Impact of non-radiative losses in near-field thermophotonic devices

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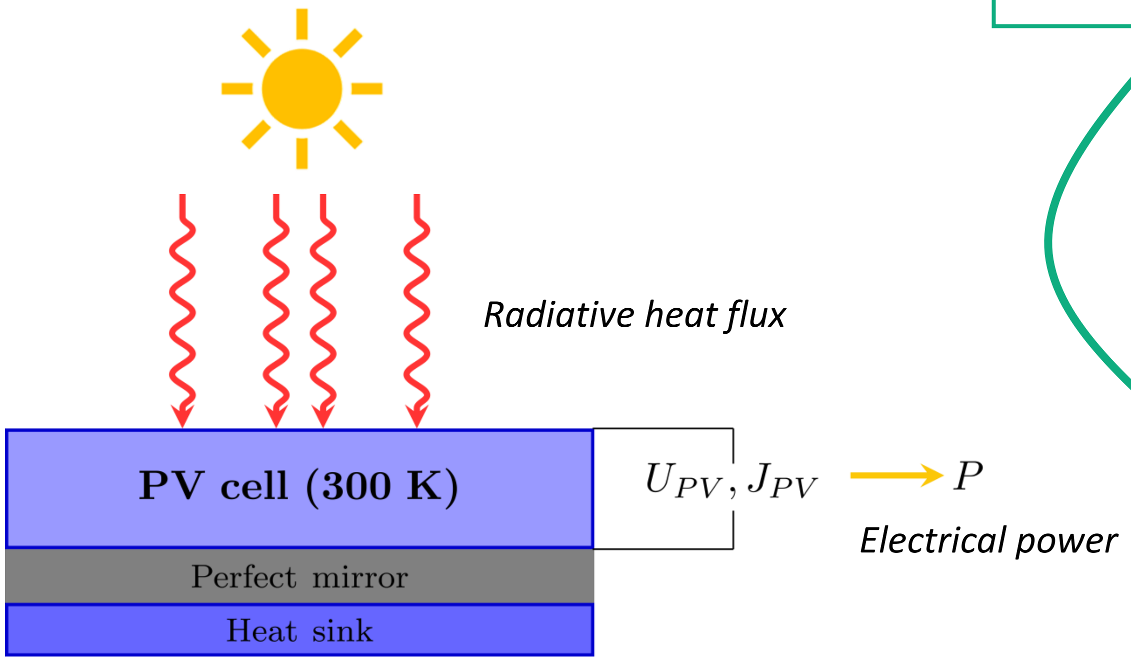
Heat recovery with photovoltaics

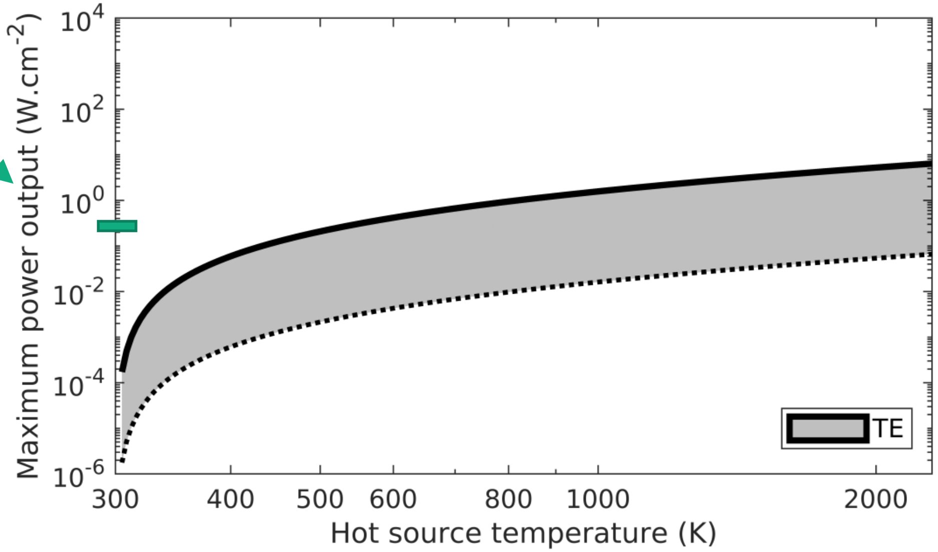
Photovoltaics
(**PV**)



Photovoltaics

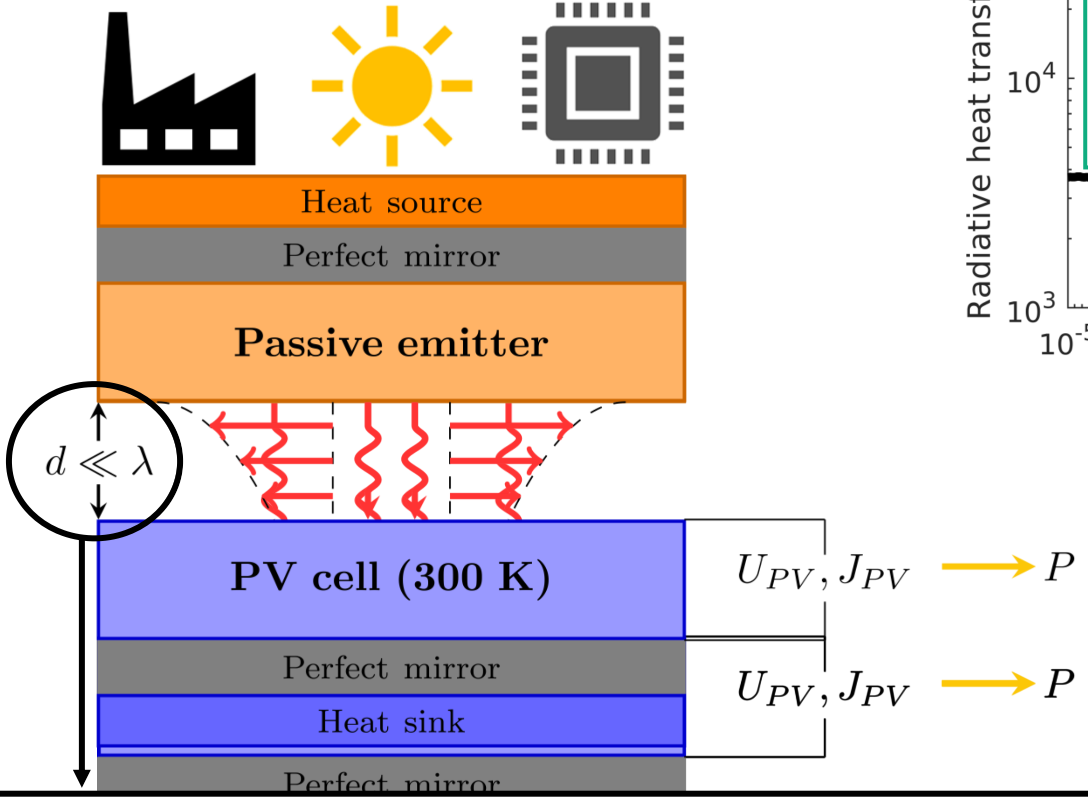
Mainly for power production from solar radiation ($P = 0.3\ \mathrm{W.cm^{-2}}$).

