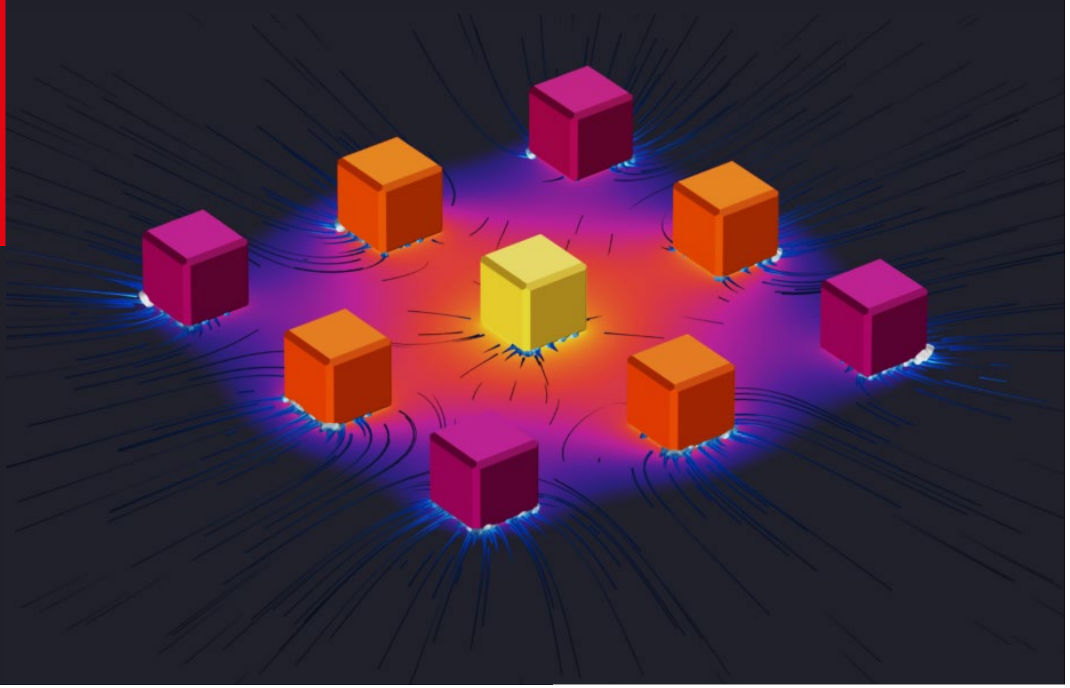
Nanoscale Heat Transfer (and Energy Conversion) ME469



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École polytechnique fédérale de Lausanne

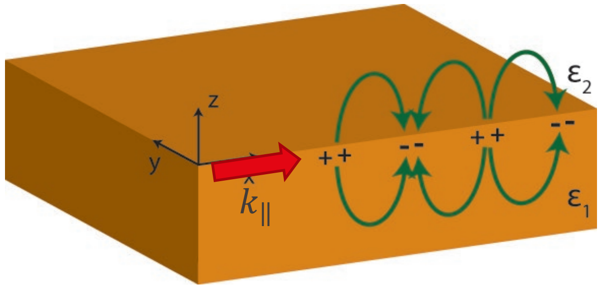
Spring Semester

Nanophotonics for Thermal Control

- **Absorption/Emission Engineering**
  - **LDOS engineering and Near field heat transfer**
  - Thermophotovoltaics and Radiative cooling
- Thermoplasmonics and Thermonanophotonics
  - Thermo-plasmonics for thermocatalysis
  - Thermo-plasmonics for solar evaporation/desalination

Nanophotonic Engineering – Surface Polaritons and Resonators

Surface Polaritons (SPs)

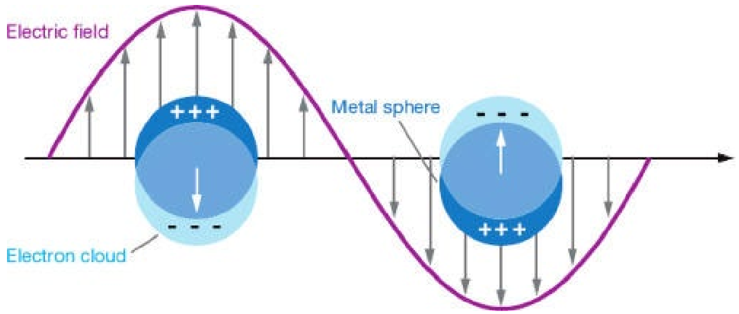


Quasiparticle originates from the strong-coupling of a photon with electrons (metal) or optical phonons (dielectric). The associated propagating wave is confined to an interface.

- **Surface plasmon polariton (SPPs)**
- **Surface phonon polariton (SPhPs)**

➡ Modified dispersion relation (high DOS)

Resonators (Nanoantennas)



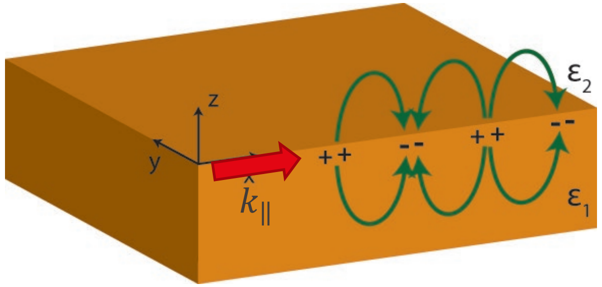
An incident electromagnetic wave induces resonant responses in finite nanostructures. Metallic and dielectric resonators exhibit different types of modes that are called, respectively:

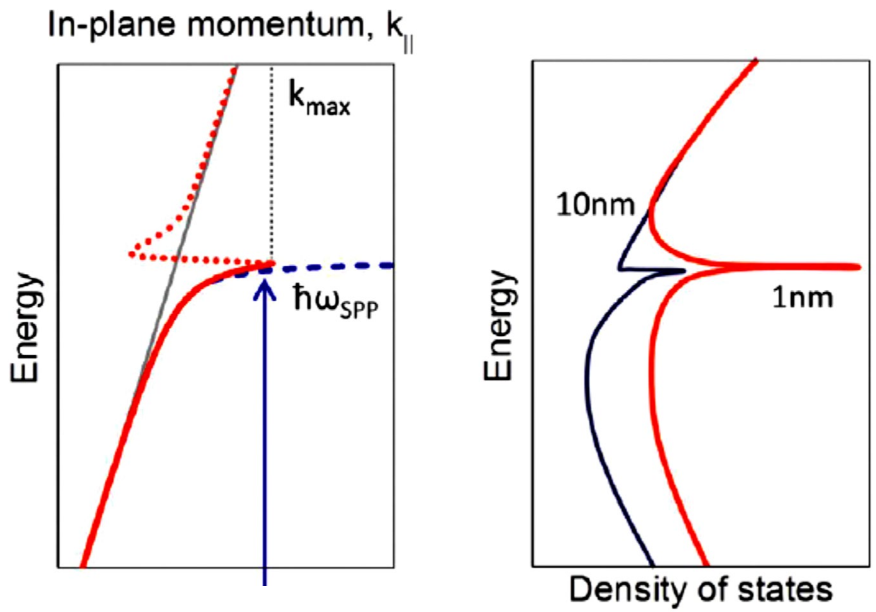
- **Localized surface plasmons (LSP)**
- **Mie resonances**

➡ Resonance condition (high DOS)

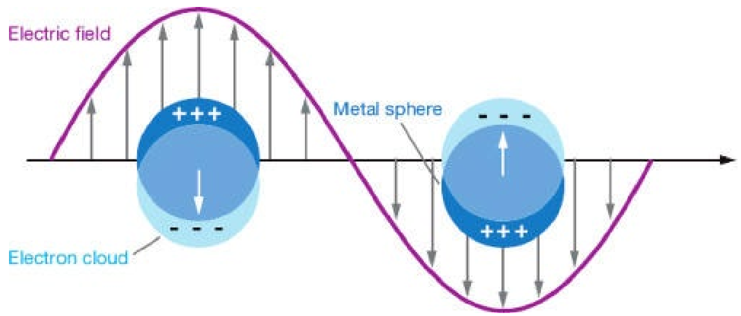
Nanophotonic Engineering – Surface Polaritons and Resonators

