How nanophotonics can speed up photon detection

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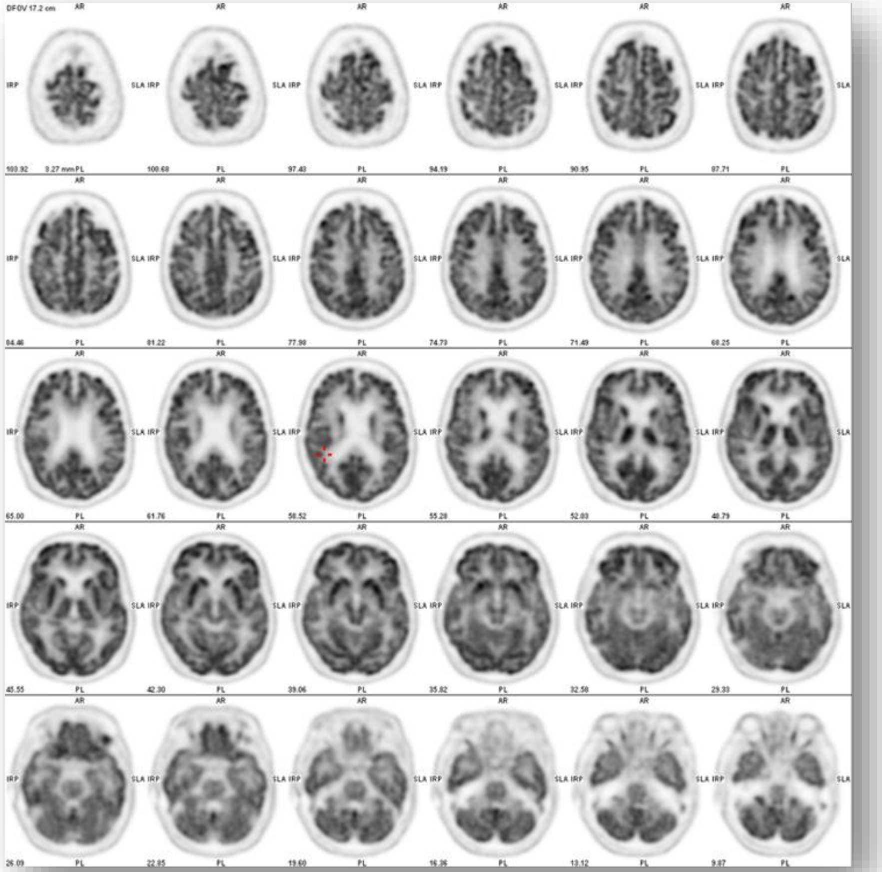
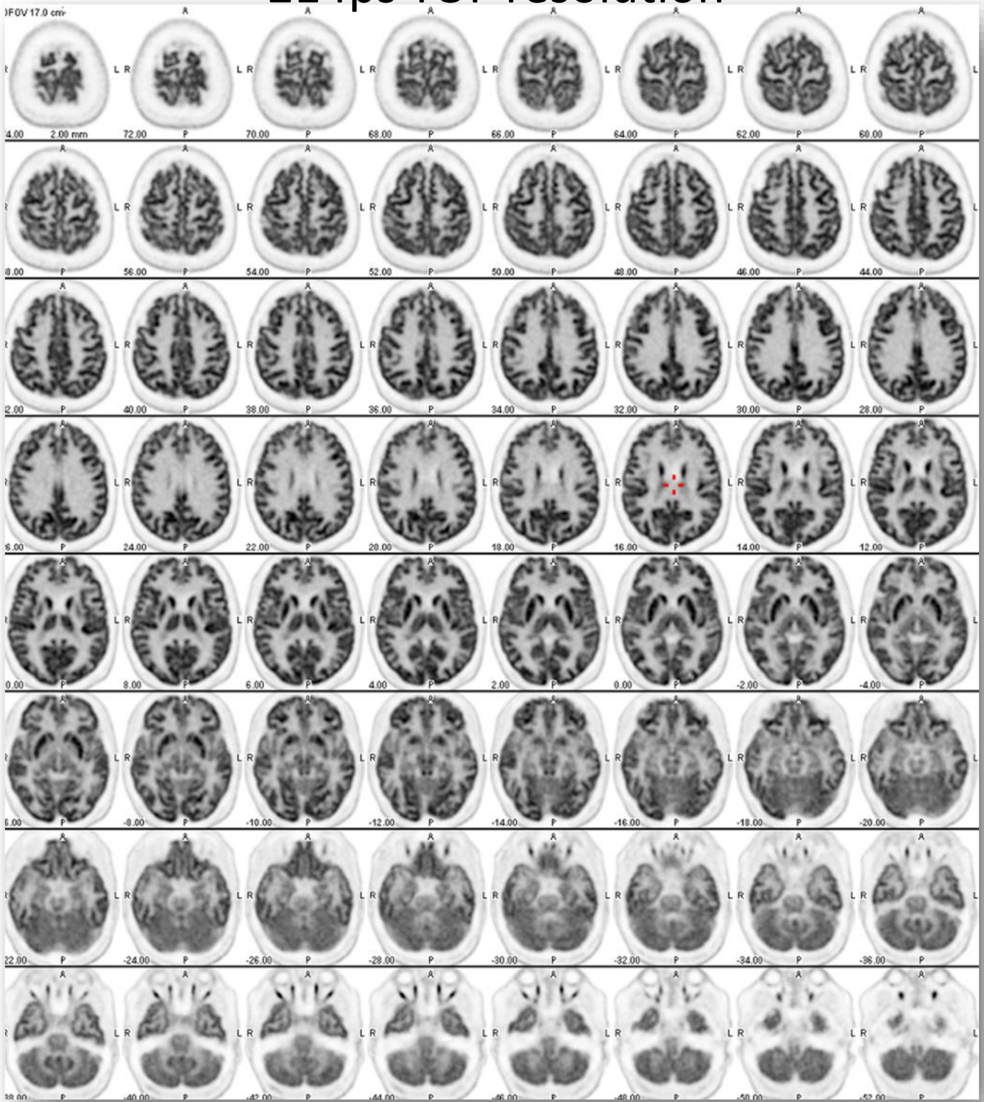
Main motivation: TOF-PET