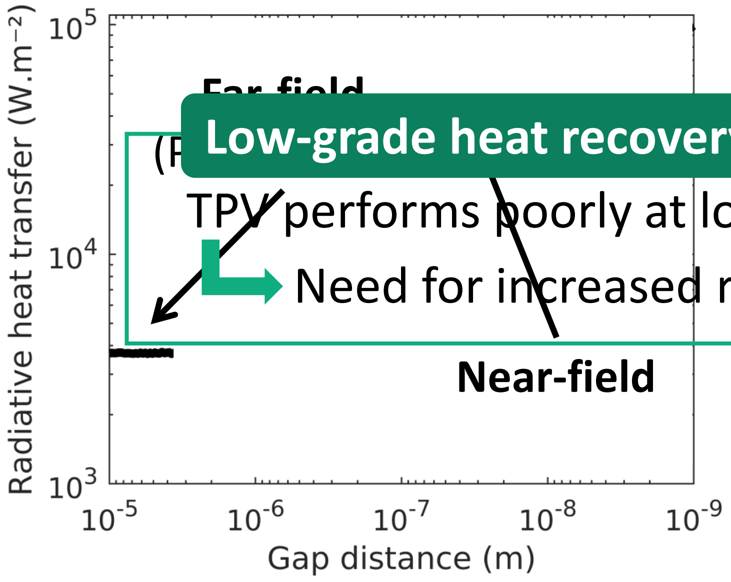
↳ Application for heat recovery?



Heat recovery with photovoltaics

Near-field Thermophotovoltaics (NF-TPV)

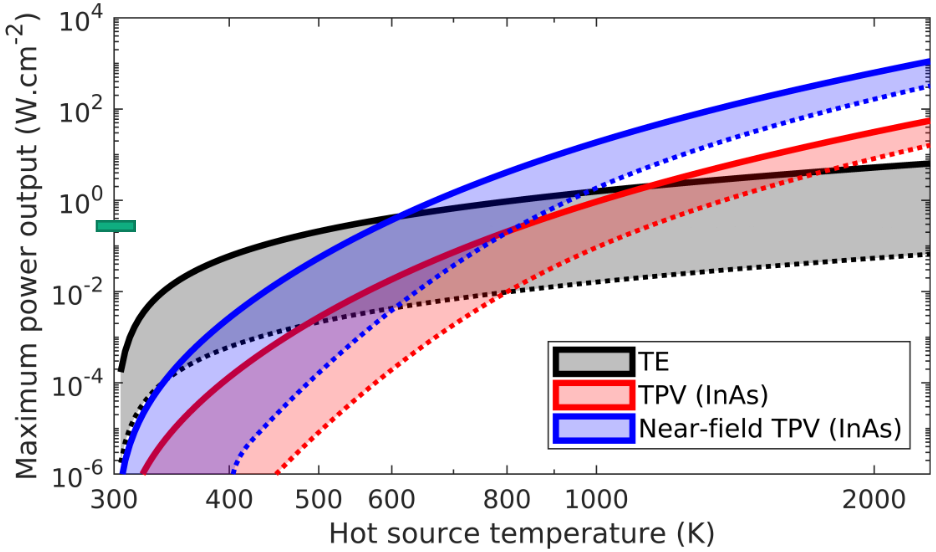




Low-grade heat recovery (400-700 K)

