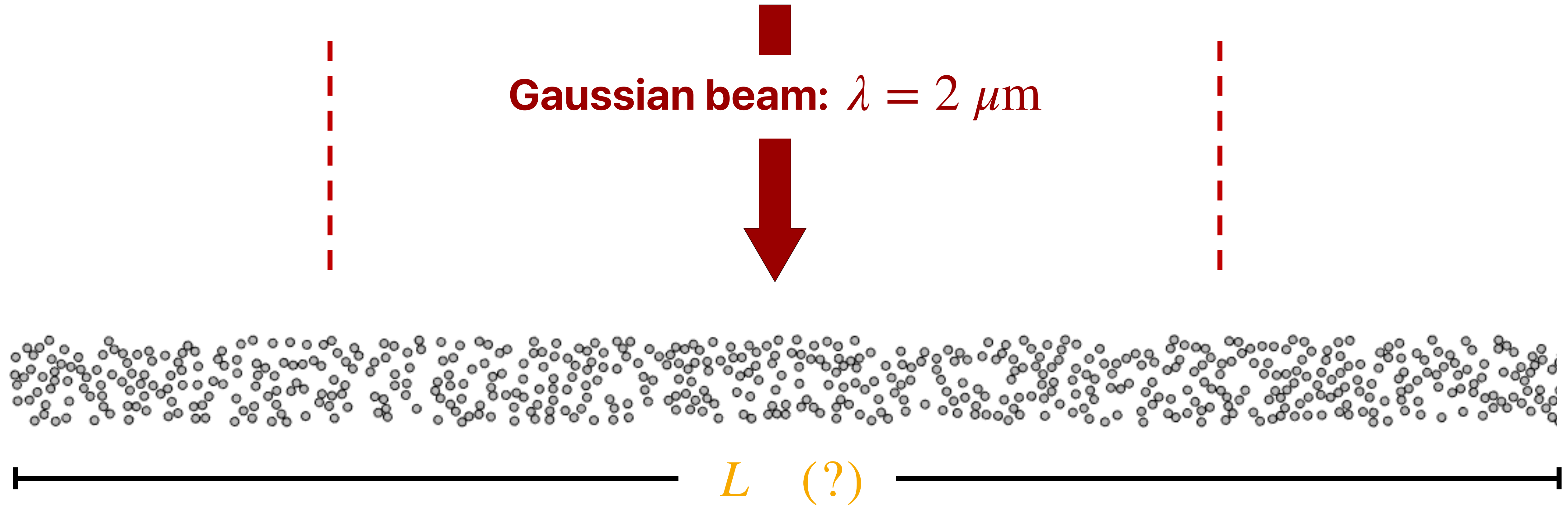

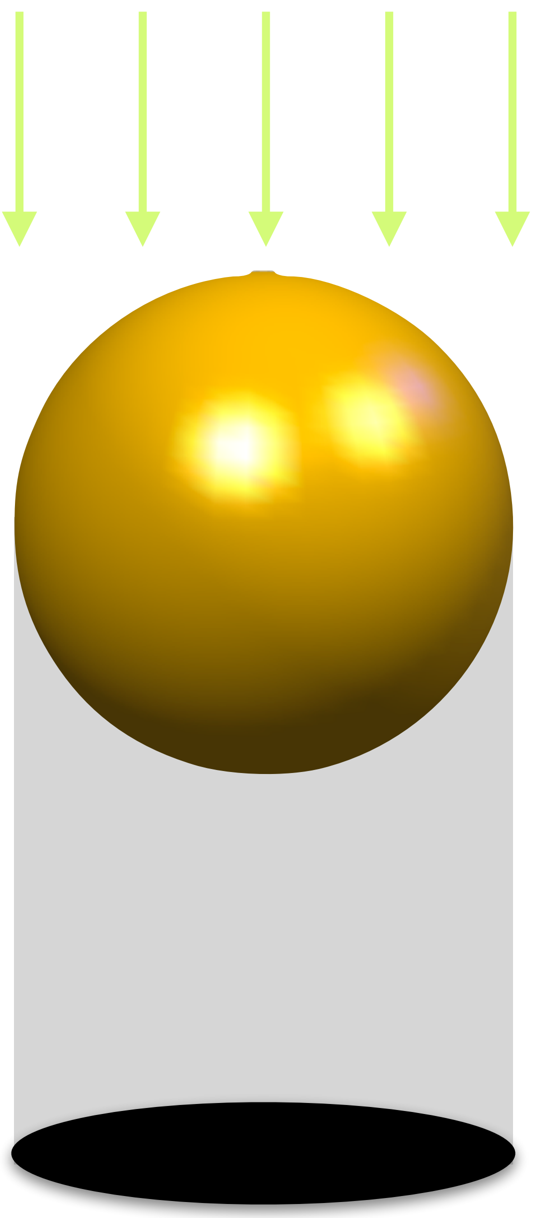

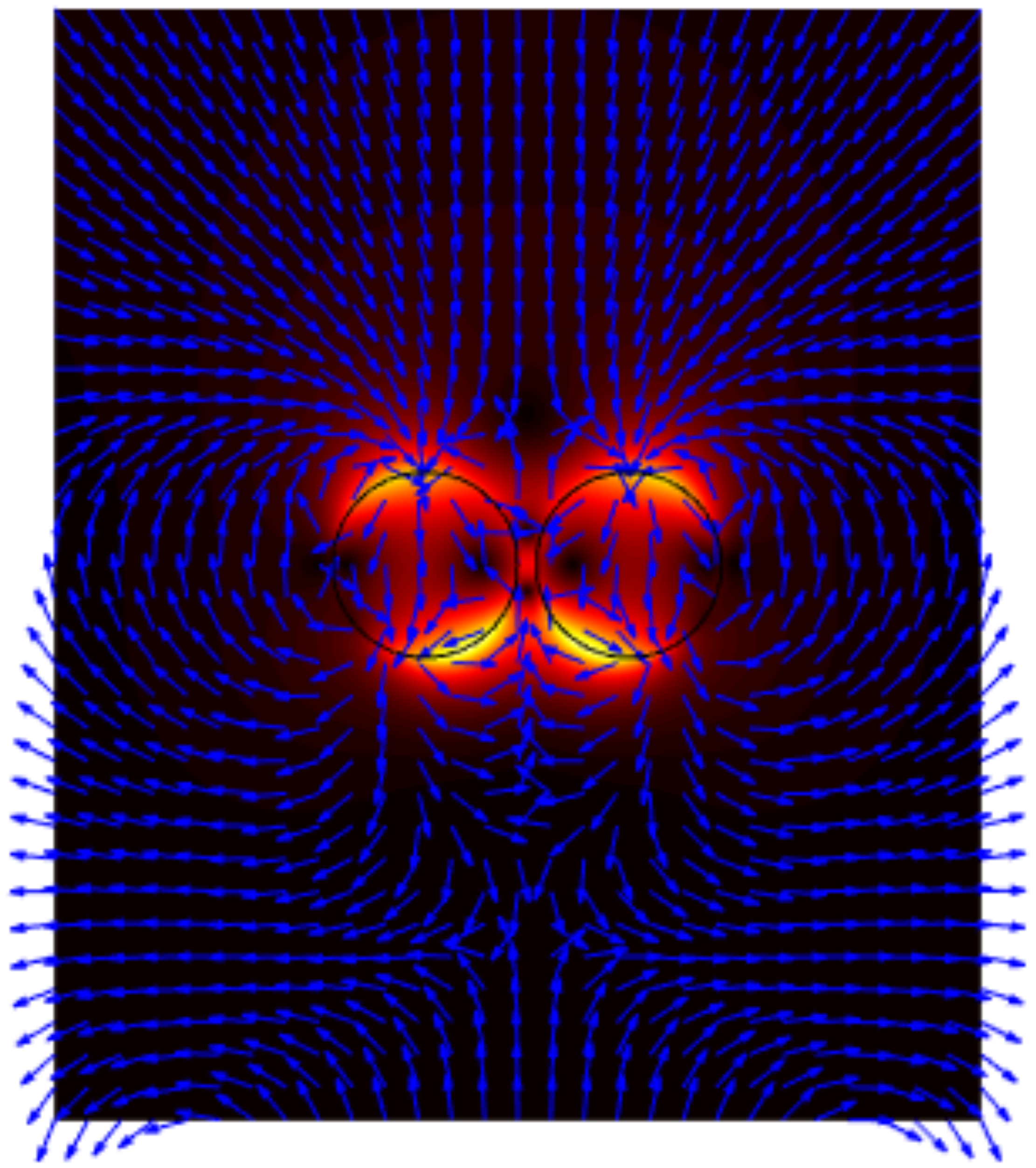

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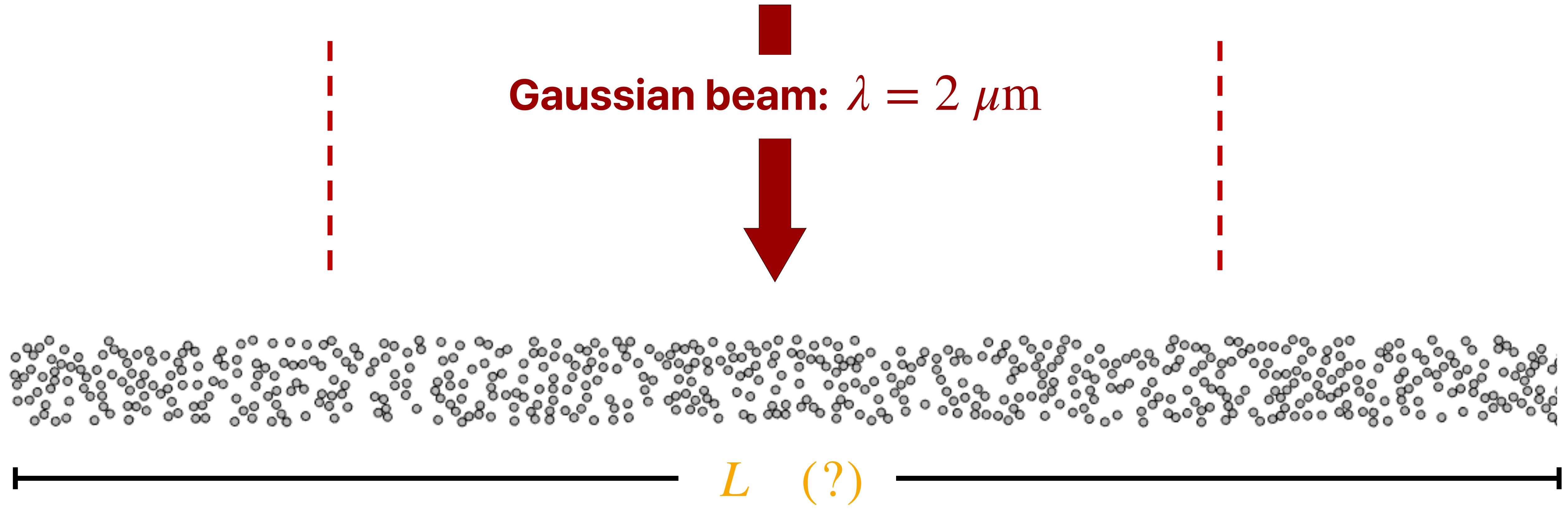

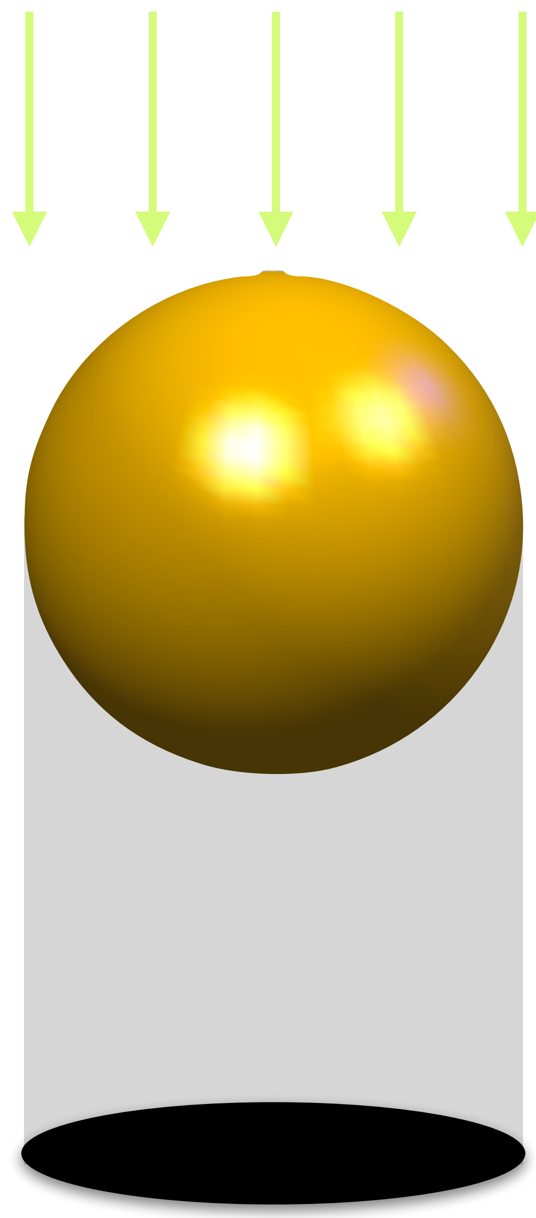

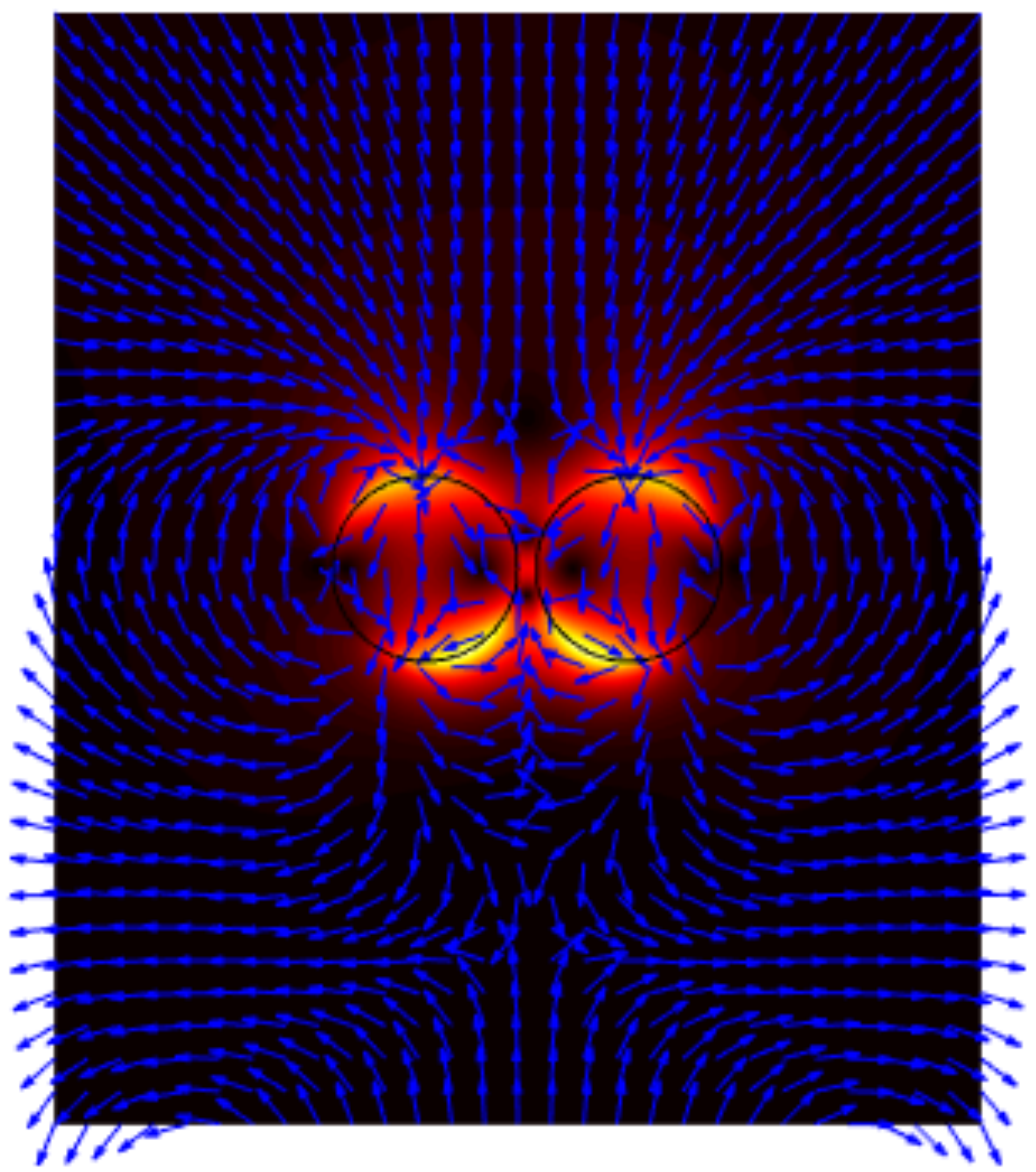

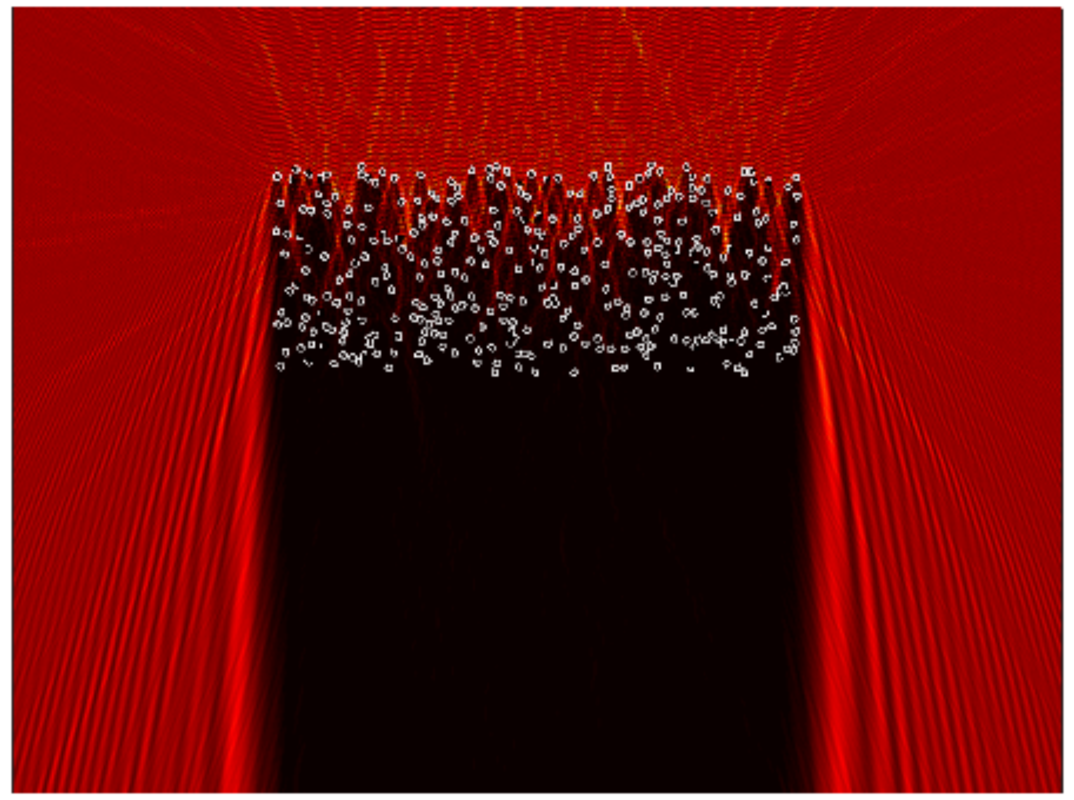

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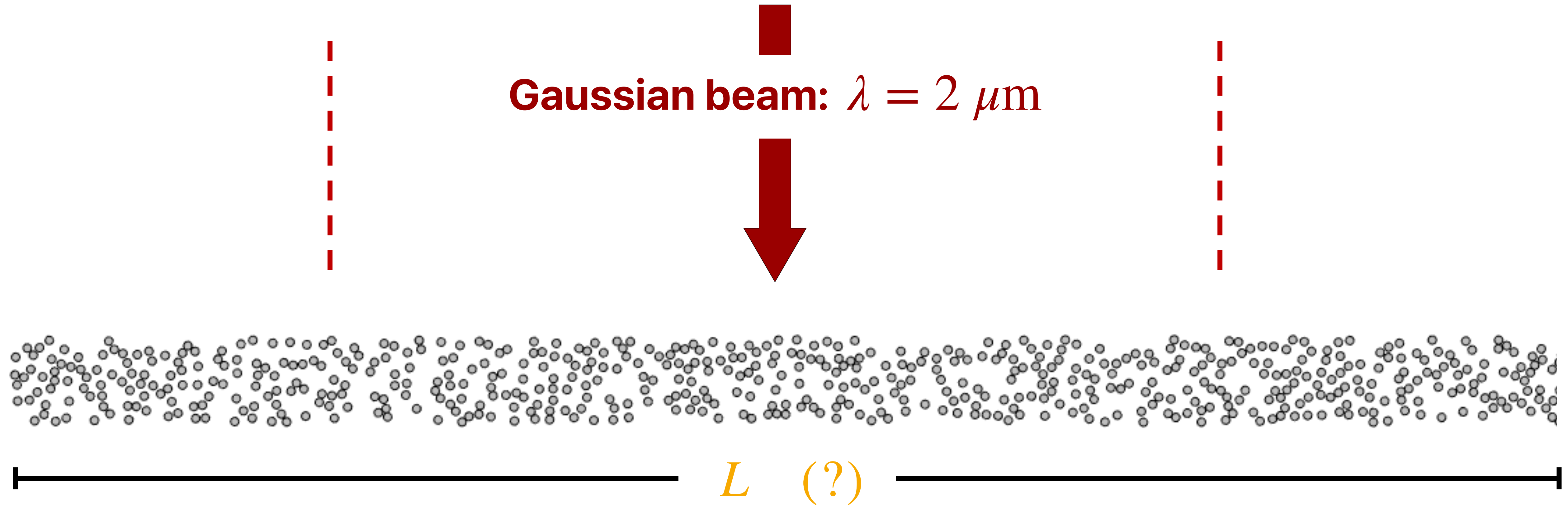

$$Q_{\text{abs}} = \sigma_{\text{abs}}/L$$

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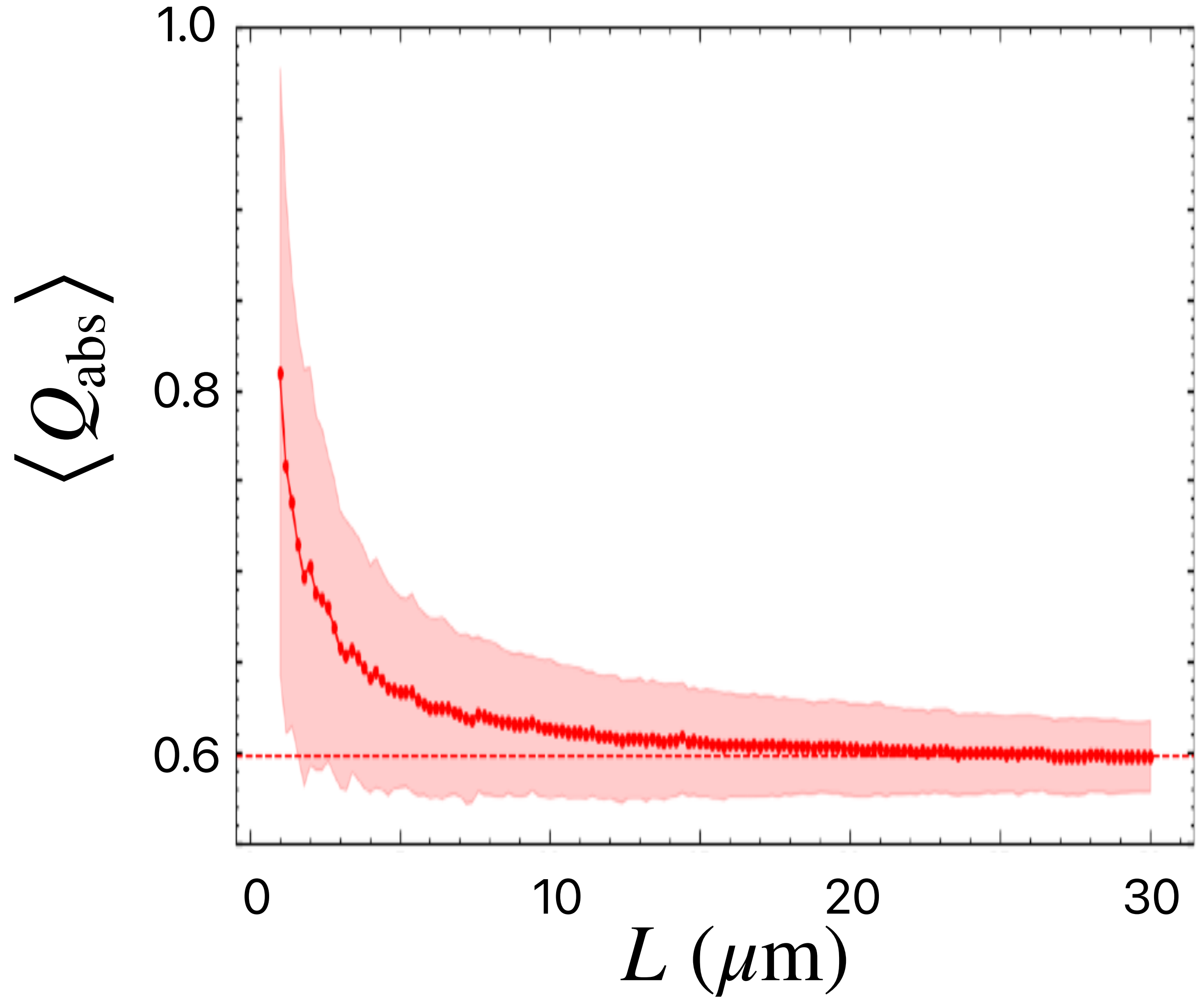
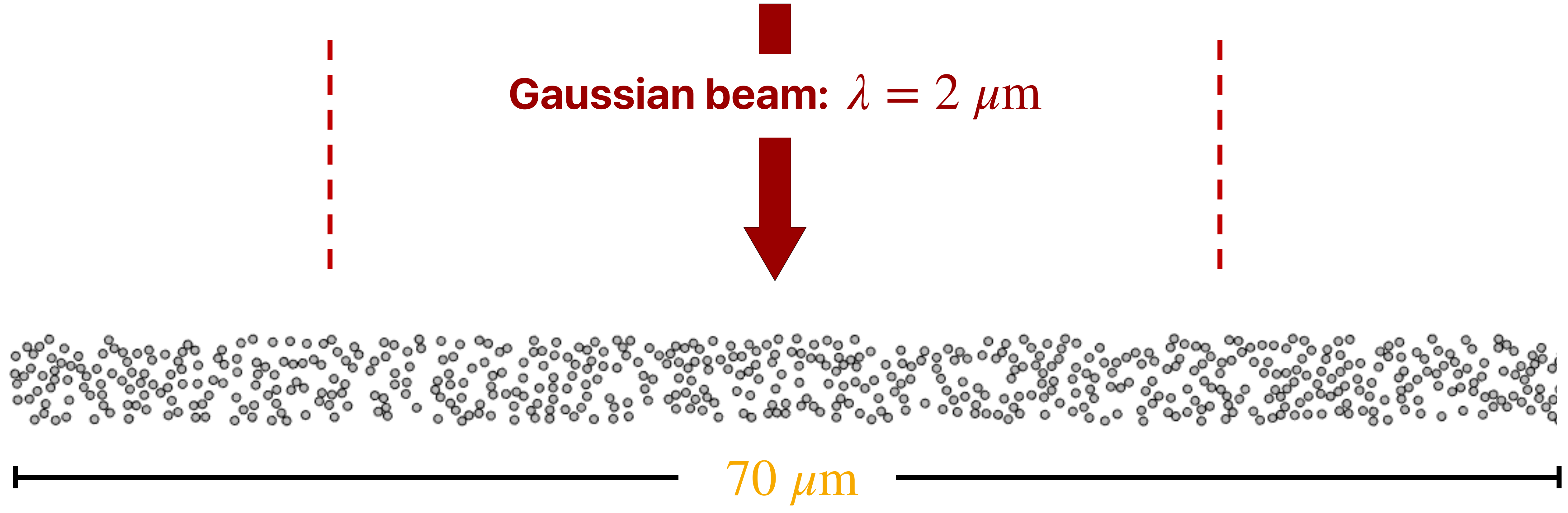


Near perfect absorption: critical coupling mechanism

Why this $60 - 70\,\%$ limit?



