Free-electron-light interactions in nanophotonics

Charles Roques-Carmes[1,2]

[1] *Ginzton Laboratories, Stanford University*

[2] *Department of Physics, MIT*

67th ICFA Beam Dynamics Workshop on Future Light Sources

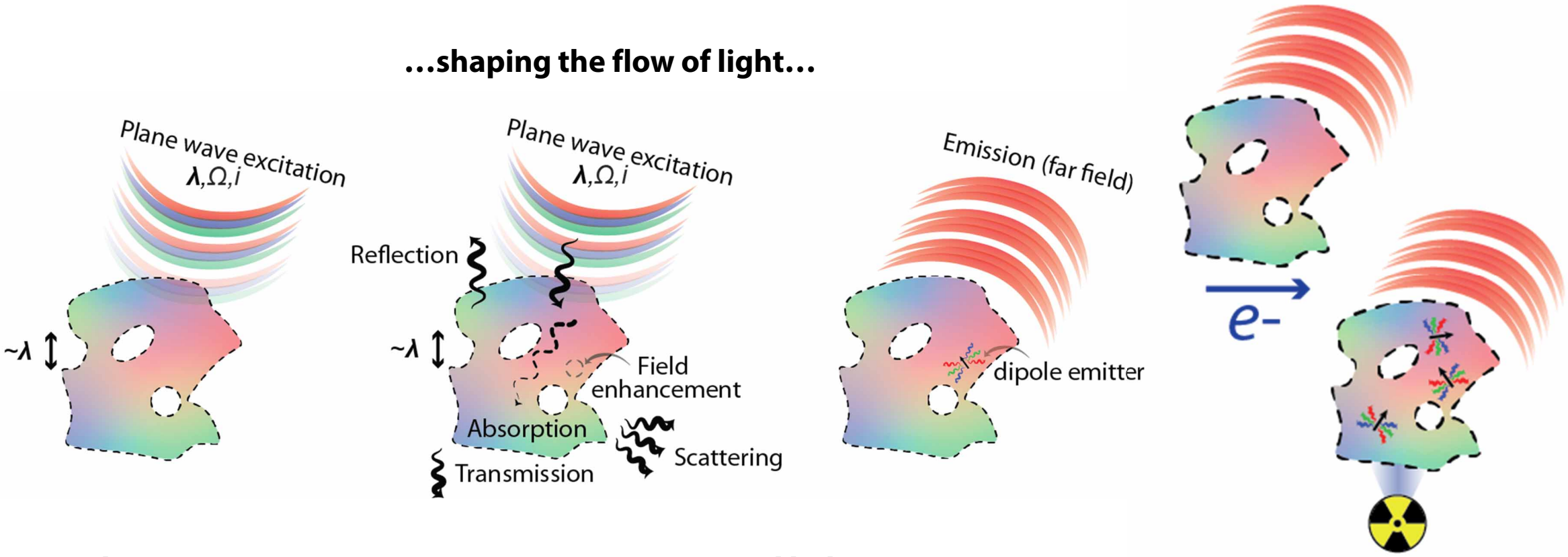
August 28th, 2023

chrc@stanford.edu – roques-carmes.com

Nanophotonics = molding the flow of light at the nanoscale

…even with high-energy particles!