TPV performs poorly at low temperature

Need for increased radiative heat flux

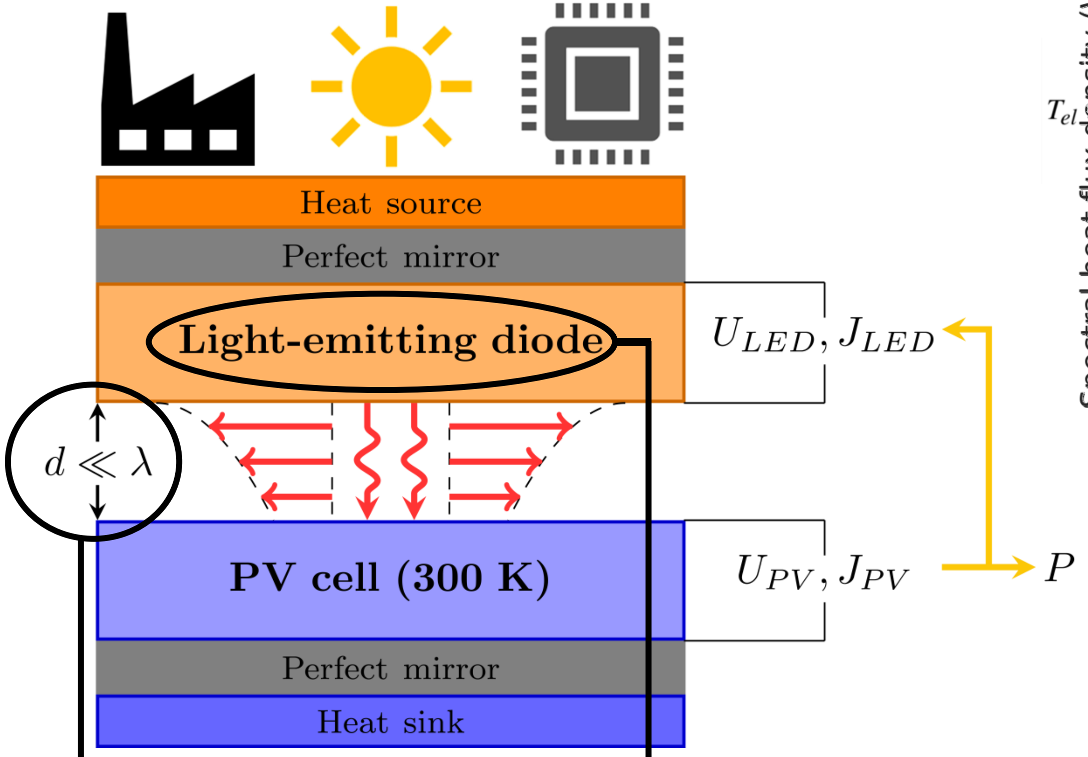


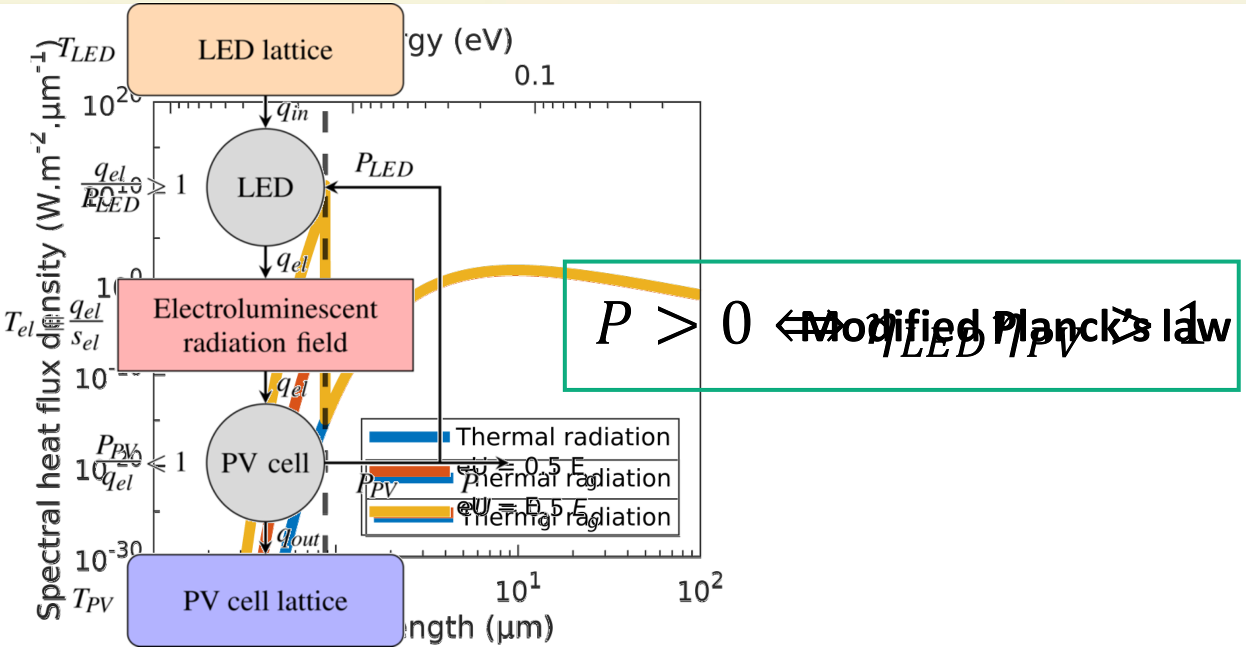
Enhancement of the heat flux density exchanged thanks to:

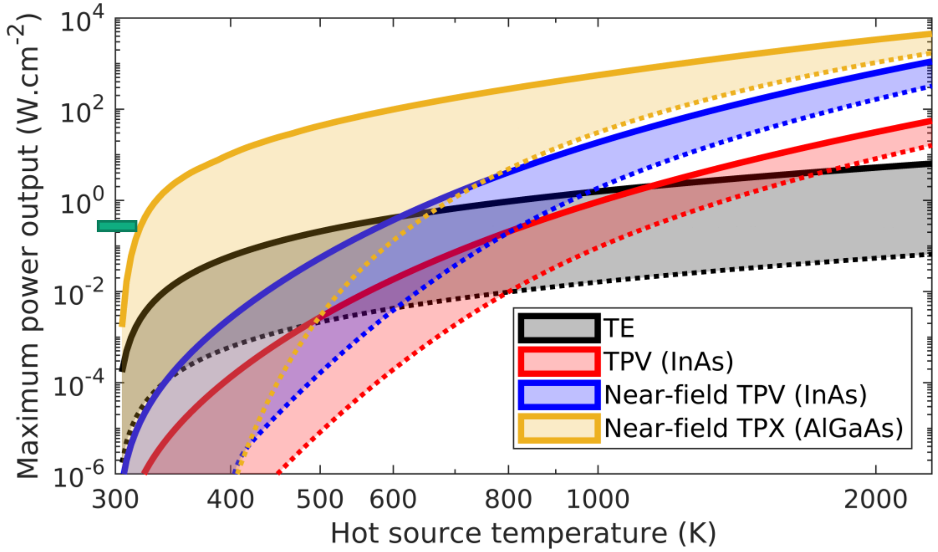
- the participation of **evanescent waves** at short distances

Heat recovery with photovoltaics

Near-field Thermophotonics
(**NF**-**TPX**)







Enhancement of the heat flux density exchanged thanks to:

- the participation of **evanescent waves** at short distances
- the LED **electroluminescence** above the bandgap

Model: near-field radiative heat transfer

Fluctuational Electrodynamics

Spectral photon flux density →

$$\gamma_\omega(z_j) = \frac{\Delta n_{ij}^0}{4\pi^2}\int_0^\infty \mathcal{T}_{i,z_j} k_\rho \, dk_\rho$$