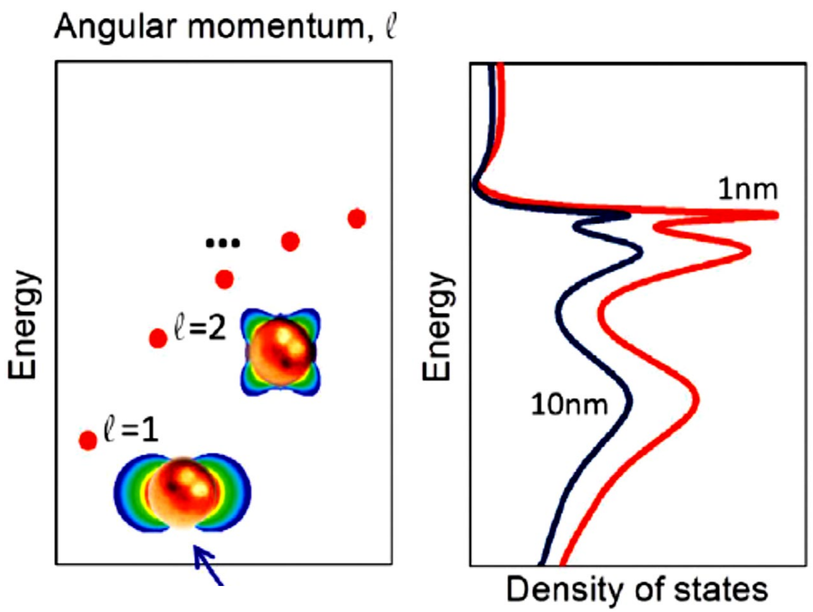
Surface Polaritons (SPs)



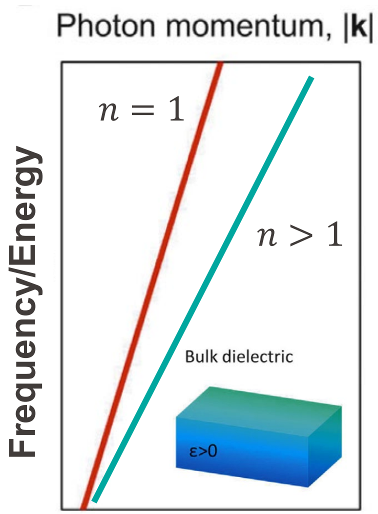


Resonators (Nanoantennas)





The Photon Density of States and the Blackbody Emission



We known that photons are quanta of electromagnetic field oscillations and that they are bosons. For an electromagnetic wave propagating in an homogeneous bulk medium (i.e. air, glass, water) we have obtained (L10,slide11) a linear dispersion relation:

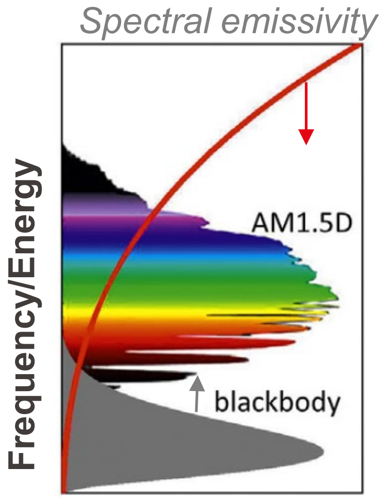
$$\omega = \frac{c_0 k}{n}$$

Where $c_0 = speed\ of\ light\ in\ vacuum$ and $n = real\ part\ of\ the\ refractive\ index$

By analogy with the phonons in the Debye approximation, (L7, slide33) it is possible to obtain the density of states (DOS) for photons:

$$D(\omega) = \frac{\omega^2}{\pi^2 c^3} = \frac{n^3 \omega^2}{\pi^2 c_0^3}$$

Where $c = group\ velocity = \frac{d\omega}{dk}$ that for a propagating wave in a n homogeneous medium corresponds to c_0/n



Density of States

This quantity is indeed critical for determining the black-body emission spectrum. Indeed, we define the spectral emissivity as:

$$e_\lambda = \pi I_\lambda = \pi I_\omega \left|\frac{d\omega}{d\lambda}\right| = \pi \frac{c\boldsymbol{U_\omega}}{4\pi}\left|\frac{d\omega}{d\lambda}\right|$$

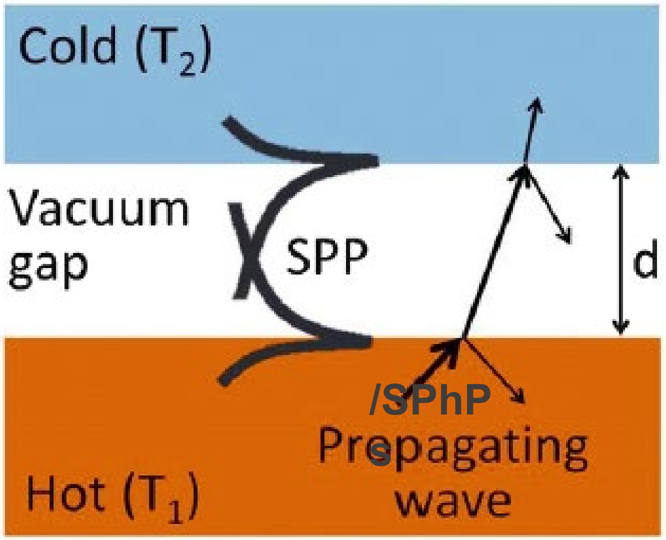
where:

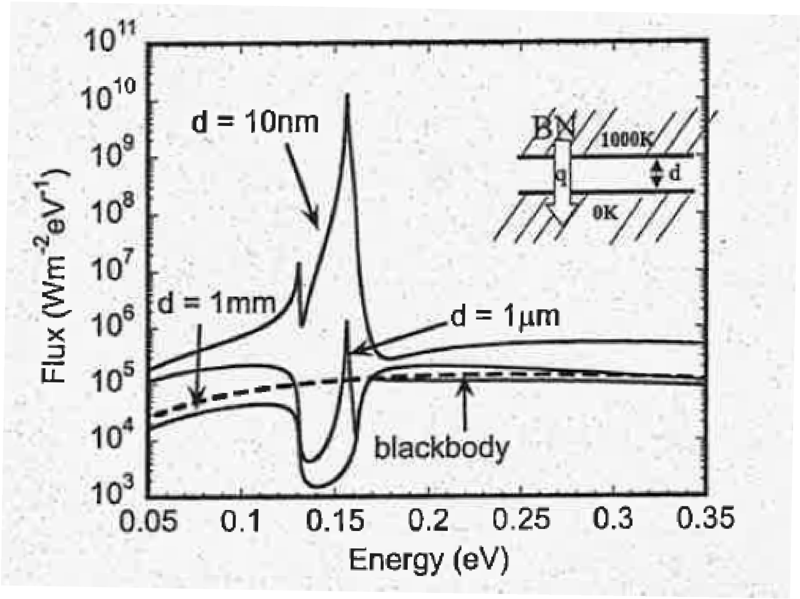
$$U_\omega = \hbar\omega f(\omega, T)\, \boldsymbol{D(\omega)} = \frac{\hbar}{\pi^2 c^3} \frac{\omega^3}{exp\left(\frac{\hbar\omega}{\kappa_B T}\right) - 1}$$