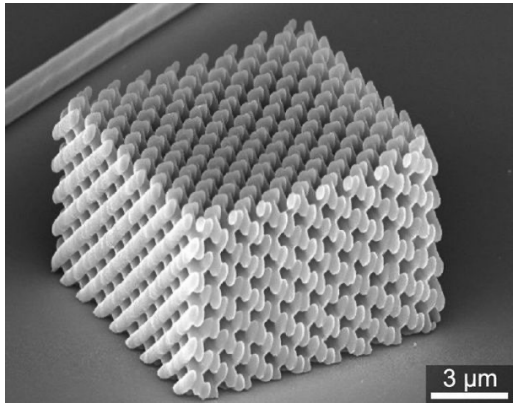
…shaping the flow of light…

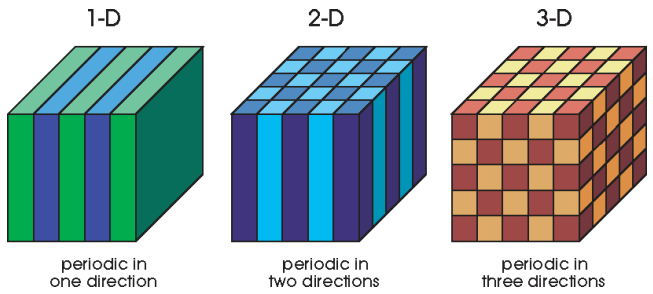


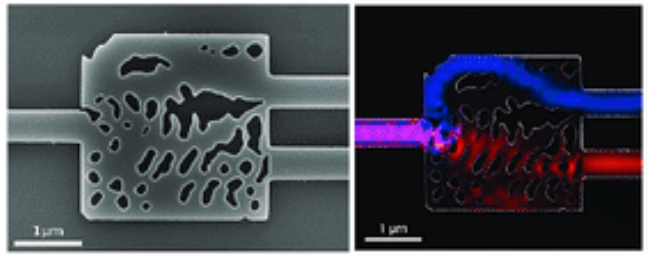
Nanophotonic structures…

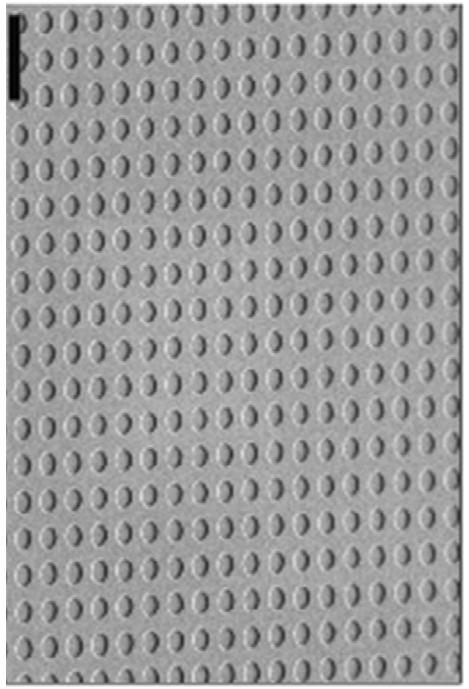
…and light-matter interactions…

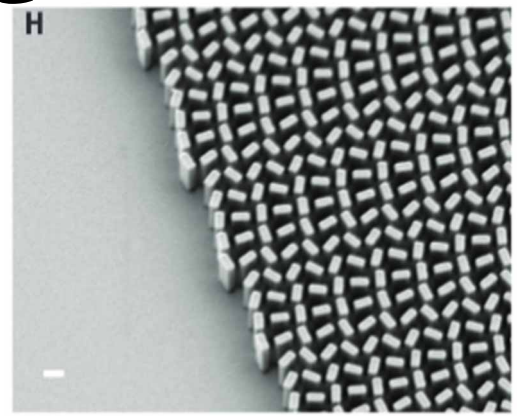
Structural design at the nanoscale

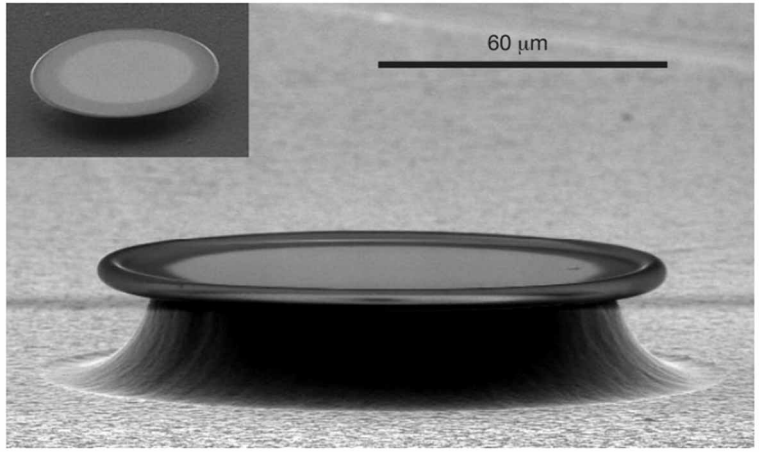


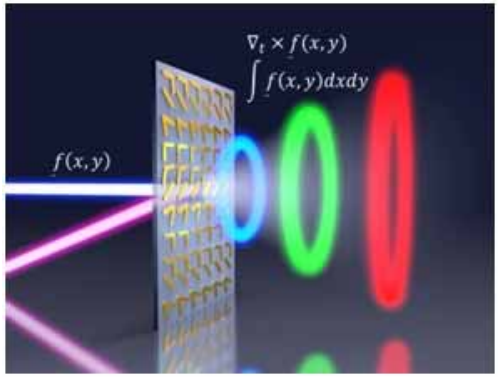












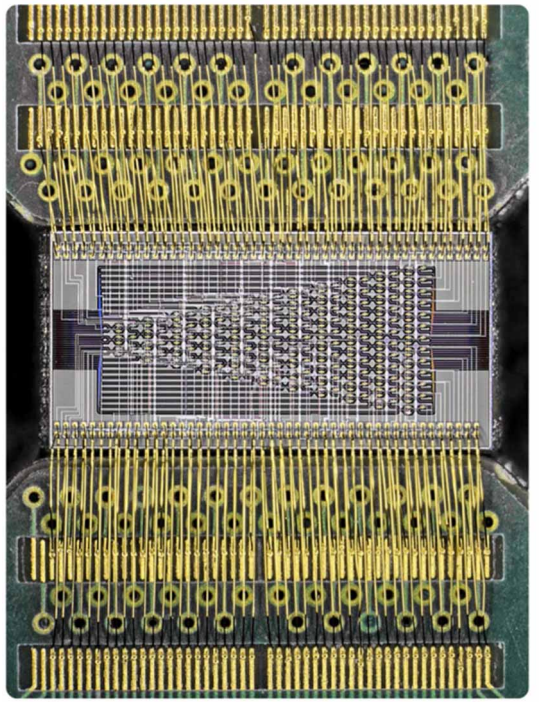
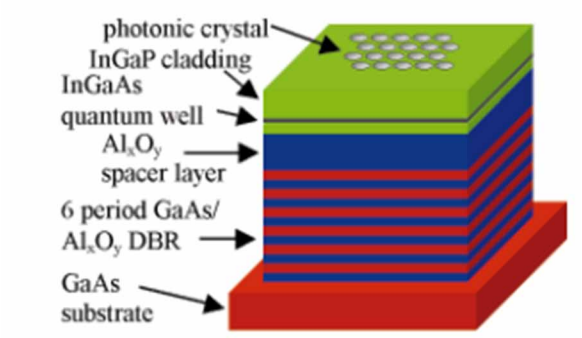


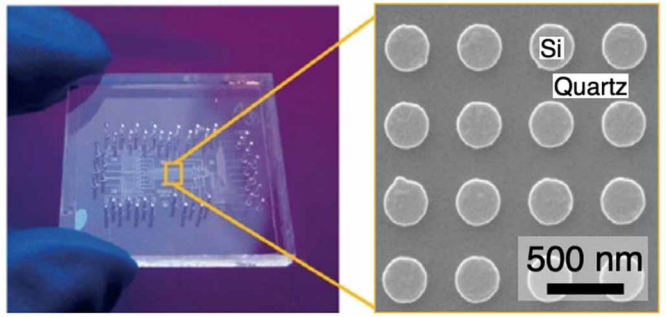
Image sources: Capasso (Harvard), Soljačić (MIT), Joannopoulos (MIT), Johnson (MIT), Polman (AMOLF), Vuckovic (Stanford), Vahala (Caltech), Englund (MIT) research groups, and many others.

Controlling light-matter interactions

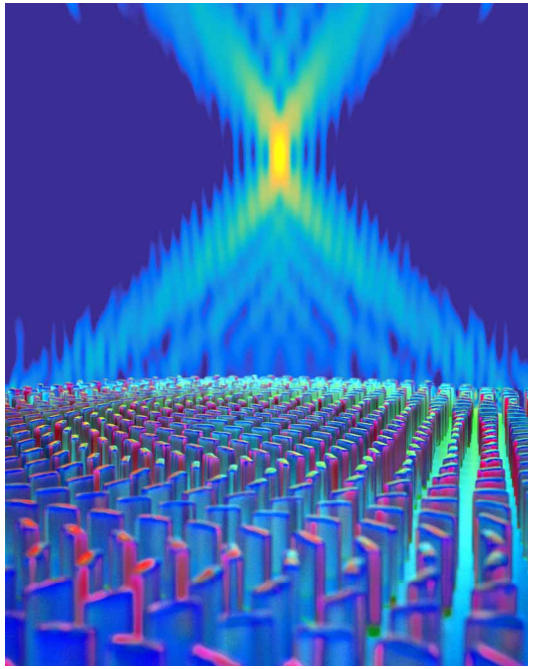
LED and lasers



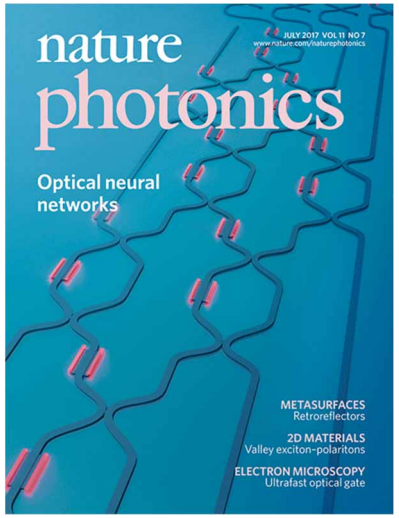
Biosensors



Flat optics



Photonic computing



Thermal emitters

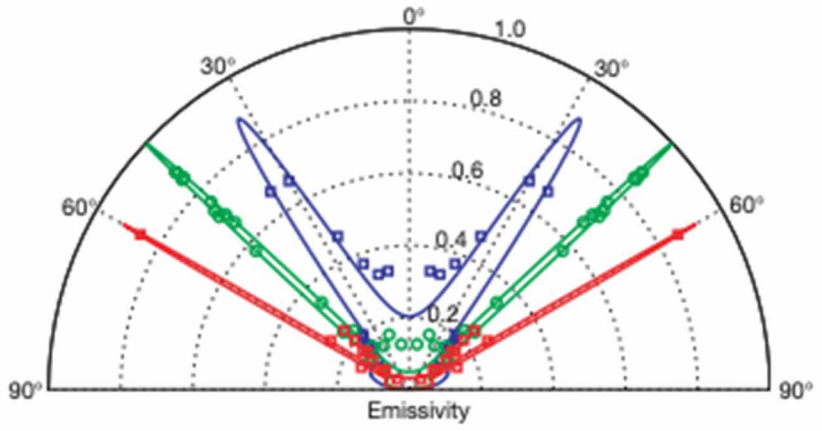
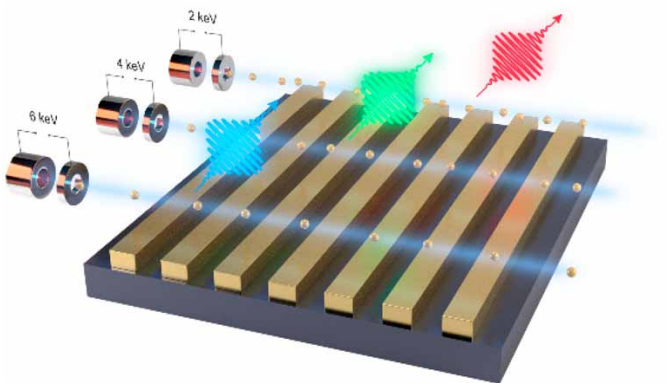


Image sources: Capasso (Harvard), Soljačić (MIT), Polman (AMOLF), Vuckovic (Stanford), Vahala (Caltech), Englund (MIT), Altug (EPFL), Quidant (ETH) research groups, and **many others.**