$$q_\omega(z_2) = \hbar\omega \cdot \gamma_\omega(z_2)$$

Spectral heat flux density

→ $\mathcal{T}_{i,z_j}$: **Electromagnetic transmission coefficient**

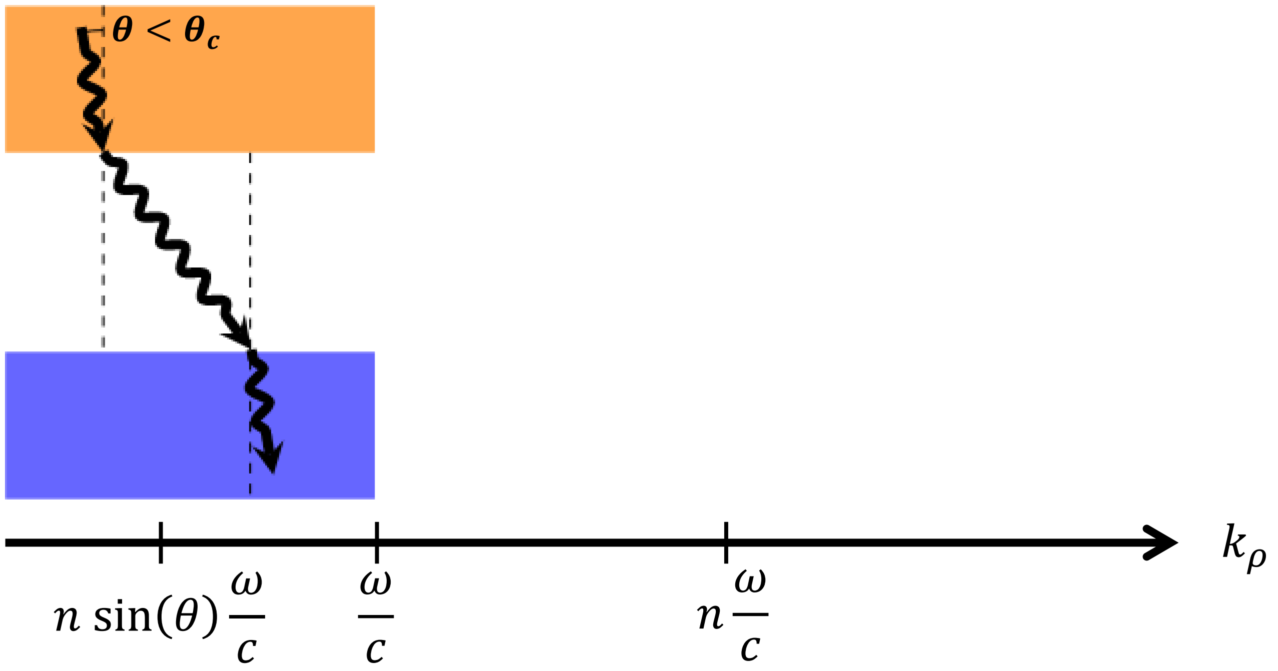
$$\Delta n_{ij}^0 = n^0(\omega, U_i, T_i) - n^0(\omega, U_j, T_j)$$

$$n^0(\omega, U, T) = \begin{cases} \left[e^{\frac{\hbar\omega}{k_B T}} - 1\right]^{-1} & , \hbar\omega < E_g \\ \left[e^{\frac{\hbar\omega - eU}{k_B T}} - 1\right]^{-1} & , \hbar\omega \geq E_g \end{cases}$$

Modified Bose-Einstein distribution

Radiation modes

Propagative



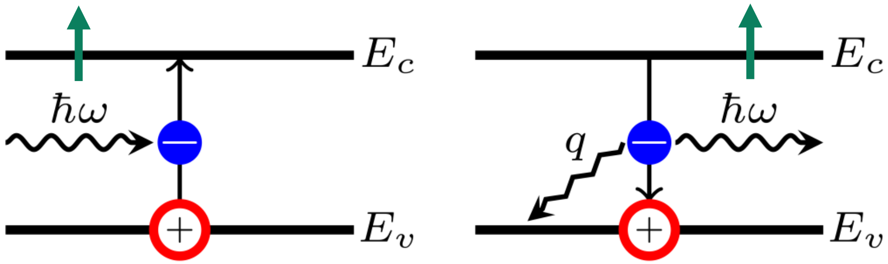
Model: charge transport

0D (Detailed balance)

- **ideal** model
  - **Semi-infinite** LED, PV cells
  - **1 photon** ↔ **1 electron-hole** (e-h) **pair** participating to the current

$$J = e \cdot \gamma_{net} = e(\gamma_{abs} - \gamma_{em})$$

Radiative generation **Radiative recombination**



1D (Drift-diffusion)

→ **iterative** process

- Non-linearities
- Coupled equations

Poisson:

$$\frac{dE}{dz}(z) = -\frac{e}{\varepsilon}(n(z) - p(z) + N_a(z) - N_d(z))$$

Continuity:

$$\frac{dJ_n}{dz}(z) = -e(R(z) - G(z))$$

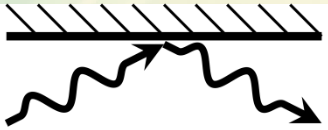
$$\frac{dJ_p}{dz}(z) = e(R(z) - G(z))$$

Drift-diffusion:

$$J_n = e \cdot n(z)\mu_n E(z) + e \cdot D_n \frac{dn}{dz}(z)$$

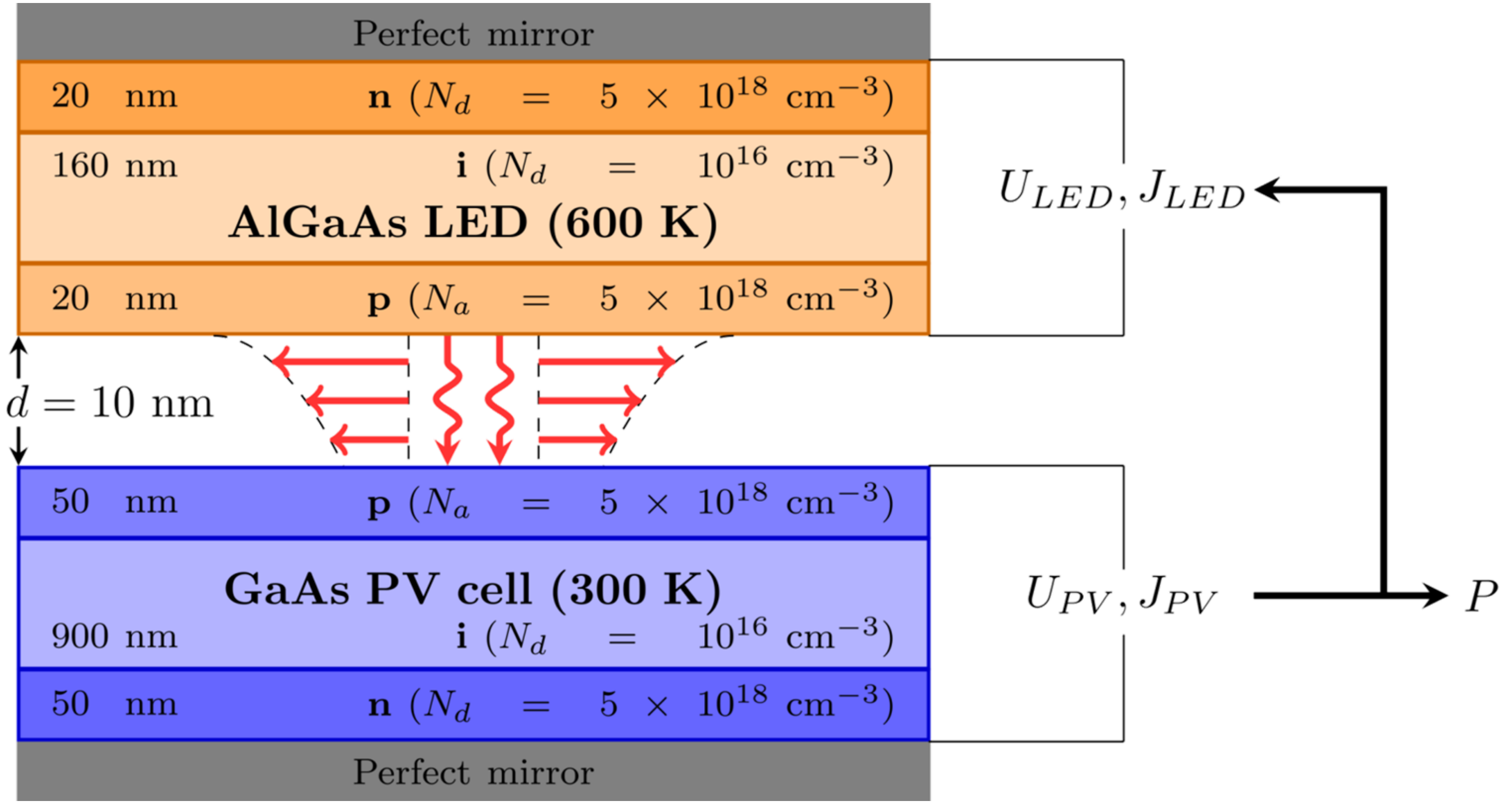
$$J_p = e \cdot p(z)\mu_p E(z) - e \cdot D_p \frac{dp}{dz}(z)$$