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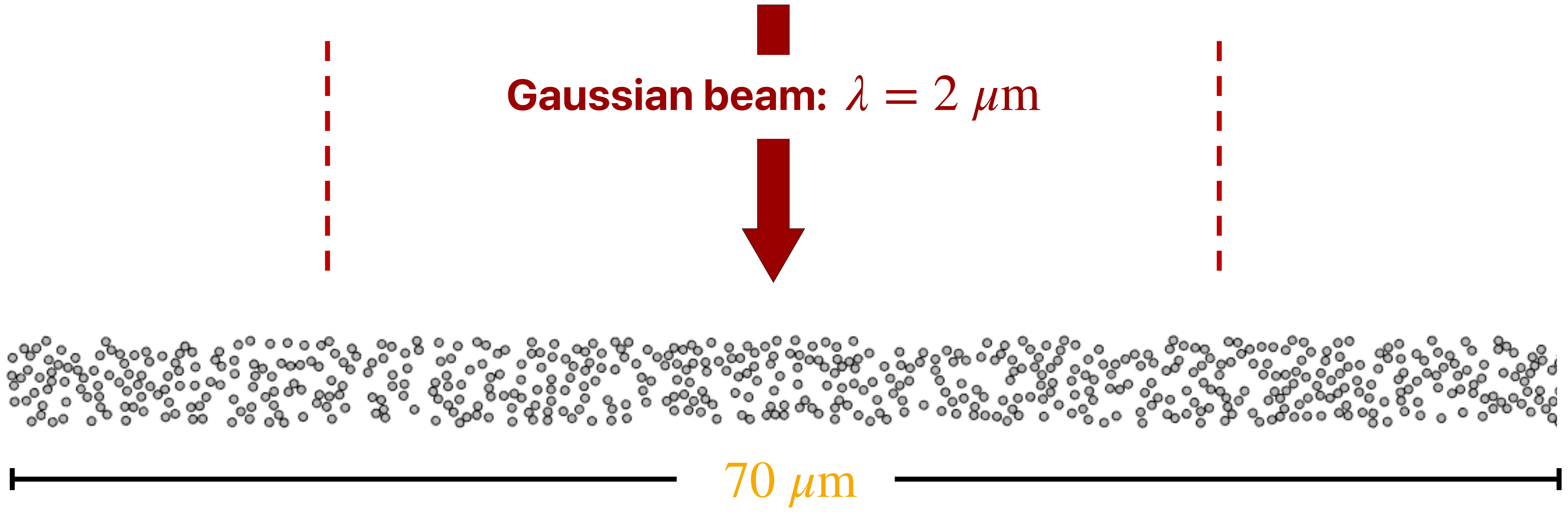

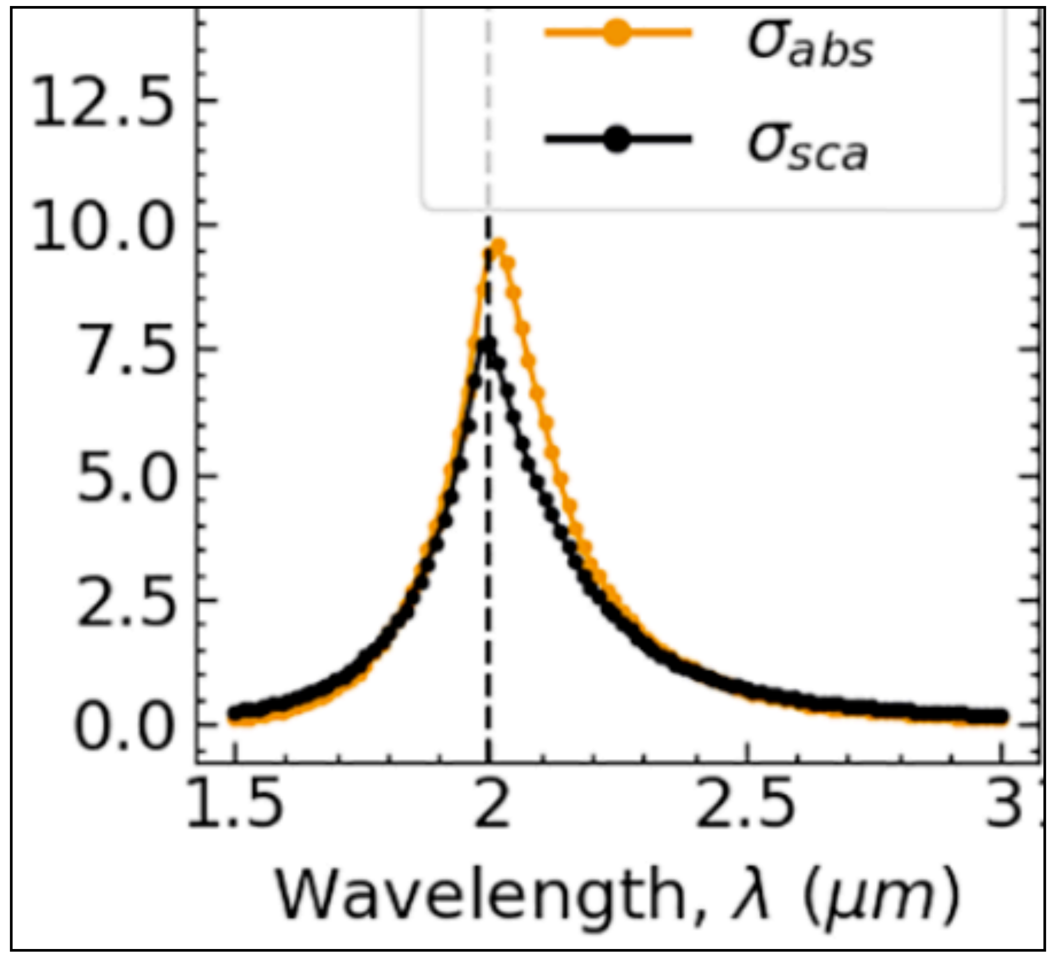

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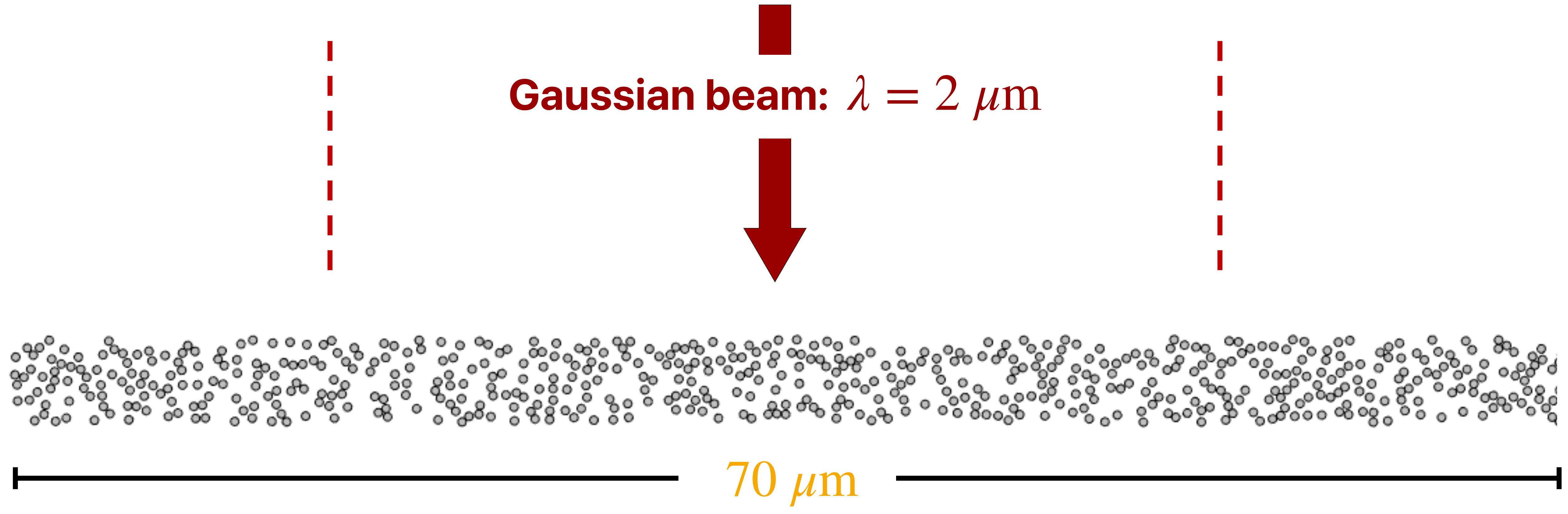

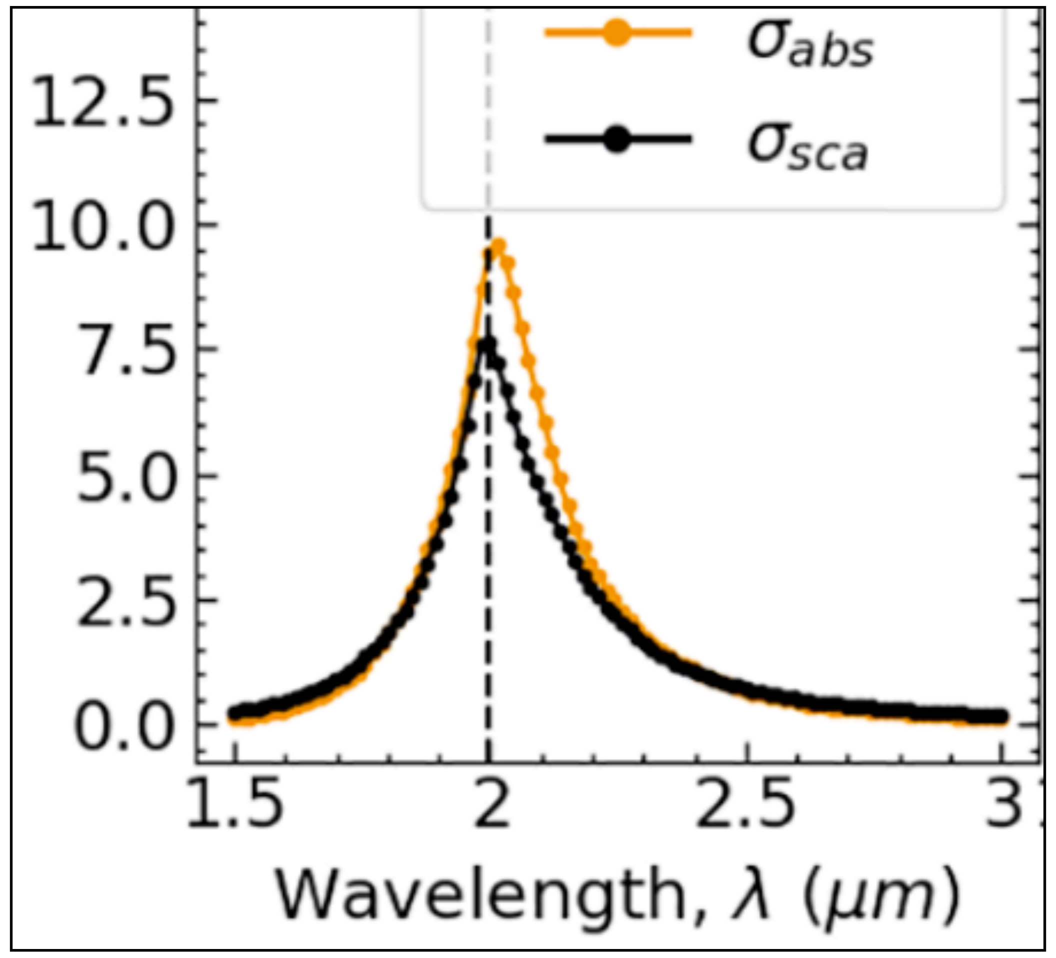

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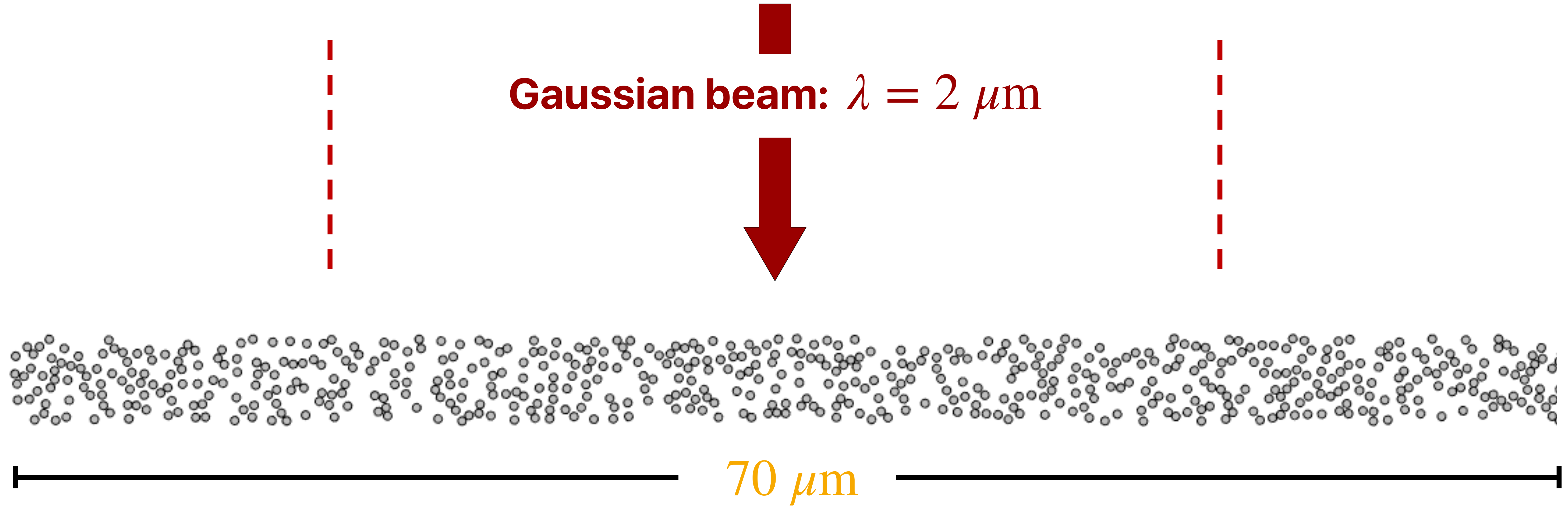

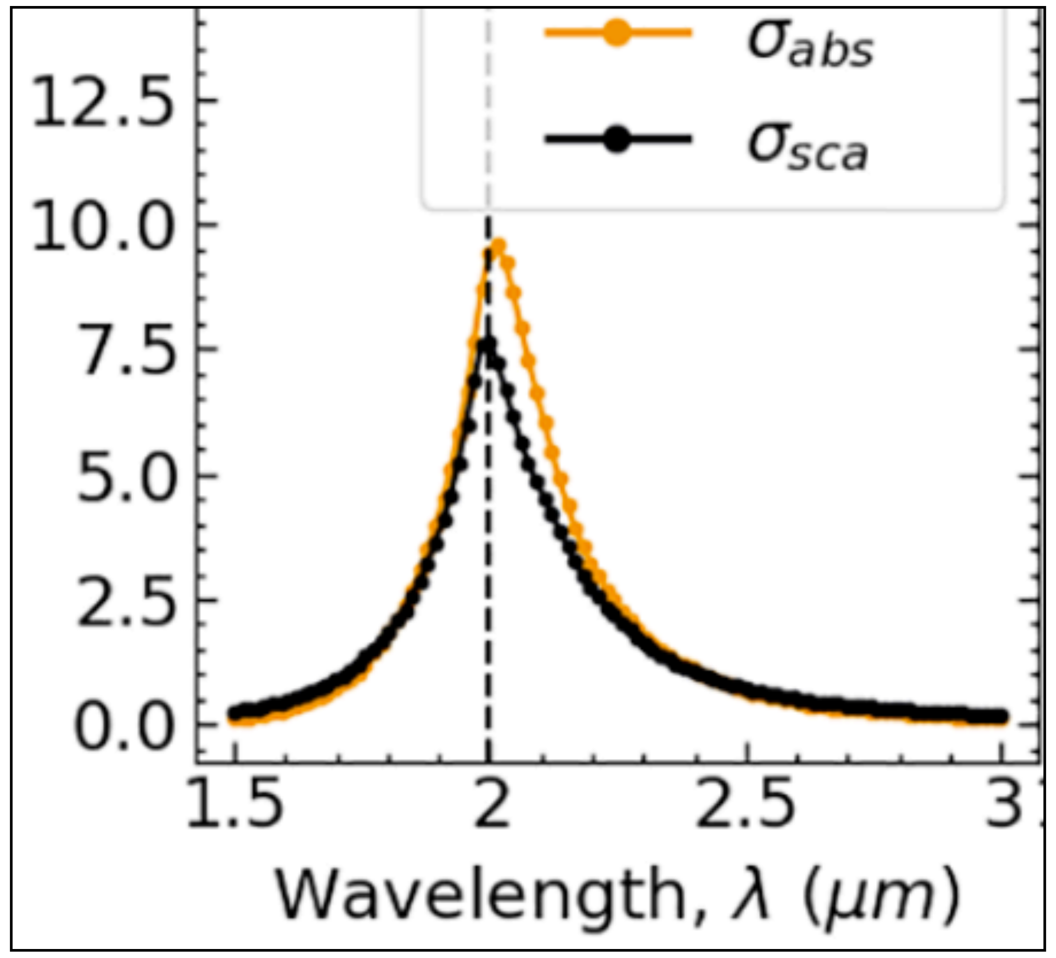

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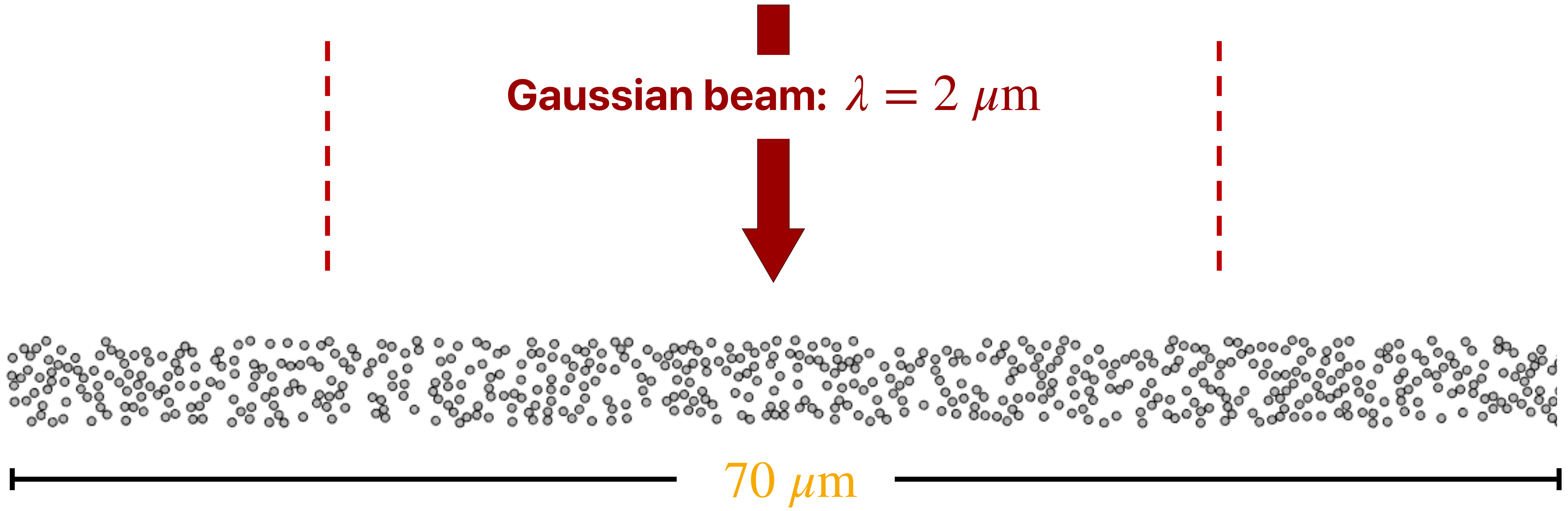
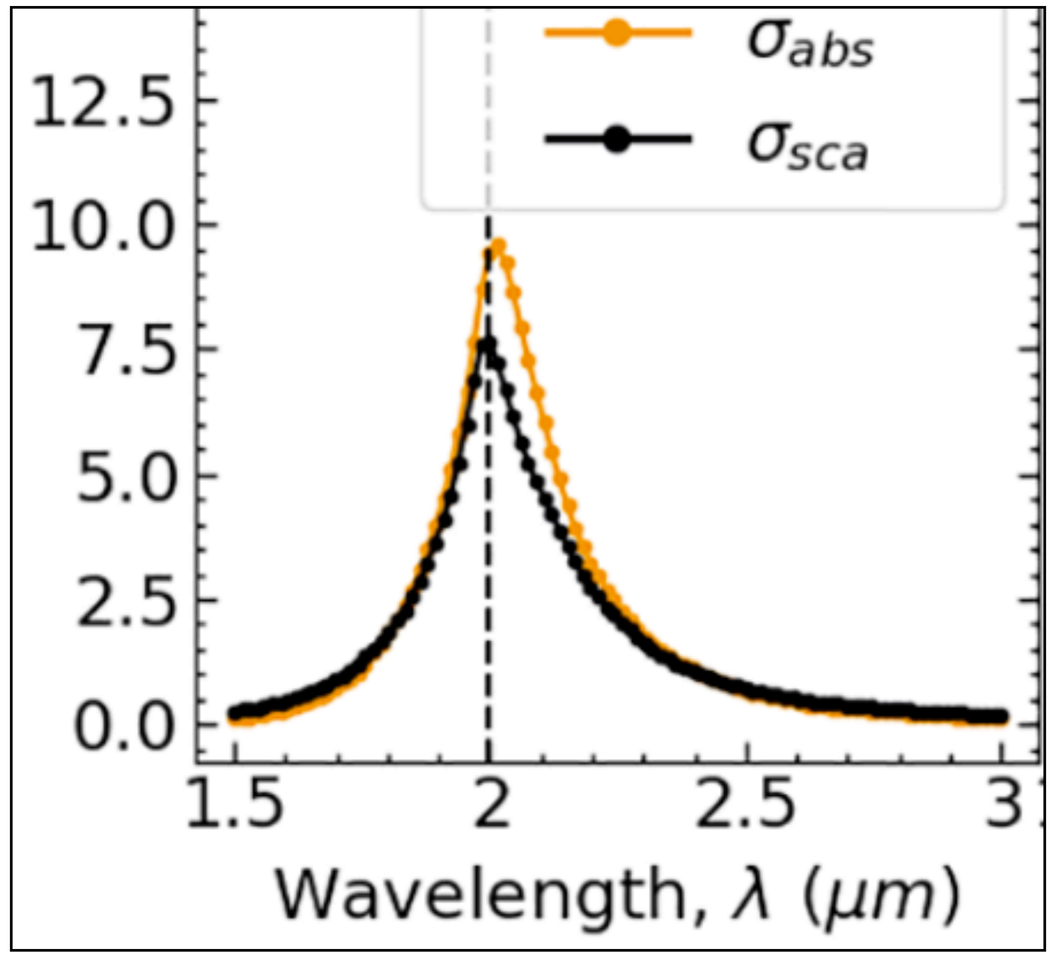
The critical coupling condition is not fulfilled (?)

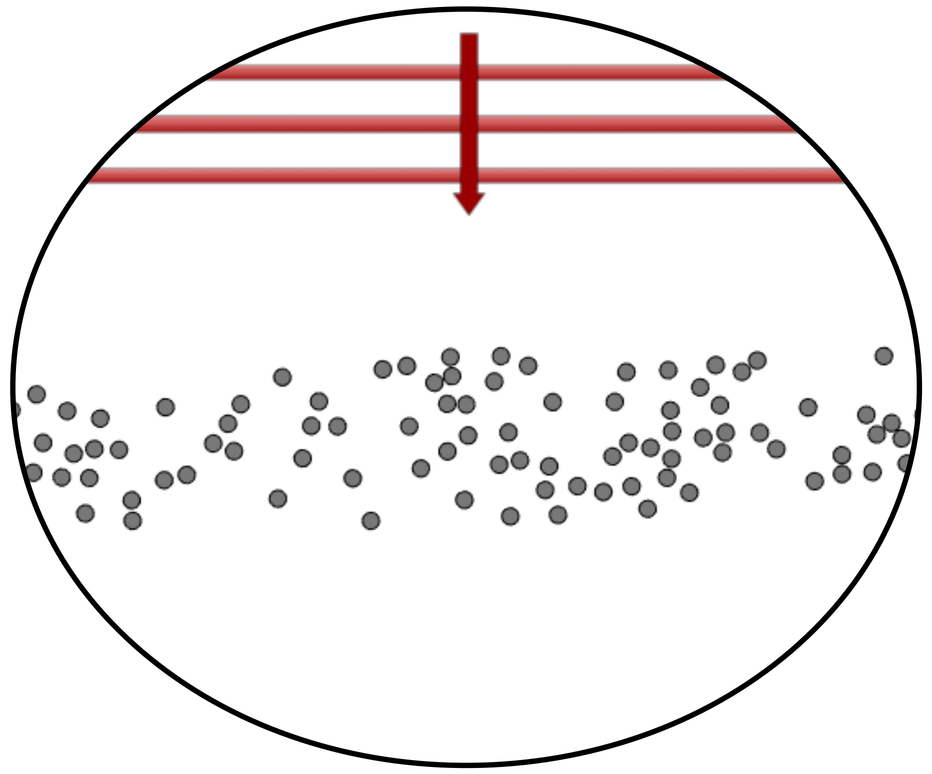
Particles don't scatter a sufficient amount of light (?)