GE-Discovery D690TOF 2011
500ps TOF resolution

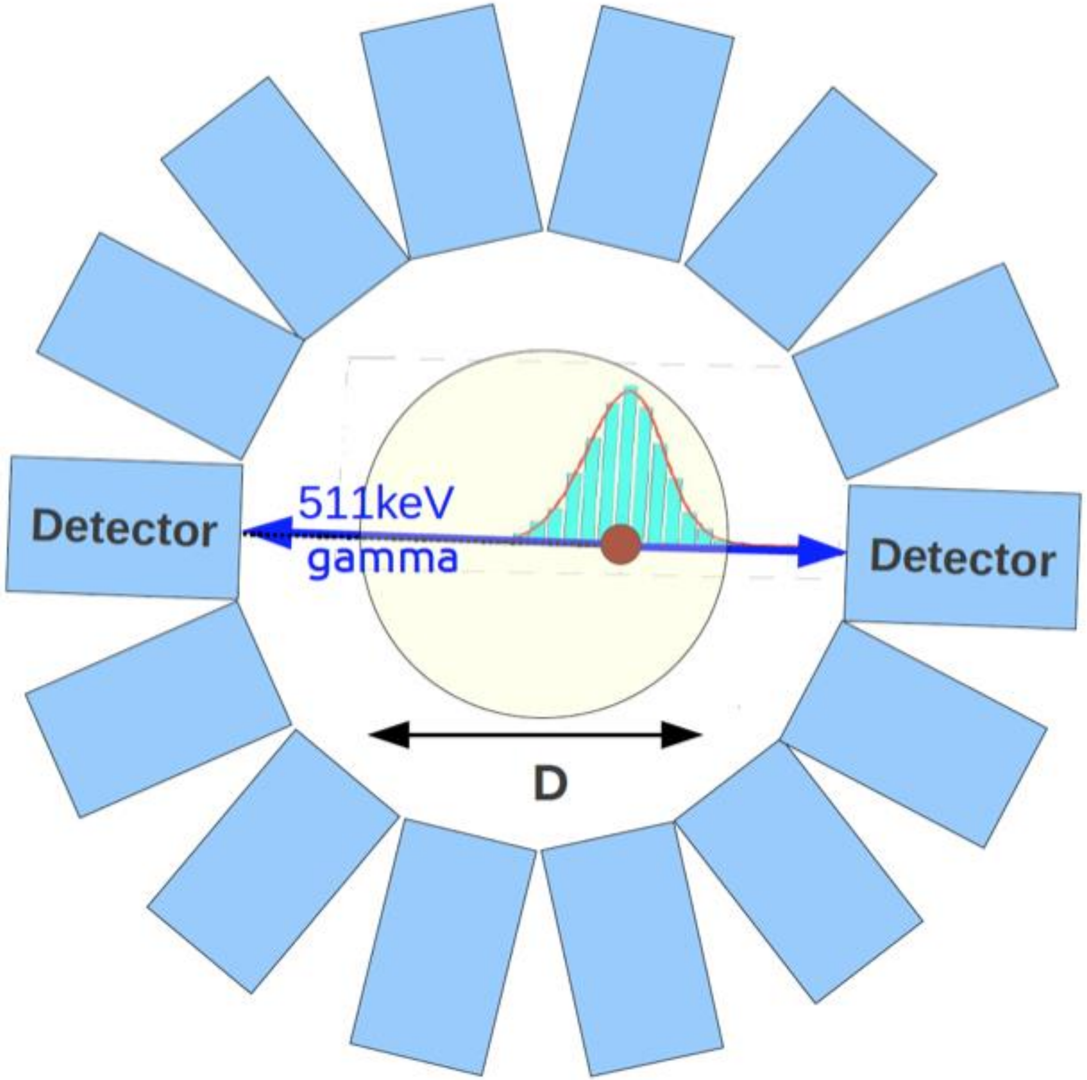


Siemens- Biograph Vision-2018
214ps TOF resolution



Courtesy of J. Prior, CHUV, Lausanne

Why TOF-PET and ↘ 10ps FWHM CTR?



$$SNR_{TOF} = SNR_{non\,TOF} \cdot \sqrt{\frac{D}{c * CTR}}$$

PET Effective sensitivity scales like the square of the SNR gain

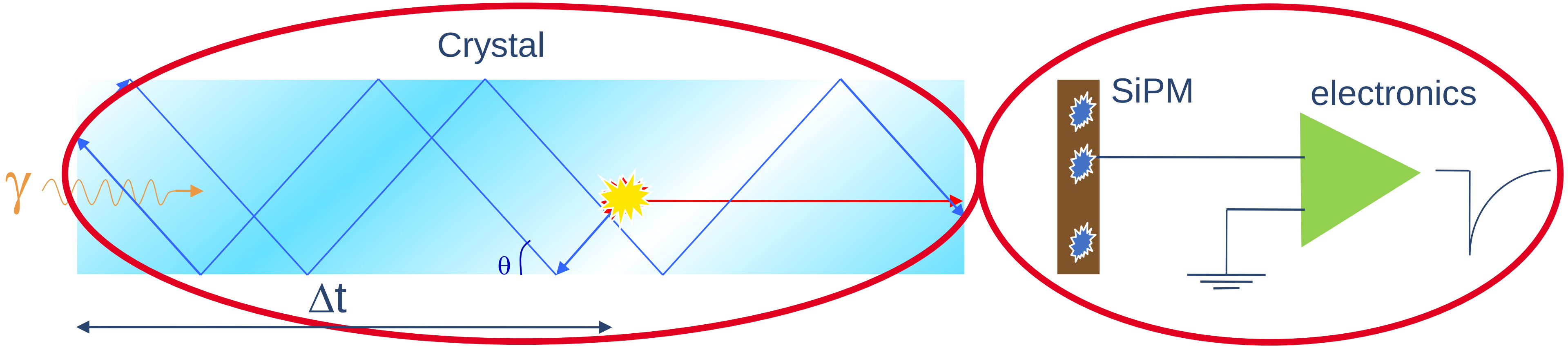
For whole body PET
with FOV D = 40cm

CTR=200ps → SNR_{gain}= 3.5 → η_{eff} X 12.5

CTR=100ps → SNR_{gain}= 5.2 → η_{eff} X 25

CTR=10ps → SNR_{gain}= 16 → η_{eff} X 250

The Detection Chain



OBJECTIVE: ***Understand and eliminate all sources of timing jitter***

CONCLUSION 1: There are no physical show stoppers to reach 10ps time resolution

CONCLUSION 2: A number of emerging technologies in

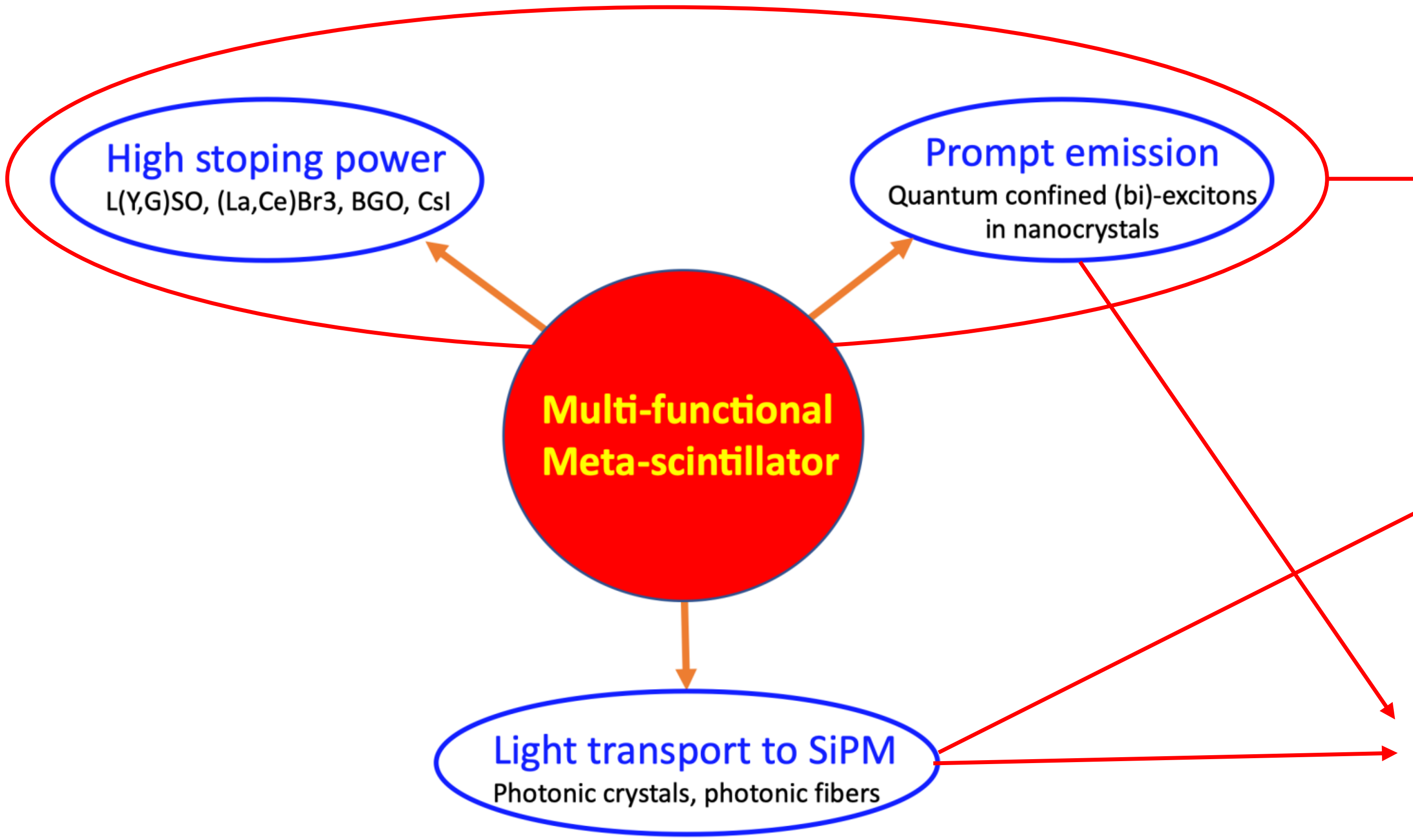
- *scintillator science,*
- *nanophotonics,*
- *microelectronics*

can make it possible

Roadmap toward the 10 ps time-of-flight PET challenge

IOPscience P. Lecoq, C. Morel, J.O. Prior, D. Visvikis *et al.*, *Phys. Med. Biol.*, **65** (2020) 21RM01