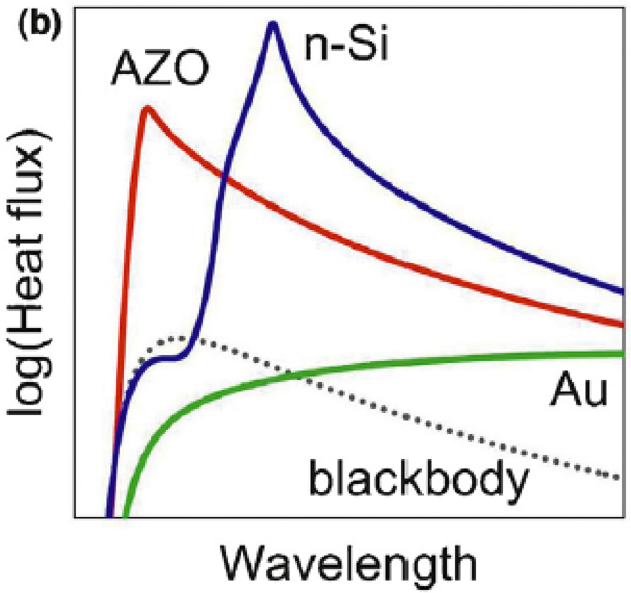
- **By modifying the photon density of states we can alter the spectral emissivity of a surface/object**
- **To modify the photon density of states we need to modify the dispersion relation $\omega(k)$**
- **SPP and SPhP allow us to engineer the density of states, i.e. radiation absorption/emission**

http://dx.doi.org/10.1016/j.mattod.2013.09.003

Enhancement of Near Field Radiative Heat Transfer



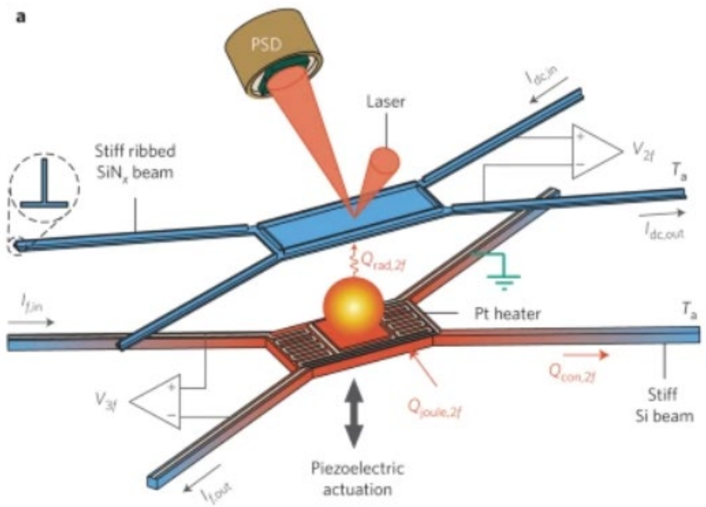


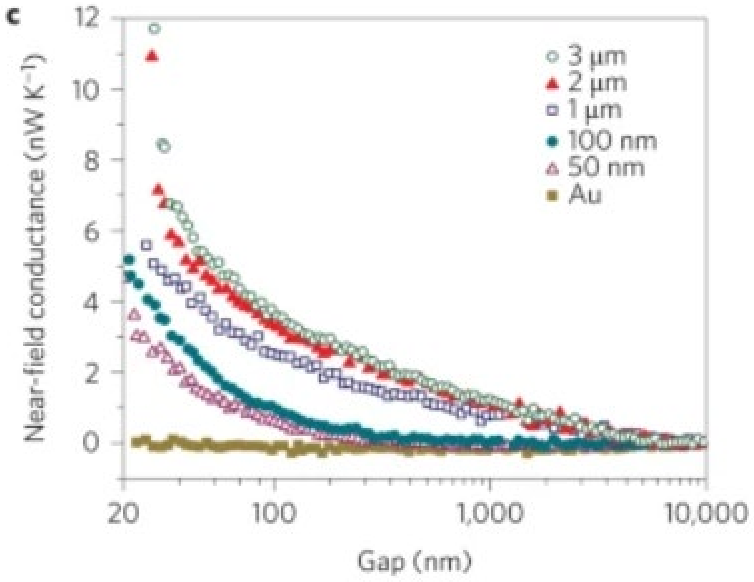


- For very small gaps SPPs or SPhPs modes can significantly enhance radiative energy transfer, exceeding the blackbody limit
- SPhPs are often more suitable because they can better match the peak blackbody emission frequency (typically in the infrared) and thus enhance the spectral region with the highest photon content

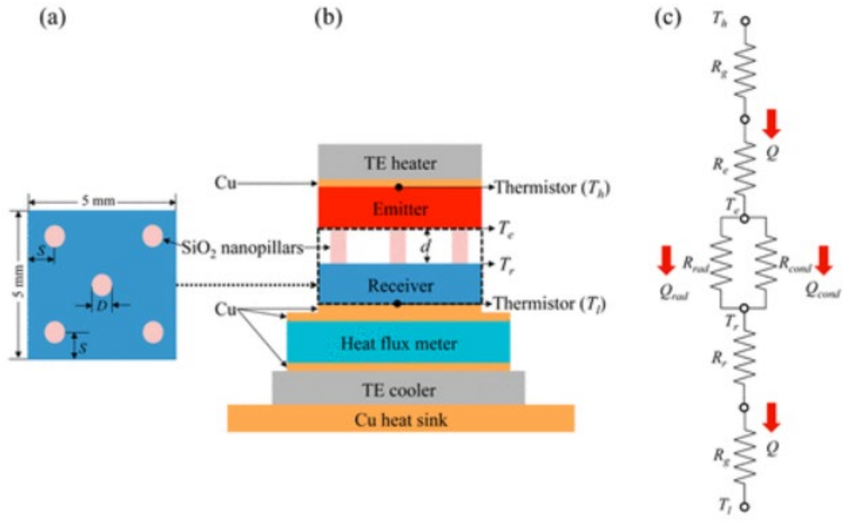
https://pubs.acs.org/doi/full/10.1021/acsphotonics.0c00404

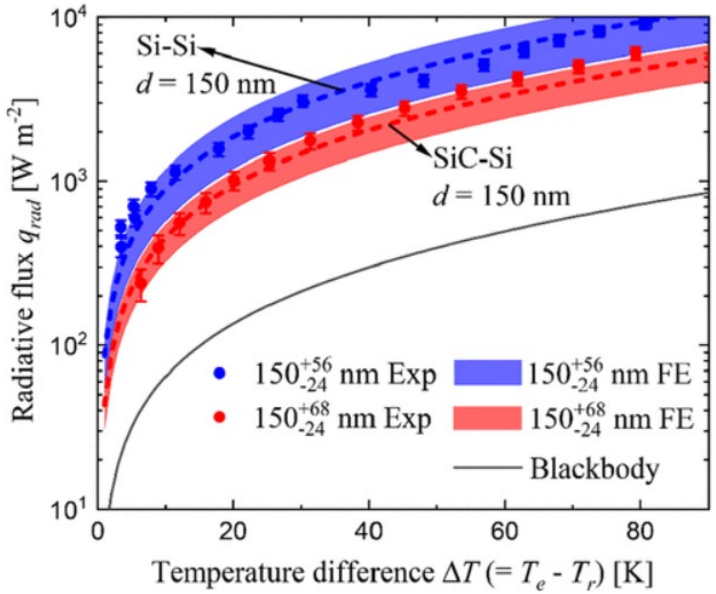
Enhancement of Near Field Radiative Heat Transfer





https://www.nature.com/articles/nnano.2015.6





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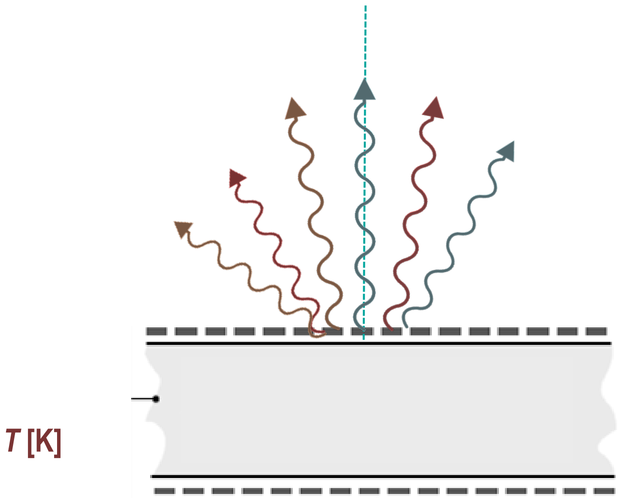
Absorption/Emission Engineering