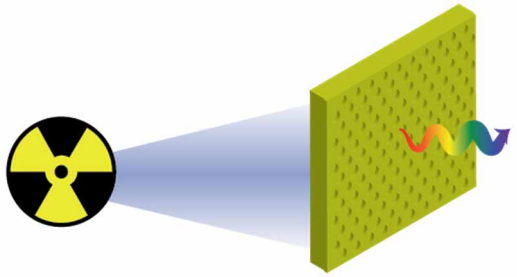
Nanophotonics for light-matter interactions with high-energy particles

On-chip tunable emitters



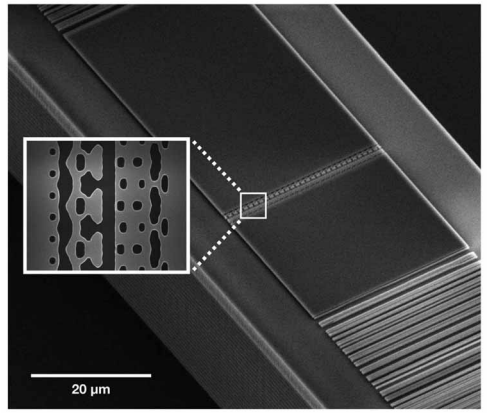
Massuda, **Roques-Carmes**, *ACS Photonics* (2018)

Nanophotonic scintillators



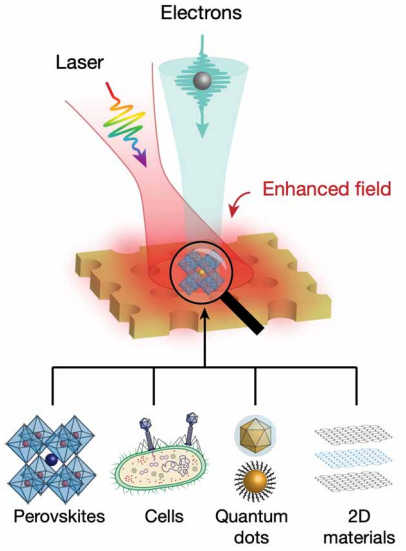
Roques-Carmes*, Rivera*, et al., *Science* (2022)

Accelerators on-chip



Vuckovic group, *Science* (2020)

Novel microscopy techniques



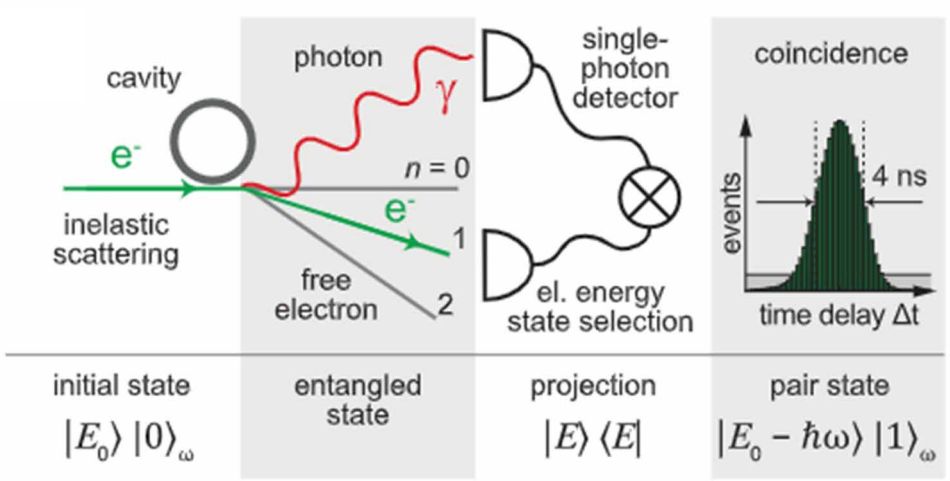
Kaminer group, *Nature* (2020)
Ropers group, *Nature* (2020)

Combining electron microscopy resolution with photonic control of light-matter interaction

See review: **Roques-Carmes** et al., *Applied Physics Reviews* (2023)

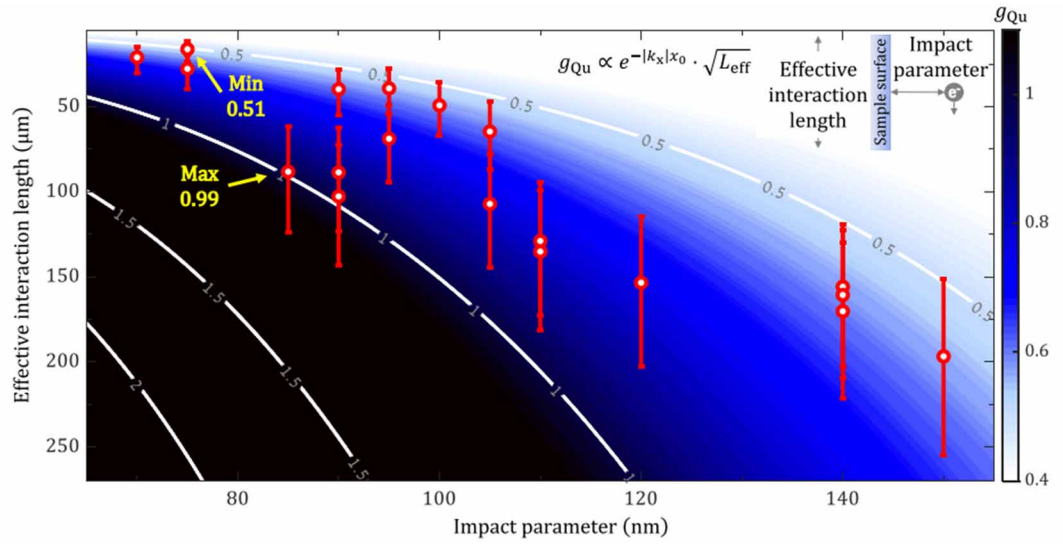
The next frontier: strong interactions between electron and other quantum particles

Single-electron-single-photon interactions



Feist et al., Ropers and Kippenberg groups, *Science* (2022)

The key: strong interactions between electrons and photons



Record for reported value of g_{Qu} ~ 1

Adiv, et al., Kaminer group, *PRX* (2023)

Key questions:

- What are fundamental limits to electron-light interactions?
- What nanophotonic structures can enhance electron-light interactions?

Talk overview

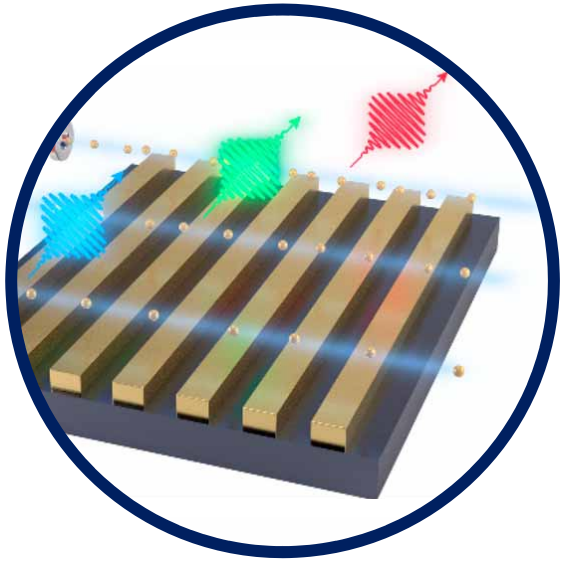
Free-electron-light interactions

Roques-Carmes et al., Applied Physics Reviews (2023)

Yang, Massuda, **Roques-Carmes**, et al., *Nature Physics* (2018)