The 3 generations of Metacrystals



1st generation

- 200ps CTR at system level, BGO-based
- 100ps CTR at system level, LYSO-based

2d generation

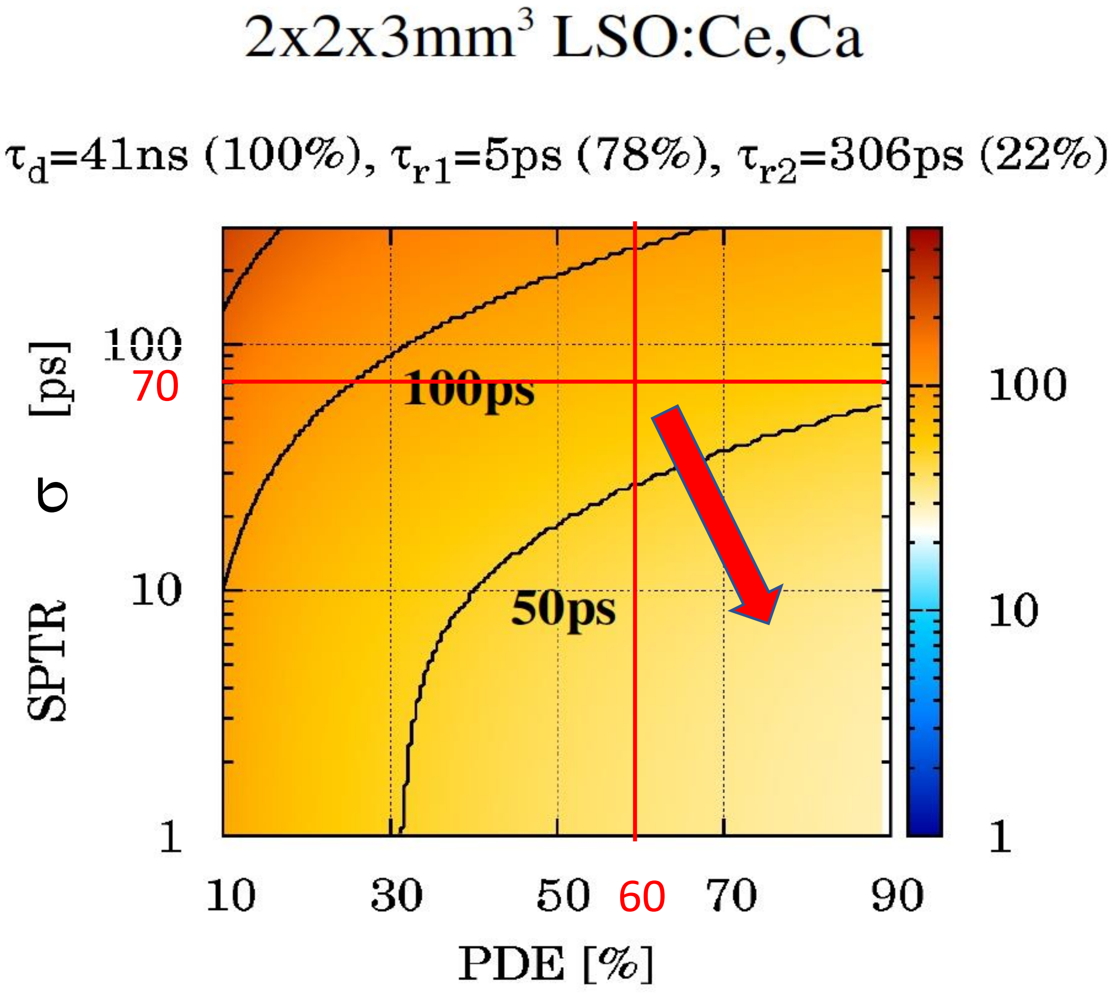
- 50-70ps CTR at system level, LYSO-based
- 100ps CTR at system level, BGO-based

3d generation

- 10-30ps CTR at system level
- New nanoscintillators
- New nanophotonic features

2 filed patents, 2 more in preparation

Ultimate CTR for small LSO:Ce,Ca



Clue coupling LTE = 68%

S. Gundacker, CERN

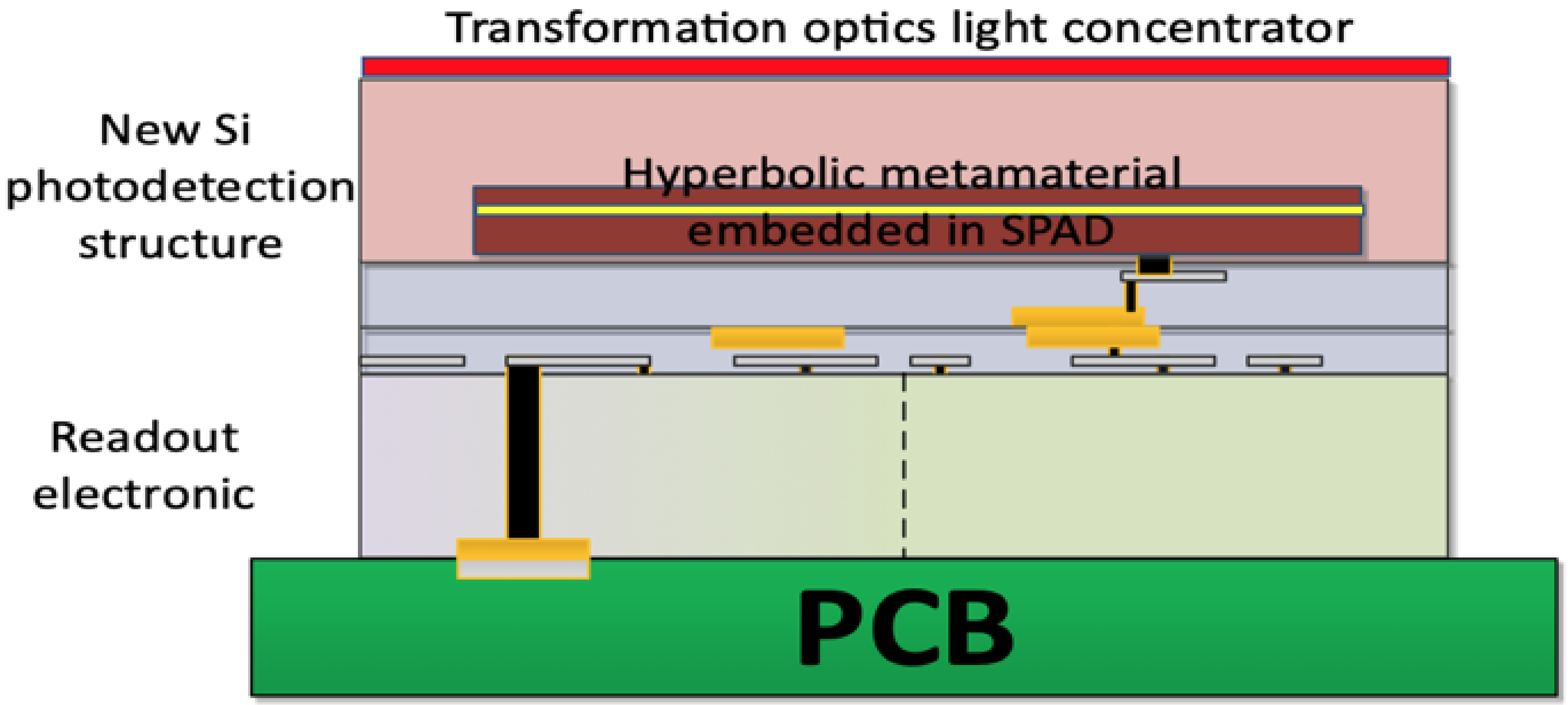
New SiPM concept

The Quantum Silicon Detector

From EU funded project ATTRACT PHOTOQUANT

PI M. Salomoni

To bring the SPTR of the fastest SiPMs today from 70ps (FBK NUV HD) to 10ps



S. Enoch, A. Gola, P. Lecoq, A. Rivetti, ***Design considerations for a new generation of SiPMs with unprecedented timing resolution,*** *2021 JINST 16 P02019*