EPFL

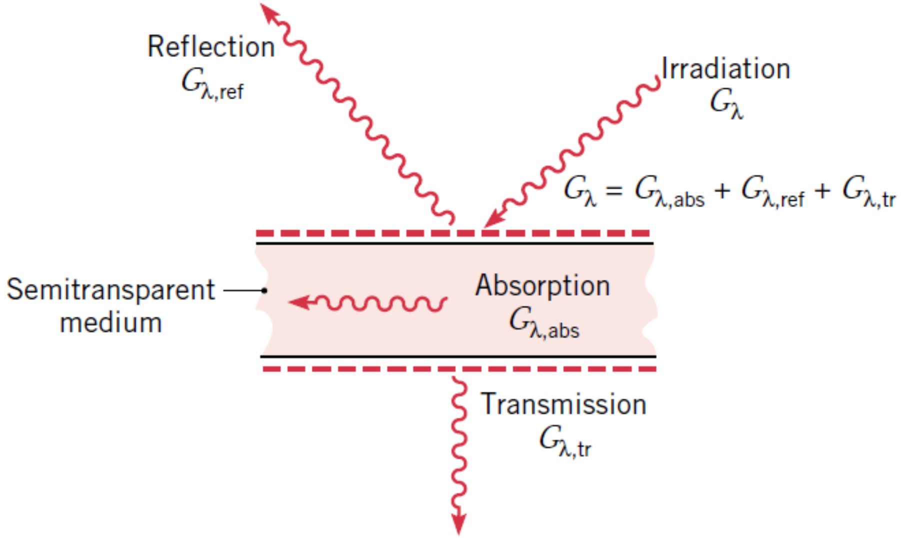
Emission of Thermal Radiation

$$I_{\lambda,e}(\lambda, \theta, \Phi, T)$$



Interaction of Radiation with Matter

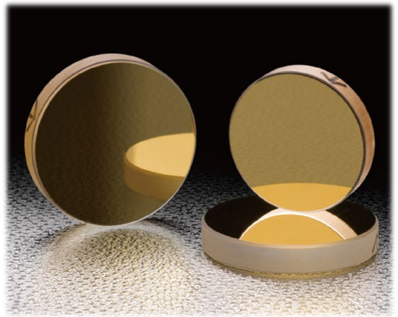
$$1 = \alpha_\lambda + \rho_\lambda + \tau_\lambda$$



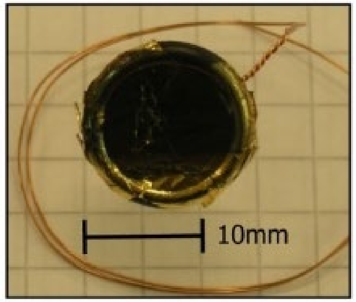
- From Kirchhoffs law we know that $\epsilon_{\lambda,\theta} = \alpha_{\lambda,\theta}$.
- We can use nanostructures to control the spectral and angular absorption of surfaces
- ➢ We can engineer the emissivity of surfaces.

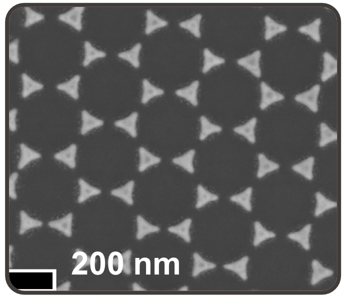
Absorption/Emission Engineering

Planar Au



Nanostructured Au





Tagliabue et al. Nanoscale 5 (2013);

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Absorption/Emission Engineering

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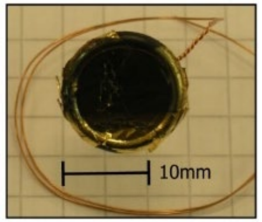
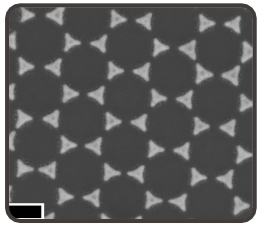
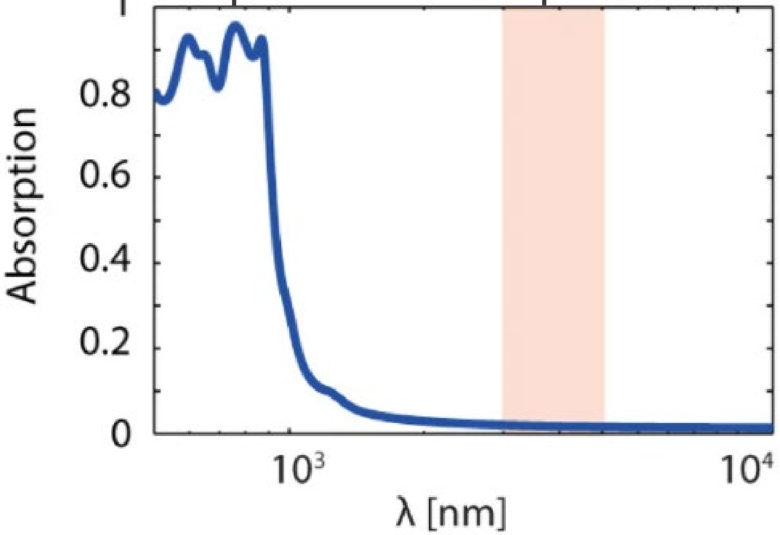




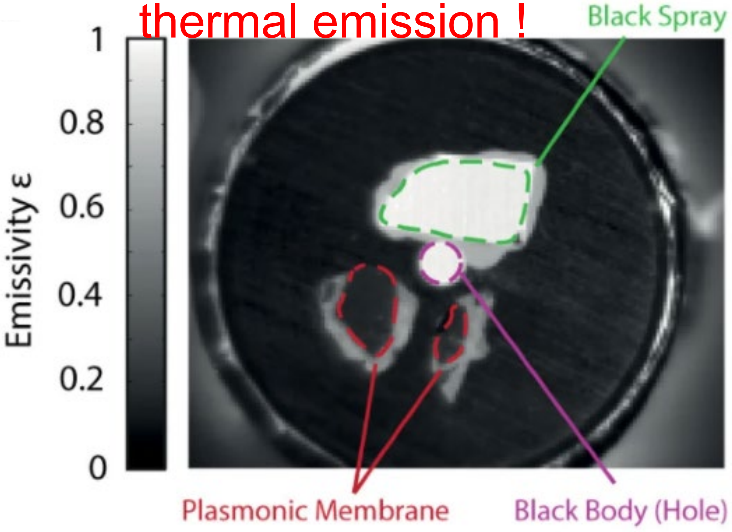
Strong visible absorption

Negligible infrared absorption



Tagliabue et al. Sci. Rep. (2014);

Energy absorbed from visible light is not lost as thermal emission !