Realistic device design



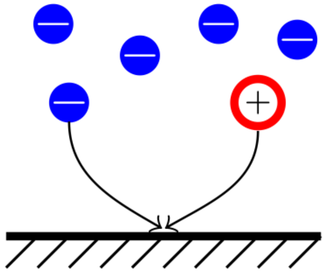
Perfect mirror
↪ Cavity effect, no photon loss

AlGaAs LED
↪ bandgap-matched with PV cell



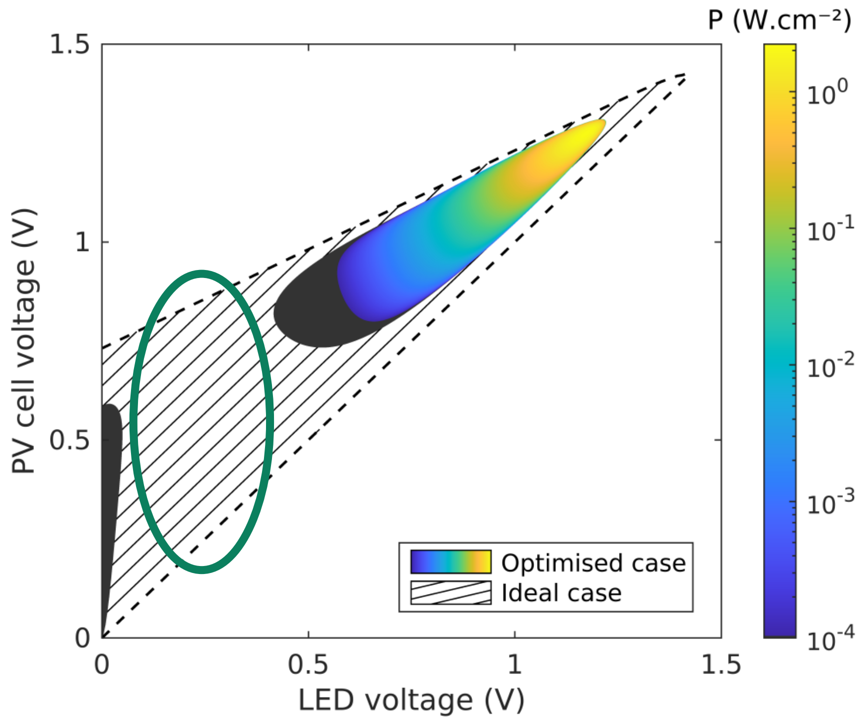
GaAs PV cell
↪ high conversion efficiency

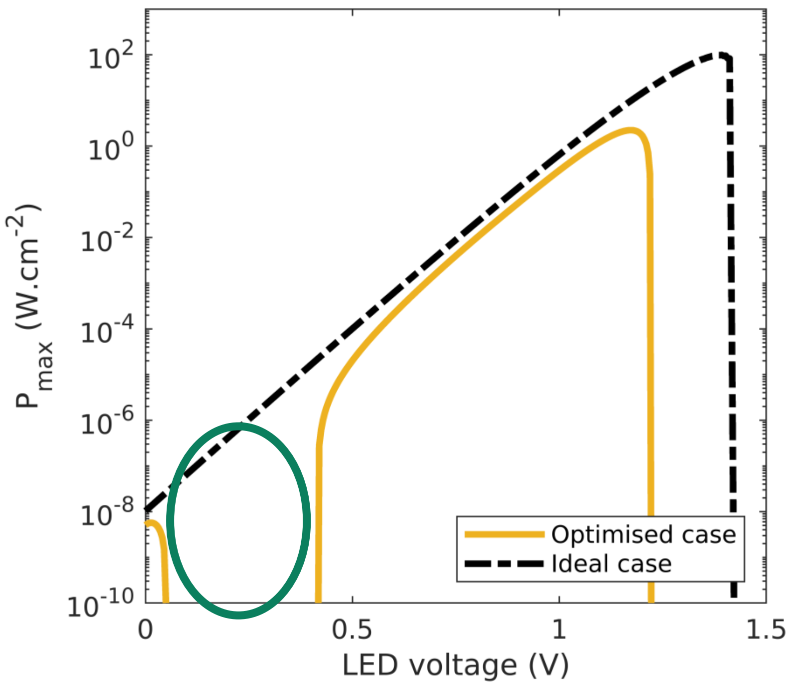
Surface recombinations
↪ $S = 1\ \mathrm{m.s^{-1}}$ for minority carriers



PIN thin films → improvement of carrier transport
Study restricted to **homojunctions**