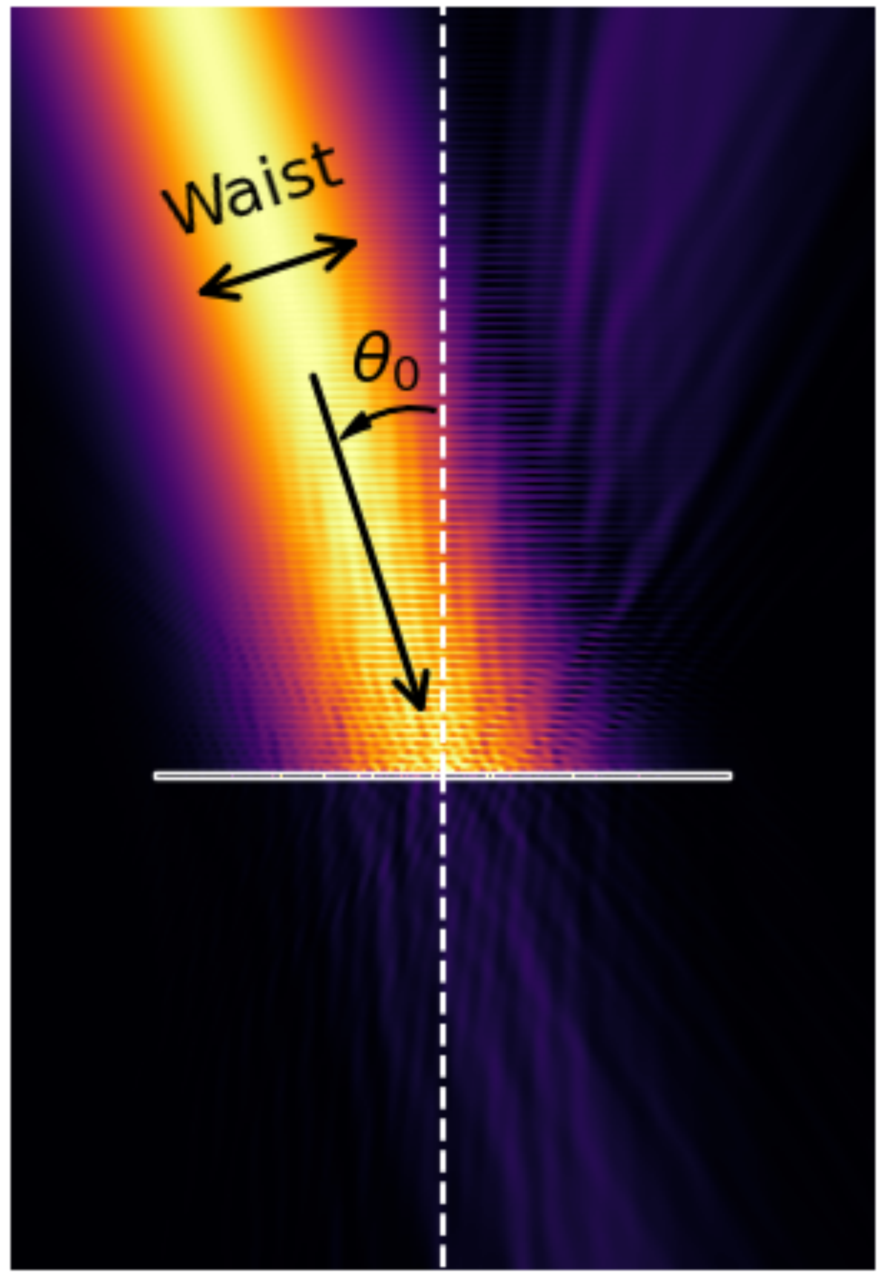




Near perfect absorption: critical coupling mechanism

Increasing the scattering rate of the system by incorporating lossless particles





$A \sim 70\,\%$

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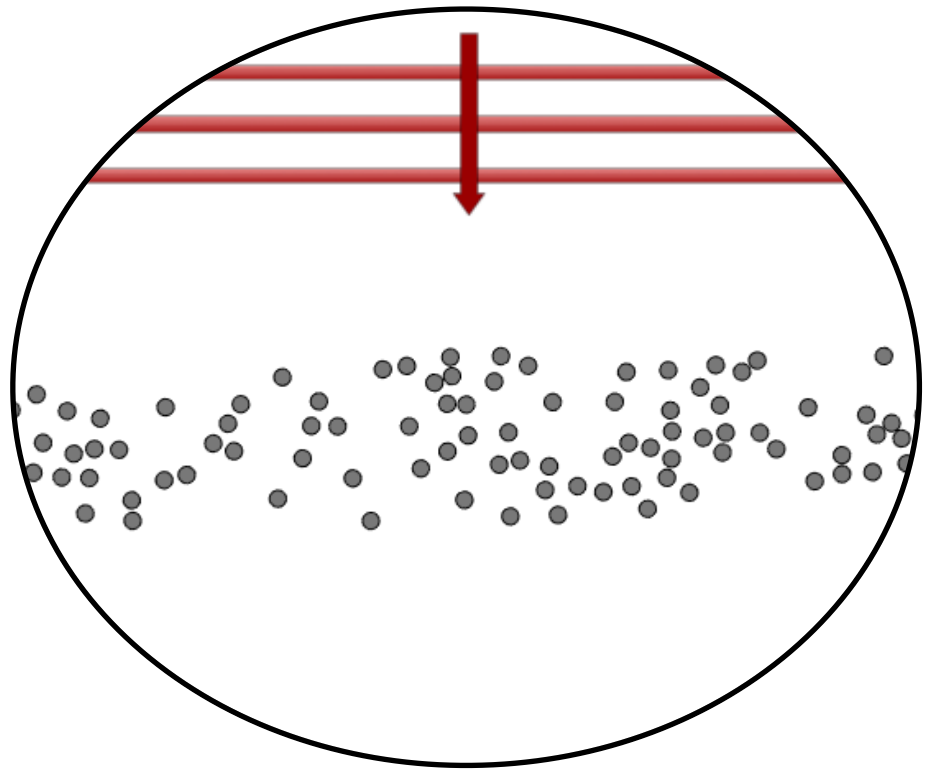

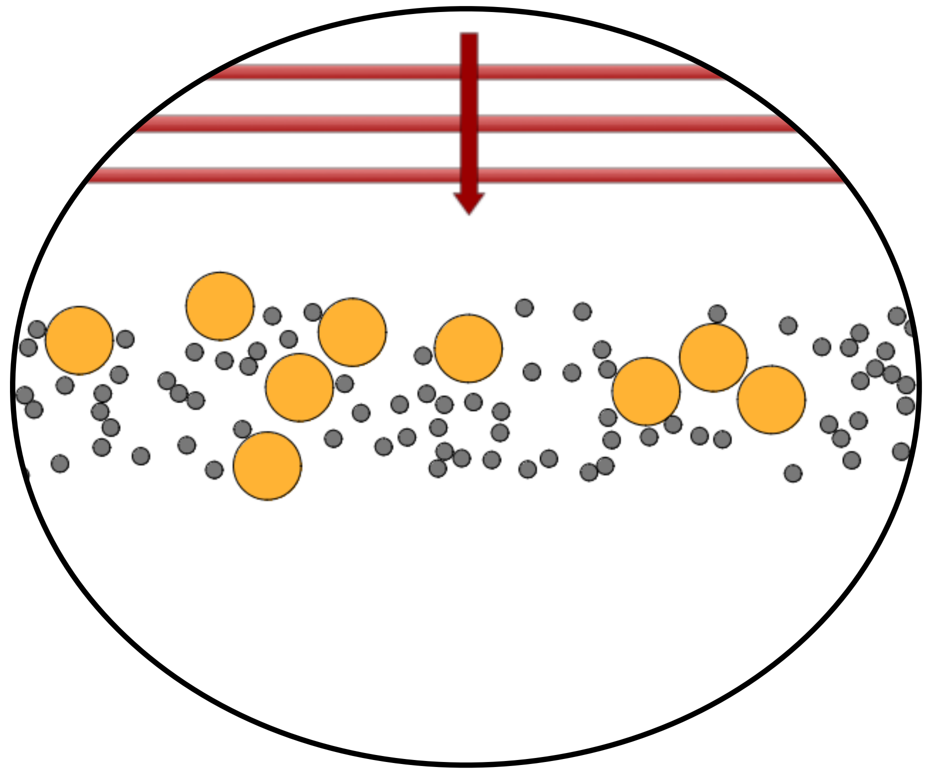

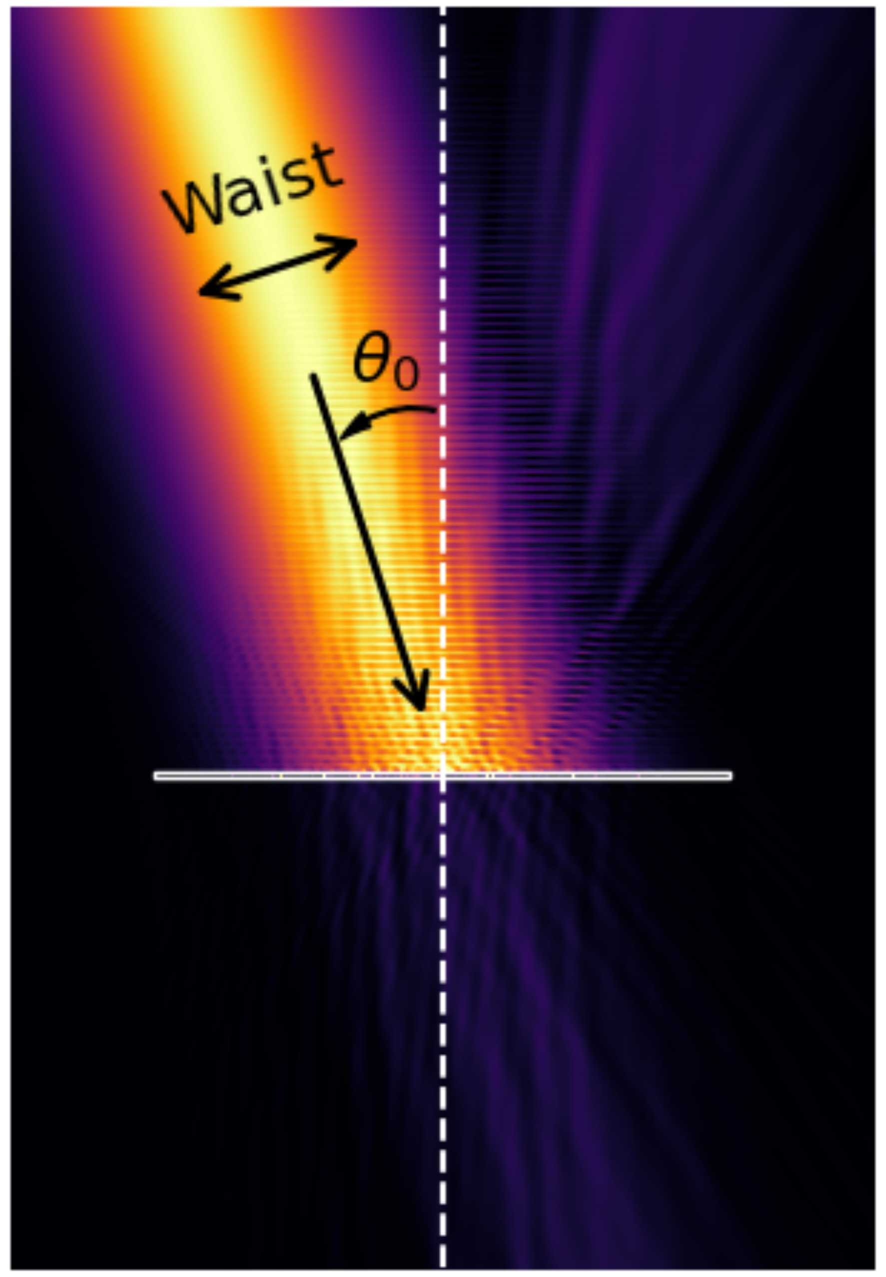

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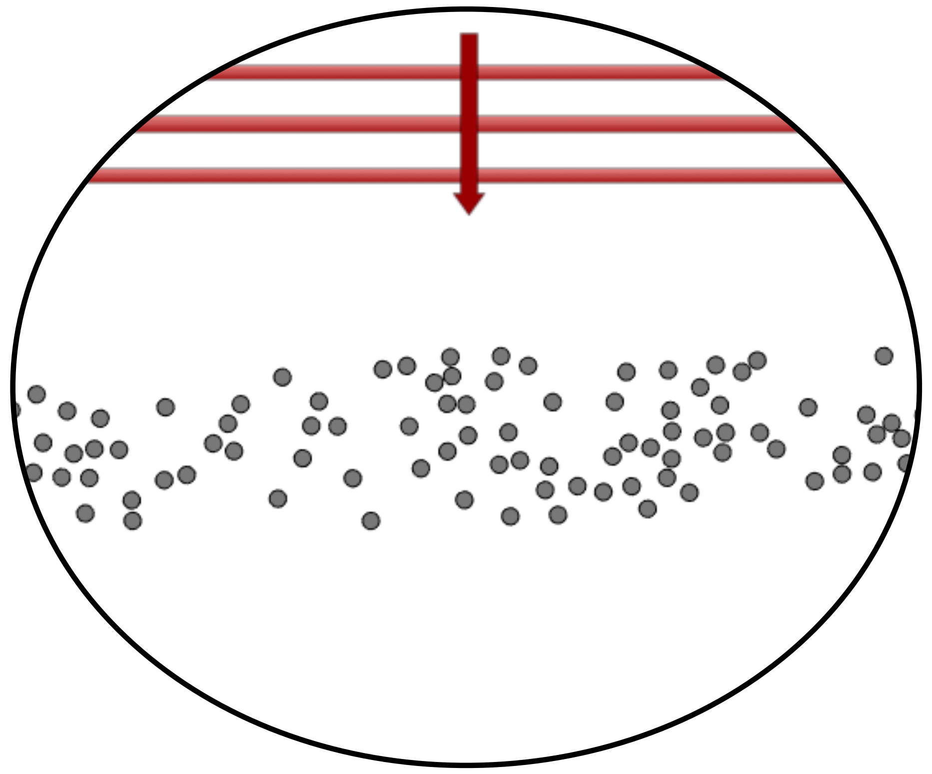

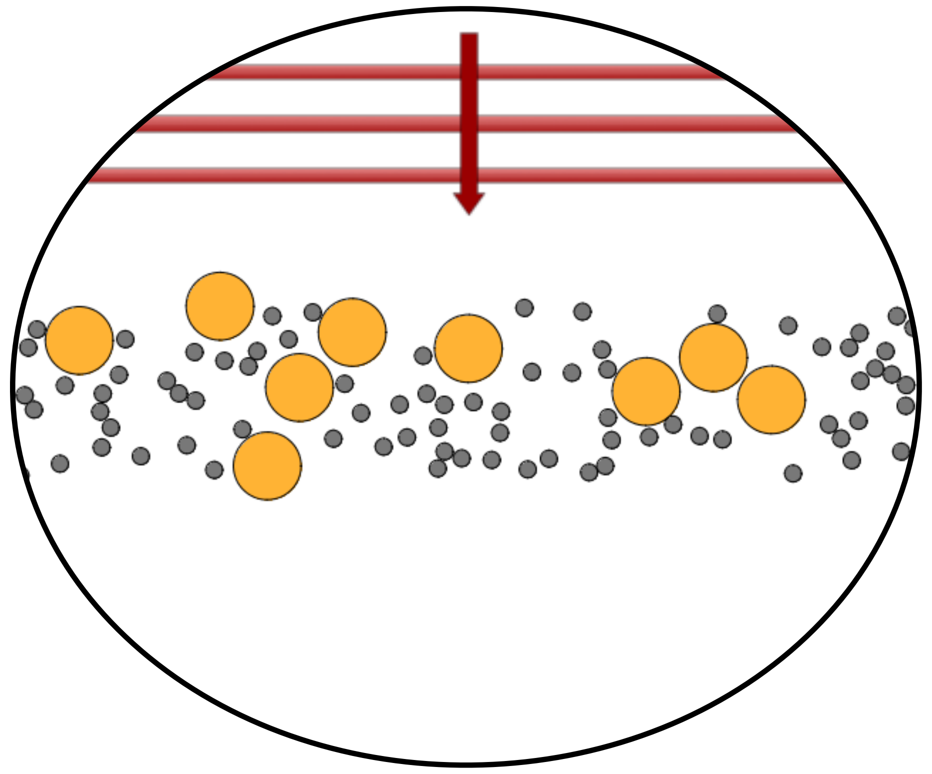

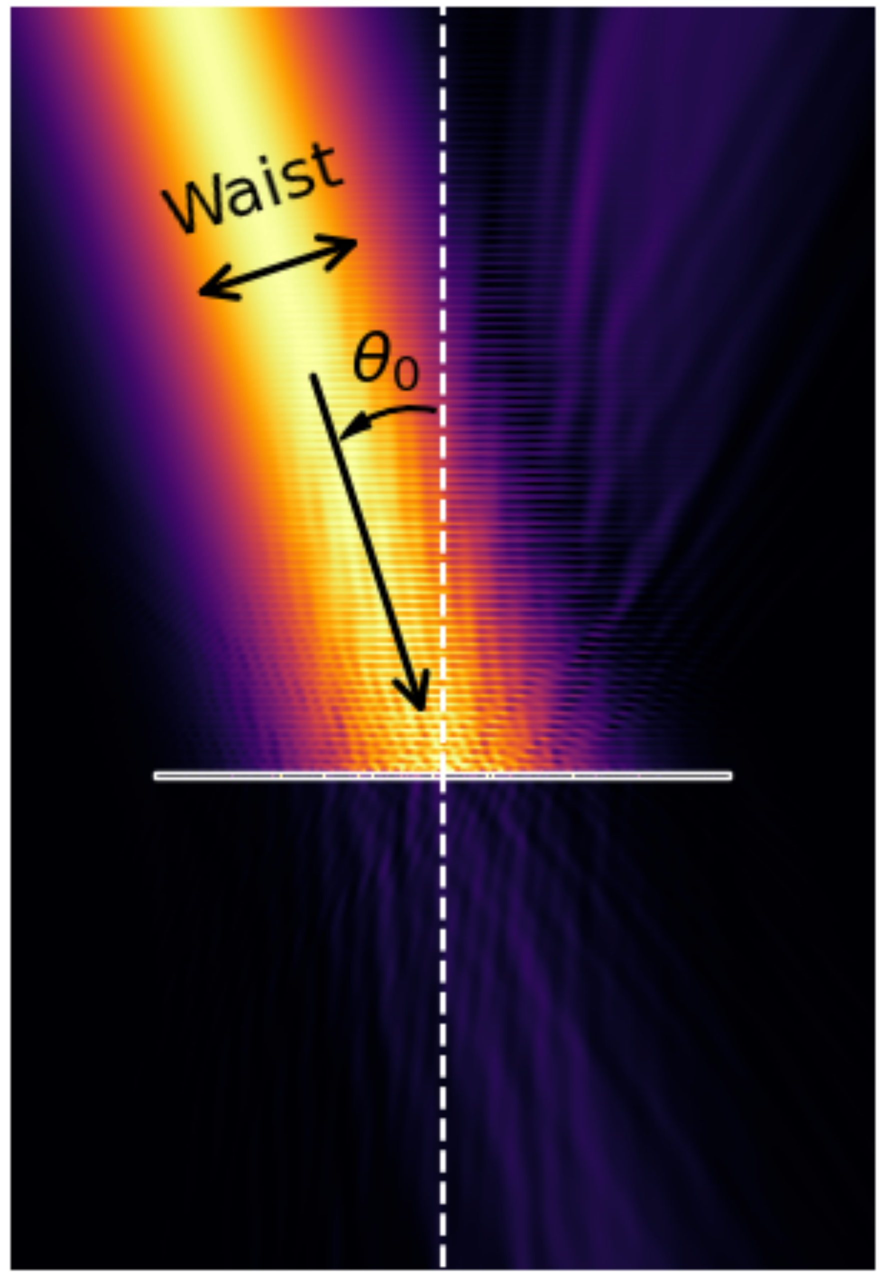

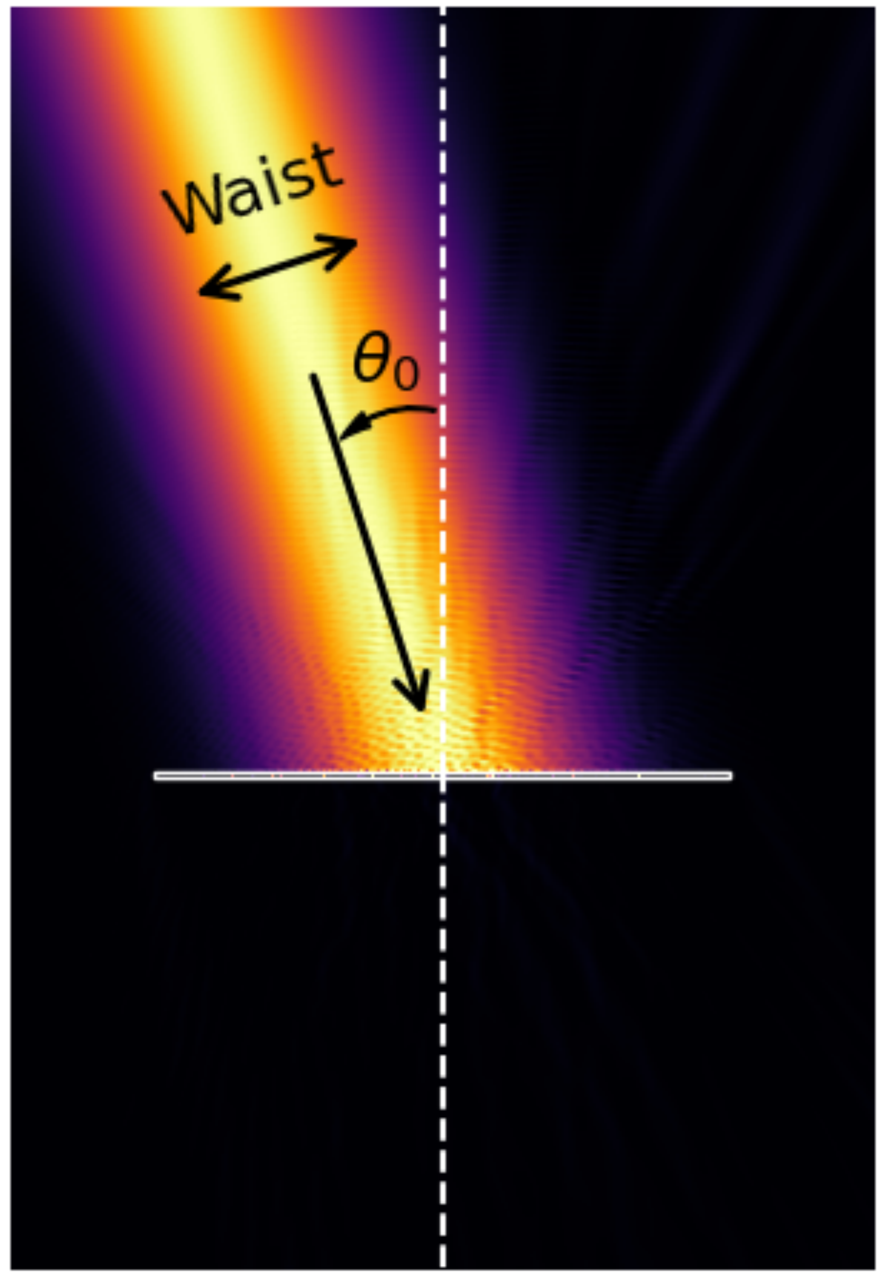

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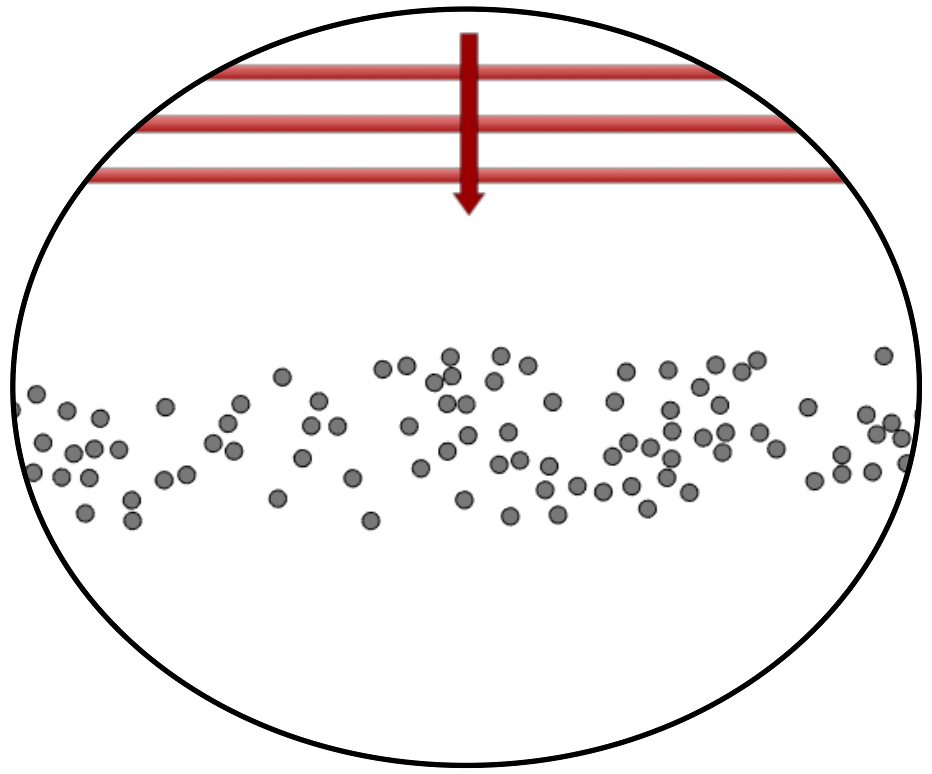