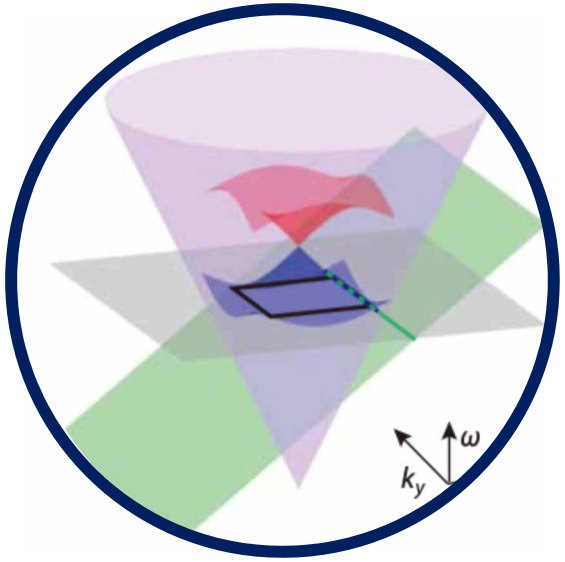
Roques-Carmes, et al. *Nature Communications* (2019)

Massuda, **Roques-Carmes**, et al., *ACS Photonics* (2018)



Controlling electron-beam radiation with nanophotonics

Enhancing electron-beam radiation with photonic flatbands



Yang*, **Roques-Carmes***, *Nature* (2023)

Talk overview

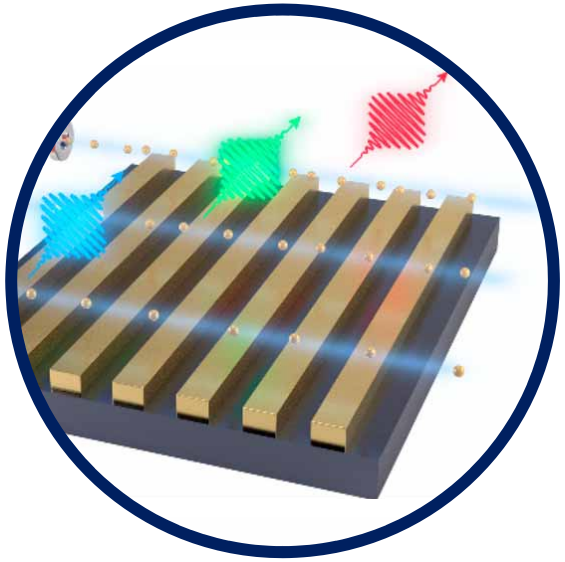
Free-electron-light interactions

Roques-Carmes et al., Applied Physics Reviews (2023)

Yang, Massuda, **Roques-Carmes**, et al., *Nature Physics* (2018)

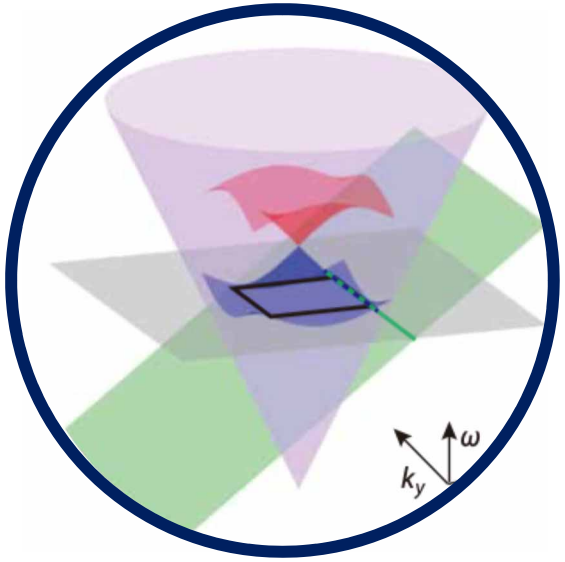
Roques-Carmes, et al. *Nature Communications* (2019)

Massuda, **Roques-Carmes**, et al., *ACS Photonics* (2018)