Performance of the AlGaAs PIN device



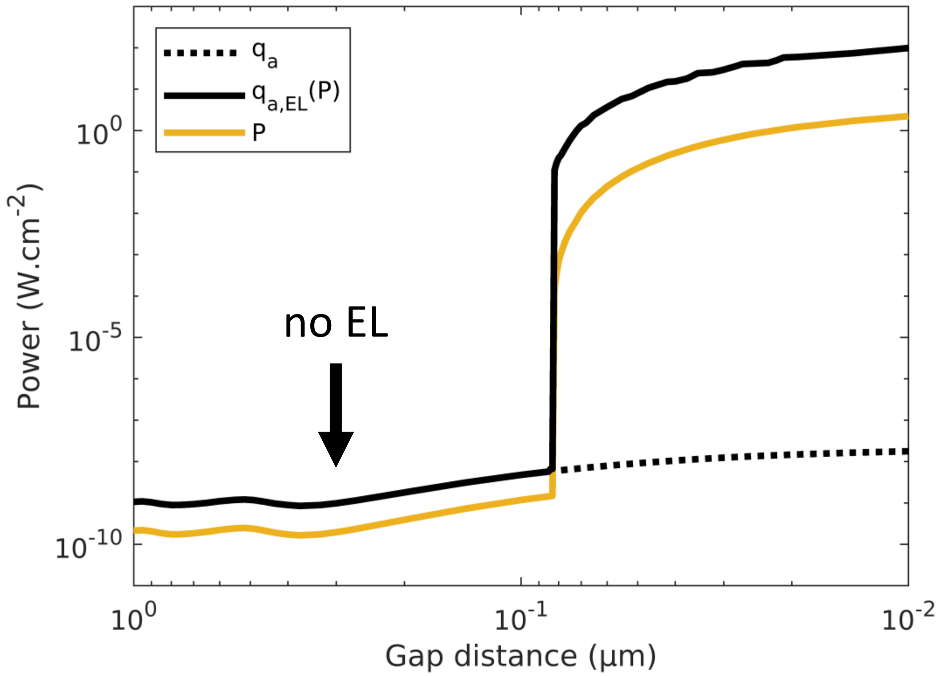


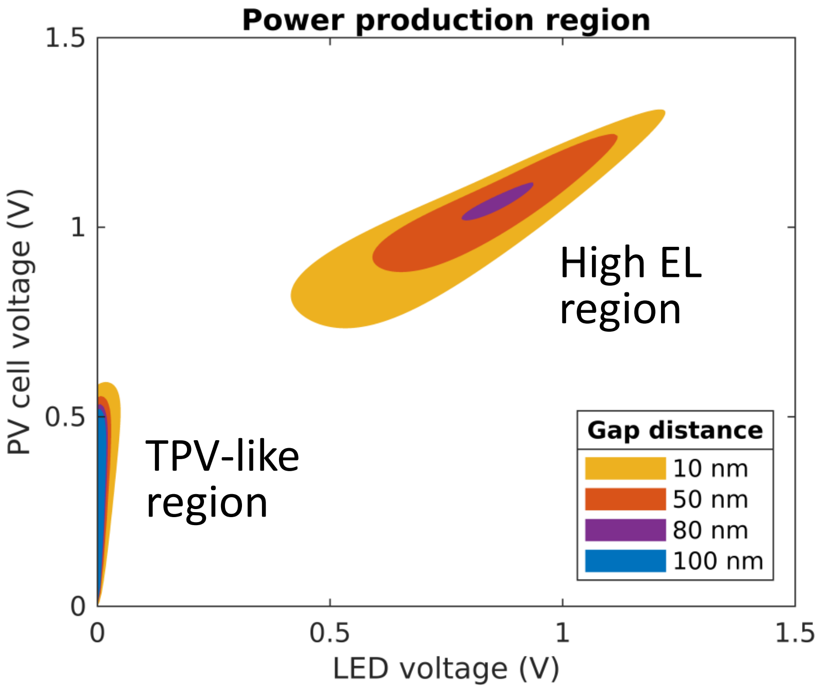
$$P_{max} = 2\ \mathrm{W.cm^{-2}}$$
$$\hookrightarrow 7\ \mathrm{mW.cm^{-2}.K^{-1}}$$

$$P_{ideal} = 100\ \mathrm{W.cm^{-2}}$$

Why is there **no power production** at **low $\boldsymbol{U_{LED}}$**?

Influence of gap distance





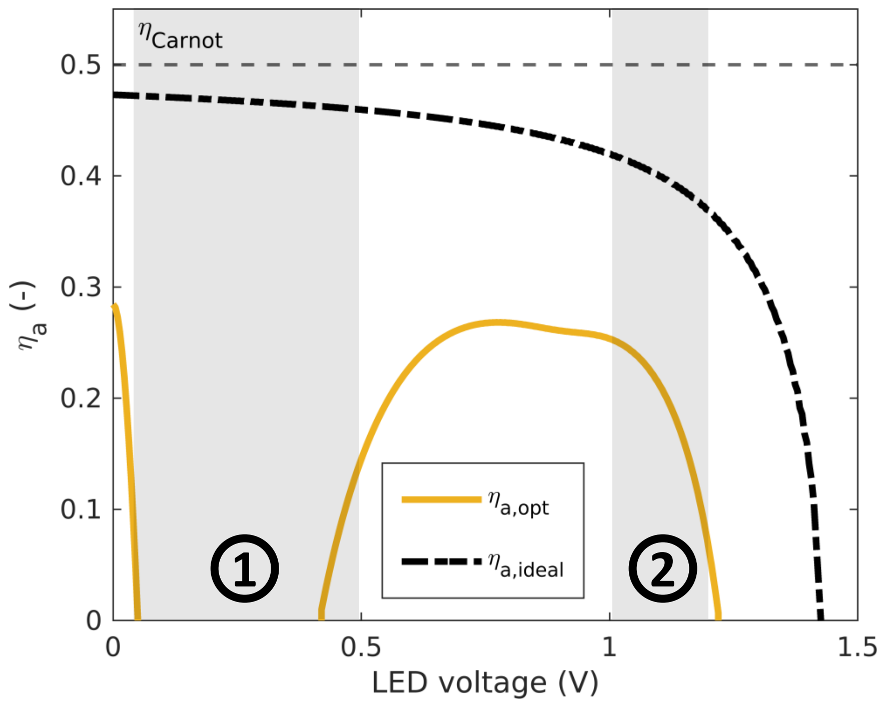
Low power involved due to $E_g \gg E_{thermal}(600\text{ K}) \approx 50\text{ meV}$
Heat flux increase rate in the near field (10 nm): $\times\ \mathbf{10}$ to $\times\ \mathbf{20}$

Thermophotonics is **not viable above 85 nm**, because the high electroluminescence region shrinks and finally disappears around 85 nm

→ **Near-field effects** are **mandatory** to reach high performance

→ Related to the lack of power production at low U_{LED}

LED non-radiative losses



Clear relation between the **LED IQE** and the **device efficiency:** Drop due to **non-radiative losses**