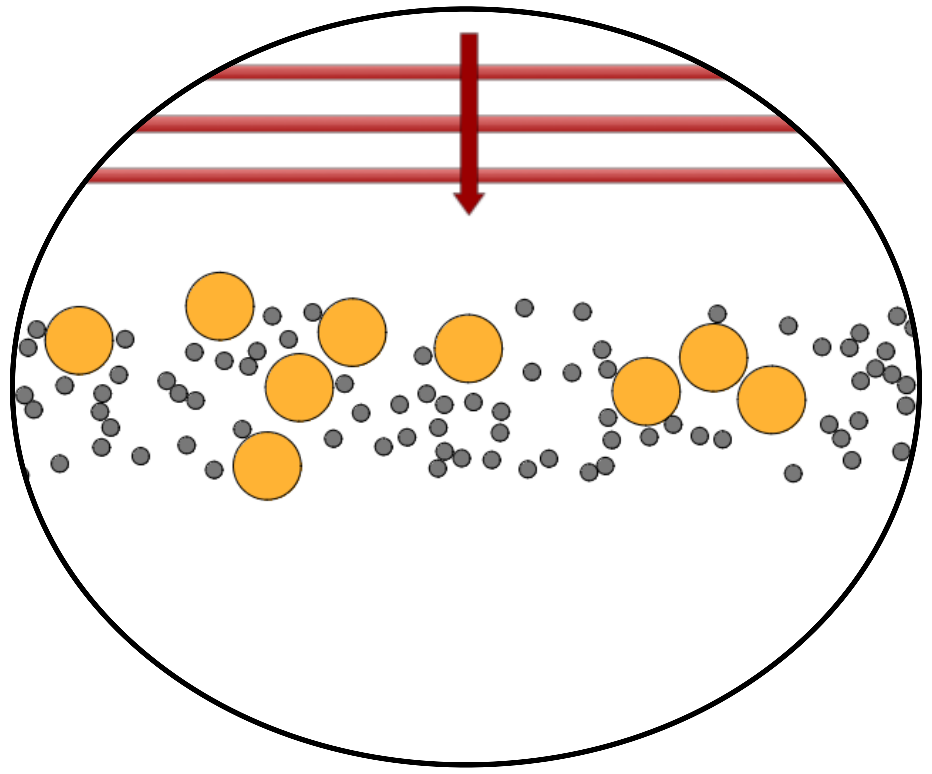

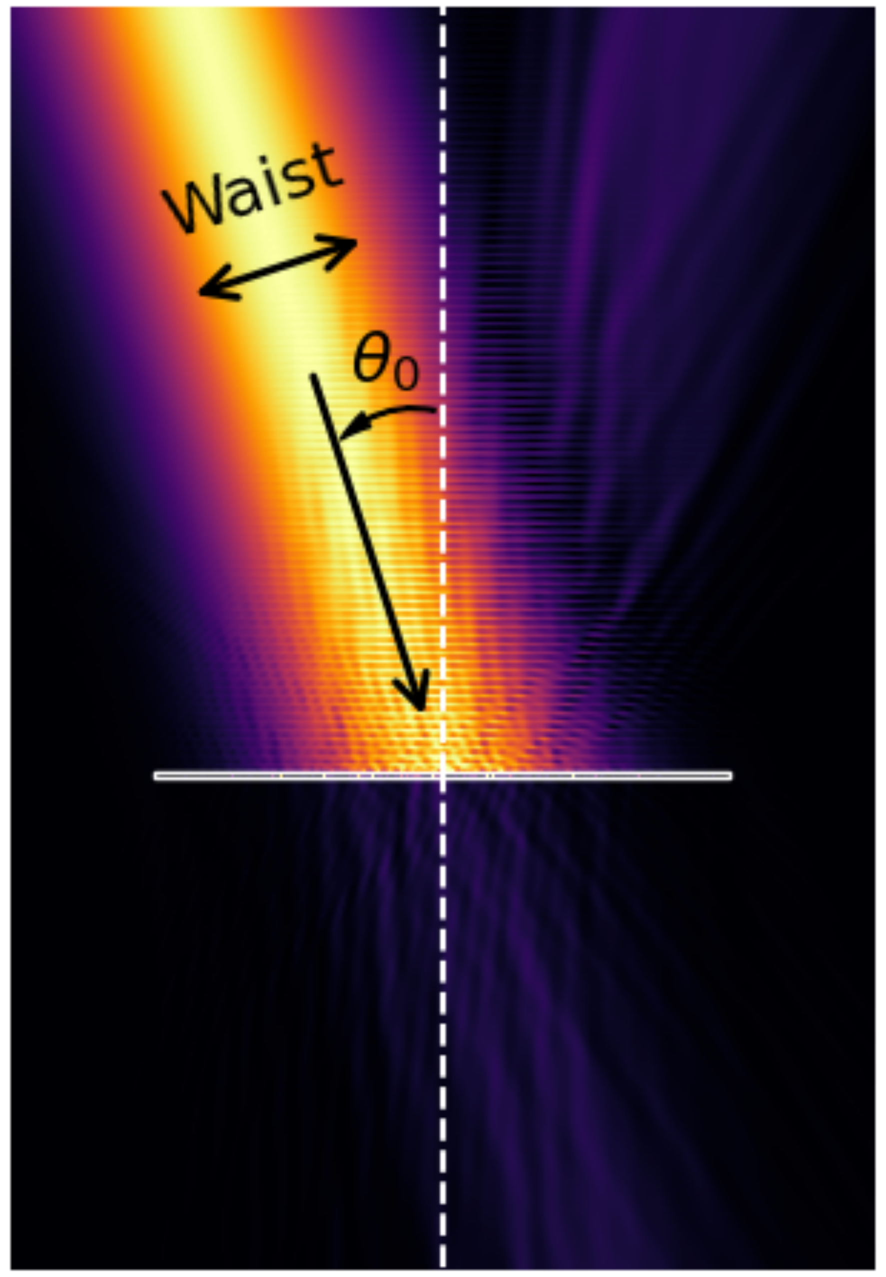

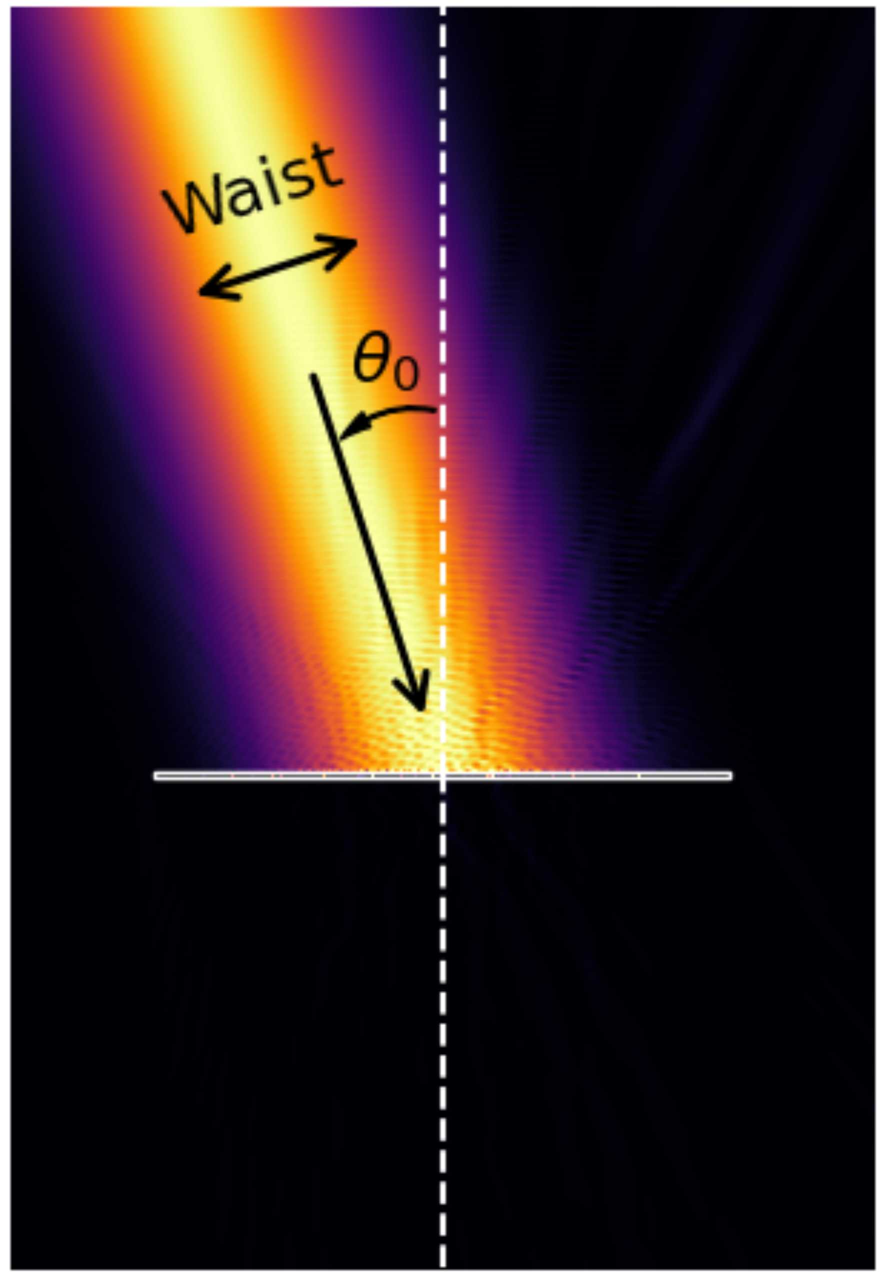

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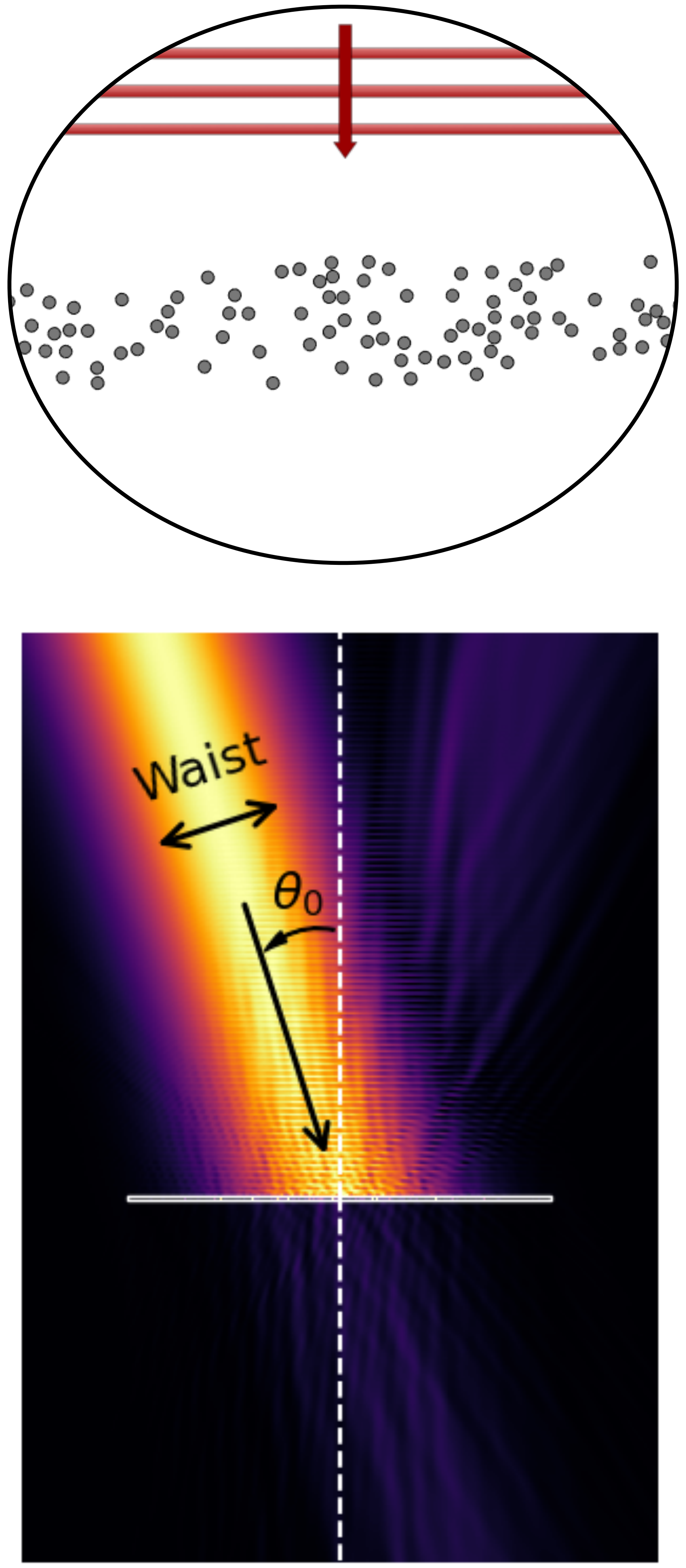

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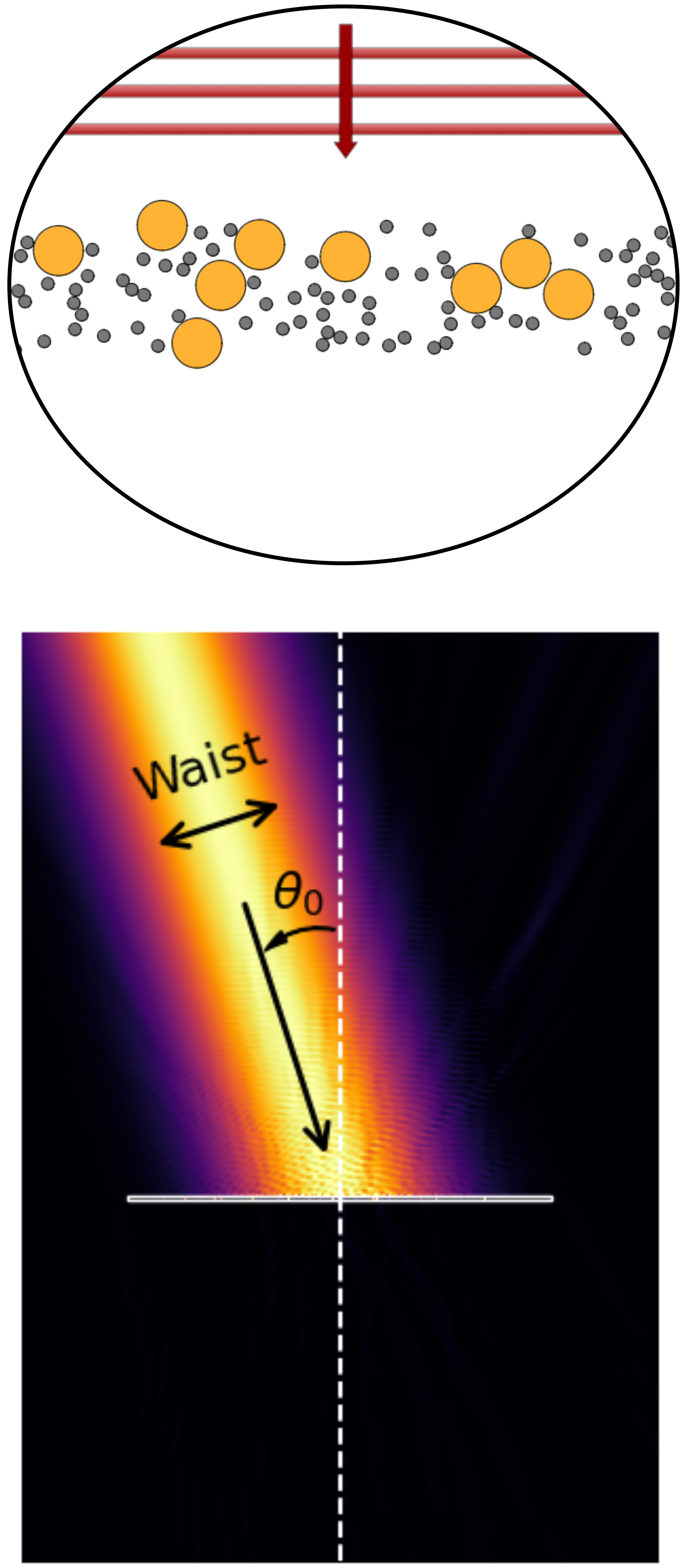

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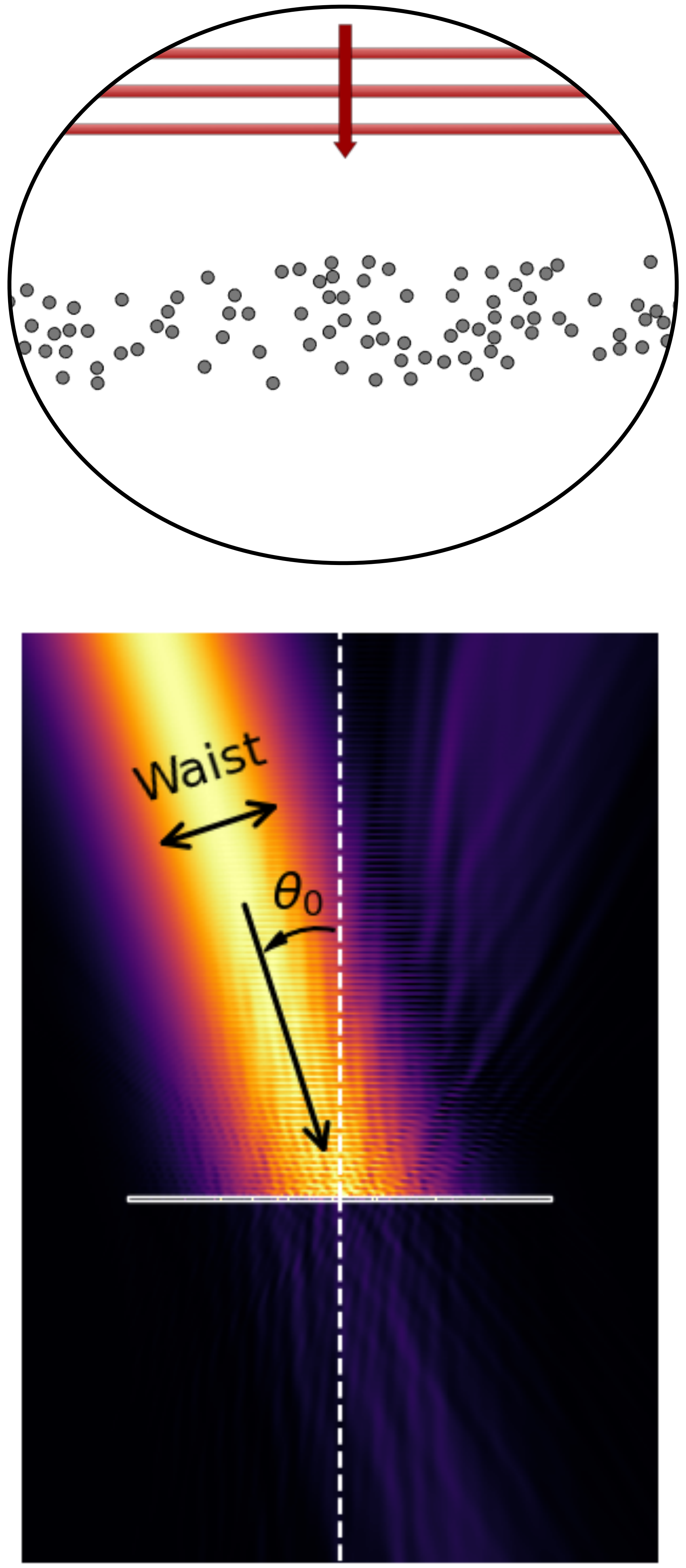
...though the slab is 5 times smaller than λ



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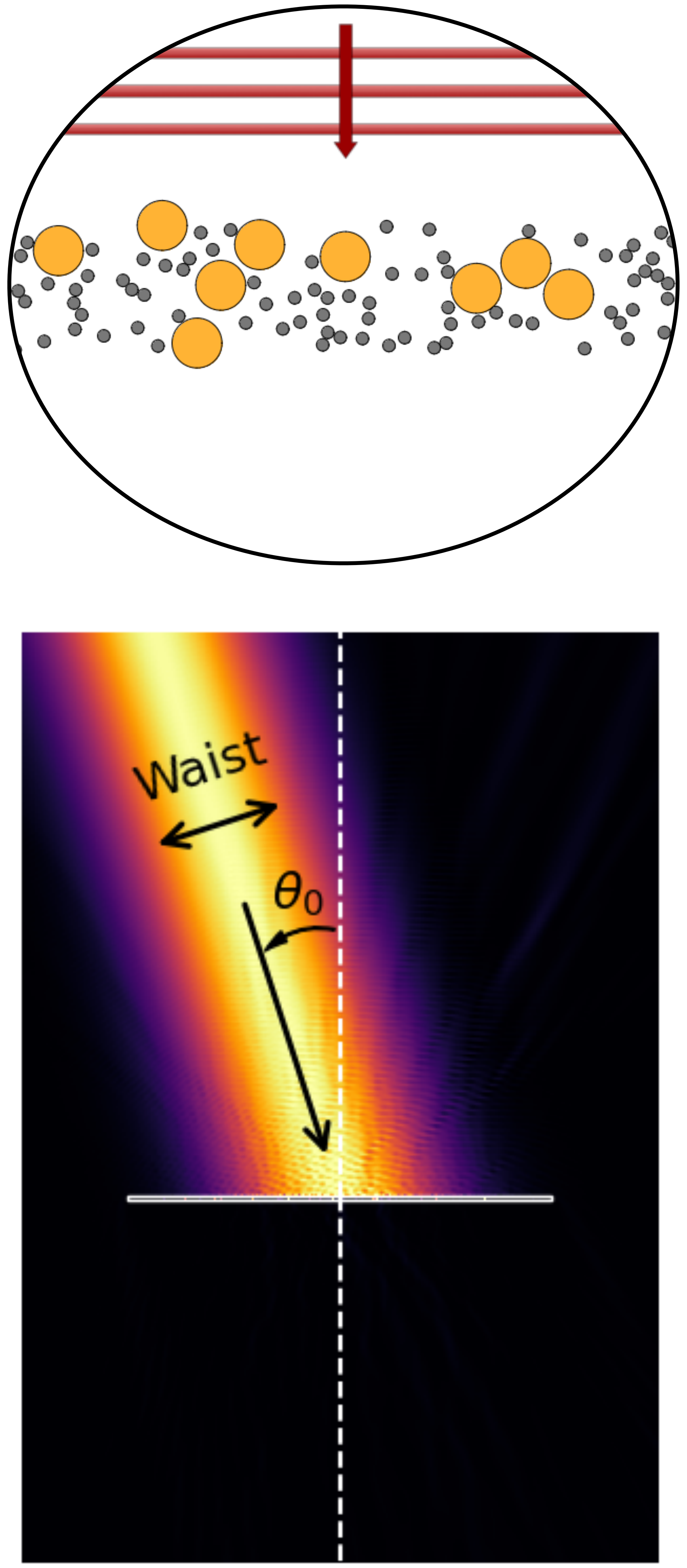

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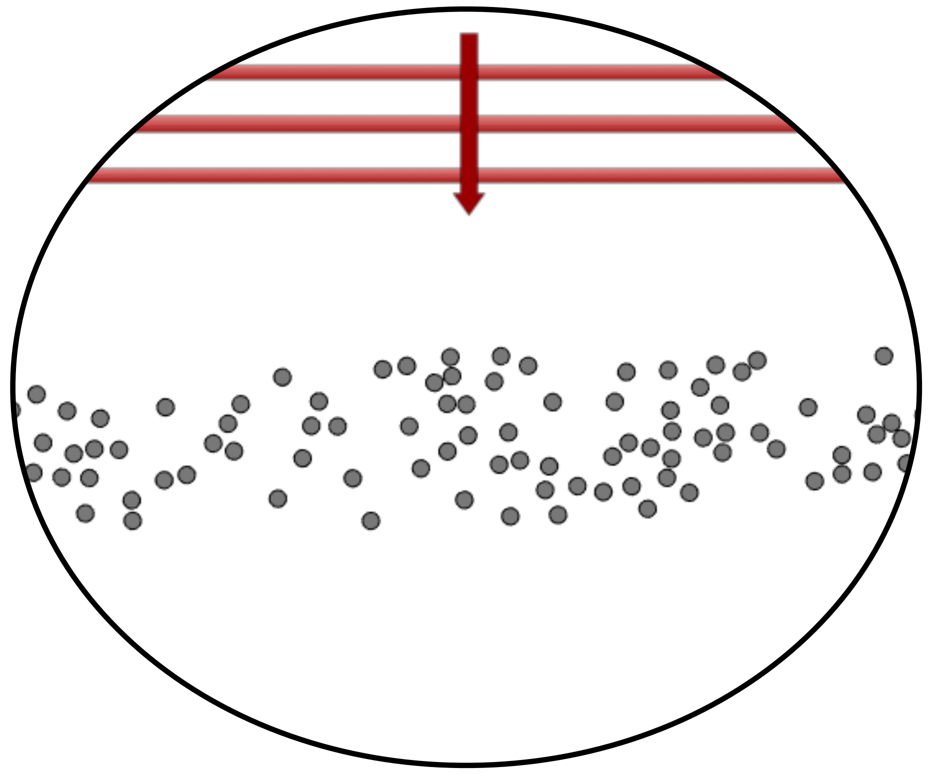

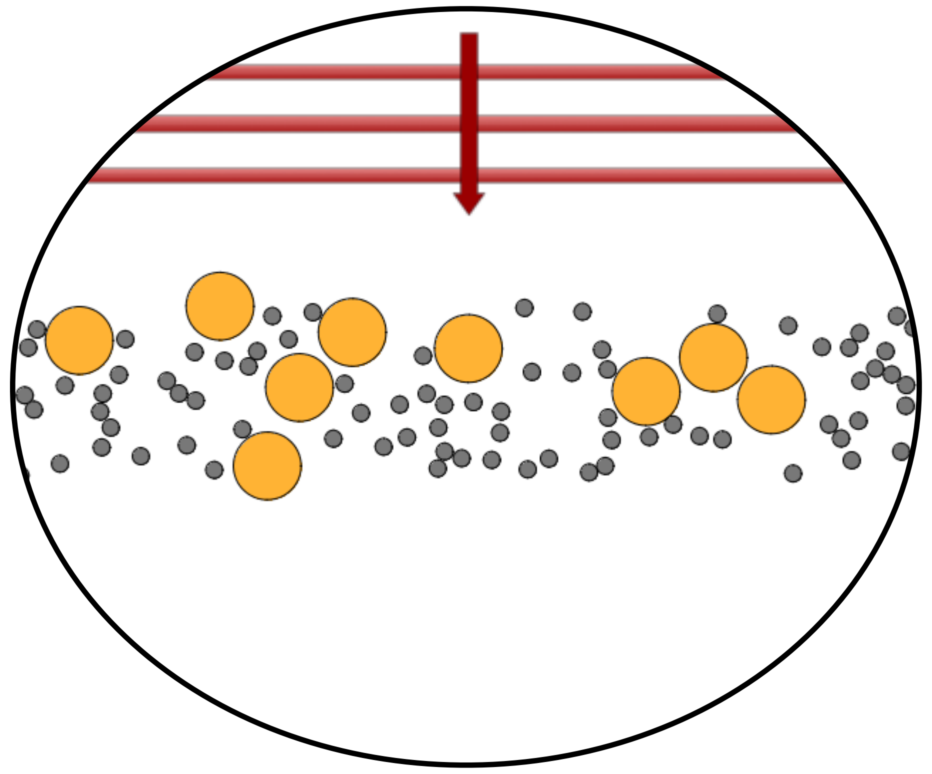

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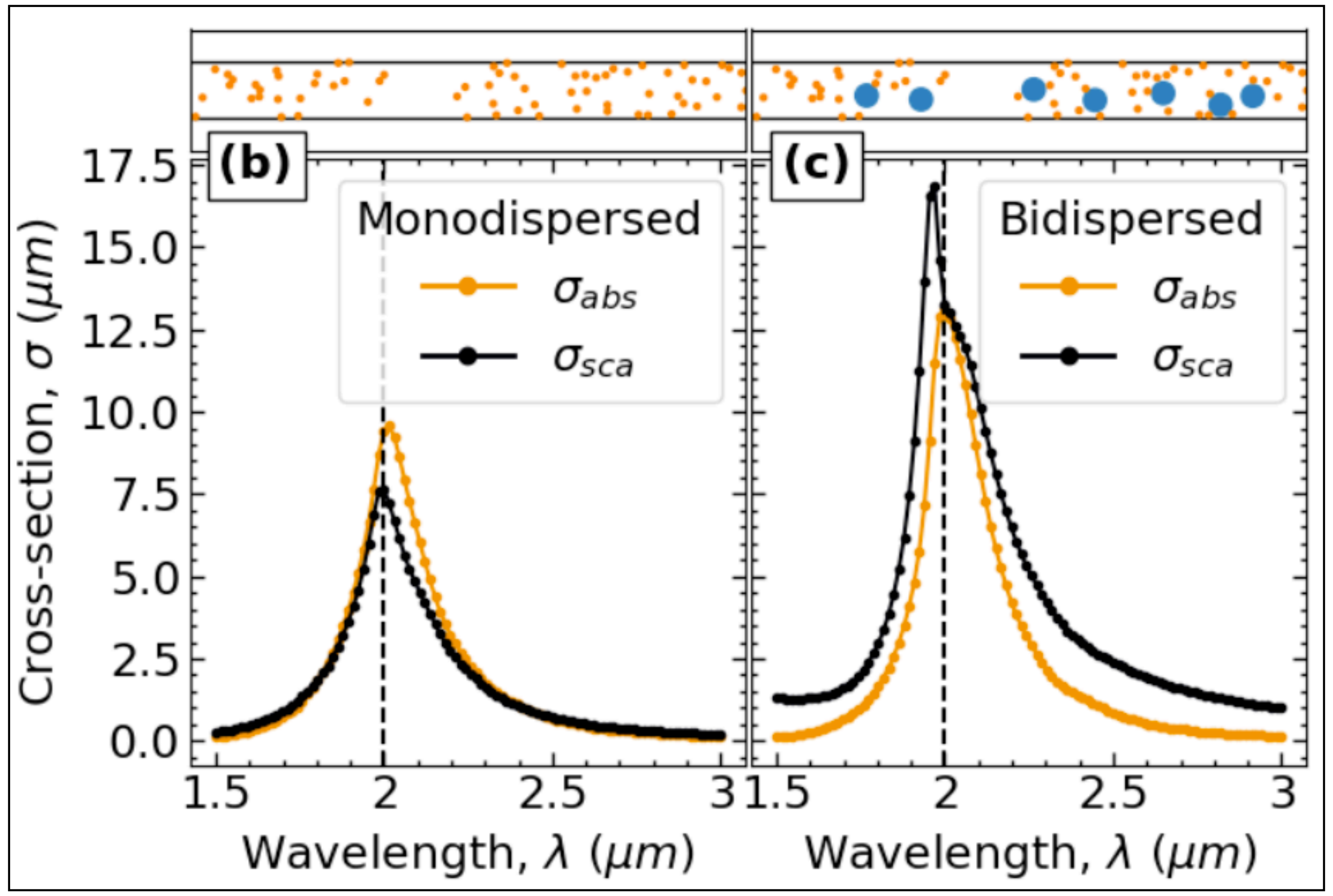