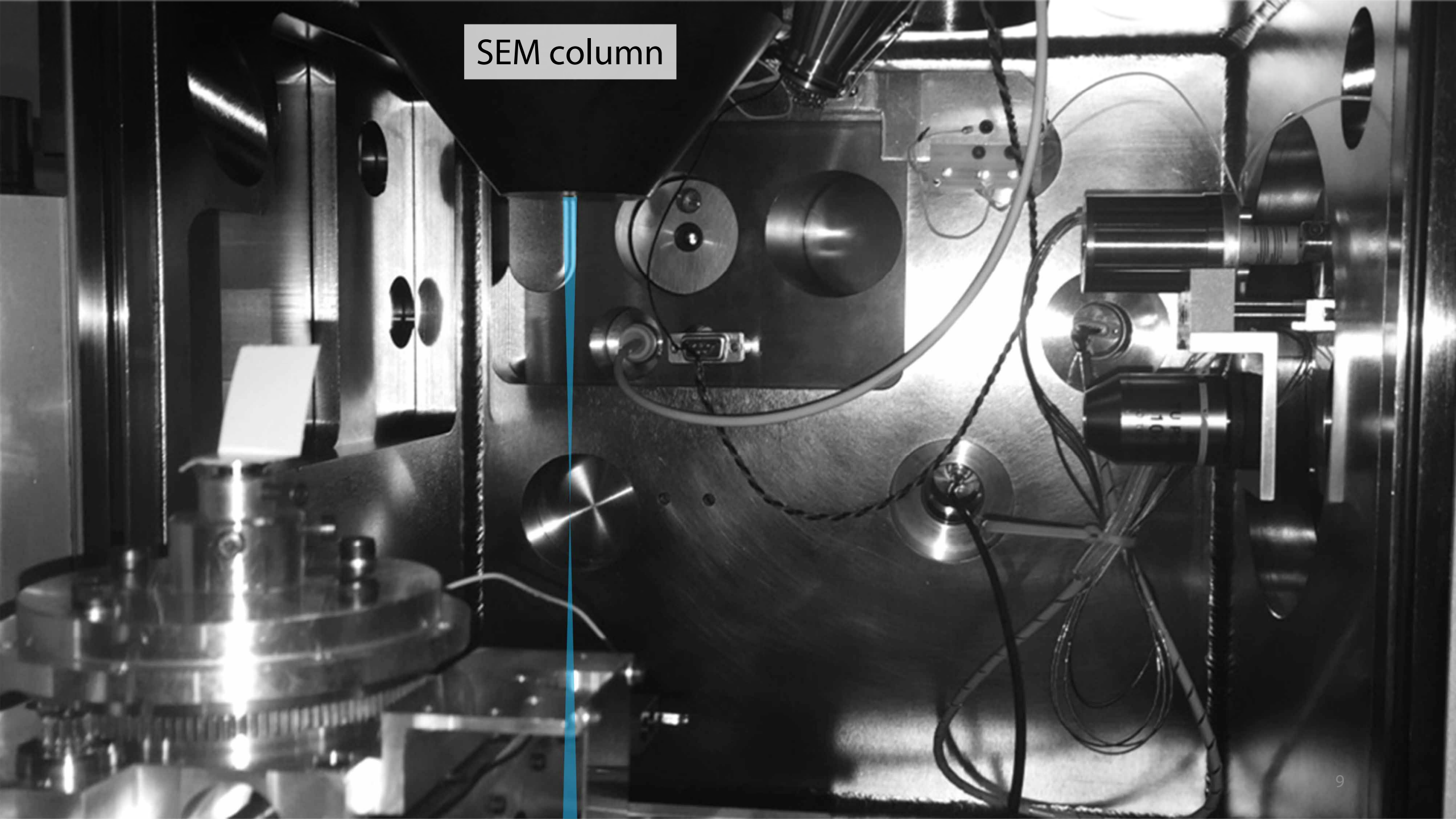


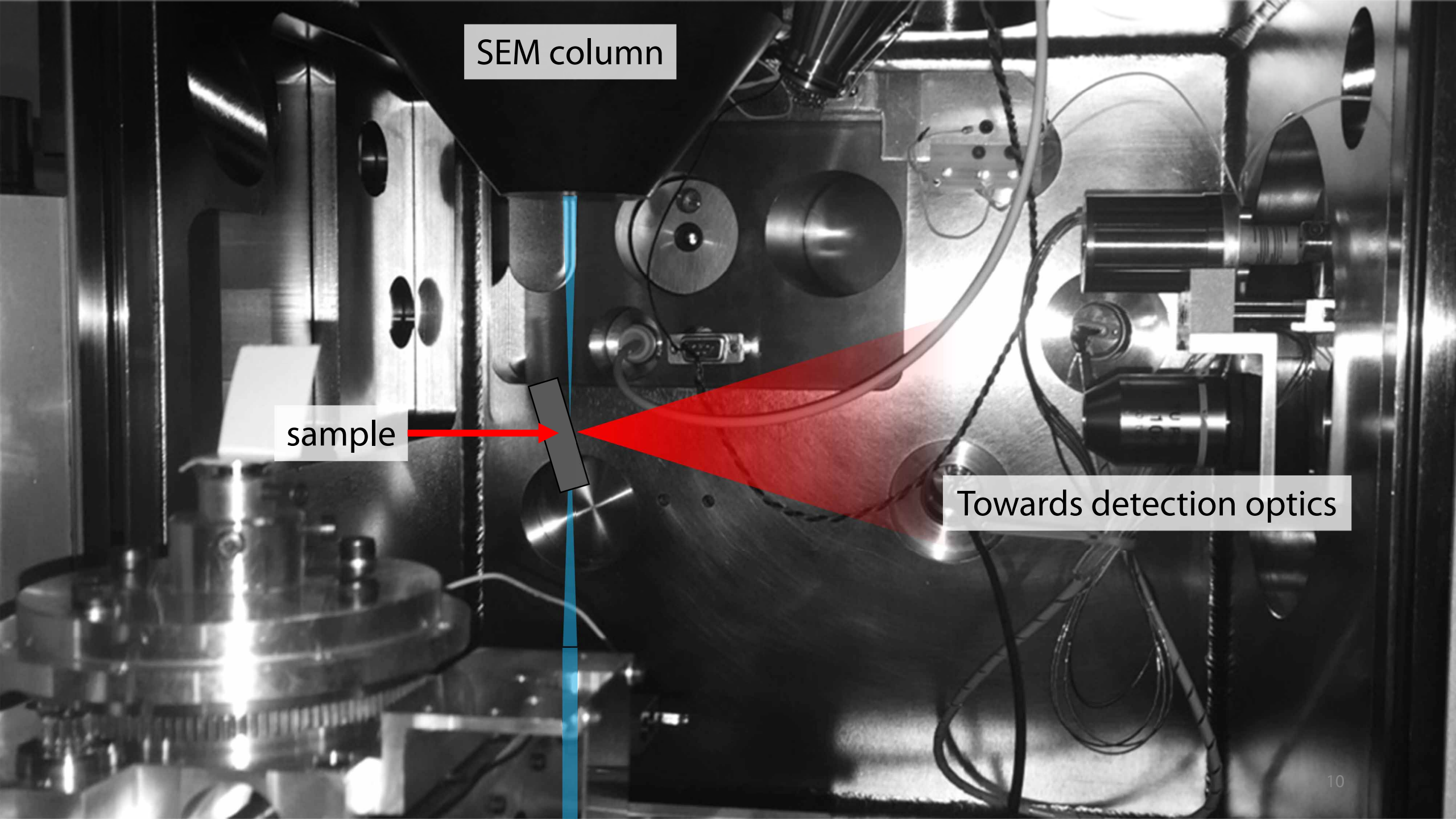
Controlling electron-beam radiation with nanophotonics

Enhancing electron-beam radiation with photonic flatbands



Yang*, **Roques-Carmes***, *Nature* (2023)


SEM column

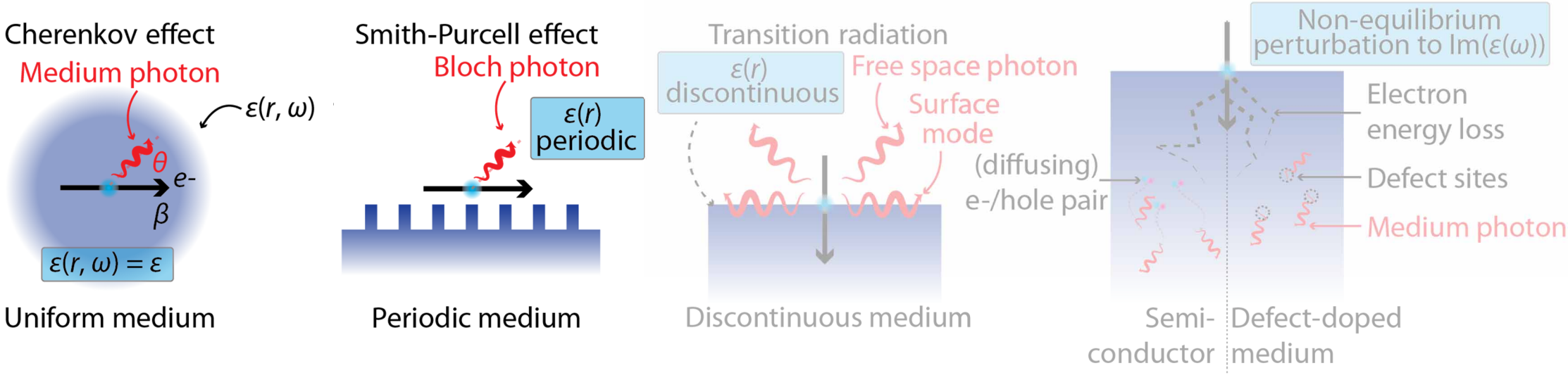

SEM column
sample
Towards detection optics

How do free electrons emit light?

Cathodoluminescence = general term for light emission from free electrons

Coherent cathodoluminescence

Incoherent cathodoluminescence
(electron scintillation)



Moving current source (coherent CL)

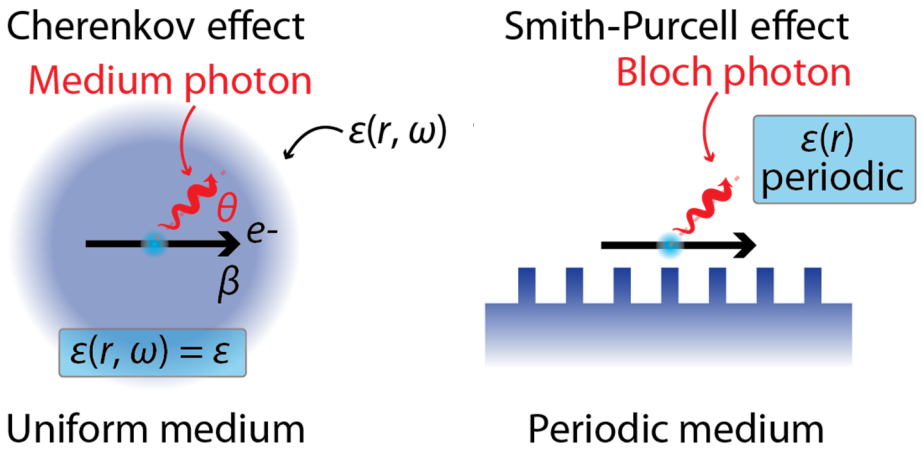
Time domain $\mathbf{J}(\mathbf{r},t) = q\mathbf{v}\delta(\mathbf{r}-\mathbf{v}t)$

Freq. domain $\mathbf{J}(\mathbf{r},\omega) = q\hat{r}_{\parallel}\delta(\mathbf{r}_{\perp})e^{i\omega r_{\parallel}/v},$

Induced current fluctuations (incoherent CL)

$$\langle J_j^-(\mathbf{r}_1,\omega)J_k^+(\mathbf{r}_2,\omega)\rangle \equiv 2\pi T S_{jk}(\mathbf{r}_1,\mathbf{r}_2,\omega)$$