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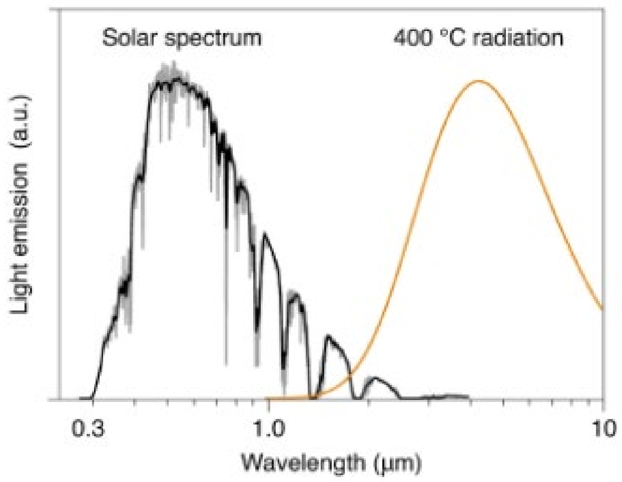
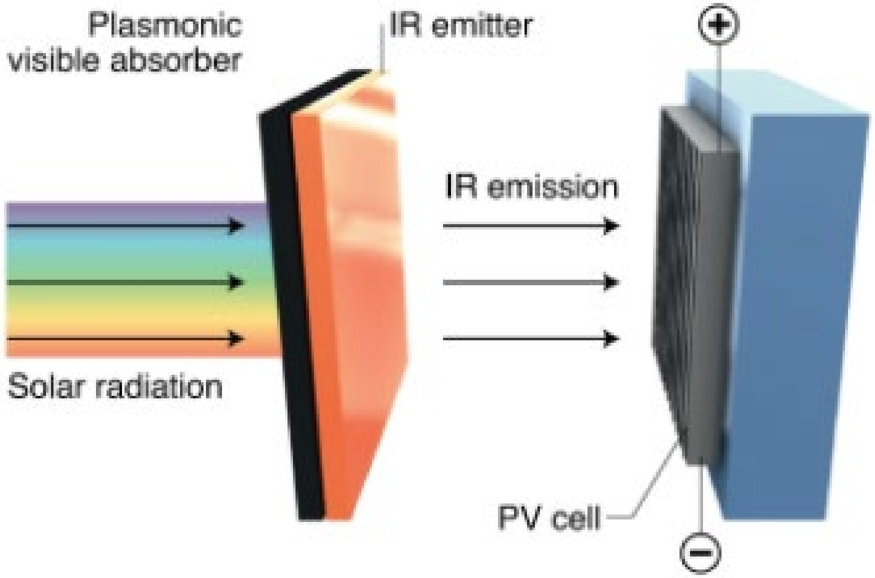
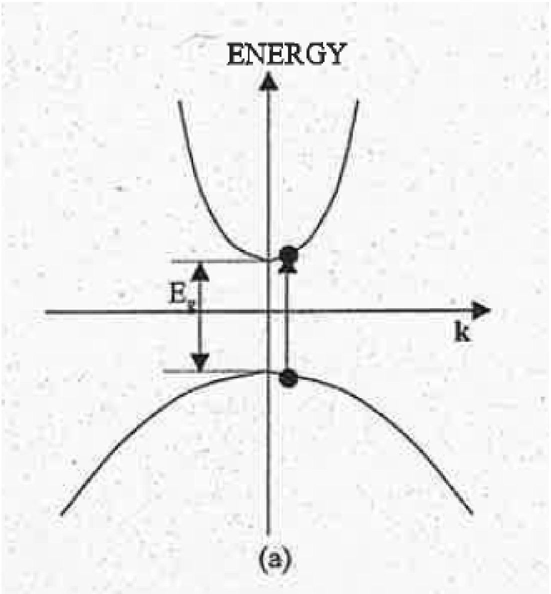
Absorption/Emission Engineering - Thermophotovoltaics



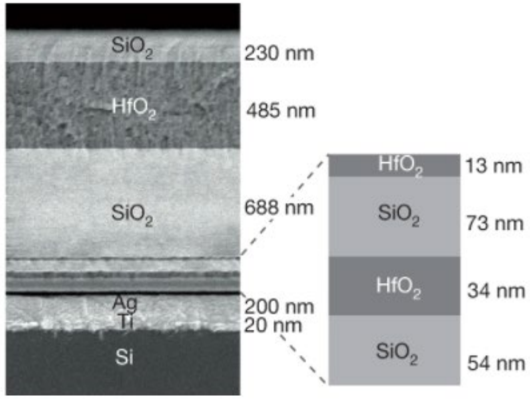




- Perfect absorption of solar light and no front emission of IR light (thermal losses)
- Back emission of IR at energies matching the solar-cell bandgap (minimize thermalization losses)

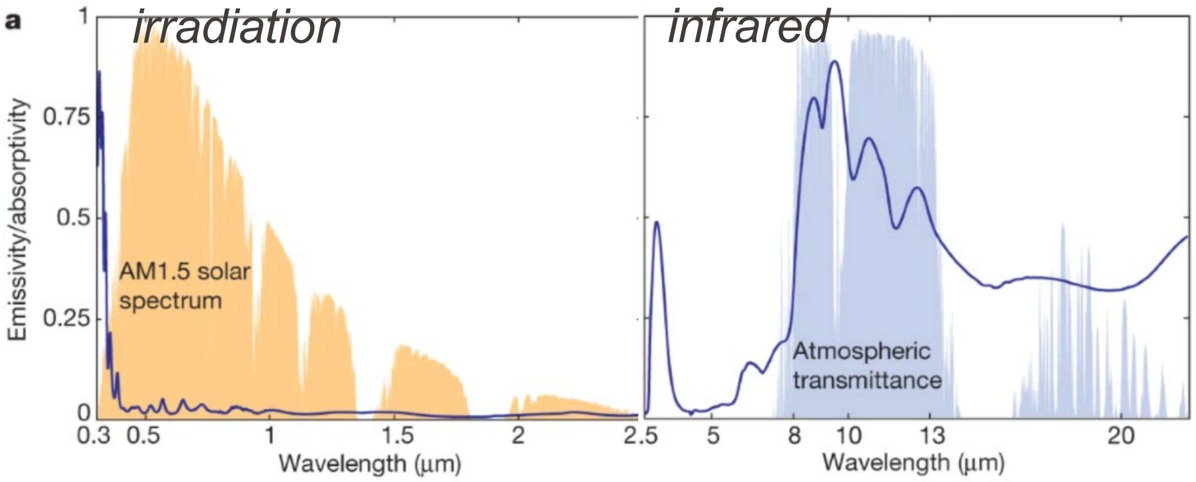
https://www.nature.com/articles/s41563-020-0740-6