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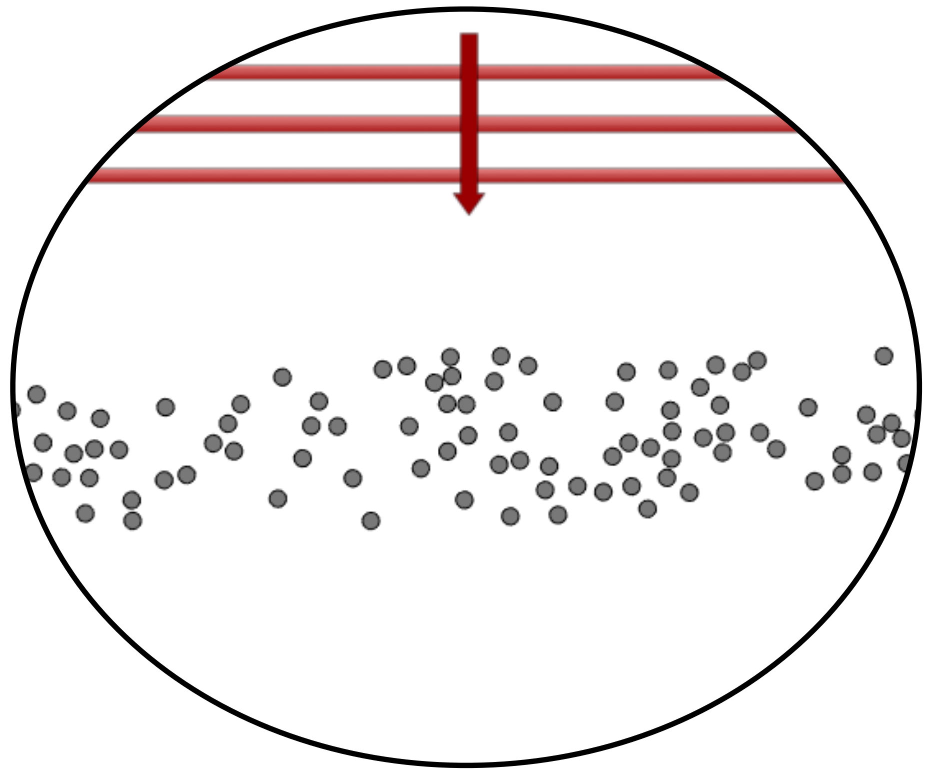

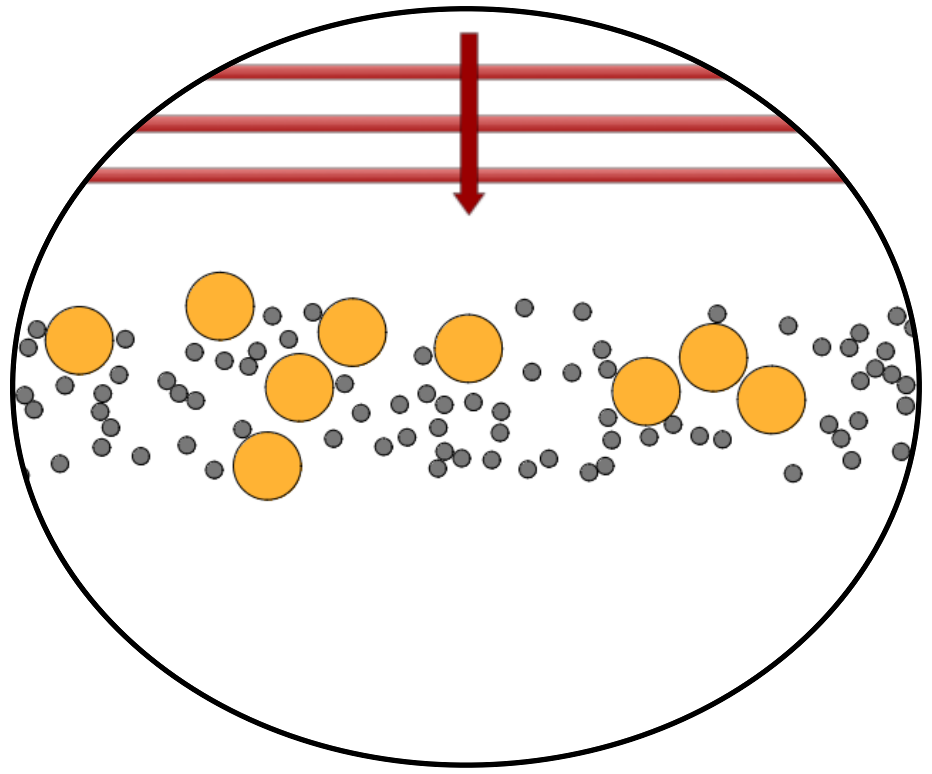

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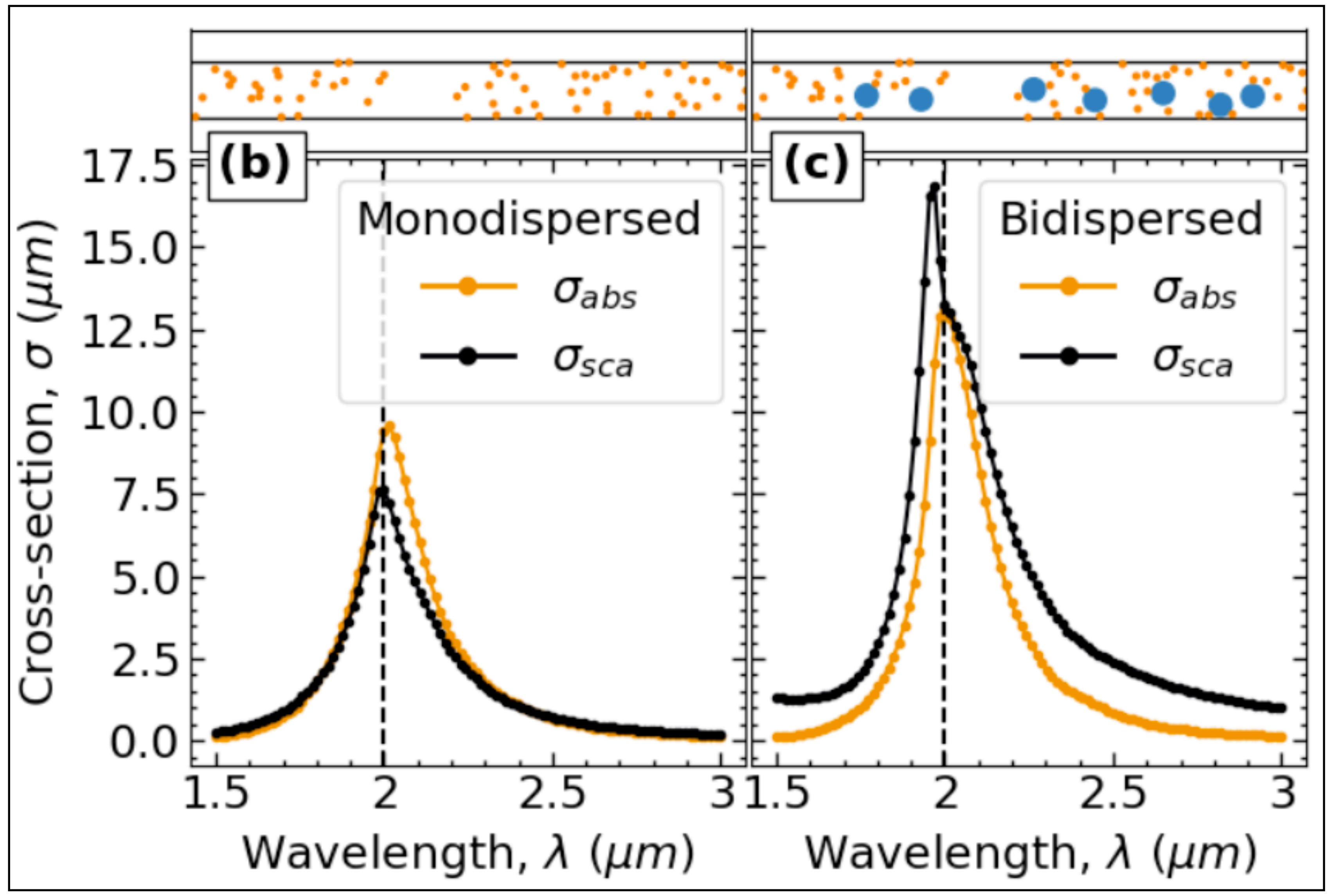

$$\sigma_{\text{abs}} = \sigma_{\text{sca}}$$

Critical coupling at $\lambda = 2\ \mu\text{m}$

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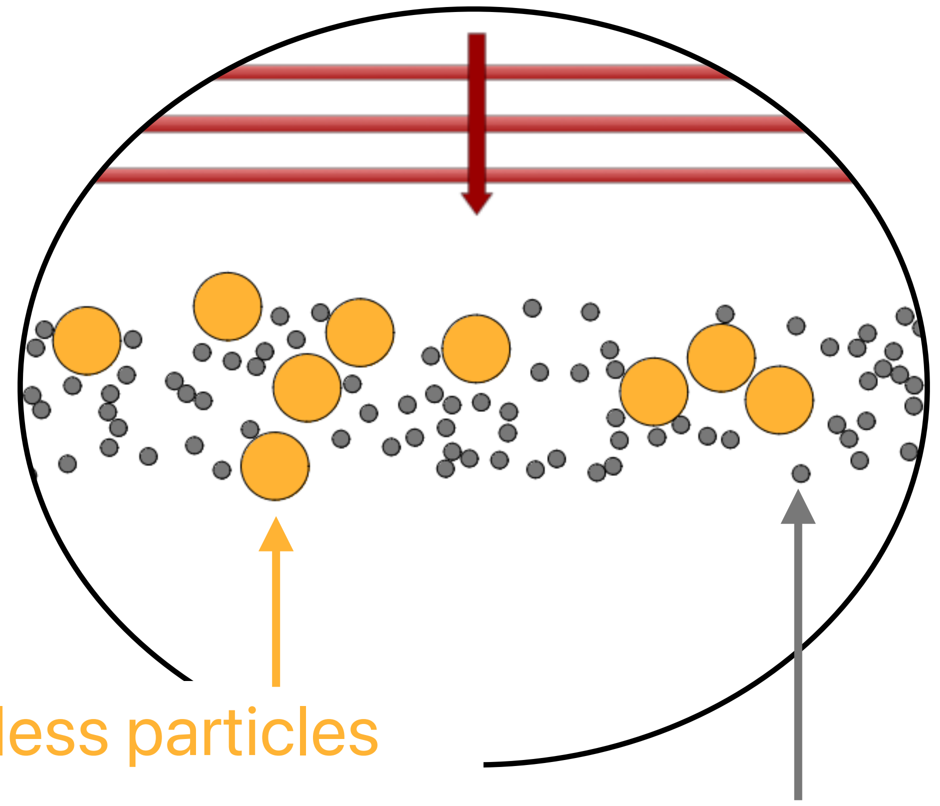
Near perfect absorption: performances



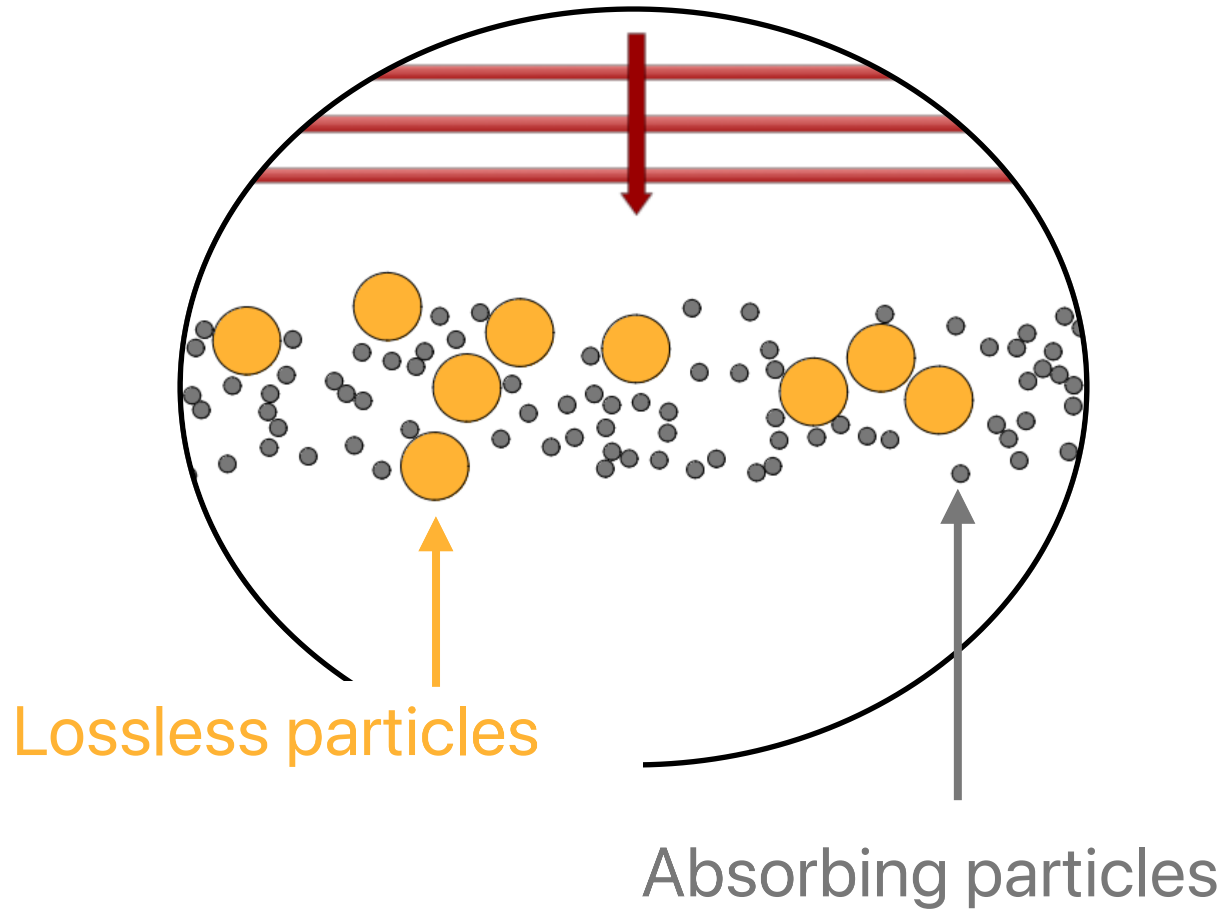
$$\varepsilon_p(\omega) = 1 - \frac{\left(\omega_0\omega_p\right)^2}{\omega^2 + i\omega\omega_0\gamma}$$

f_p	ω_p^{bi}	γ^{bi} (10^{-3})	n_d
0.01	1.418	5.893	9.561
0.02	1.418	9.971	9.518
0.03	1.421	15.30	9.499
0.04	1.424	16.99	9.534
0.05	1.424	20.18	9.503
0.10	1.435	26.57	9.607
0.15	1.439	32.26	9.608

Near perfect absorption: performances

An optimized system can be found irrespective of the fill factor

$0.01 < f_p < 0.15$



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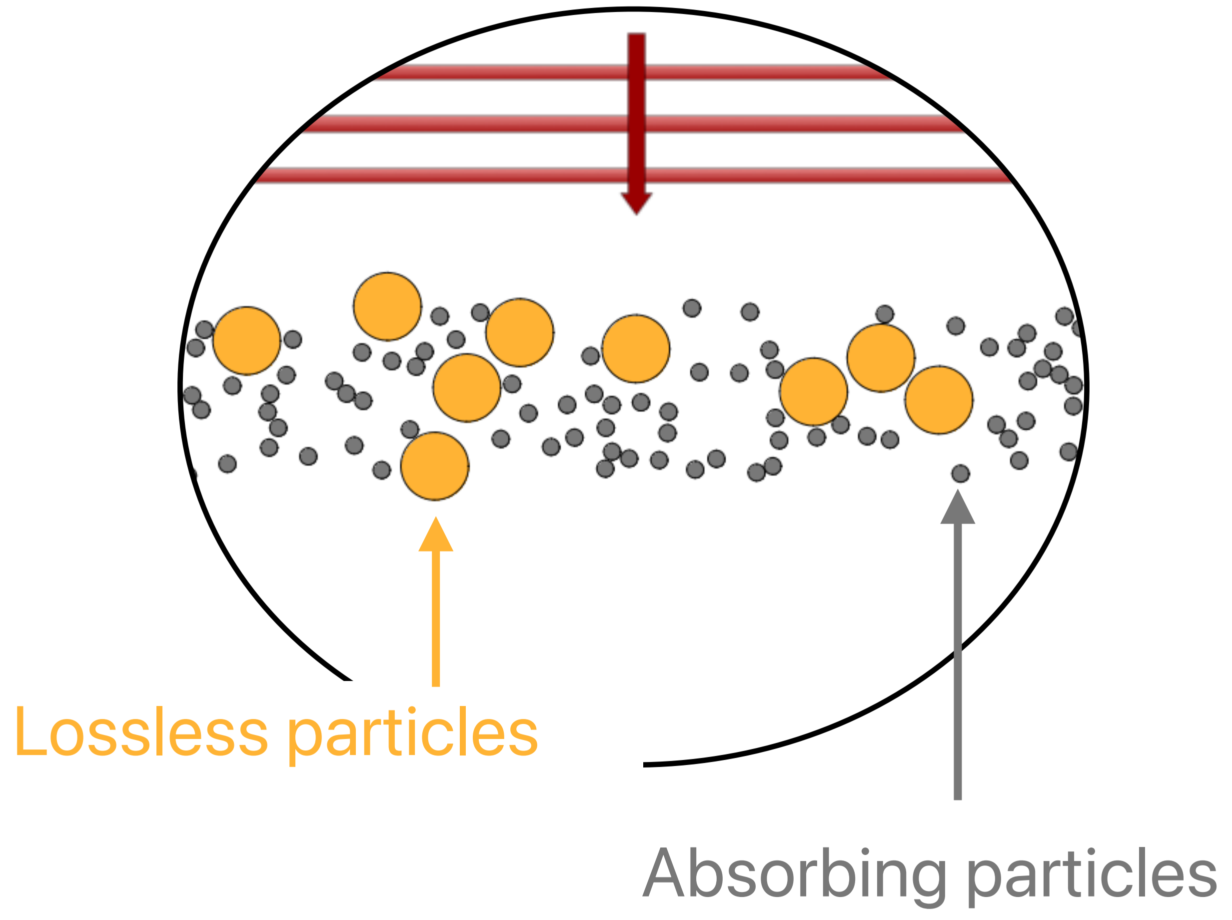

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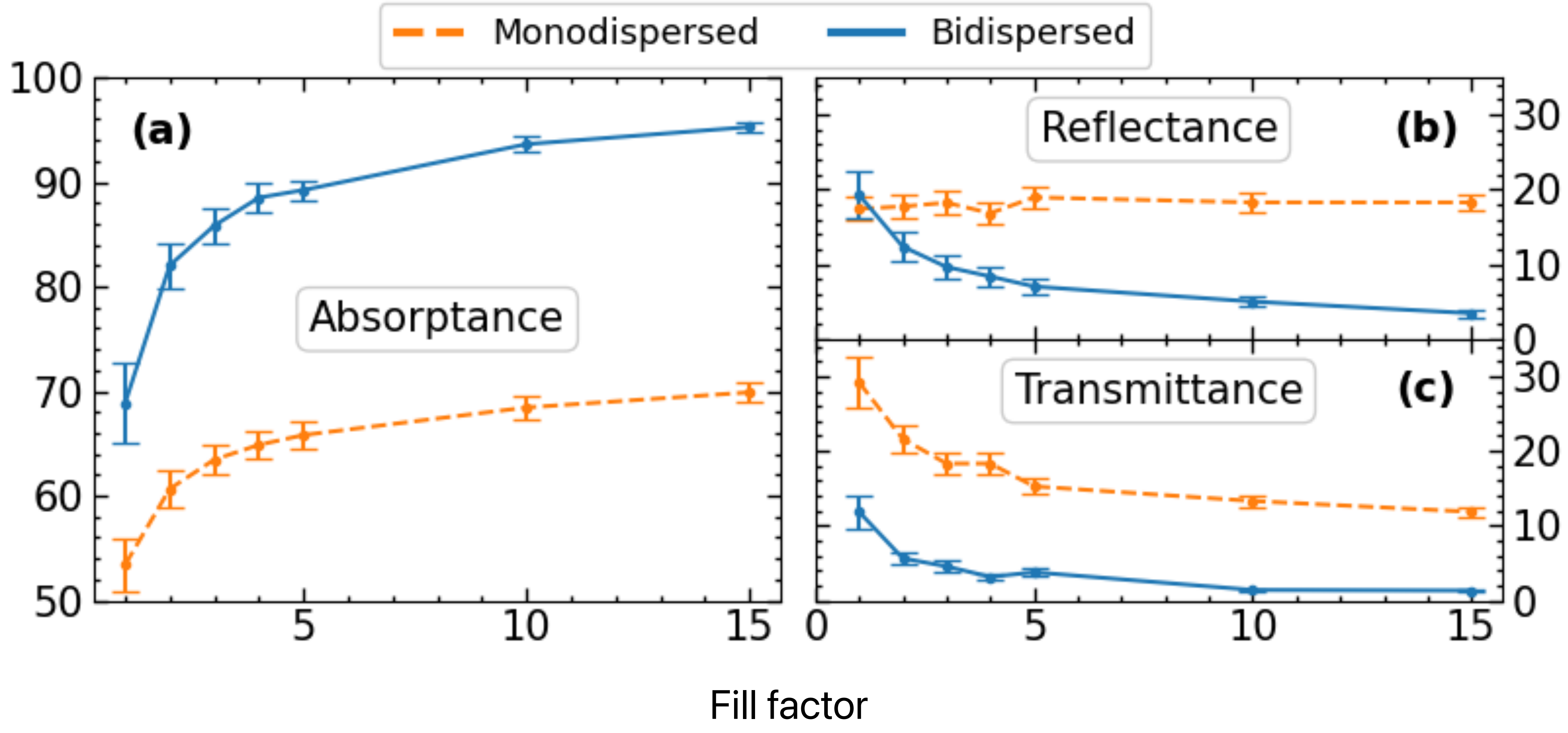

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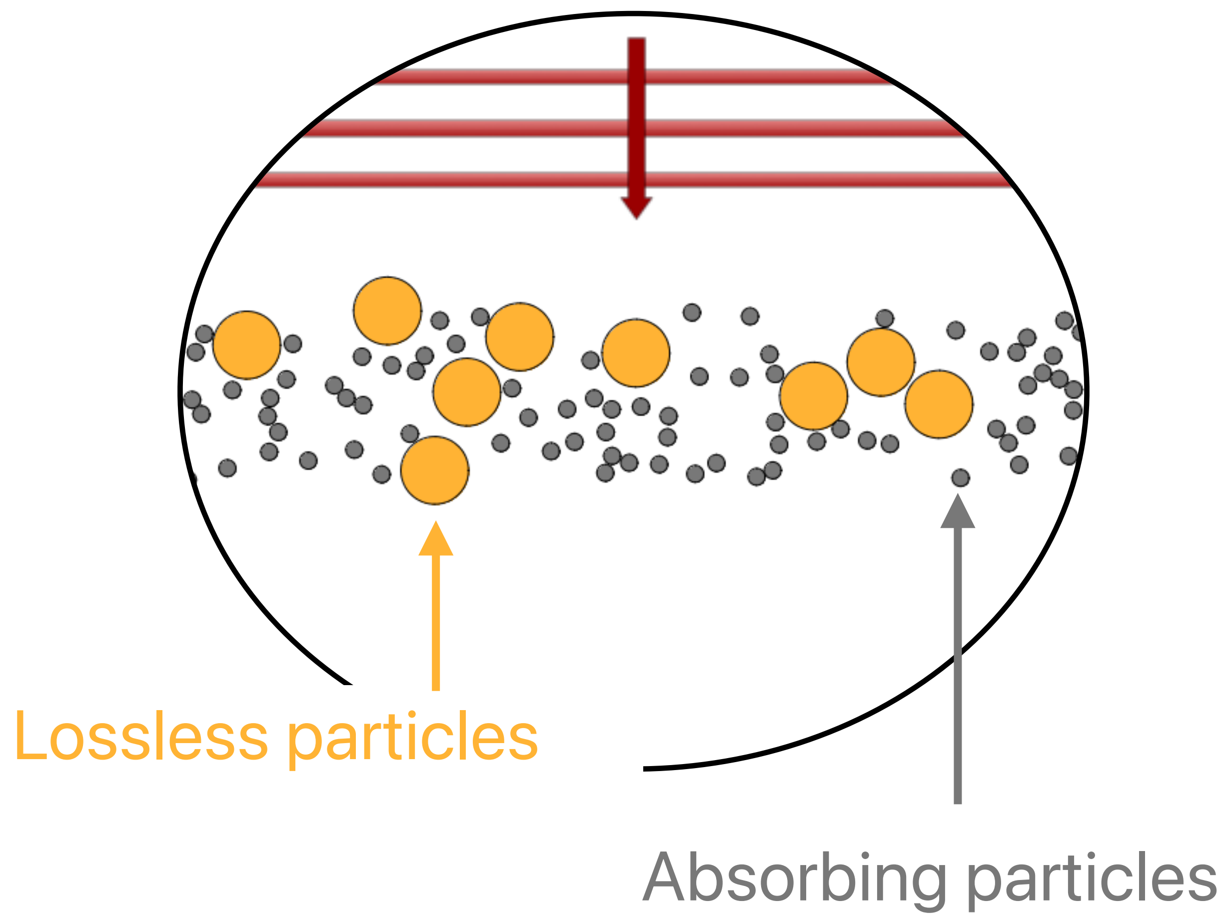
Strong increase of absorptance