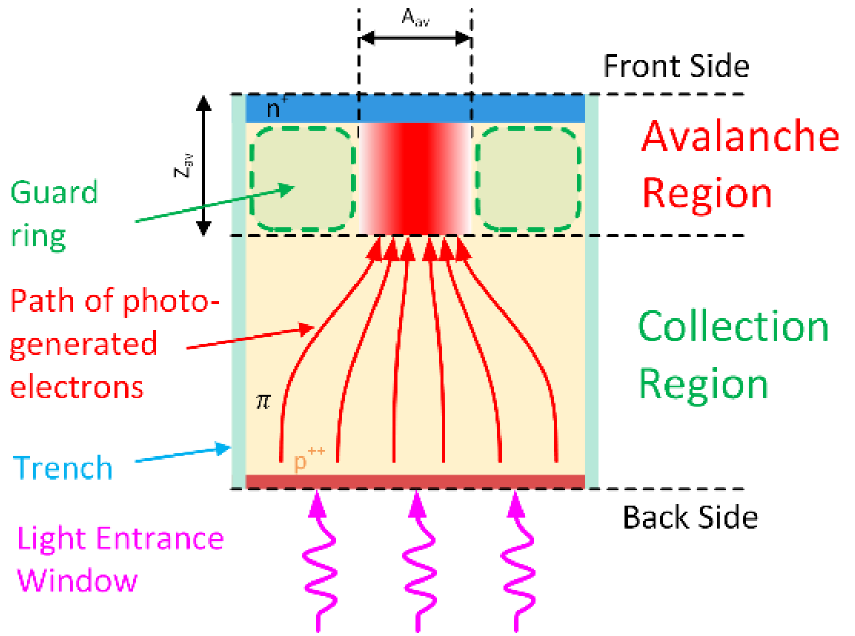
QSD microcell structure

Challenge

- Increase light-sensitive area to above 90% of cell area
- Reduce time jitter in charge collection and multiplication
- Reduce capacitance and noise at the microcell level

Solution

- **Very small microcells (4-5 µm)**
  - Also good for radiation hardness
- **Microcell functions separated in two distinct regions**
  - Charge collection region with focusing Electric field and saturated electron drift velocity
  - Avalanche region restricted to the center of the microcell

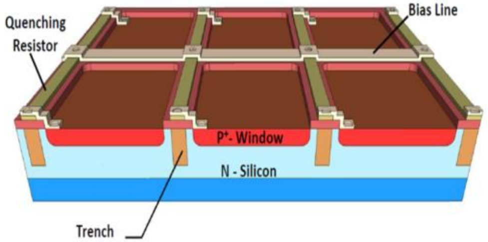


Transformation Optics Light Concentrator

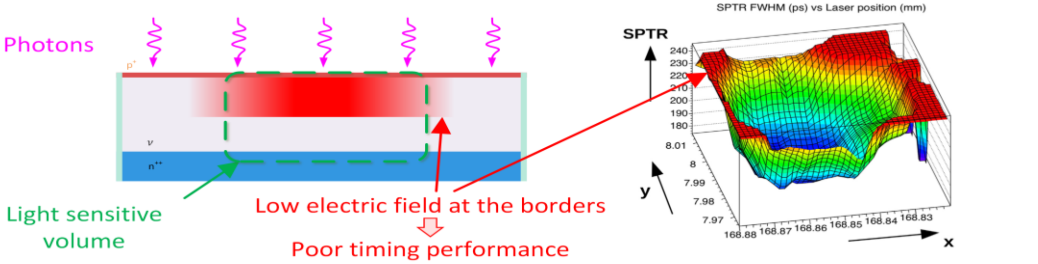
Challenge

- Electrical and optical isolation of the microcells

→ Microcell Fill Factor in SIPM



- E field inhomogeneity at the border of the microcells

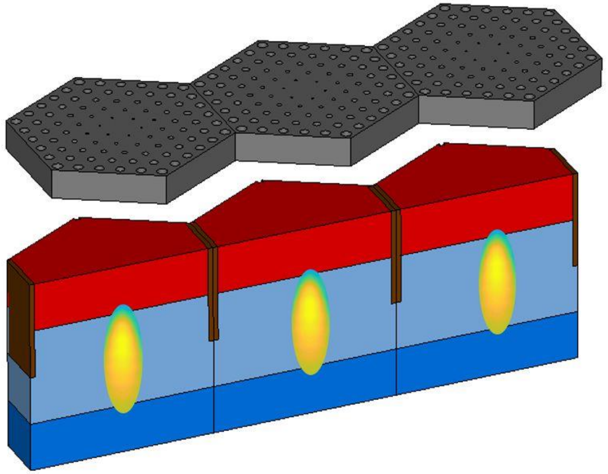


Solution

- Concentrate light in the central region of microcells

- Hyperbolic Metamaterial (HMM) hyperlenses

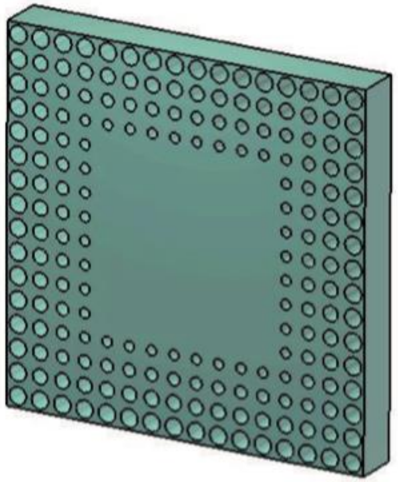
- Gradient index GRIN lenses

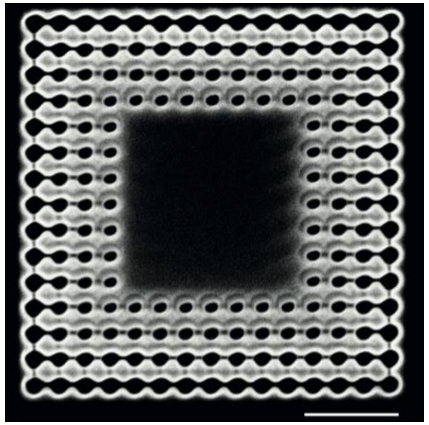


*M. Nemallapudi et al., **Singly photon time resolution of state-of-the-art SiPMs,** 2016 JINST 11 P10016*