Absorption/Emission Engineering – Radiative Cooling



Reflect all solar irradiation

Strong-emission in the infrared

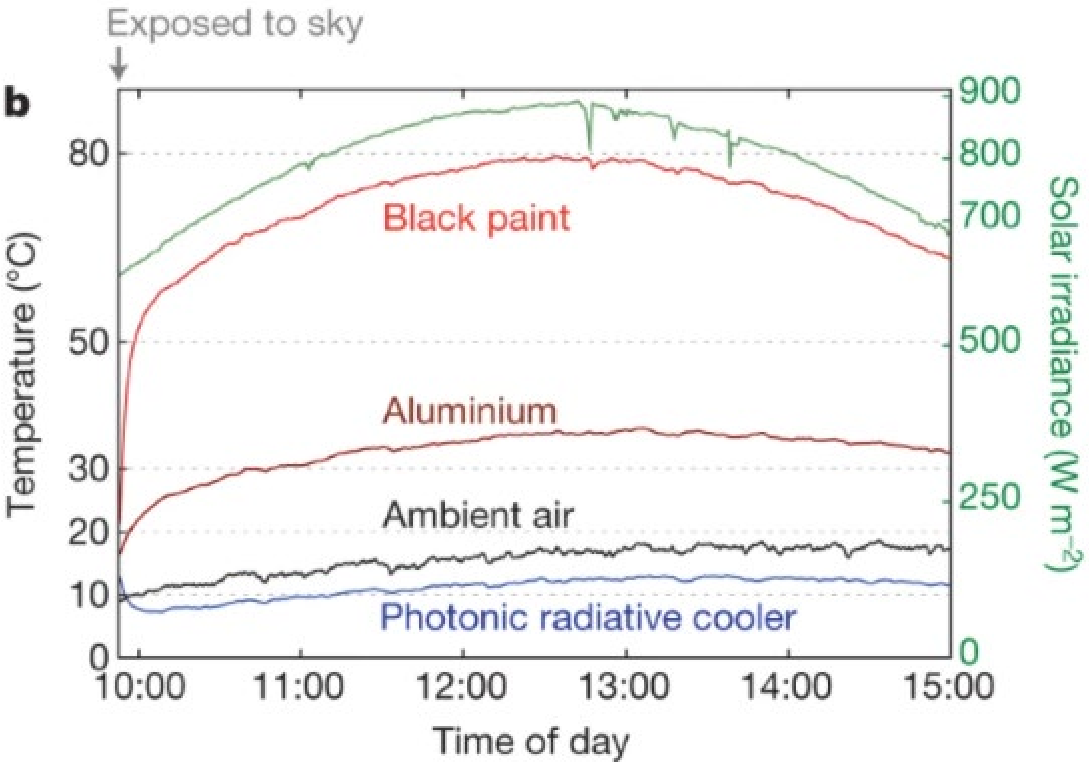


More energy is emitted than absorbed achieving radiative cooling of the object even under solar irradiation!

- Perfect reflection of sunlight in order to avoid any thermal input
- Strong emission of infrared light at wavelength corresponding to the transparency window of the atmosphere, corresponding to effective loss of energy

https://www.nature.com/articles/nature13883

Absorption/Emission Engineering – Radiative Cooling



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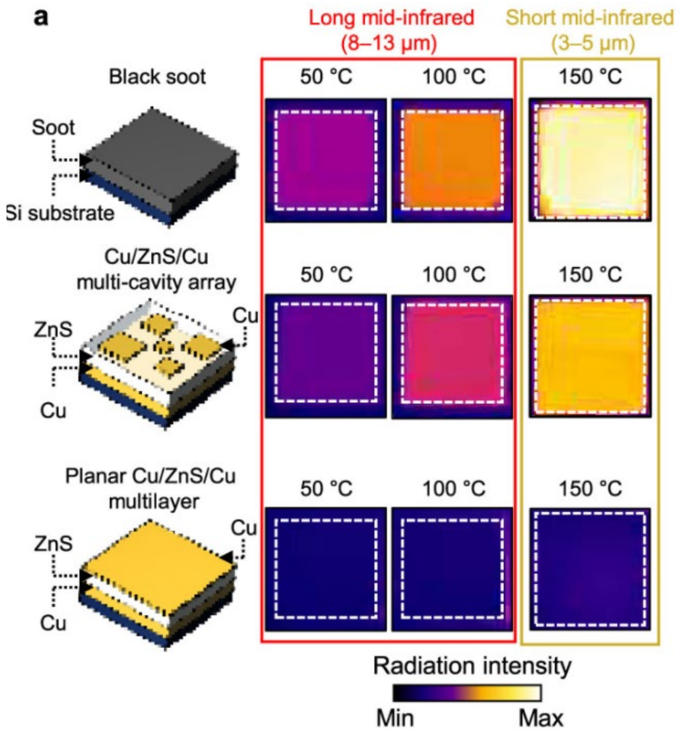
Absorption/Emission Engineering – Radiative Cooling



- A similar concept can be used also to realize cooling clothes and fabric as well as coatings than can "cloak" hot object from the view of infrared cameras

https://pubs.acs.org/doi/full/10.1021/acs.nanolett.1c00741

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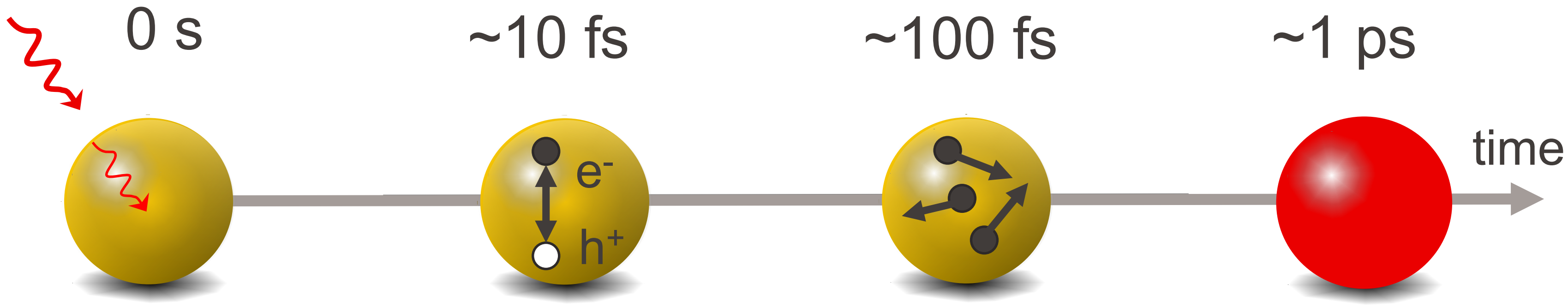
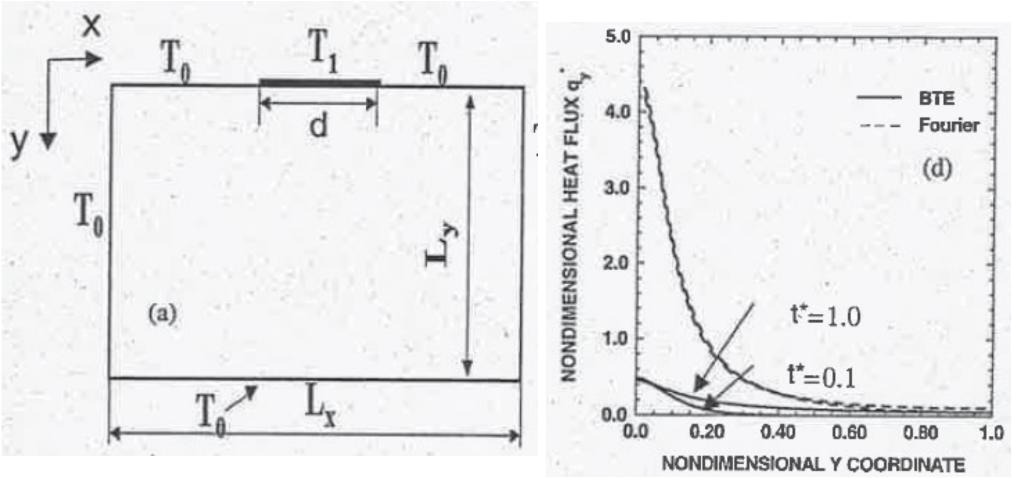
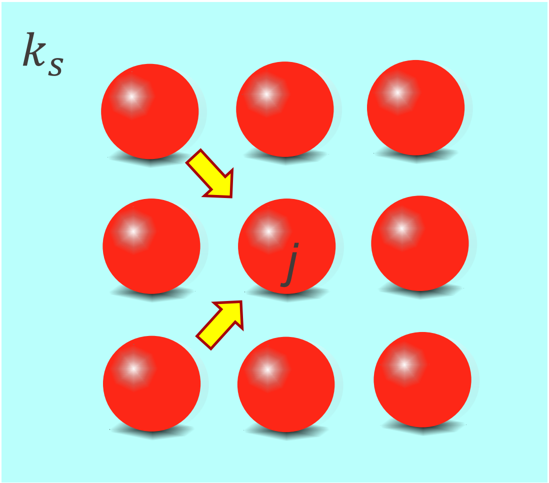
Thermoplasmonics