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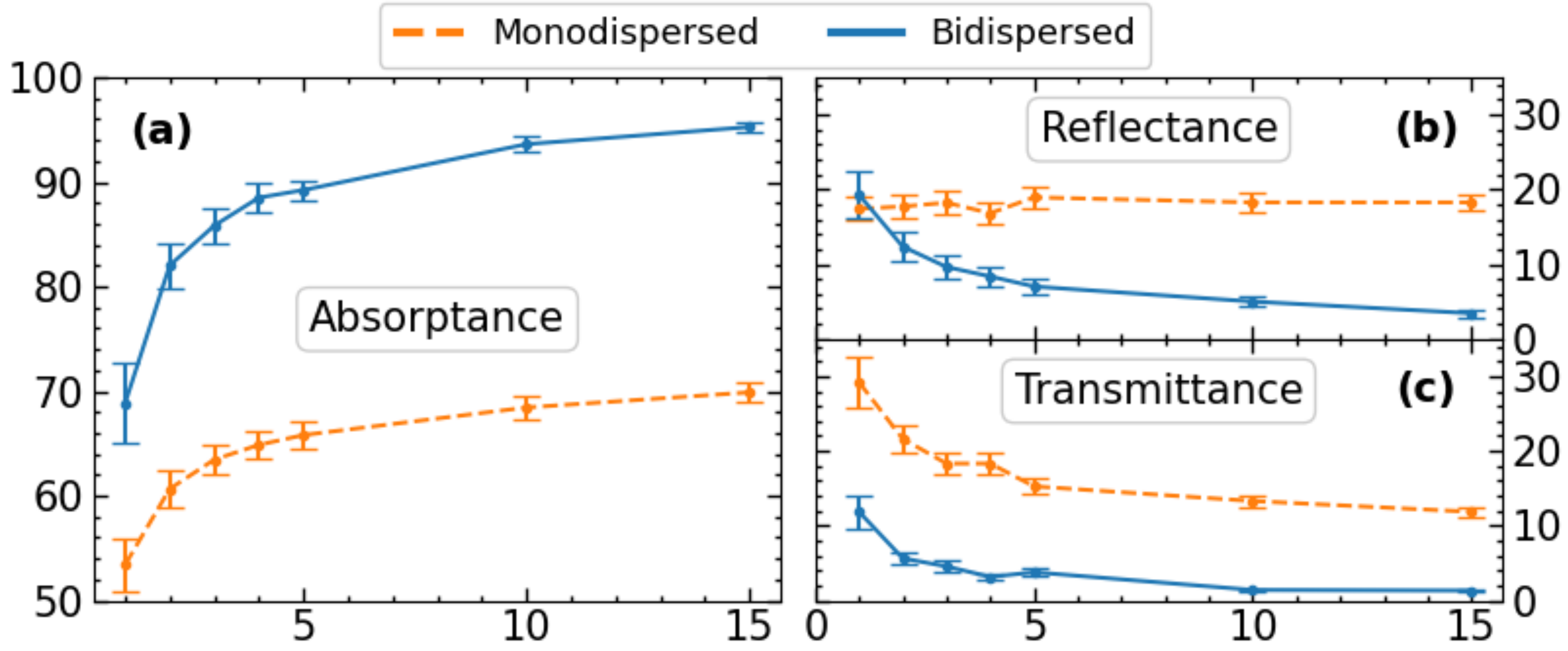

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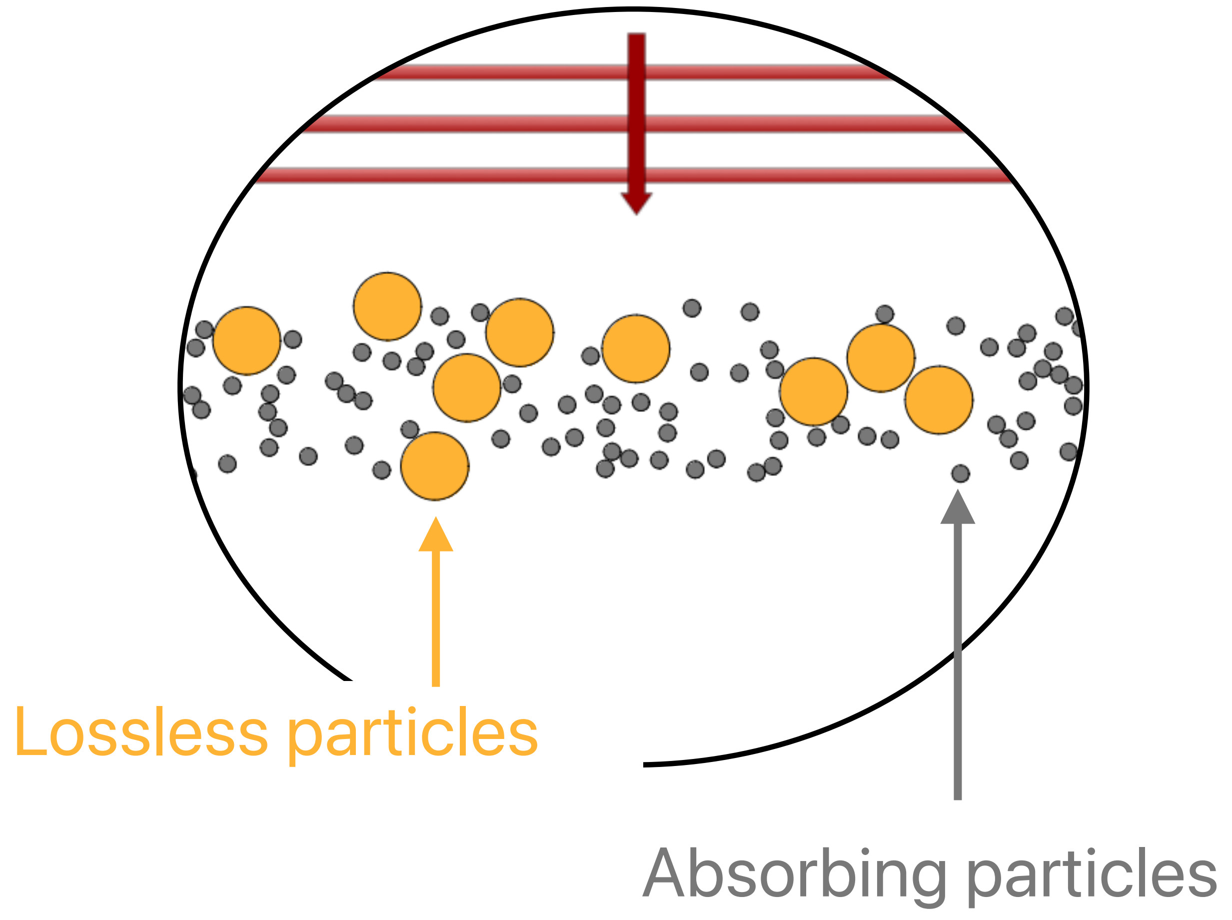

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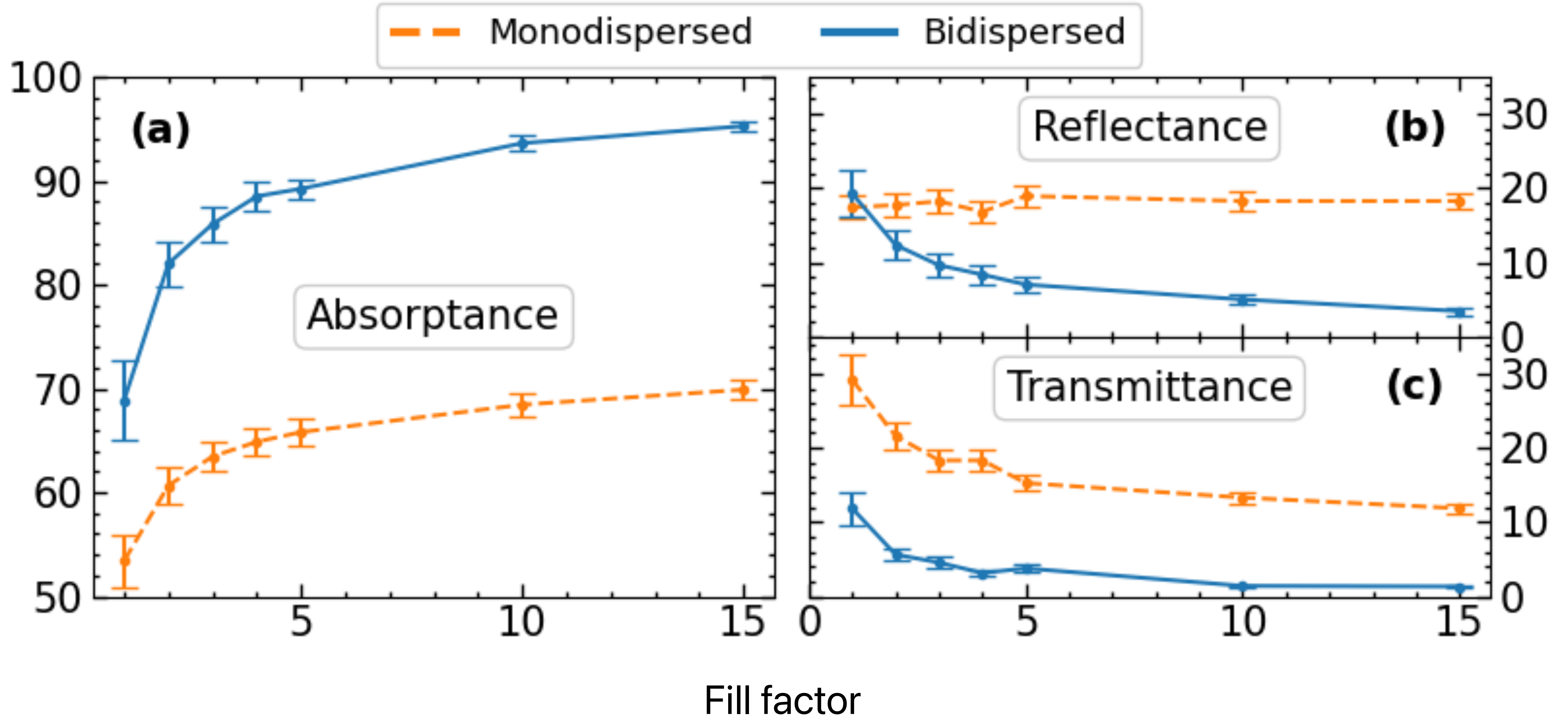
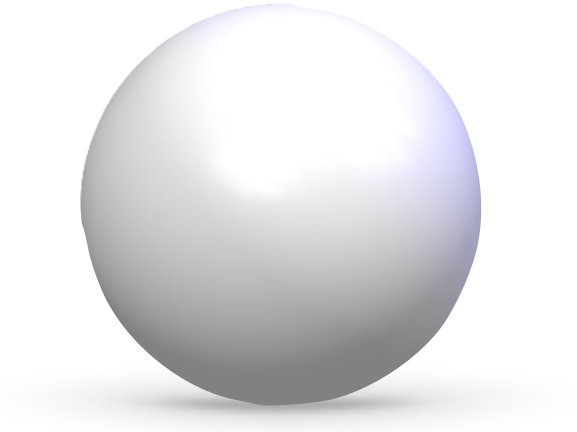


- **Monodisperse**: reflection plateaus at 20%
- **Bidisperse**: continuous tendency toward a reflectionless structure

Near perfect absorption: about the design of lossless particles



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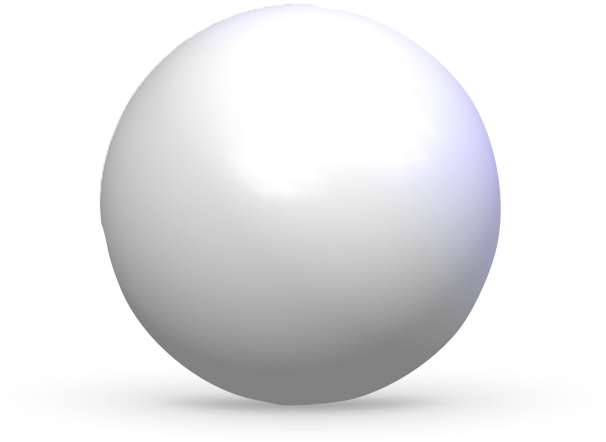
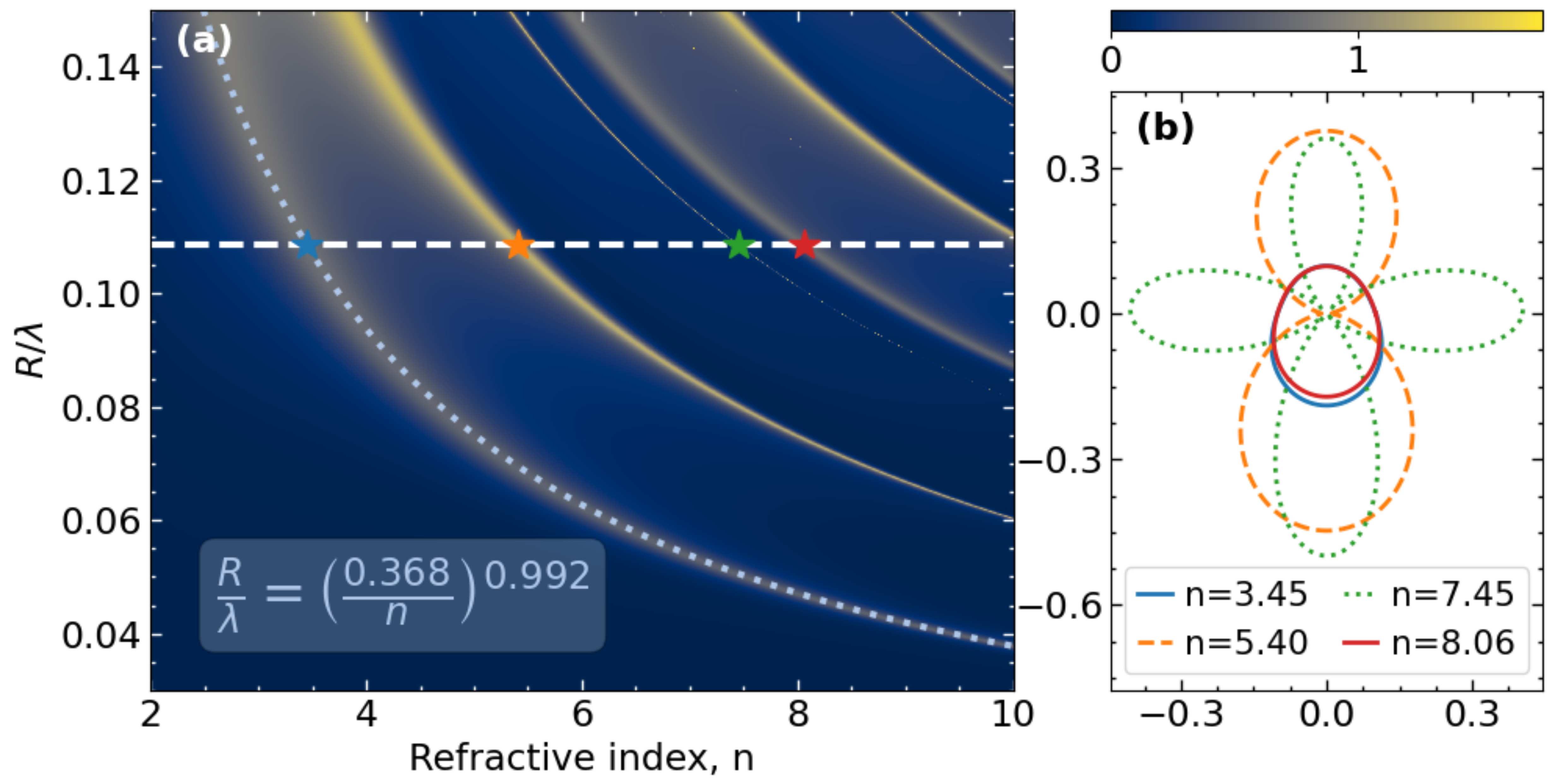
Near perfect absorption: about the design of lossless particles

Mie's theory shows branch of maximum scattering



Scattering cross-section for **one** particle

Angular plot for the **4 modes**



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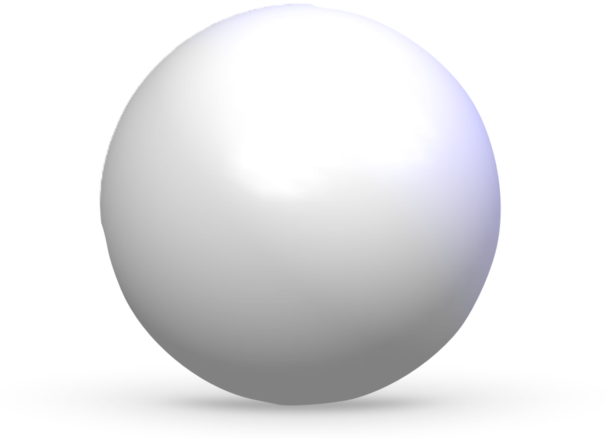
- ➡ Only isotropic radiations lead to absorption enhancement
- ➡ Otherwise the absorption is decreased compared to monodispersed systems



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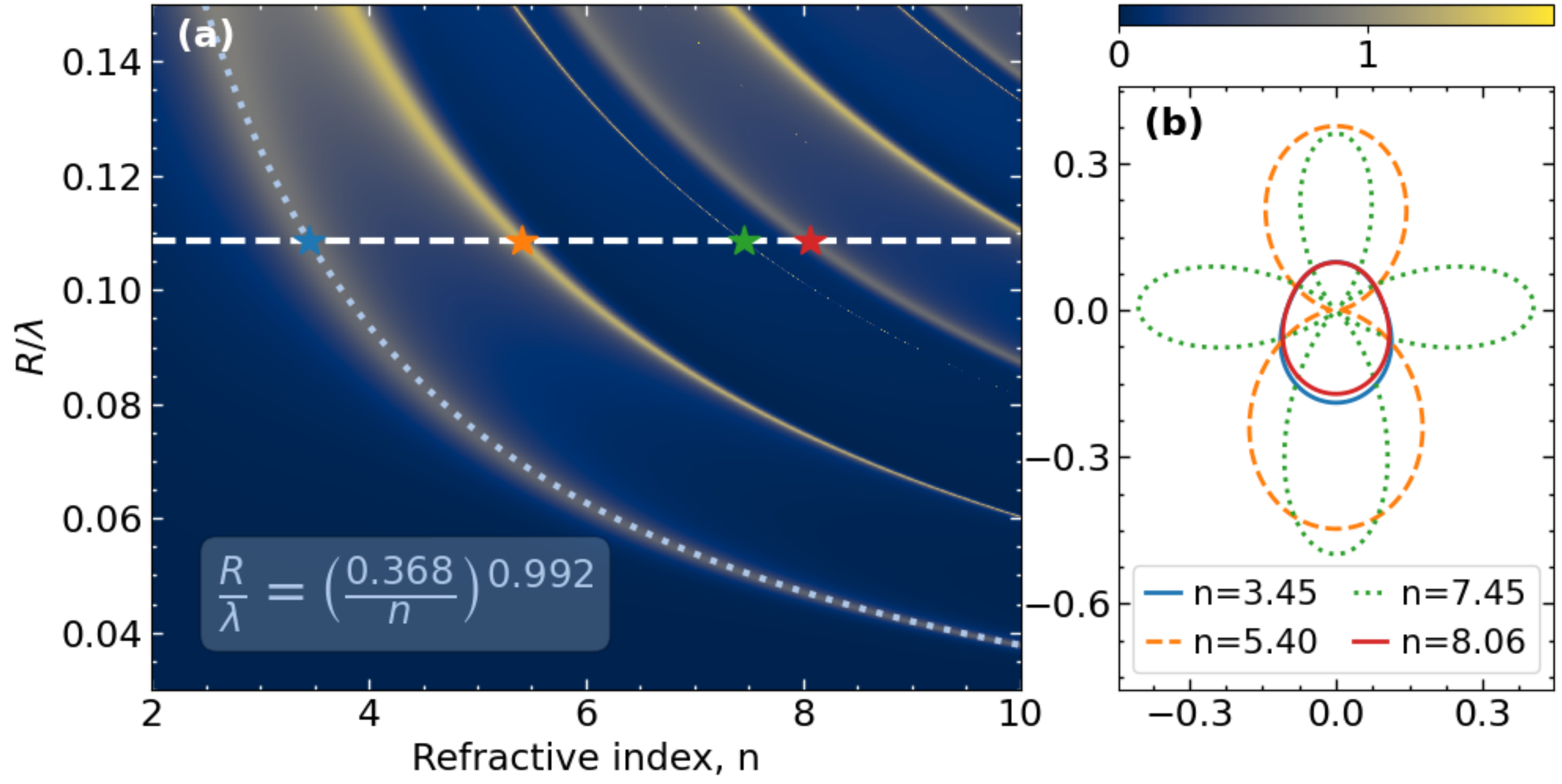

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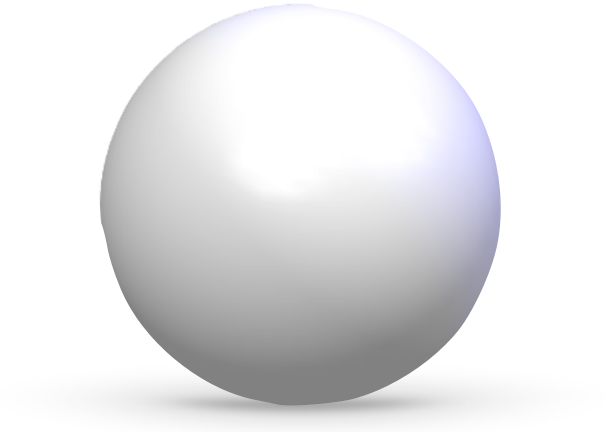

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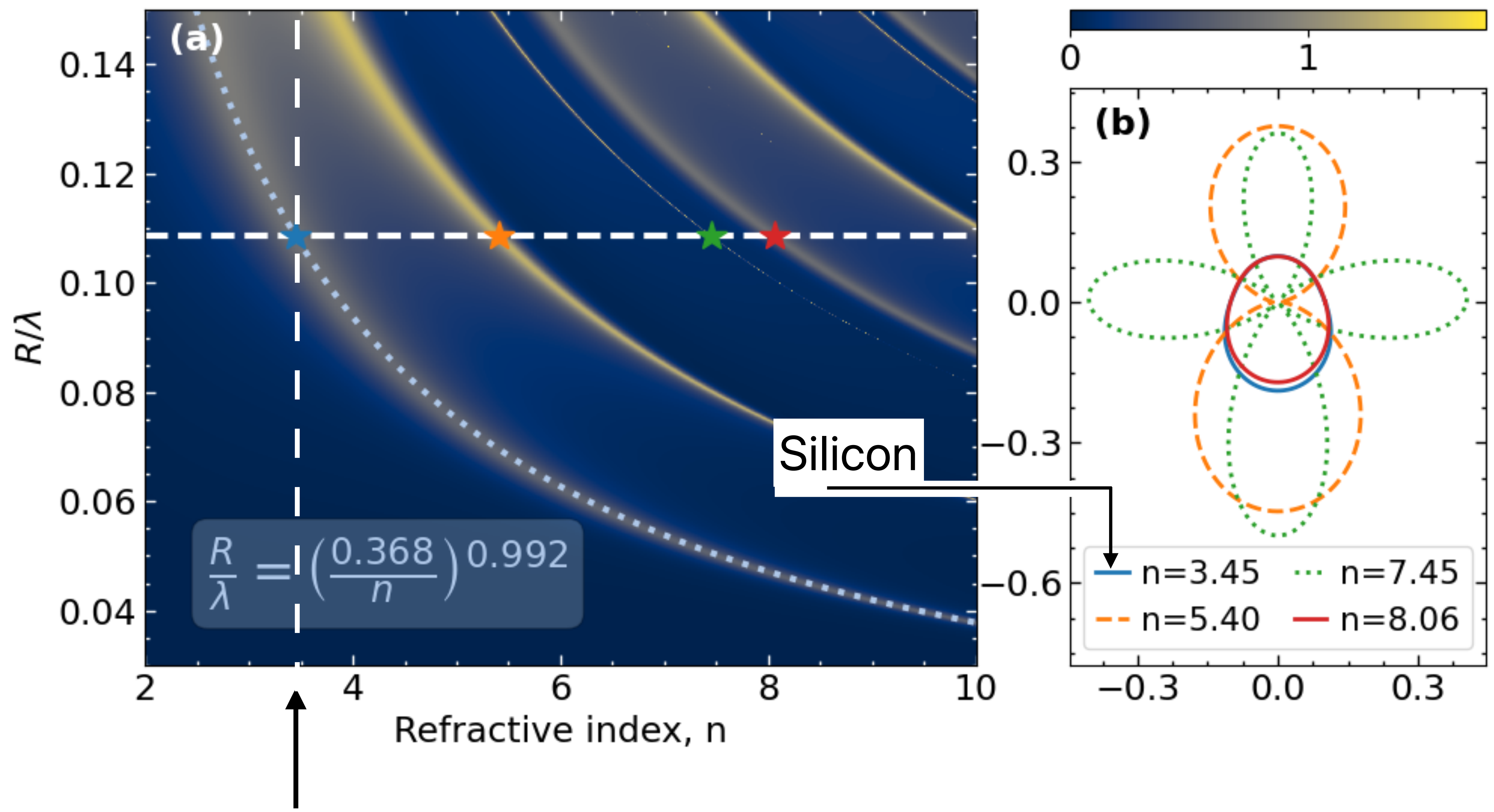