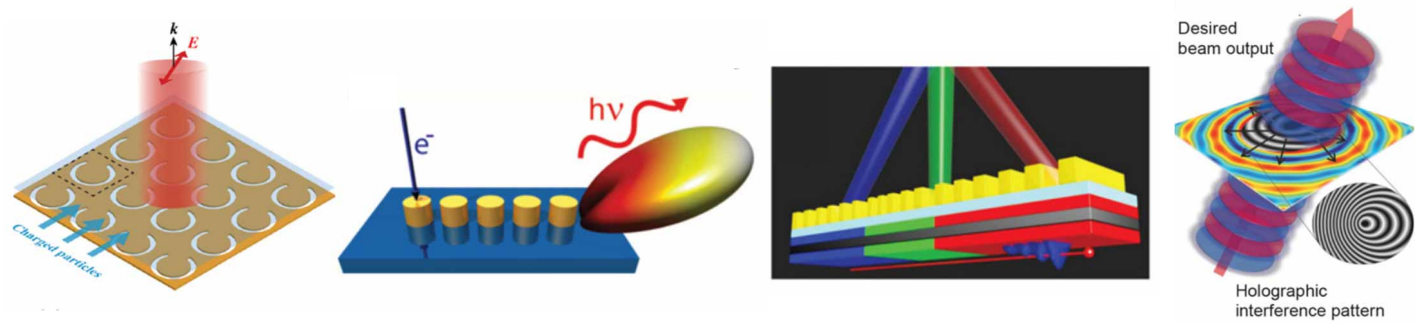
Controlling free-electron radiation with nanophotonic structures



Phase-matching photonic mode and electron excitation

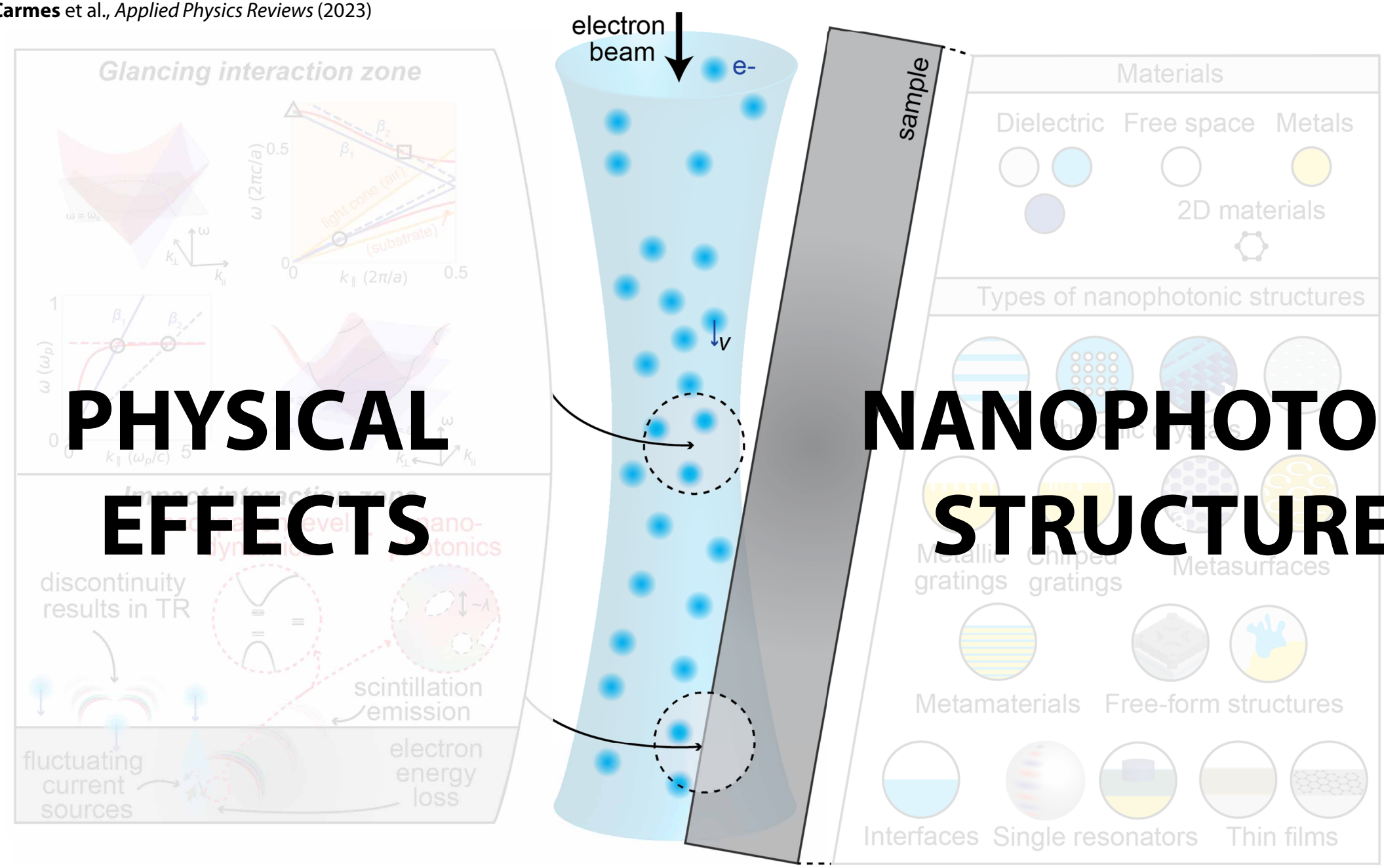
$$\omega = v k_{\parallel}$$

Complete control of free-electron radiation with nanophotonics



Coenen et al., *APL* (2011),
Wang et al., *PRL* (2016)
Lai et al., *Sci. Reports* (2017)
Remez, Shapira, **Roques-Carmes**, *PRA* (2017)
Li et al., *Nat. Commun.* (2016)
Shentcis, et al., Nature Photonics (2020)
Roques-Carmes, et al. *Nature Communications* (2019)
Yang*, **Roques-Carmes***, et al., *Nature* (2023)
Massuda, **Roques-Carmes**, et al., *ACS Photonics* (2018)
Yang, Massuda, **Roques-Carmes**, et al., *Nature Physics* (2018)

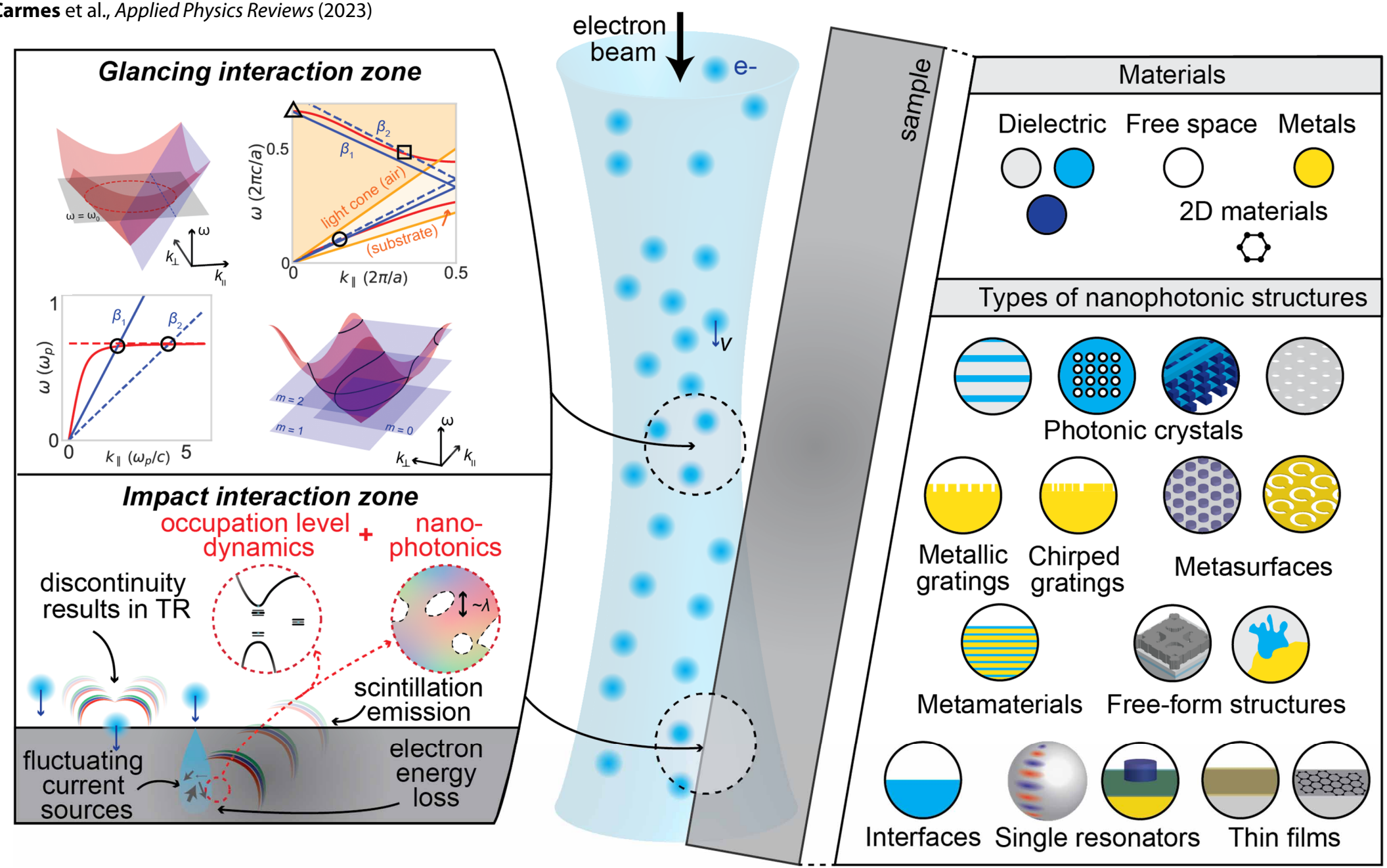
Roques-Carmes et al., *Applied Physics Reviews* (2023)