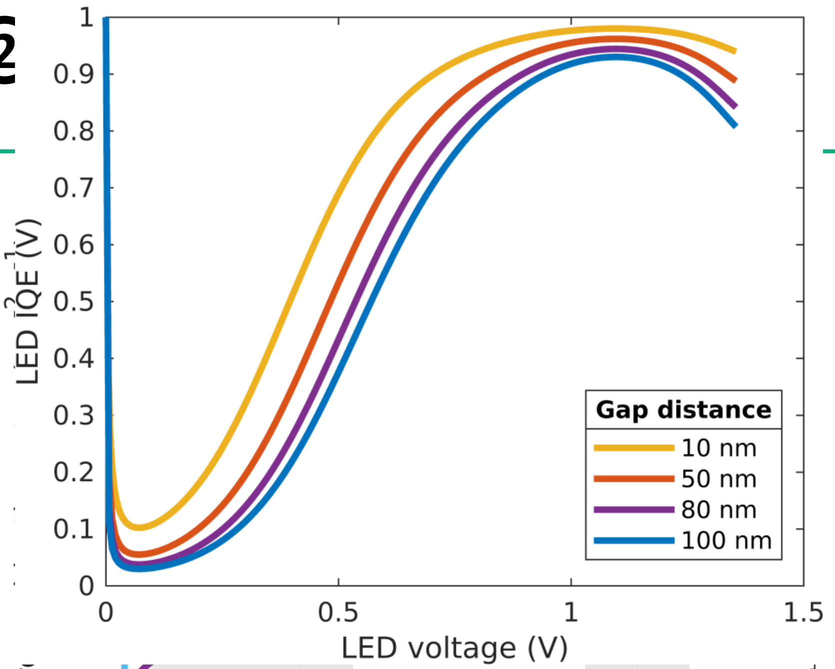
The presence of an **intrinsic region**:

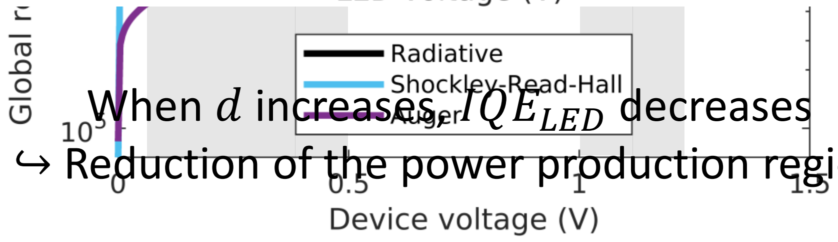
① Internal Quantum Efficiency $IQE = \frac{R_{rad}}{R_{bulk}}$

↗ **Shockley-Read-Hall** recombinations :

↘ P at low voltage

②





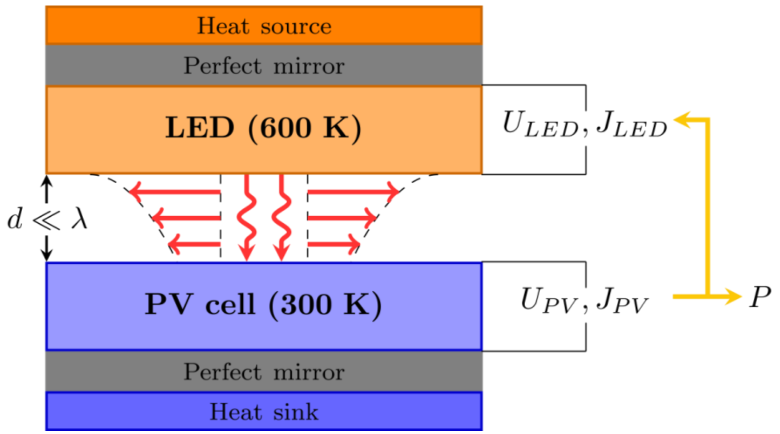
When d increases, IQE_{LED} decreases

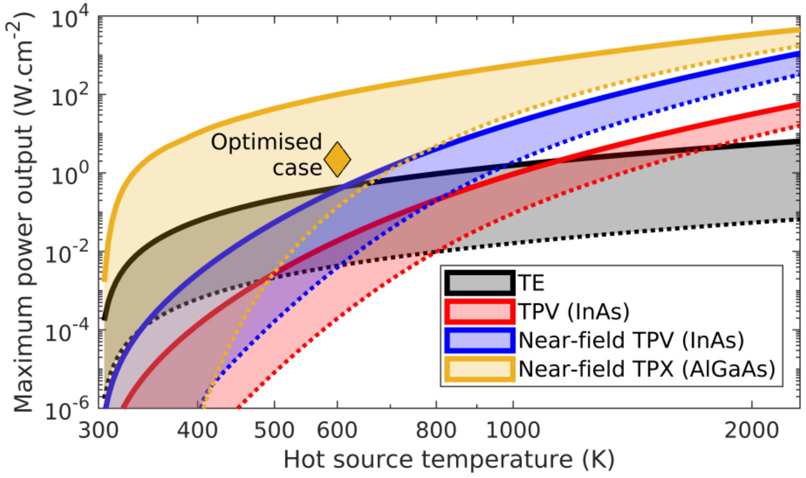
↪ Reduction of the power production region

Conclusion & Prospects

Conclusion

- Best homojunction-based NF-TPX found: $P_{max} = \mathbf{2.2\ W.cm^{-2}}$ and $\eta_{P_{max}} = \mathbf{12\%}$ for $\Delta T = \mathbf{300\ K}$.
- Using PIN junctions allows to **decrease non-radiative losses** at high LED voltage, at the expense of the low-voltage region.
- **Radiative near-field effects** may be mandatory to reach higher IQE, thus higher performance for TPX.