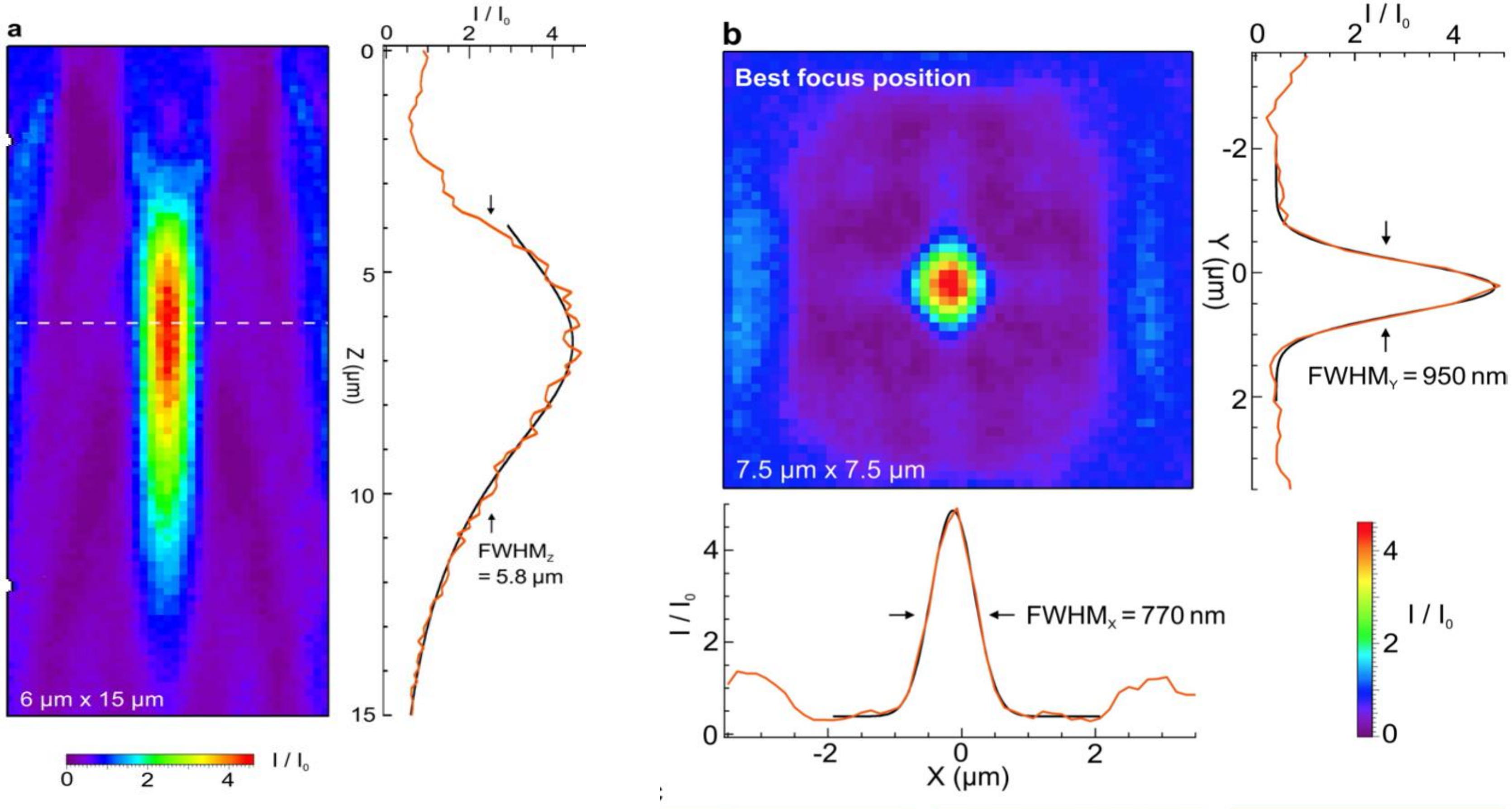
GRIN light concentrator PoC

Designed and fabricated 4x4μm Nb_2O_5 metalens with refractive index gradient introduced by holes of varying diameter



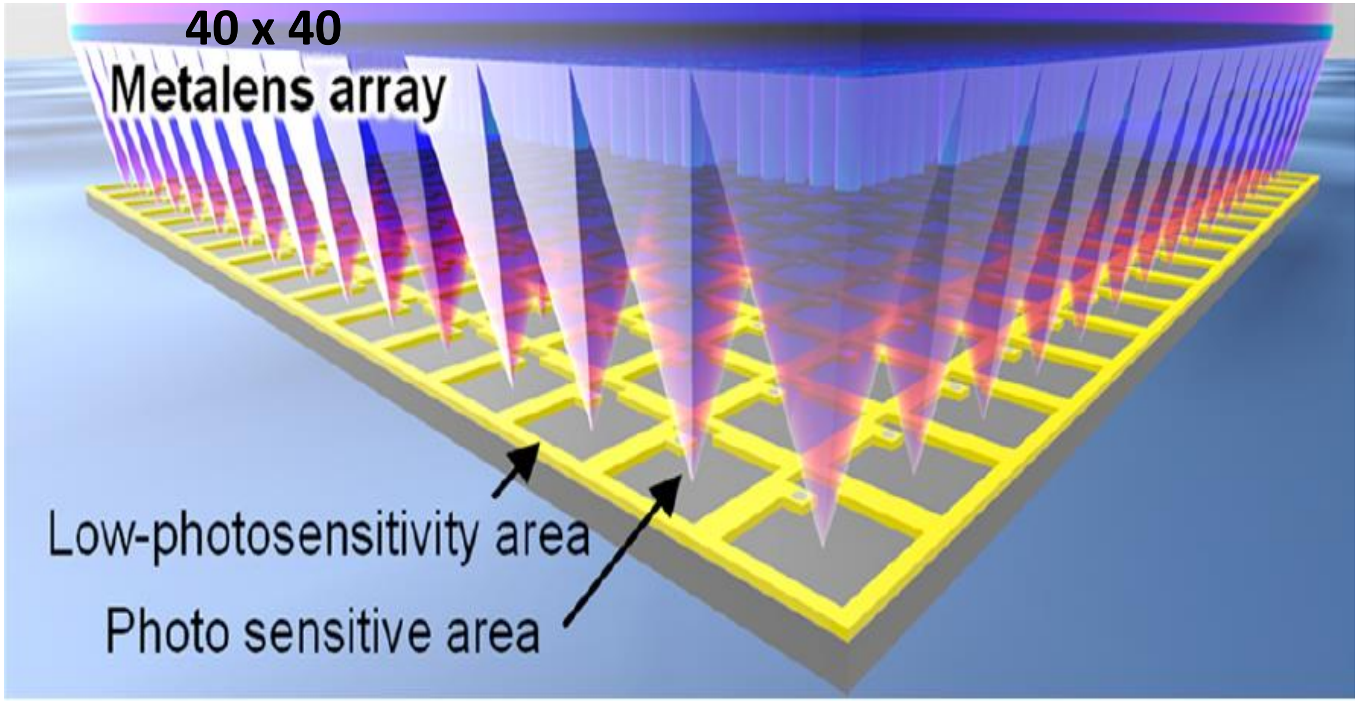


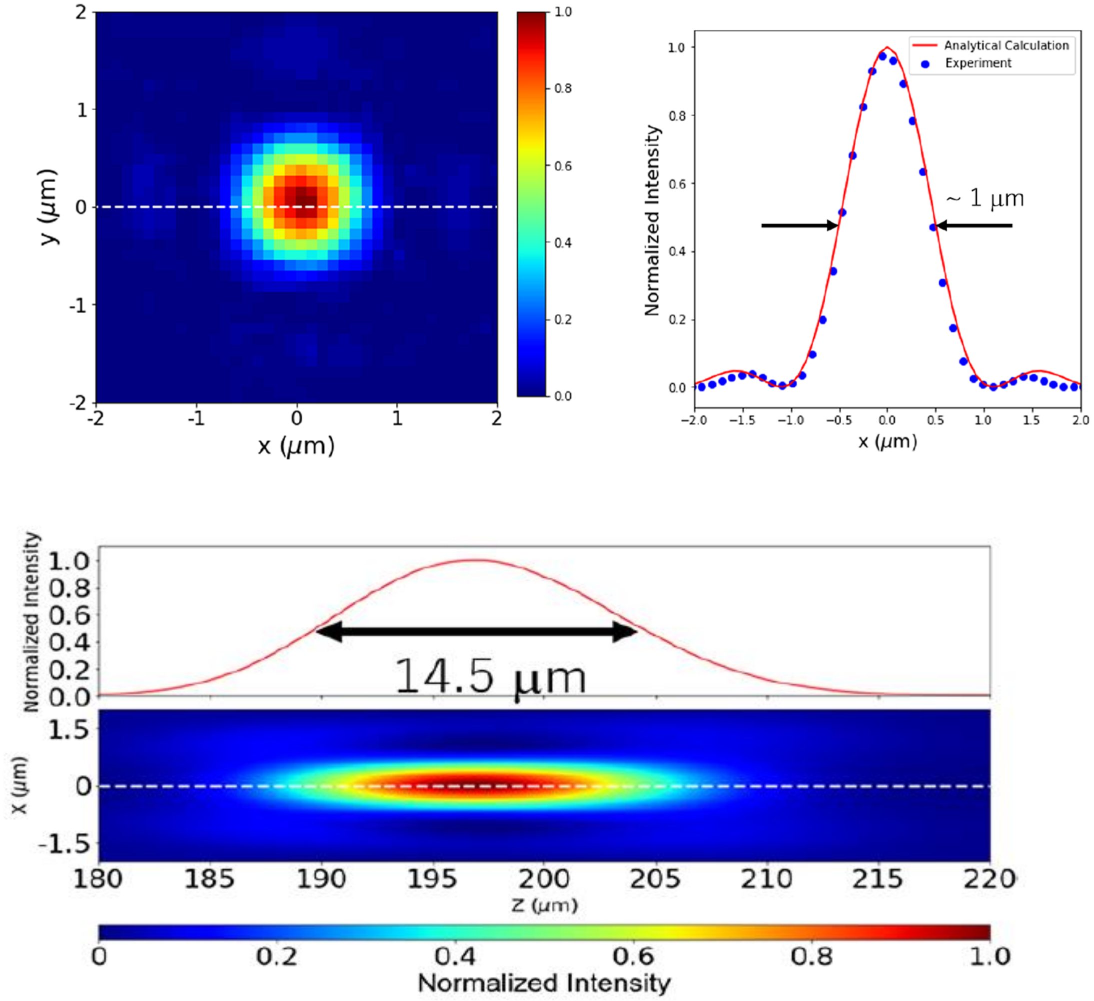
93% of incident light concentrated
In < 1μm spot diameter or <5% of total area