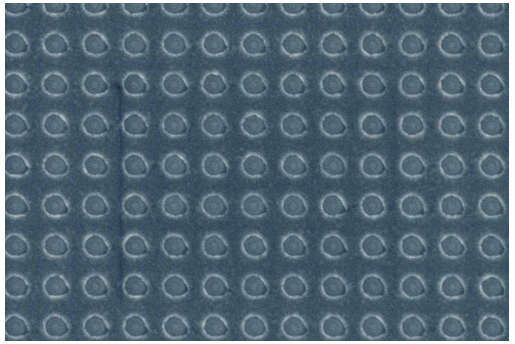
PHYSICAL EFFECTS

NANOPHOTONIC STRUCTURES

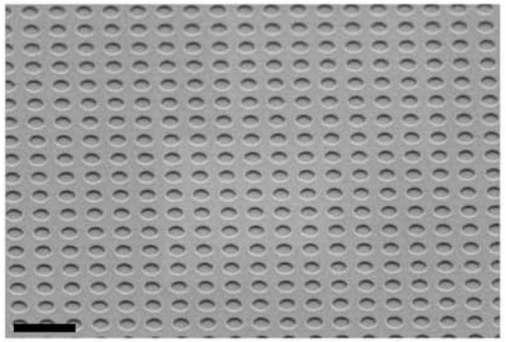
Roques-Carmes et al., *Applied Physics Reviews* (2023)



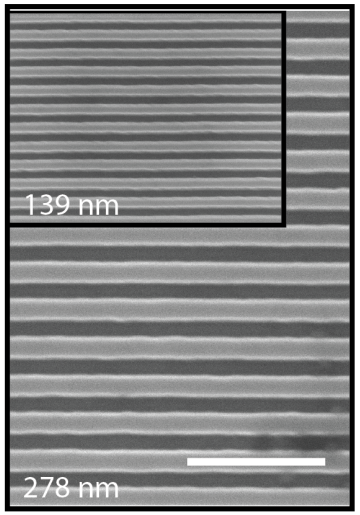
Roques-Carmes et al., *Applied Physics Reviews* (2023)



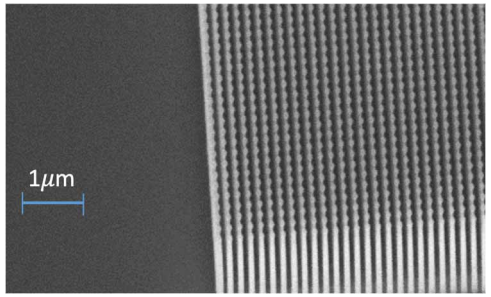
2D PhC atop YAG:Ce
(430 nm period)



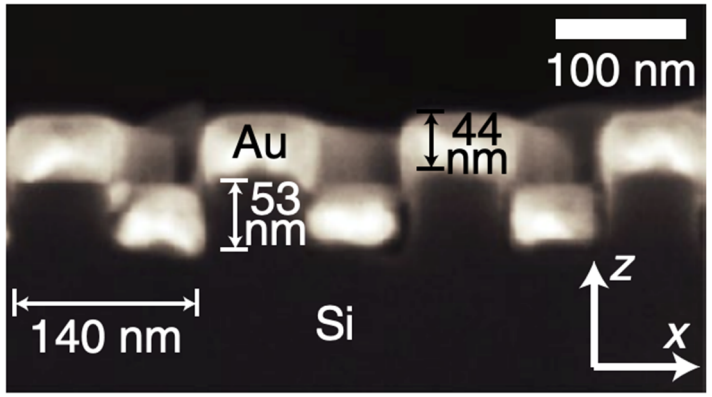
Silicon-on-insulator PhC
(scale bar 1 μm)