Nanoscale Heat Sources

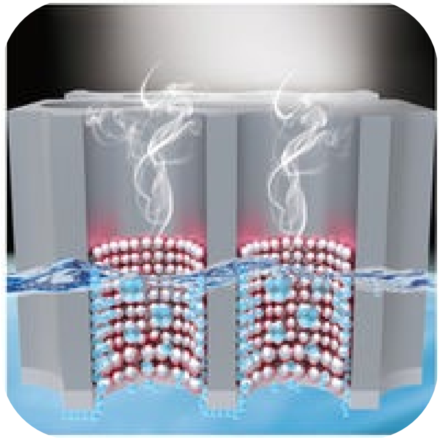


Collective Heating Effects



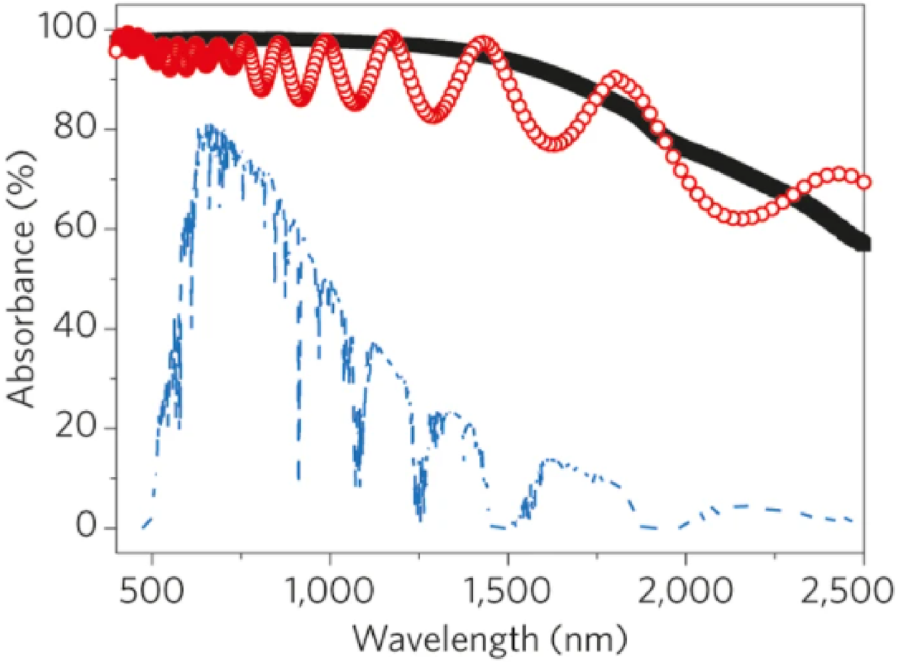
Thermoplasmonics for Solar Evaporation/Desalination

Solar Desalination & Filtration

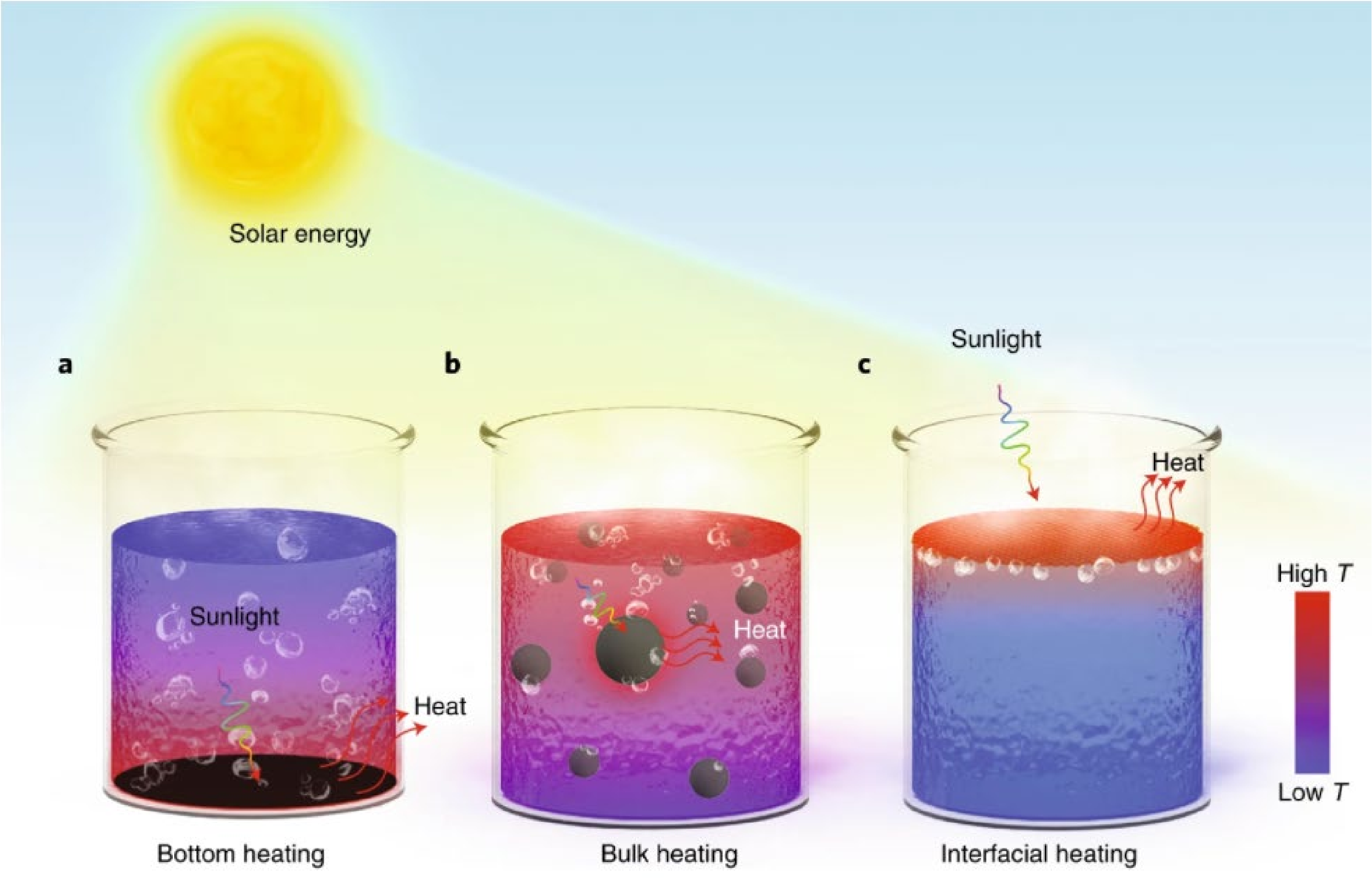


Zhou et al. Nat. Phot. 10, 2016

Figure 1: The Al-based plasmonic absorber synthesized by Zhou *et al*. absorbs most of the solar spectrum.