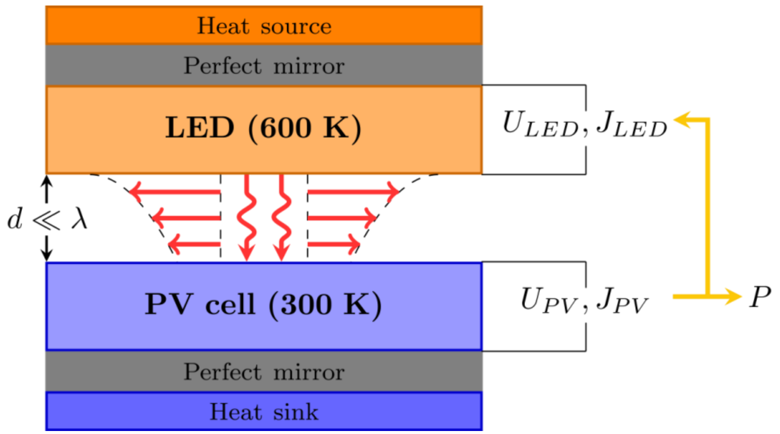


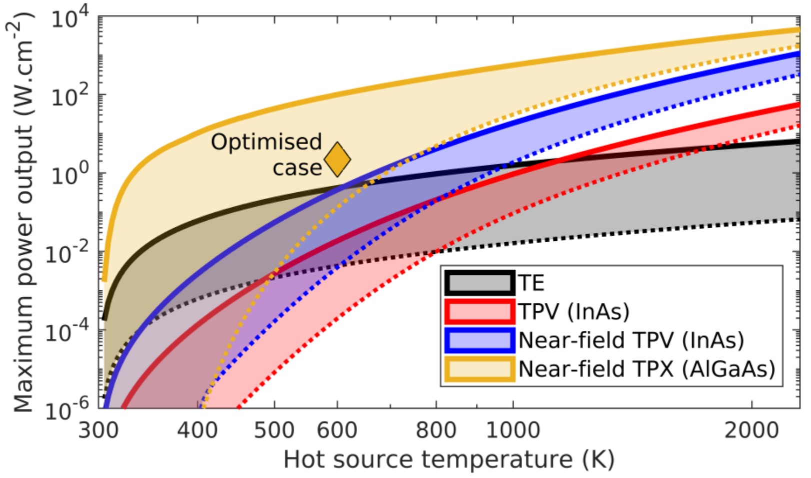


Conclusion & Prospects

Prospects

- Development of the numerical model for **heterojunctions**.
- Application of TPX to **refrigeration** → see poster of Thomas Châtelet.
- Study of efficiency loss compared to theoretical limit ($\mathbf{29\%}$ at P_{max}).
- Analysis of the **photon recycling process** in each device.
- Implementation of an **experimental setup**.





Acknowledgements

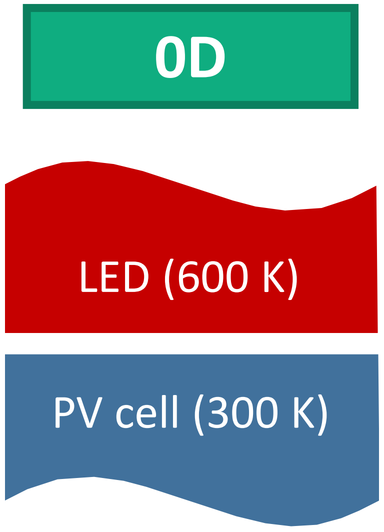
https://tpx-power-h2020.eu/
https://optagon-h2020.eu/

Thank you for your attention!

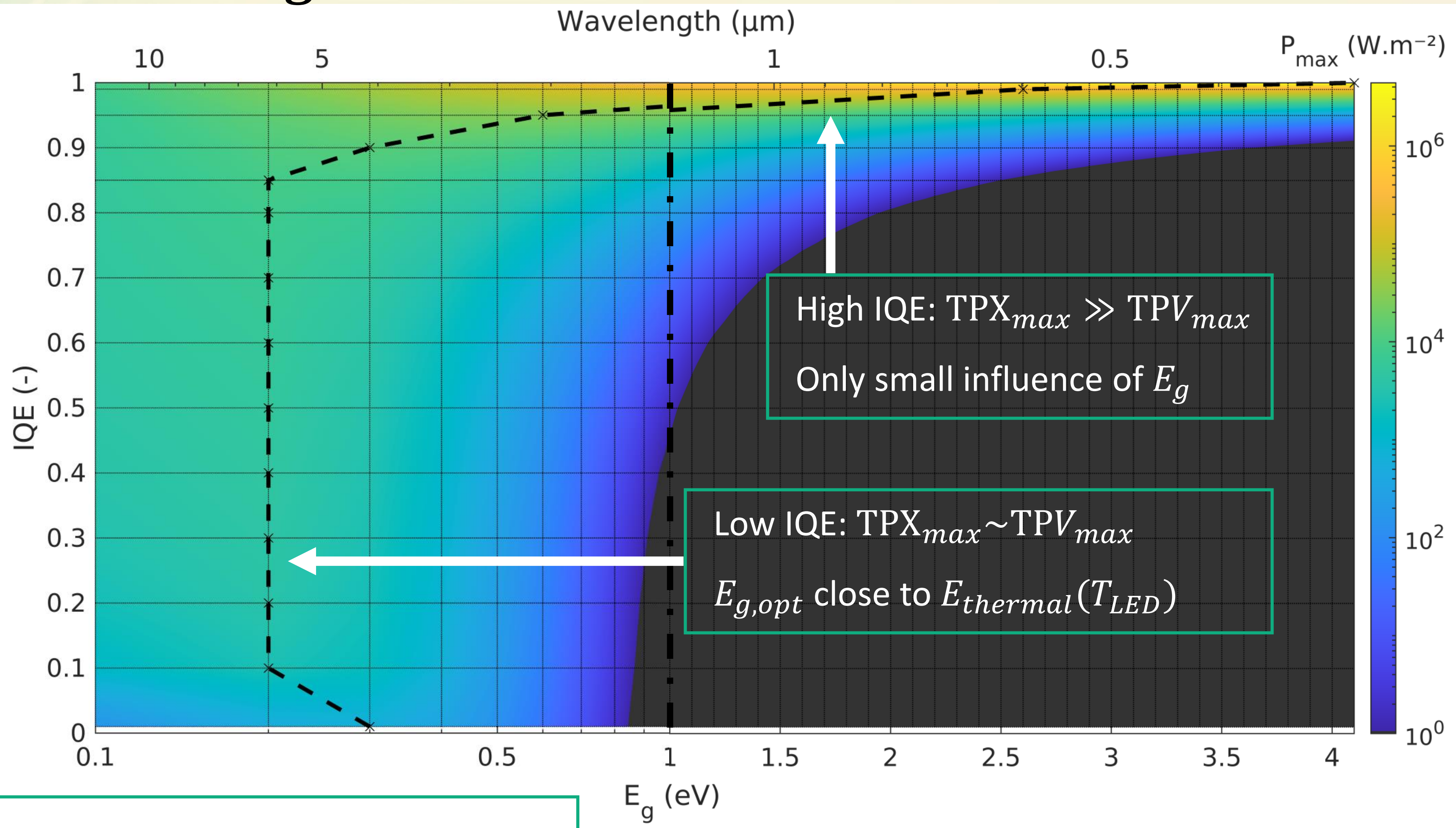
Contact: julien.legendre@insa-lyon.fr

Additional slides

General overview - E_g and IQE dependence



$d = 10$ nm
$\varepsilon = 10 + i$



- Use of **highly efficient** devices is key to exceed TPV
- $\boldsymbol{E_g}$ only has a small impact on TPX performances

→ **GaAs**