E. Mikheeva et al., ***CMOS-compatible all-dielectric metalens for improving pixel photodetector arrays,*** *Accepted in APL Photonics*

Metalens array (Hamamatsu)

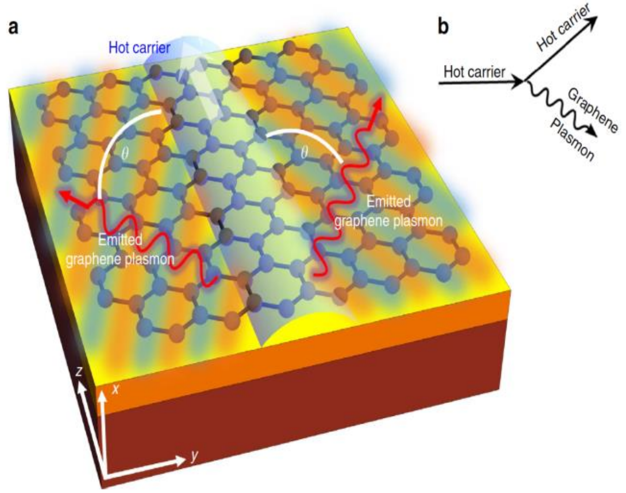




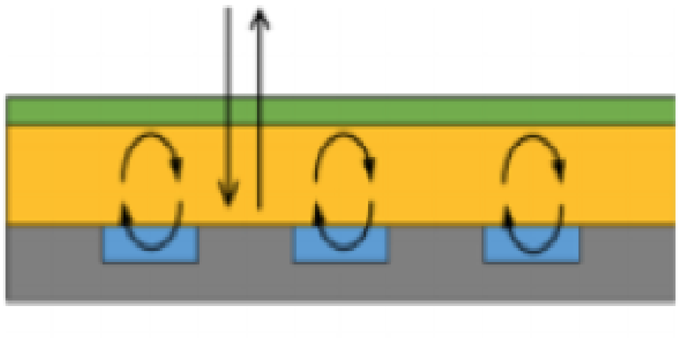
S. Uenoyama, R. Ota, ***40 x 40 Metalens Array for Improved Silicon Photomultiplier Performance,***
ACS Photonics, DOI:10.1021/acsphotonics.1c00257, May 2021

electron-hole pair generation

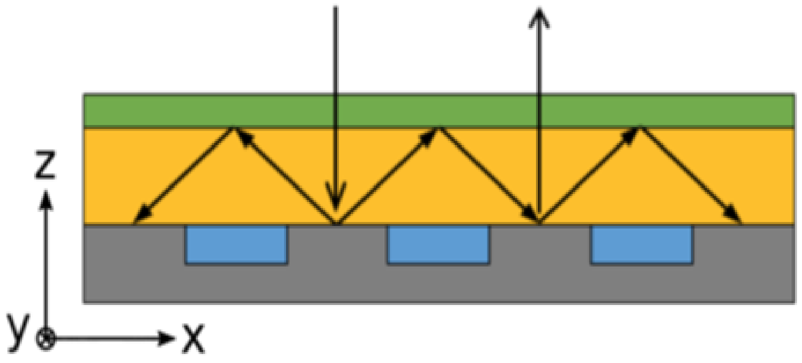
Resonant plasmonic states
in photonic crystals



Fabry-Pérot resonances



Guided-mode resonances



HMM for precise location of eh pair generation

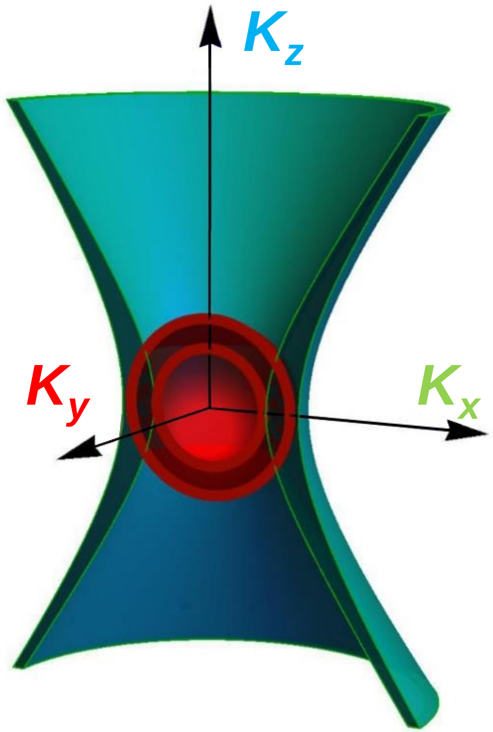
Challenge

- Angular and wavelength distribution of incident photons

→ variable depth of eh pair generation

→ efficiency losses and timing jitter in the development of the avalanches

Dispersion relation for a hyperbolic material (blue) compared with isotropic material (red)



Solution

- Locally increase the photonic density of states (PDOS) in the structure by means of HMM

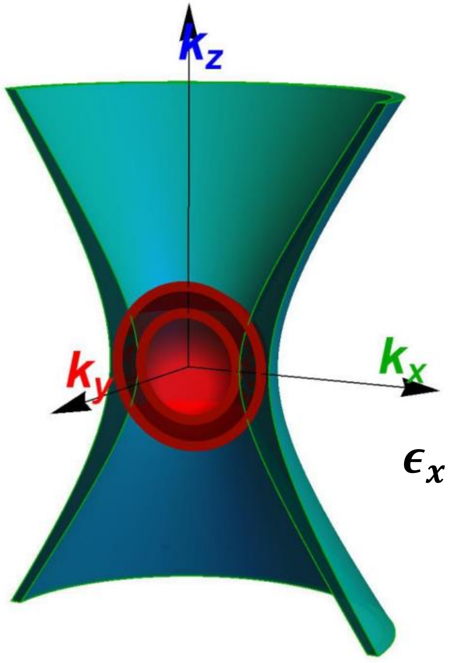
→ Huge local increase of absorption coefficient and eh pair creation

- *Backup solution 1: Near Zero Index Metamaterials (NZIM)*

- *Backup solution 2: Metasurfaces*

HMM : Photonic Density of States

HMM : Highly anisotropic material with
opposite signs electric and magnetic permitivity



$\epsilon_x = \epsilon_y < 0$

$\epsilon_z > 0$

Isofrequency contour from dispersion formula: $k = \frac{2\pi}{\lambda} \sim \omega \frac{n}{c} \sim \omega\sqrt{\epsilon}$

Hyperbolic dispersion for a hyperbolic material (blue) compared with isotropic material (red)