Solar-driven Interfacial Evaporation



https://www.nature.com/articles/s41560-018-0260-7

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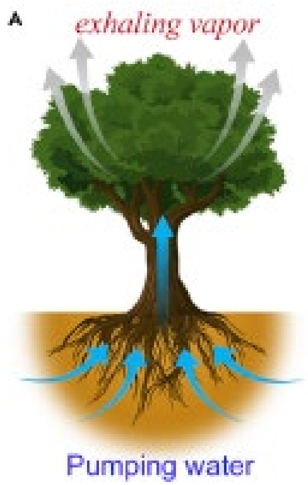

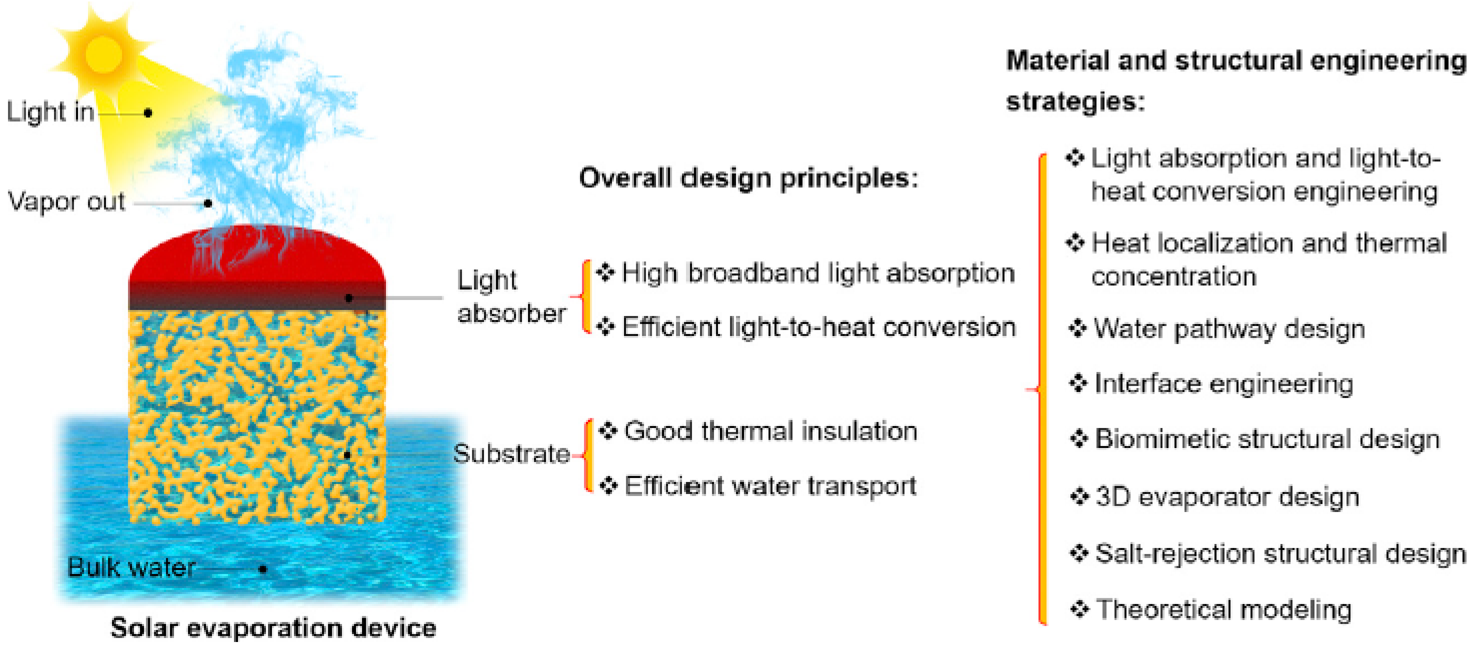

https://www.sciencedirect.com/science/article/pii/S2542435118306299

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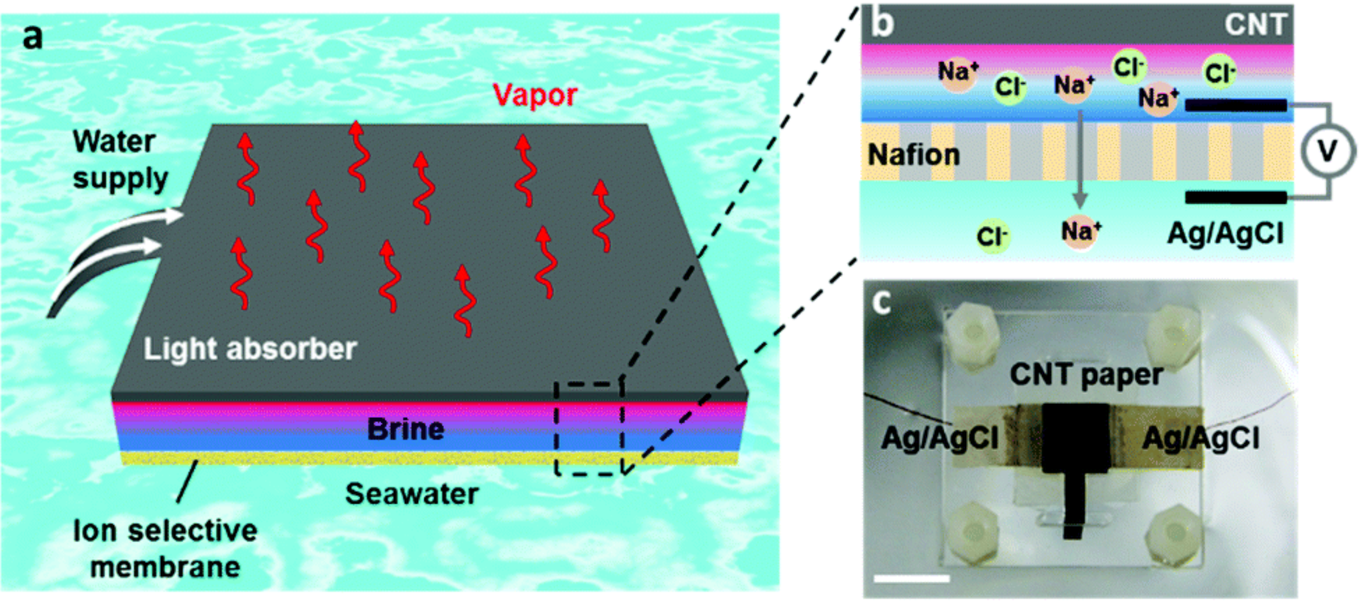

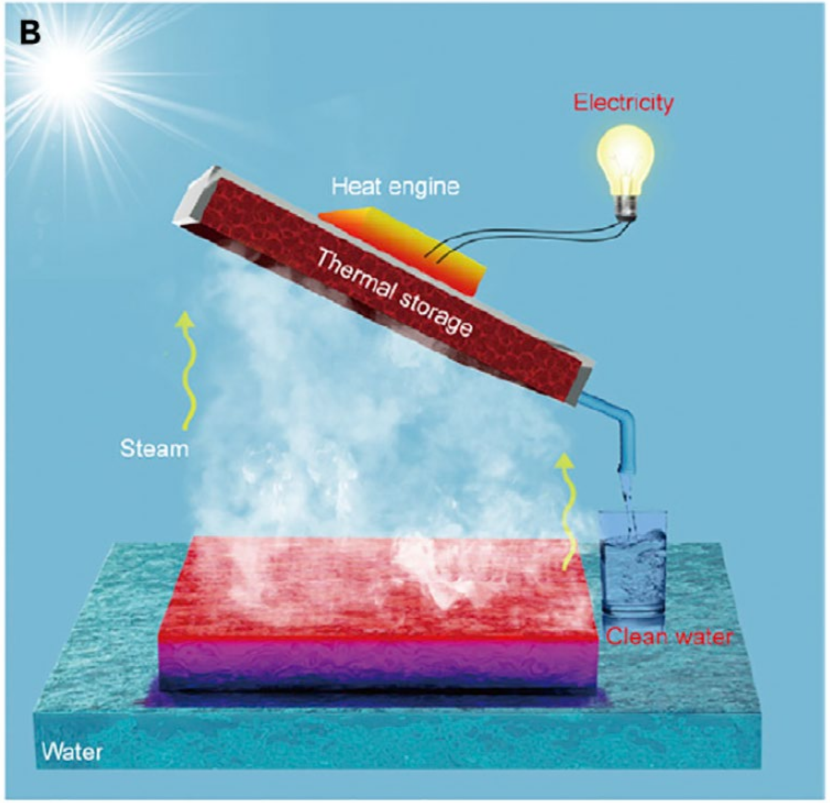

- Combine water purification with electricity production

https://www.sciencedirect.com/science/article/pii/S2542435118306299