Refractive index of silicon

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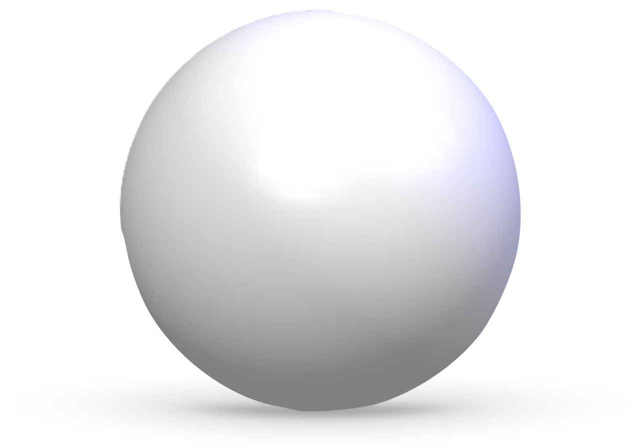
$$@\lambda = 2\ \mu\text{m}, \quad R \sim 220\ \text{nm}$$



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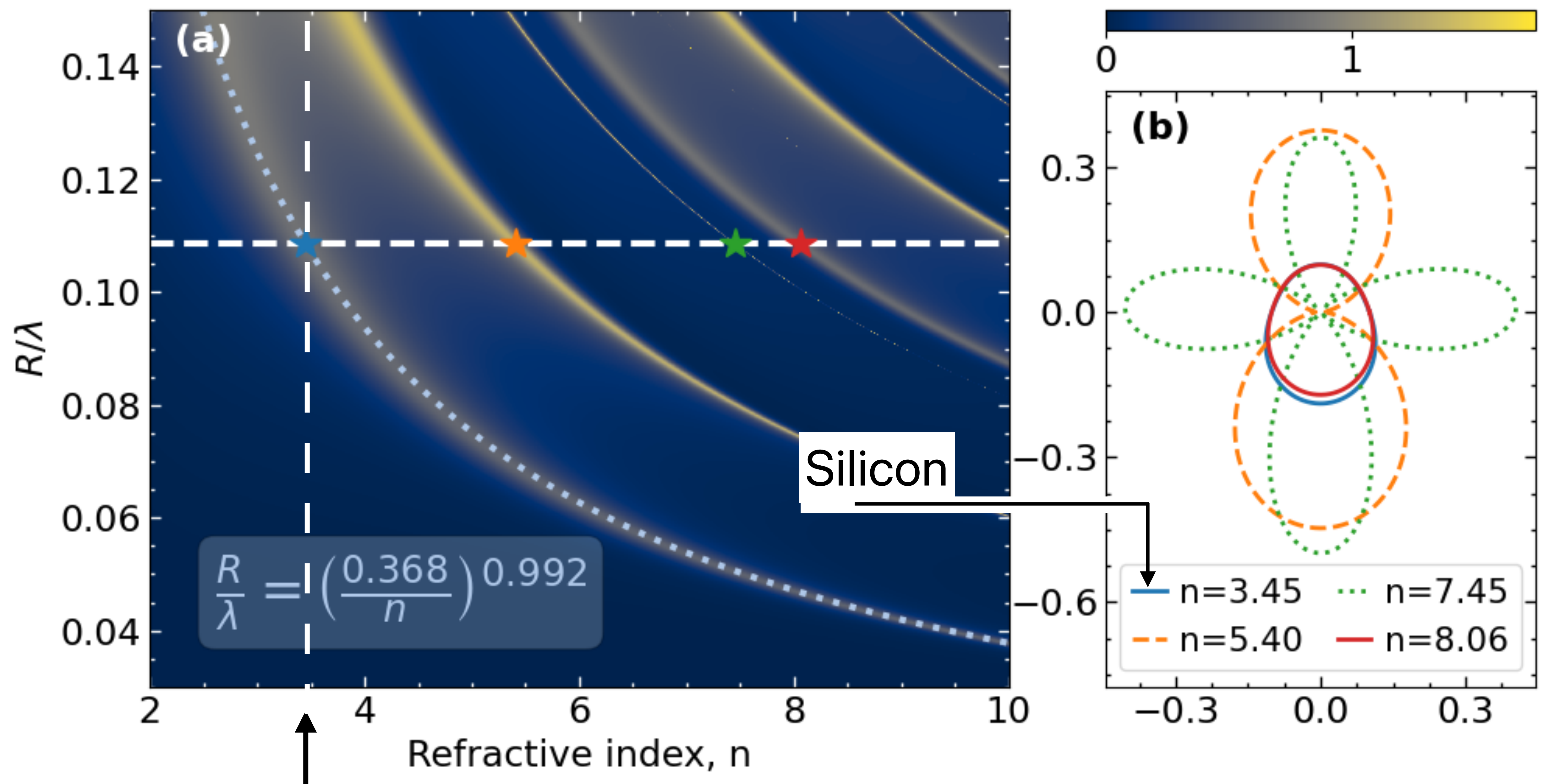

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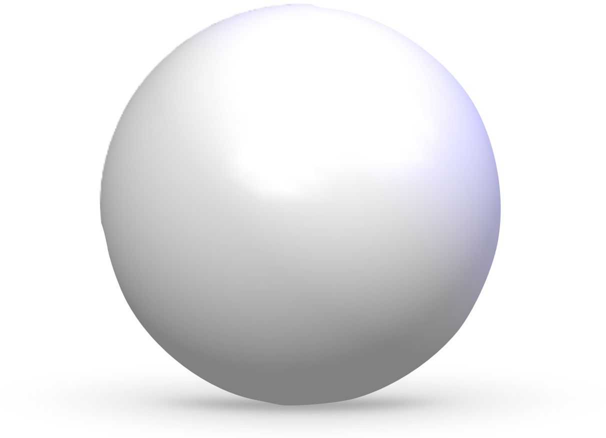
The slab cannot be $400\ \mathrm{nm}$ thick.
Less challenging: only the reflection channel to adjust...



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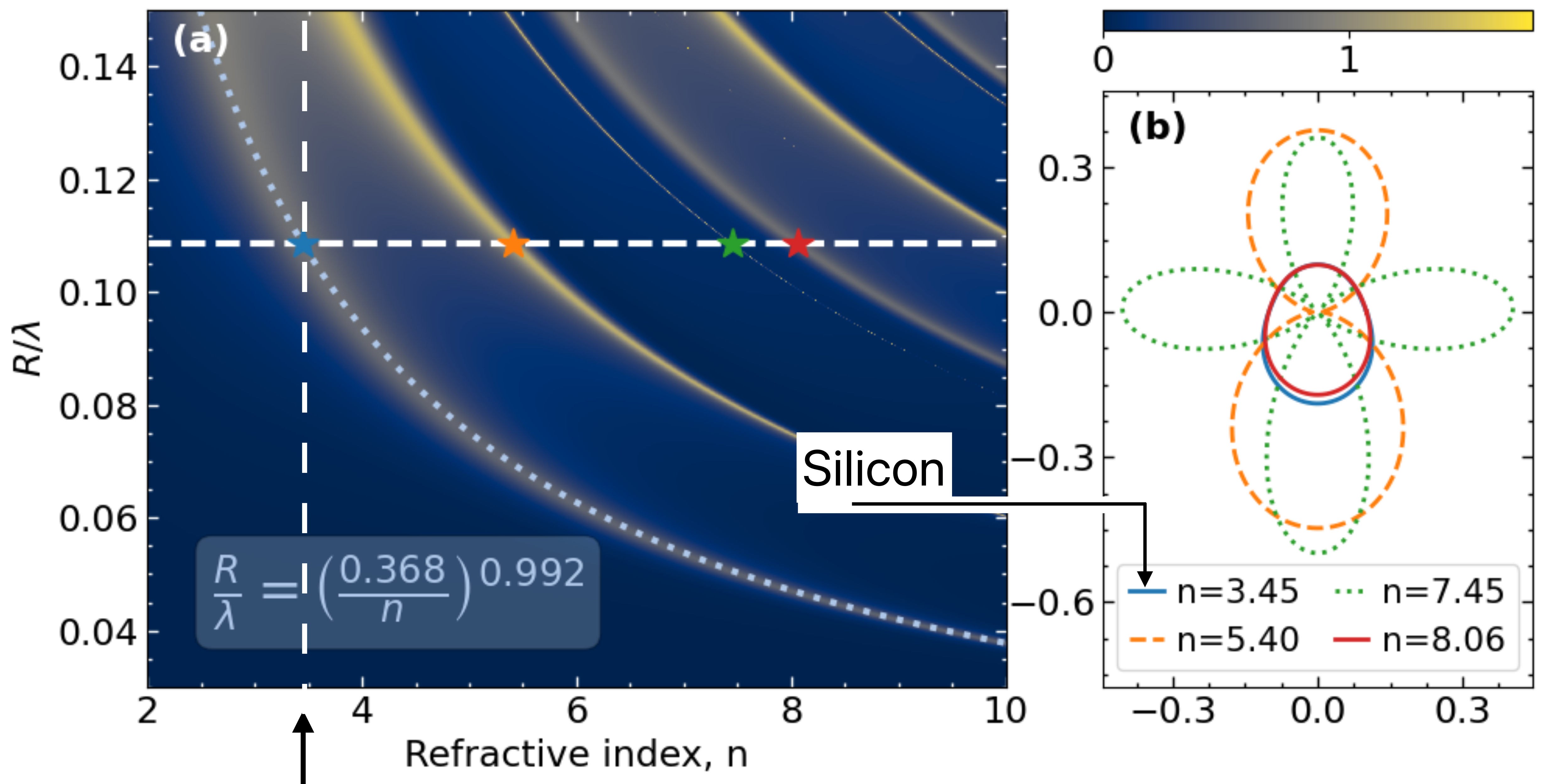

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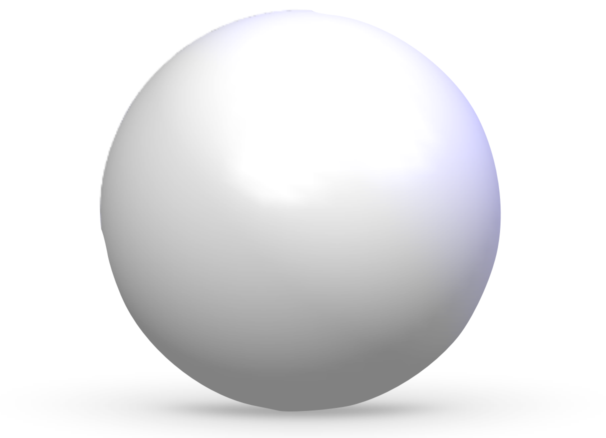
We want the lossless particles to be smaller:

$R = 80\ \text{nm}$



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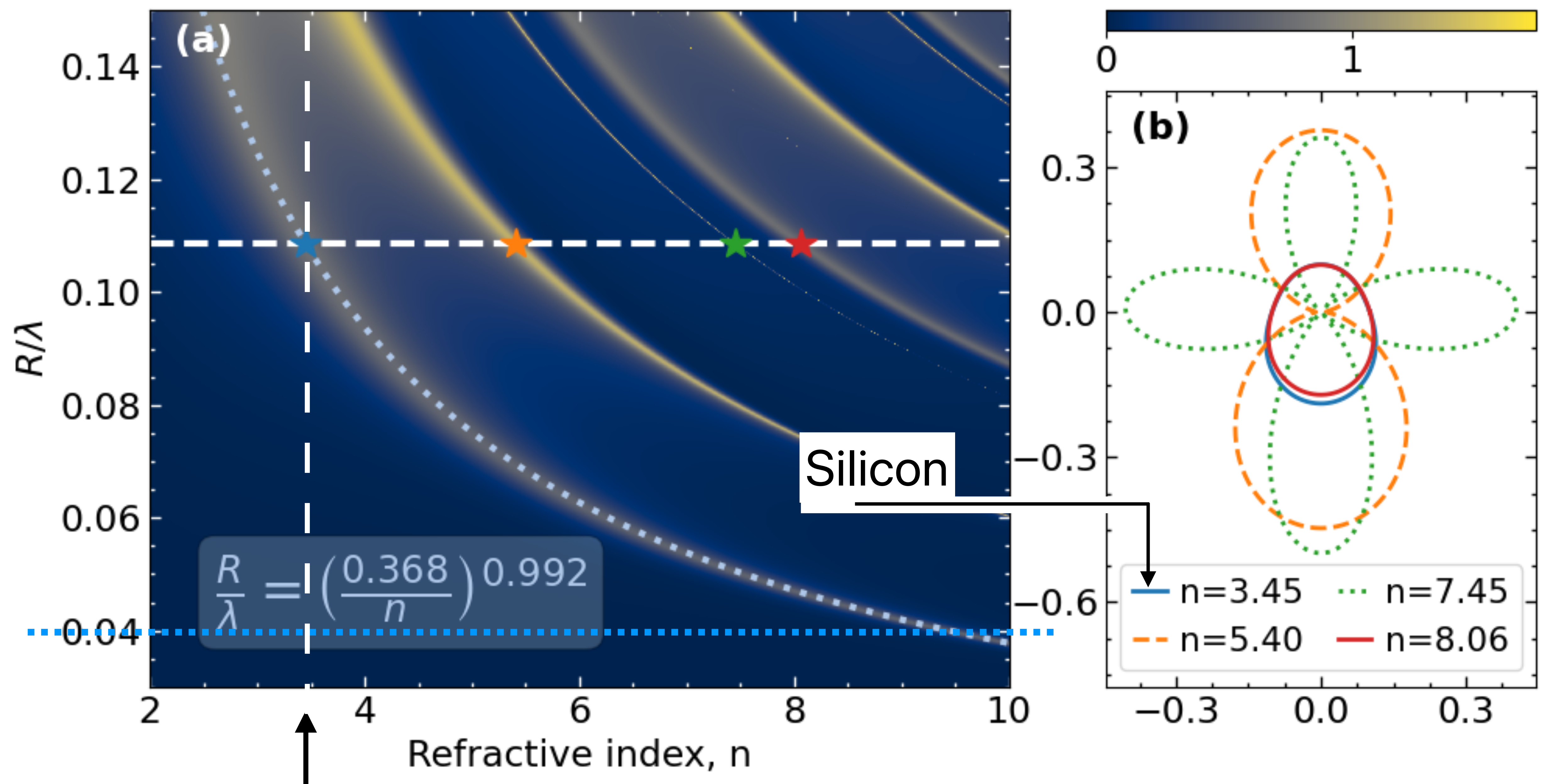

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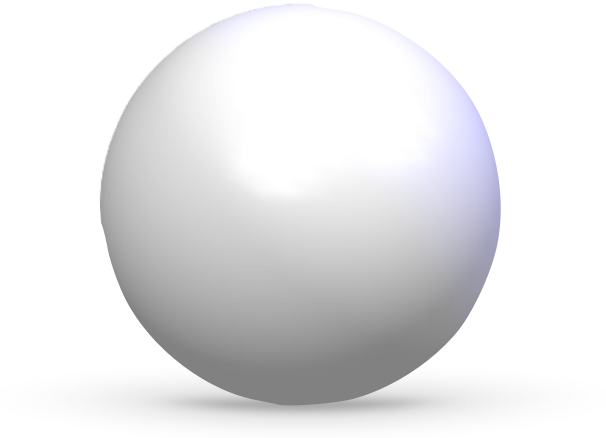

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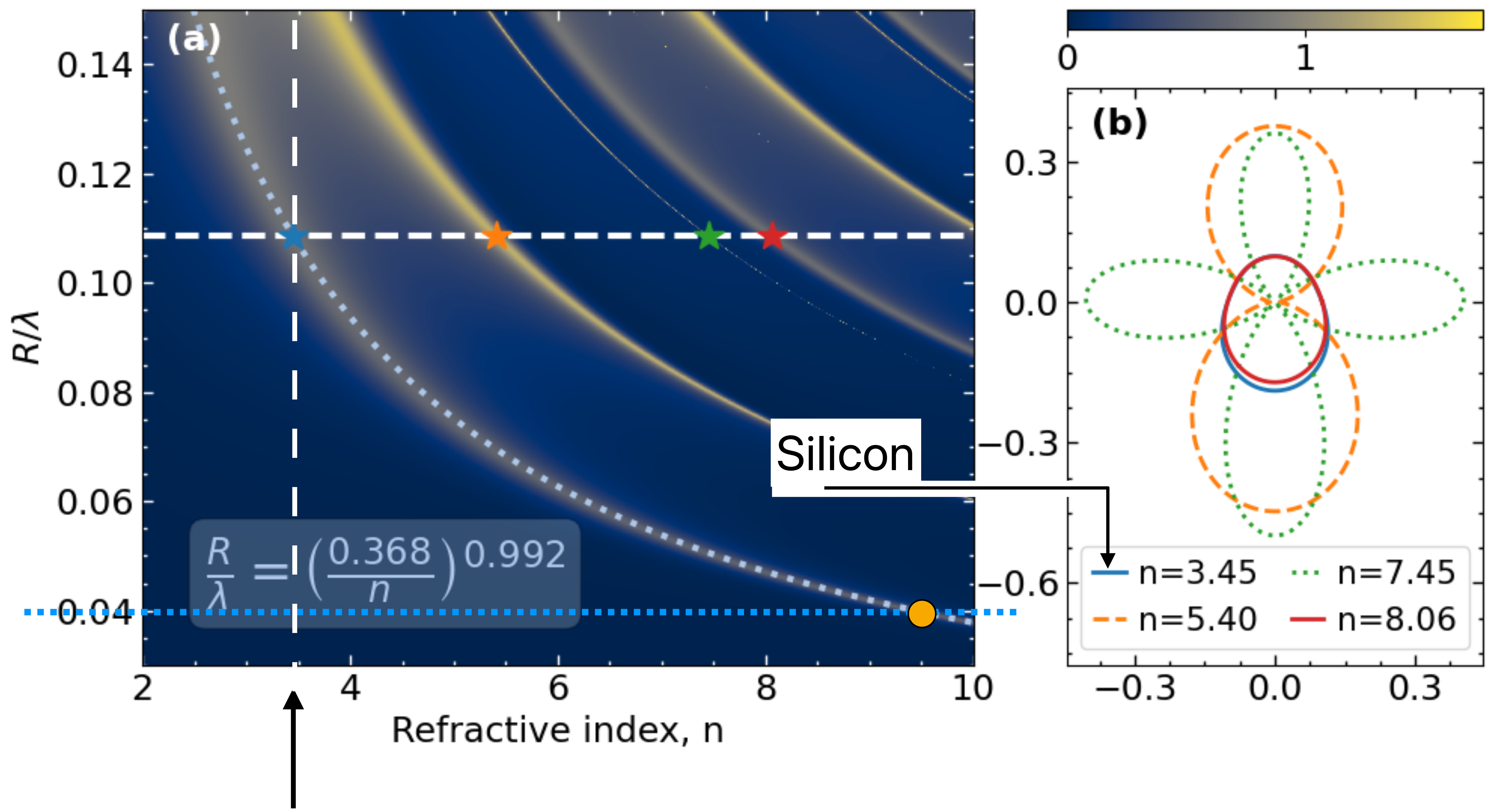

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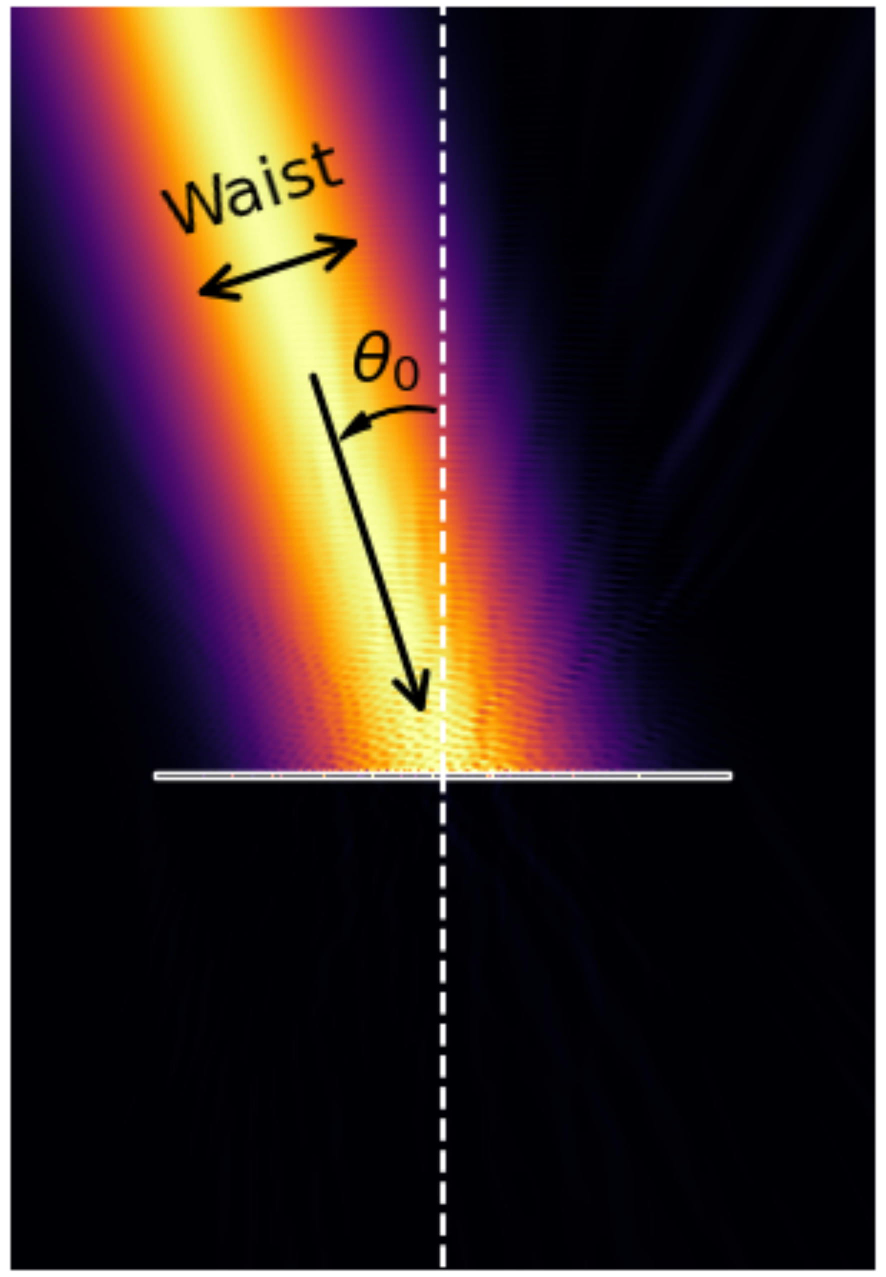
Well-designed diffusive particles is a necessary condition

But not sufficient

...they must **critically couple** with the absorbing ones



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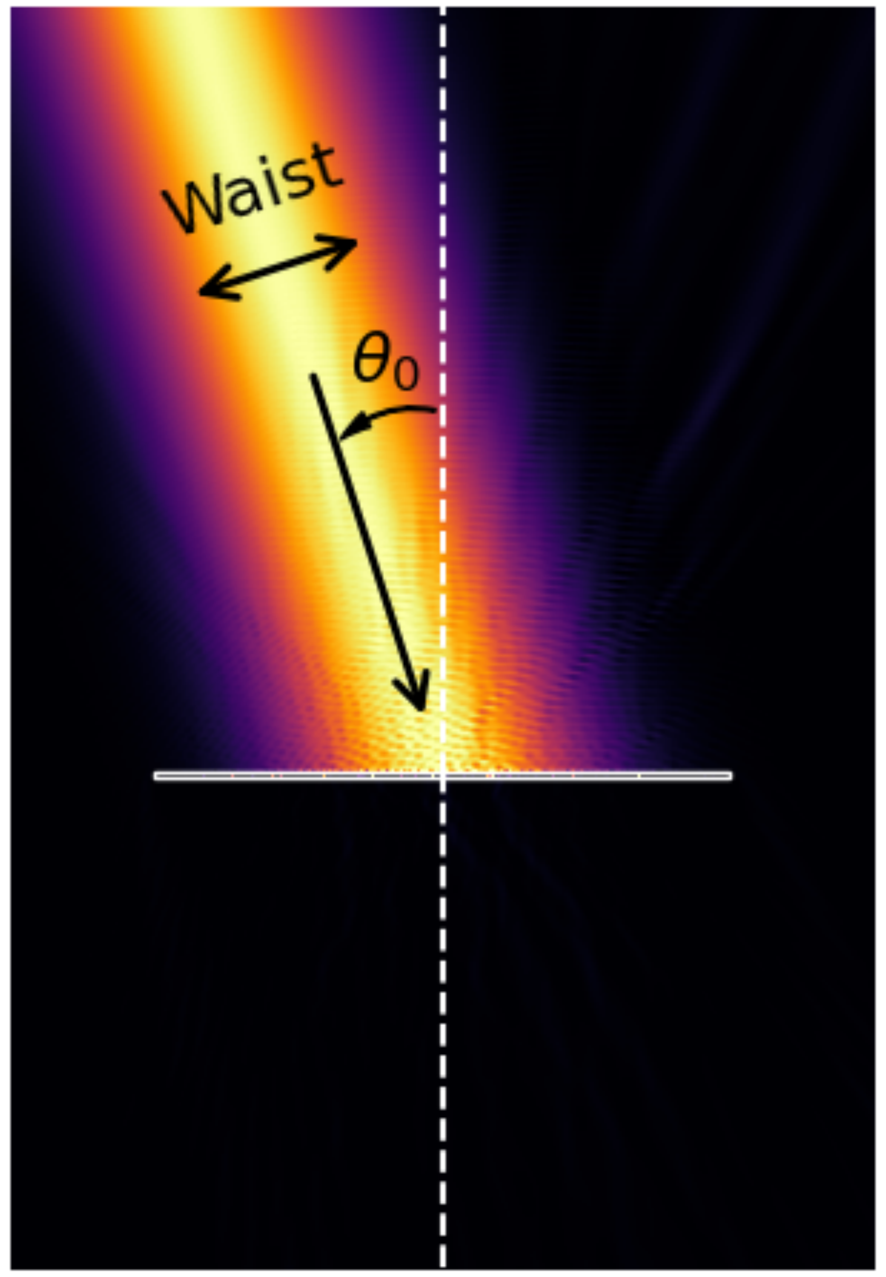
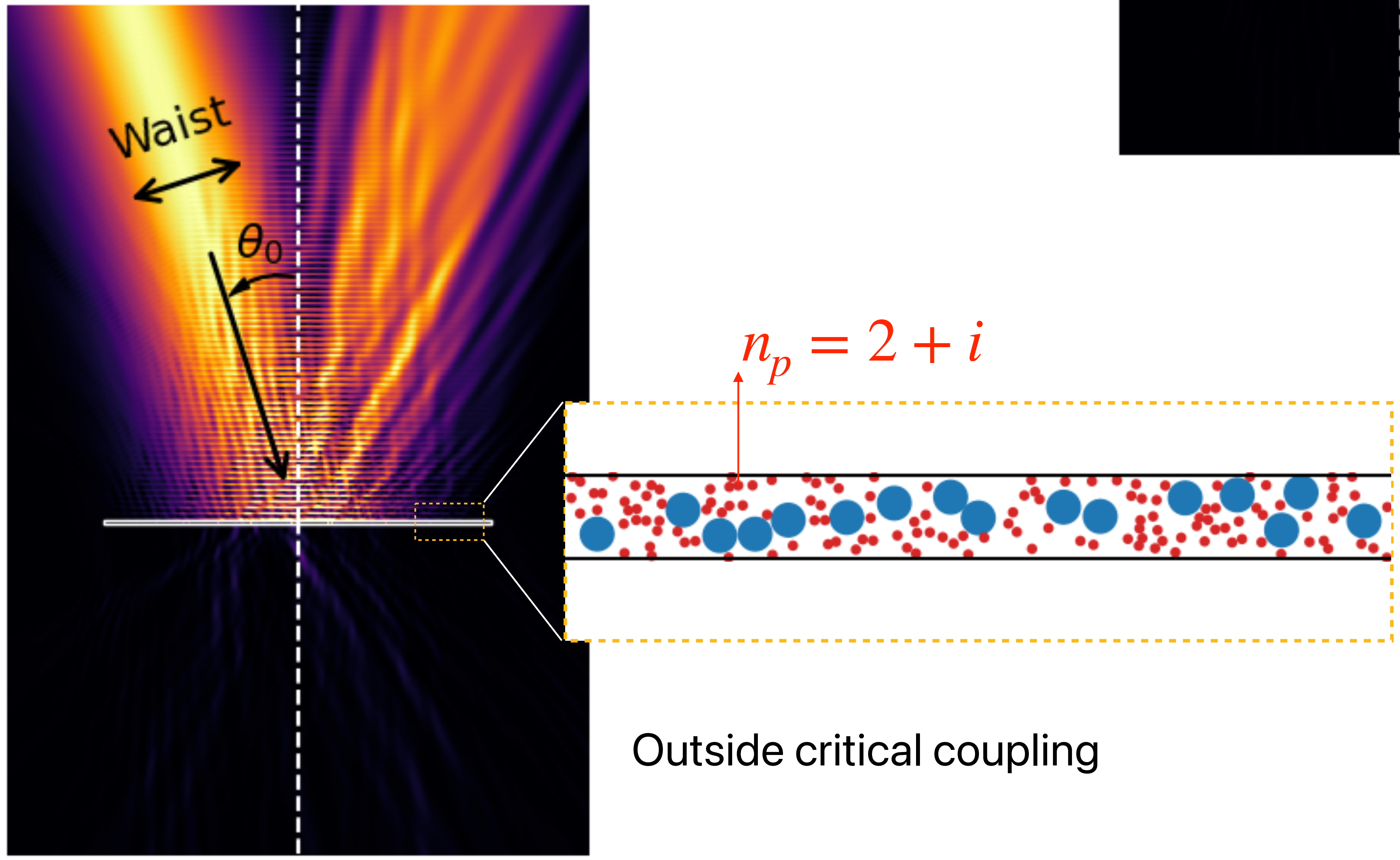
...they must **critically couple** with the absorbing ones