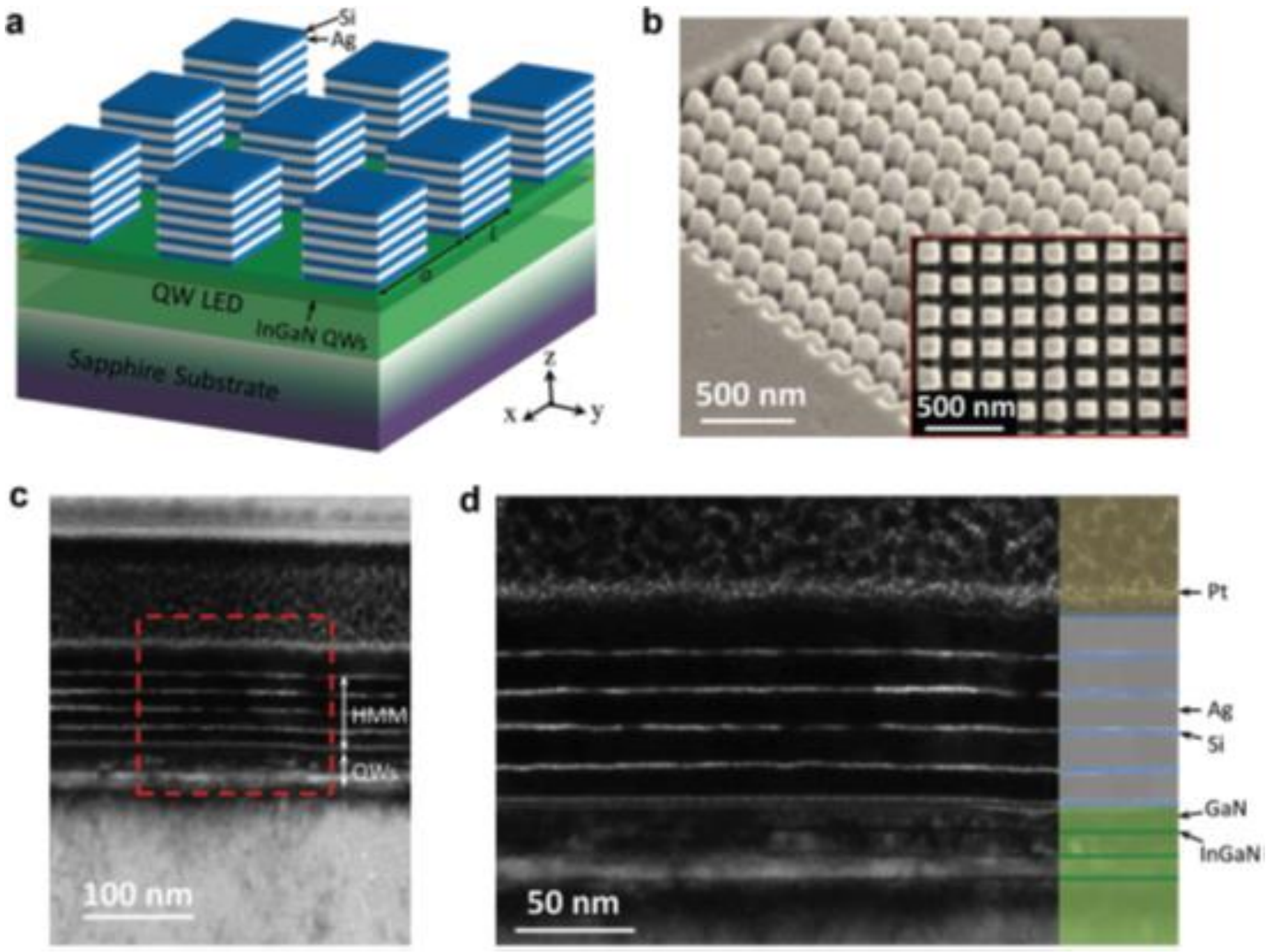
- Made of a stack of subwavelength metal-dielectric layers
- Can support propagation vectors of large magnitude
- Large density of states

$$D(\omega)d\omega = \frac{1}{(2\,\pi)^3}\iint dk^1_{//}dk^2_{//}\frac{\mathrm{d}\omega}{|\nabla\omega_k|}$$

An intuitive counting procedure in k-space consists of calculating the volume between the isofrequency contours at ω(k) and ω(k) + Δω.

electron-hole pair generation

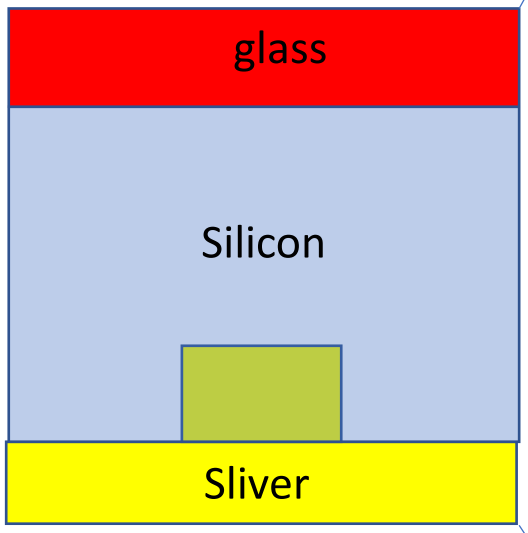
Nanostructuring multilayer hyperbolic metamaterials for ultrafast and bright green InGaN quantum wells

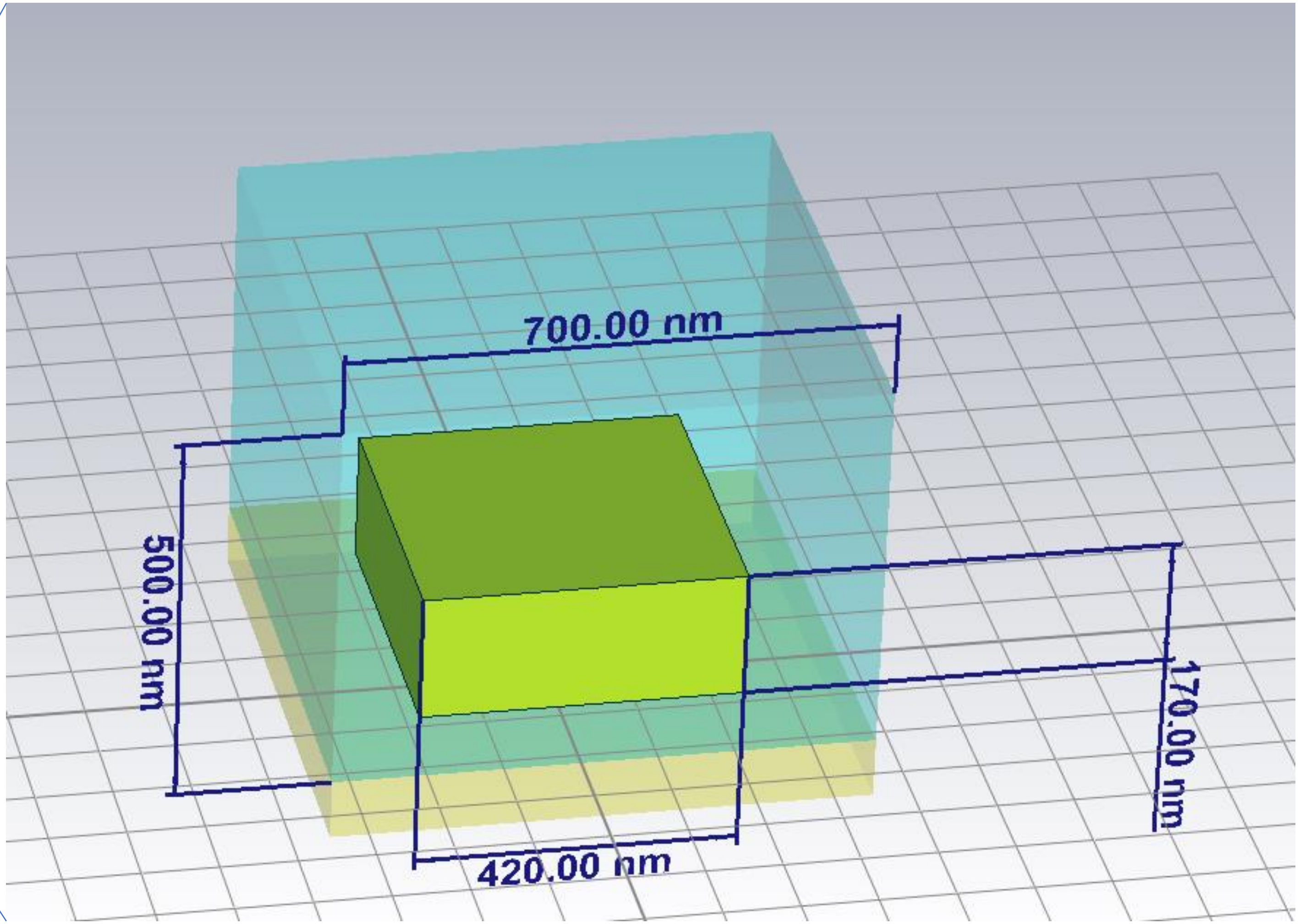


Lu, D., et al (2018).. *Advanced Materials*, *30*(15), 1706411

160x enhacement in the spontaneous recombination rate across a broadband of working wavelengths accompanied by over 10x enhancement in the QW peak emission intensity

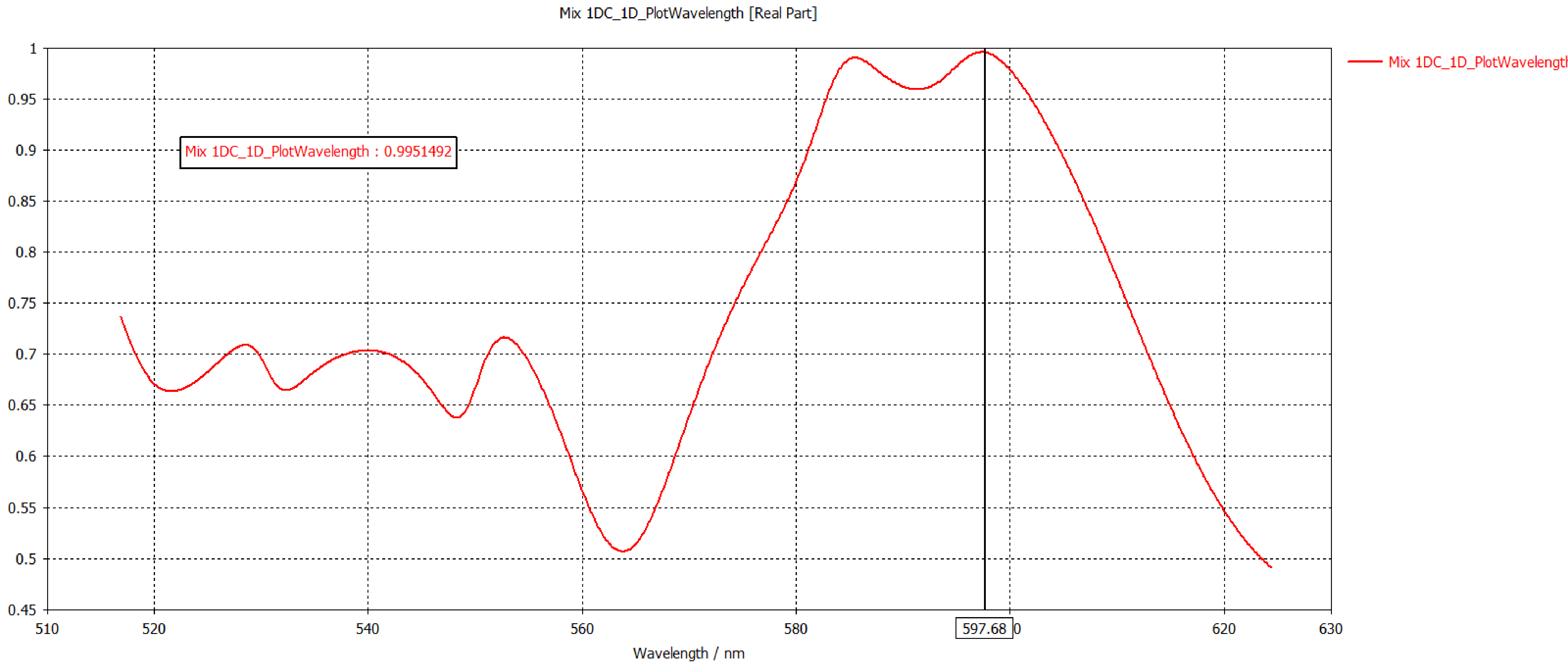
electron-hole pair generation @ 600nm





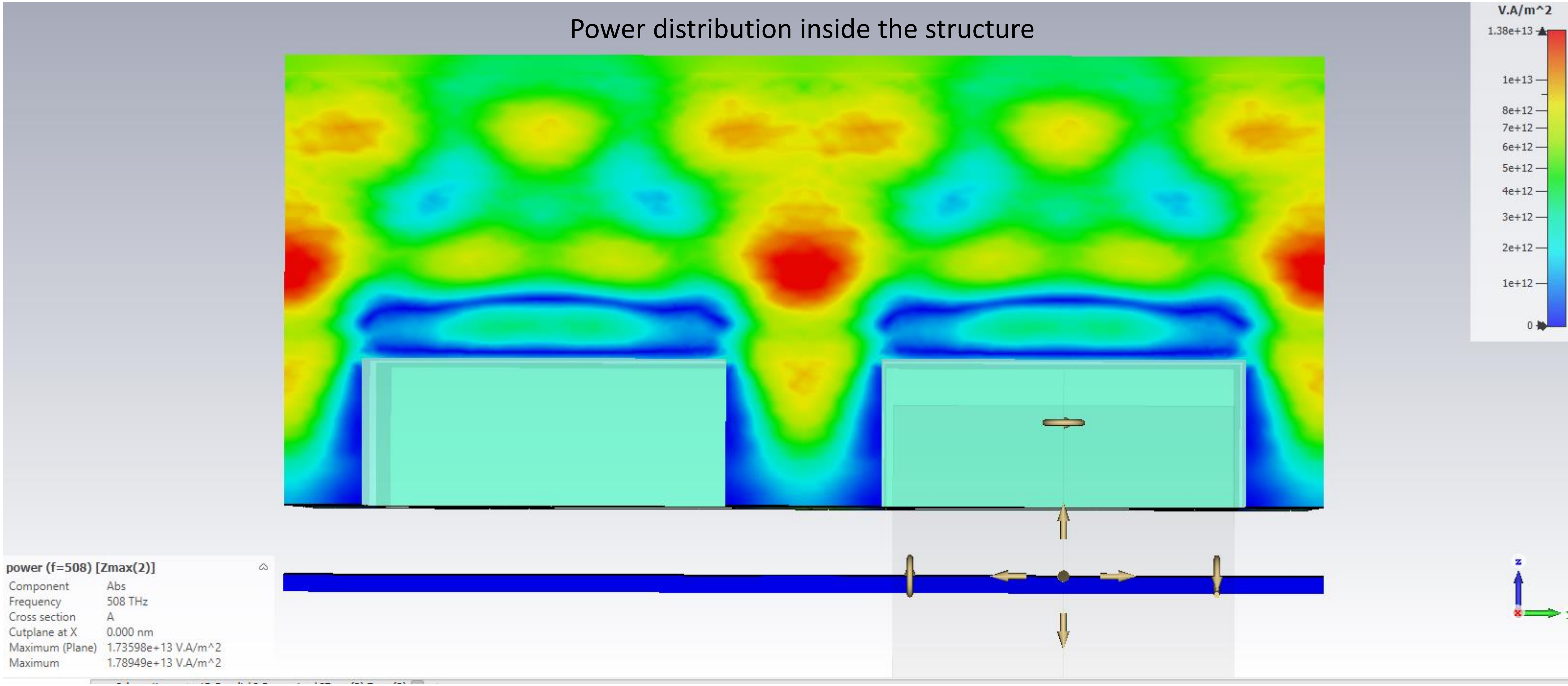
Structure: Sliver (yellow), Silicon(bleu), glass (on the Top)

electron-hole pair generation @ 600nm



Absorption in function of the Wavelength (1-R)

electron-hole pair generation @ 600nm



Conclusion- Potential of metamaterials

- By making use of light-management strategies, Nanophotonics provides a playground to make the unimaginable come closer.
- This opens the way to transformation optics (a kind of extrapolation of Maxwell's equations invariance under Lorenz transformation), allowing to envision a distortion of real space that results in a desired functionality:
  - Ultrafast emission
  - Enhanced fluorescence yield through plasmonic resonances
  - Redirect light into preferred directions
  - Electromagnetic cloaks
  - Improve thermal dissipation

In our case, this is a fertile field for developing innovative metamaterial solutions for highly efficient and ultrafast light photoconversion

Thank you