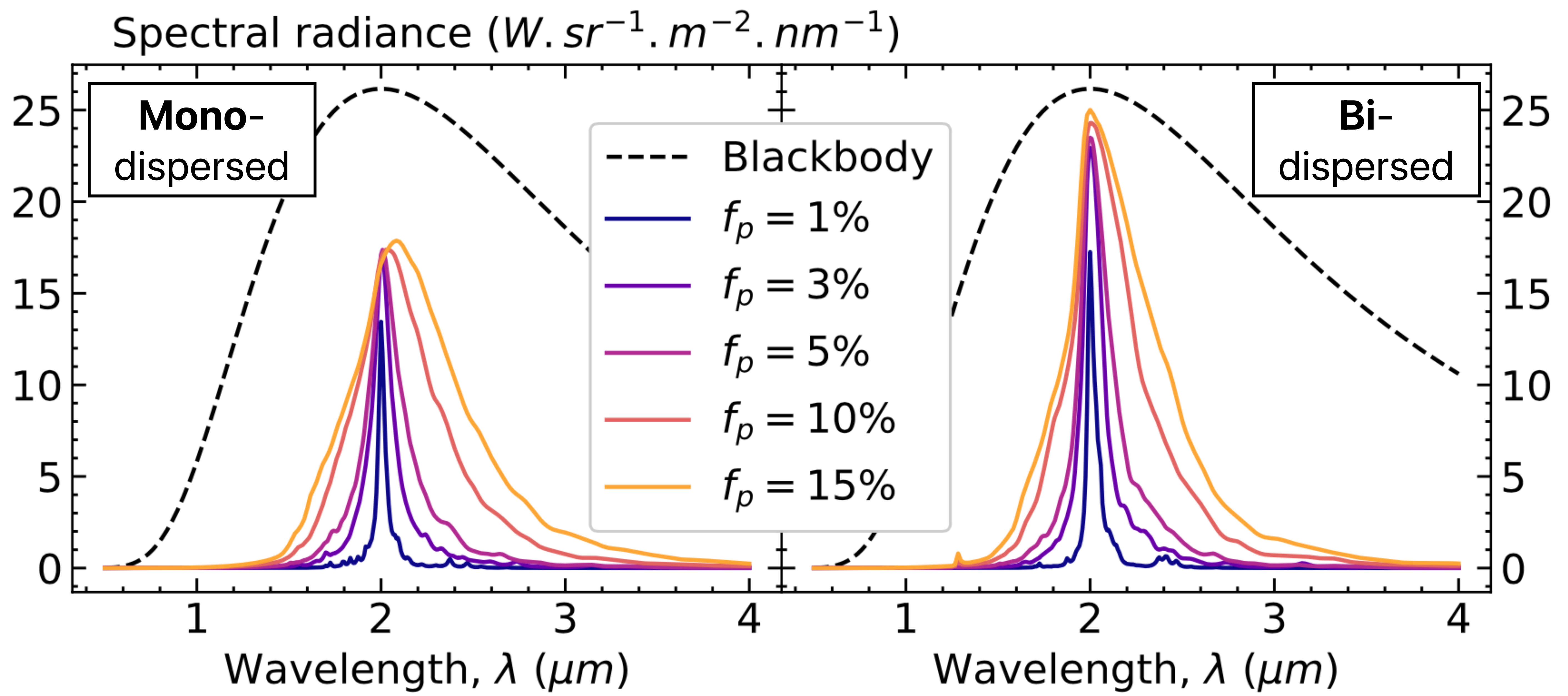




Outside critical coupling

Near perfect absorption: spectral selectivity

What about the spectral properties?



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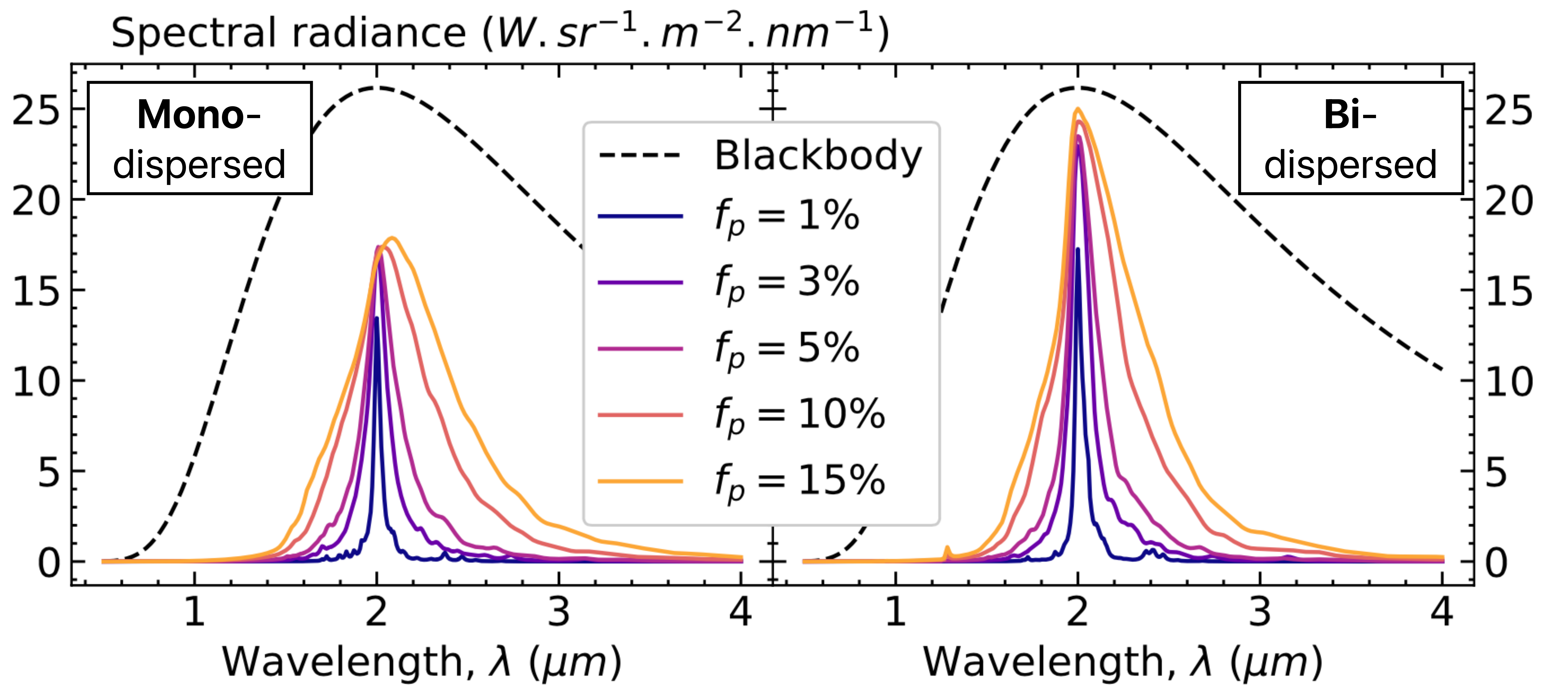
Near perfect absorption: spectral selectivity

What about the spectral properties?

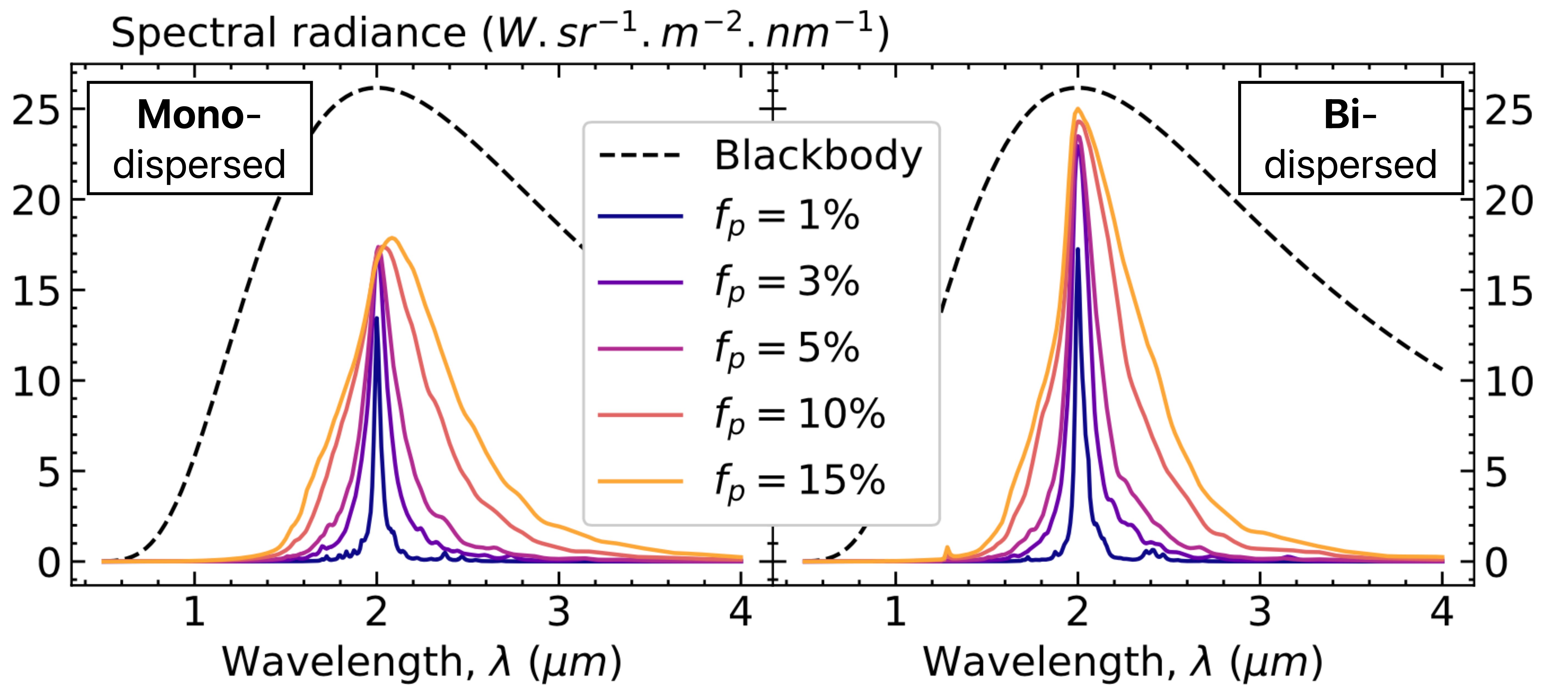
Spectral radiance (i.e. $I_\lambda = \text{emissivity} \times B_\lambda$) vs λ



Near perfect absorption: spectral selectivity

What about the spectral properties?

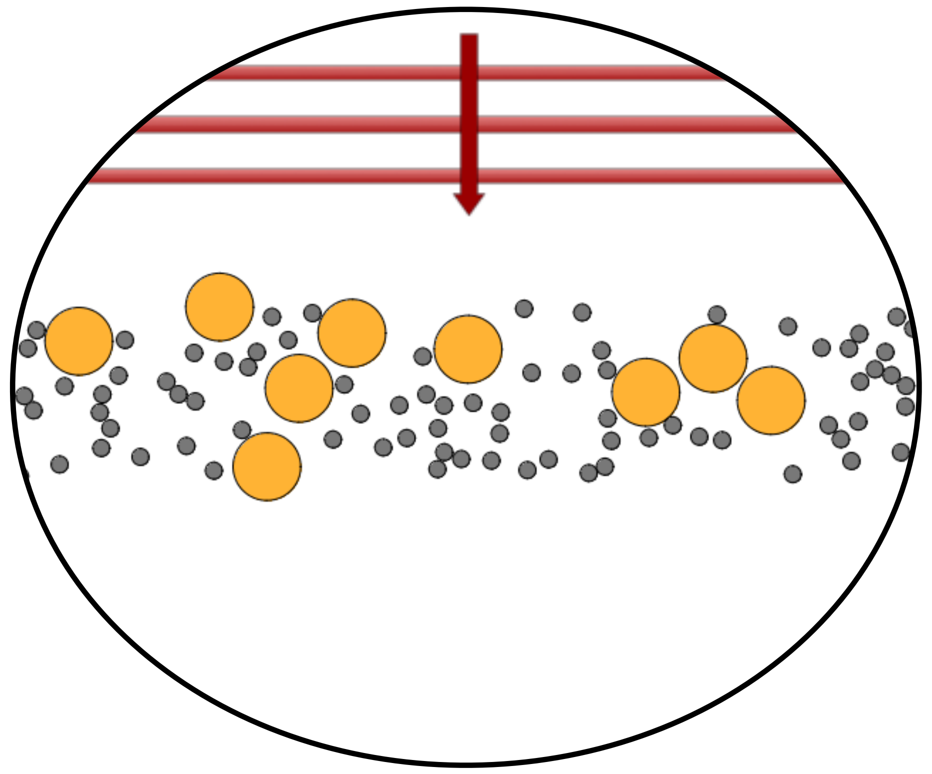
Spectral radiance (i.e. $I_\lambda = \text{emissivity} \times B_\lambda$) vs λ

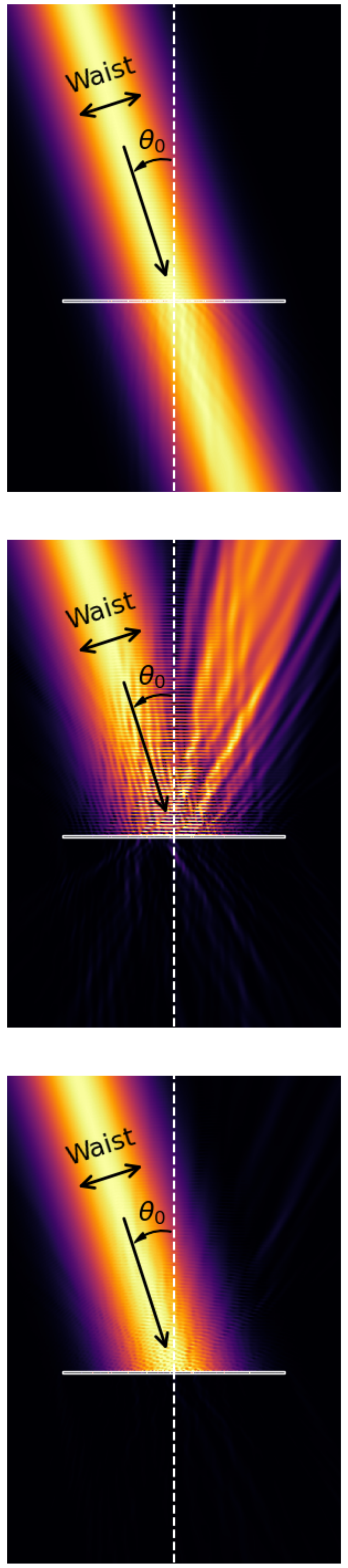


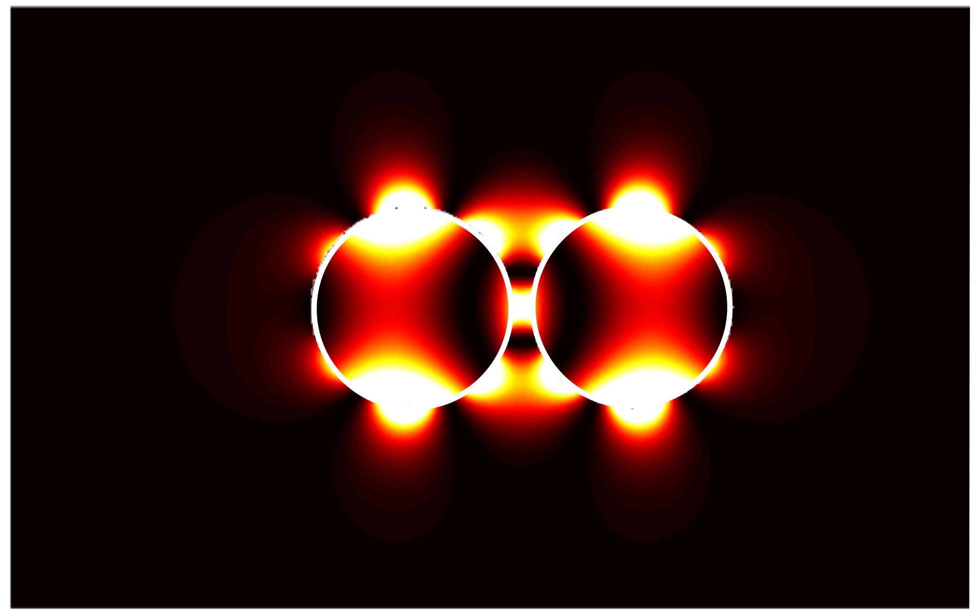
➡ Emits almost as the black body around $\lambda = 2\ \mu\text{m}$. Zero emission elsewhere.

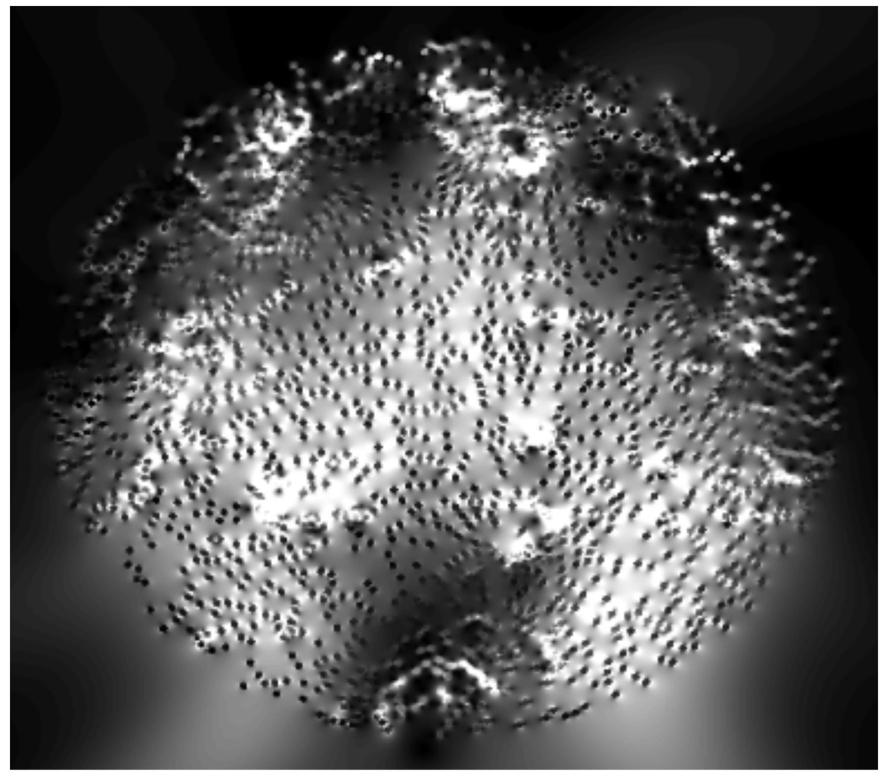
➡ The quality factor can be adjusted through the fill factor f_p.

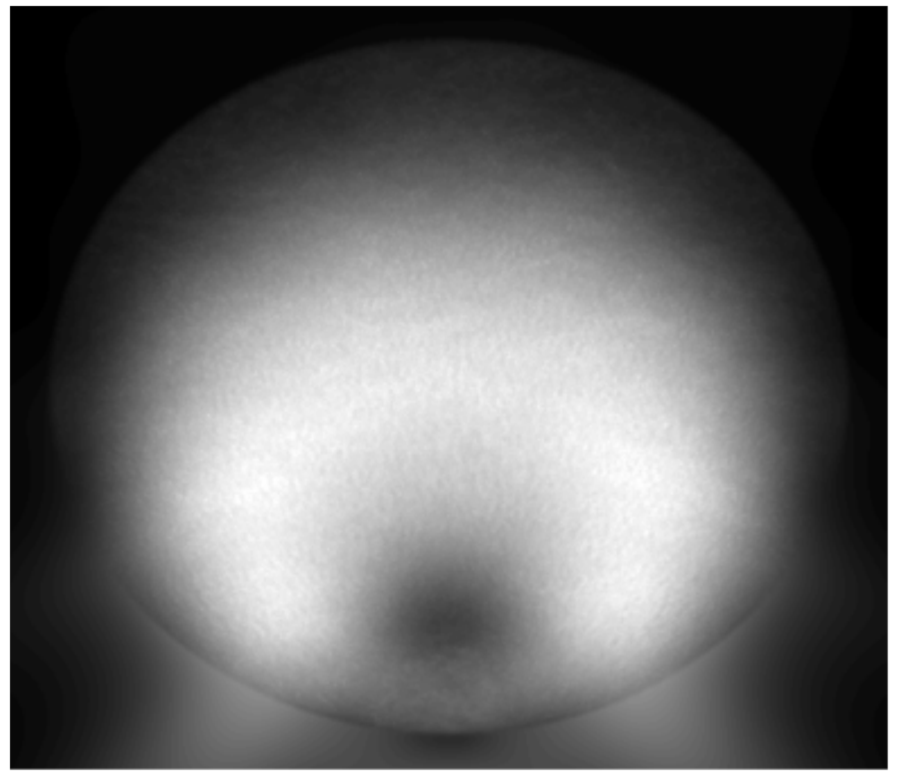
Thank you for your attention

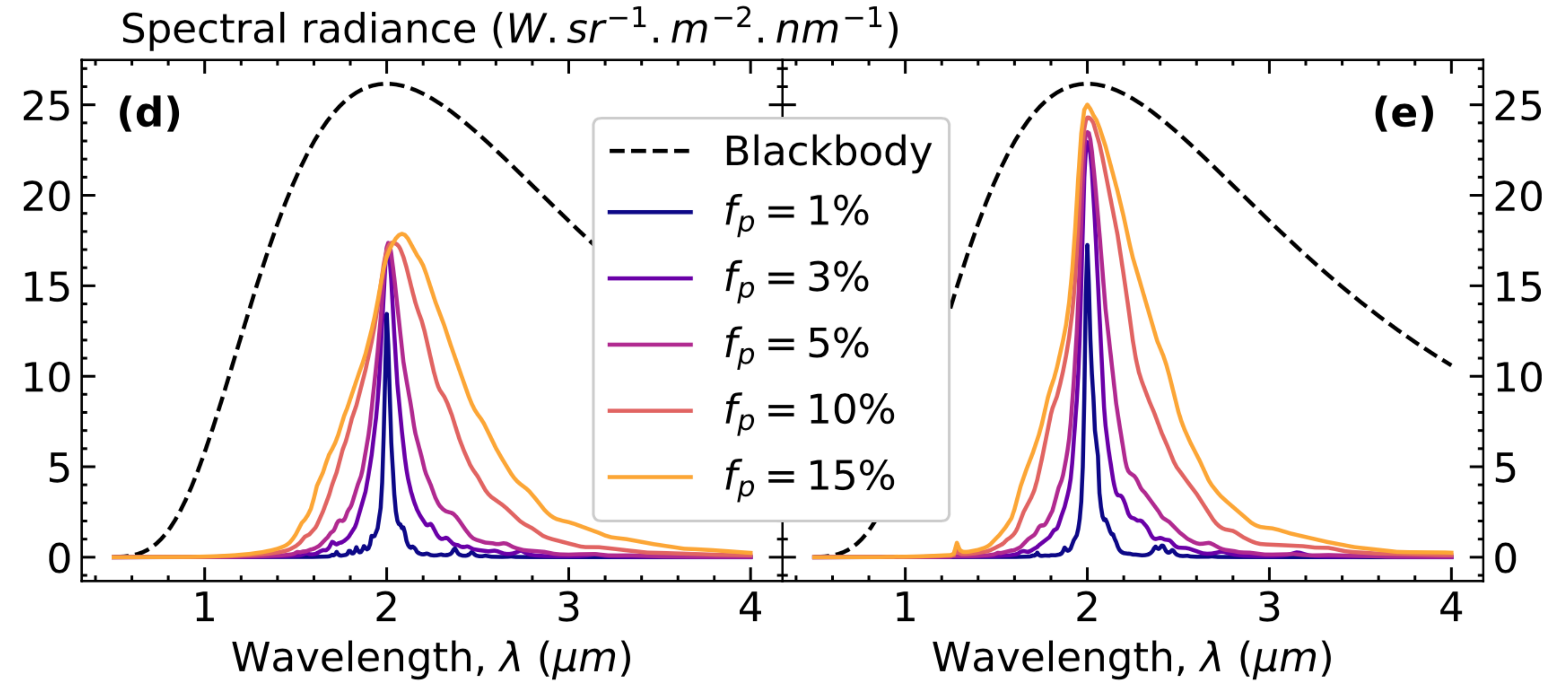












Acknowledgments

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