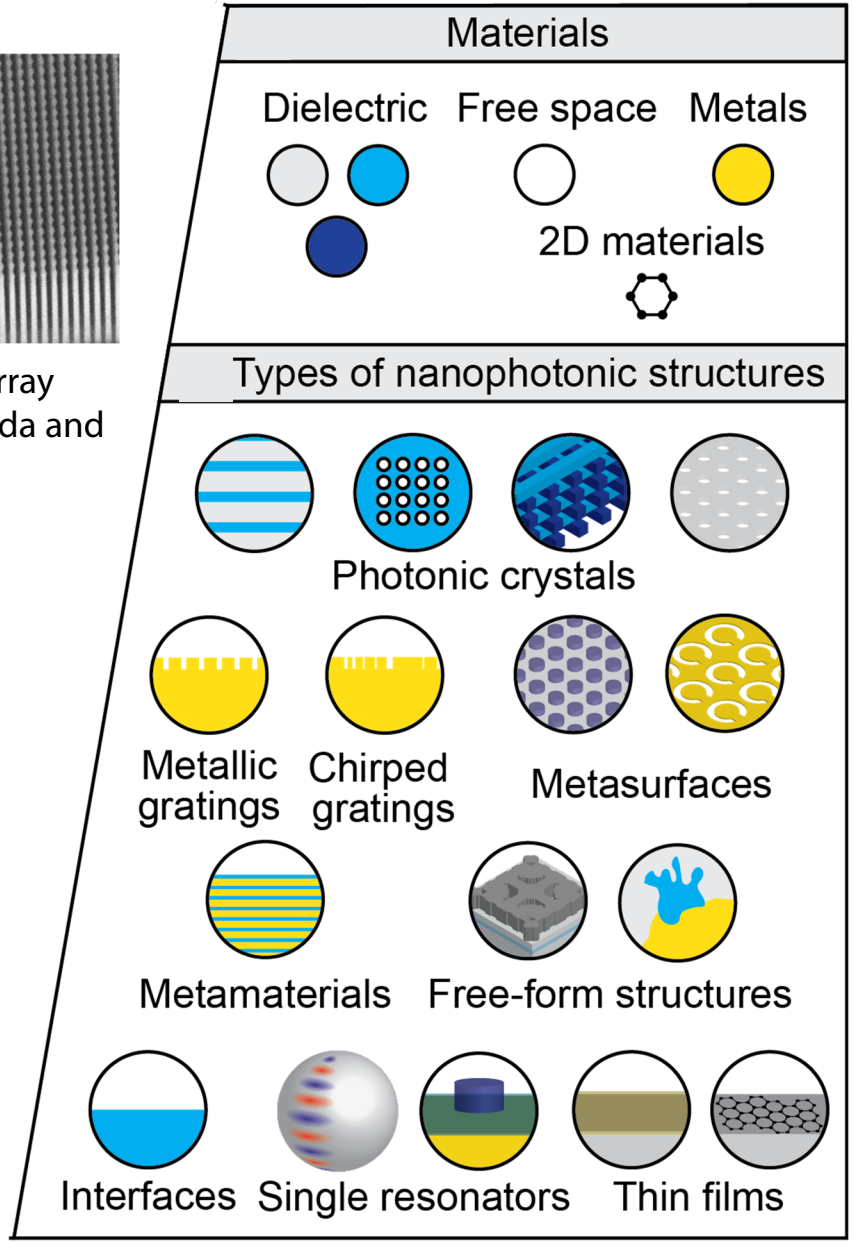
Silicon gratings



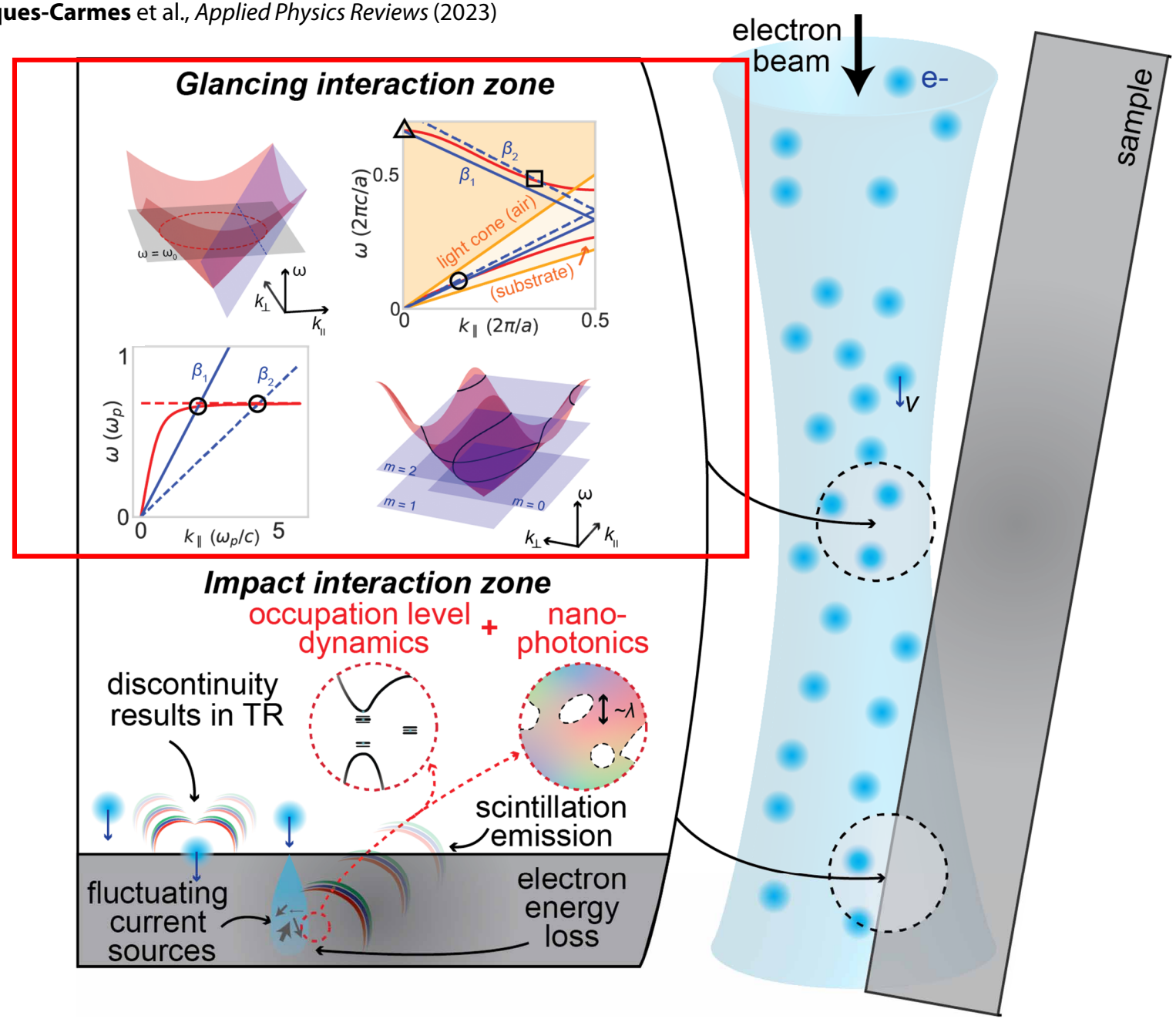
Silicon nanowires array
(image credit: A. Massuda and A. Solanki)



Gold-coated silicon gratings



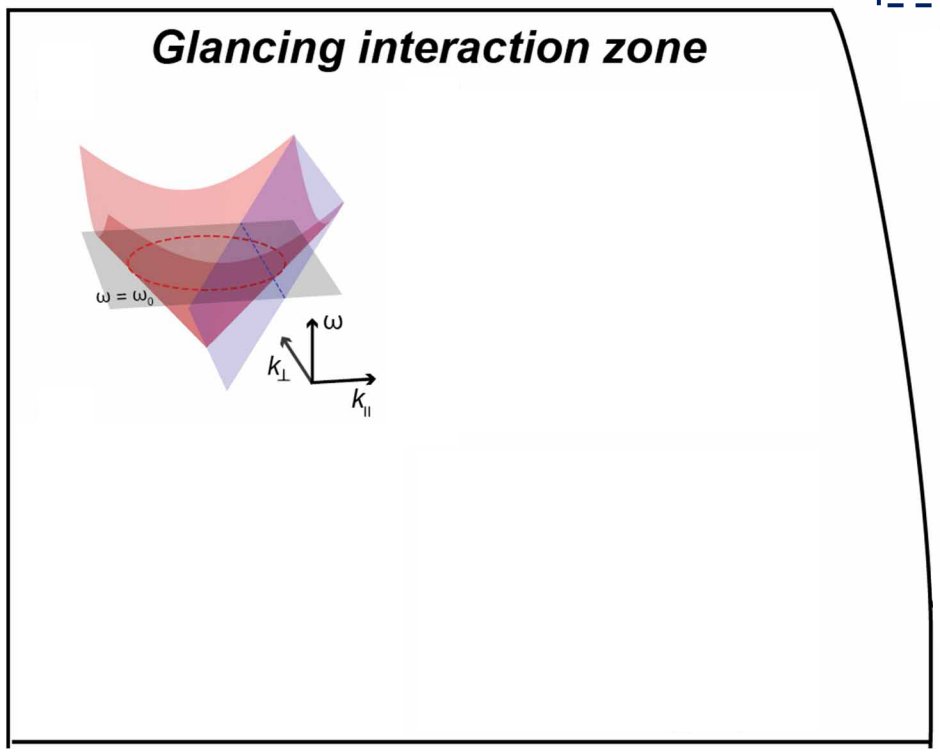
Roques-Carmes et al., *Applied Physics Reviews* (2023)



Glancing interaction zone

MASTER EQUATION (COHERENT CL)

$$U = \overbrace{\frac{\mu_0 q^2 c^2}{\pi}}^{\text{prefactor}} \int dr_{\parallel} dr'_{\parallel} \mathrm{Im} \int d\omega\, \omega \underbrace{\sum_m \left(\hat{r}_{\parallel} \cdot \mathbf{F}_m(r_{\parallel}, \mathbf{r}_{\perp}, \omega)\right)\left(\hat{r}_{\parallel} \cdot \mathbf{F}^*_m(r'_{\parallel}, \mathbf{r}_{\perp}, \omega)\right)}_{\text{mode-electron overlap}} \overbrace{e^{i\omega(r'_{\parallel} - r_{\parallel})/v}}^{\text{phase-matching}} \underbrace{g(\omega, \omega_m)}_{\text{spectral dep.}}$$



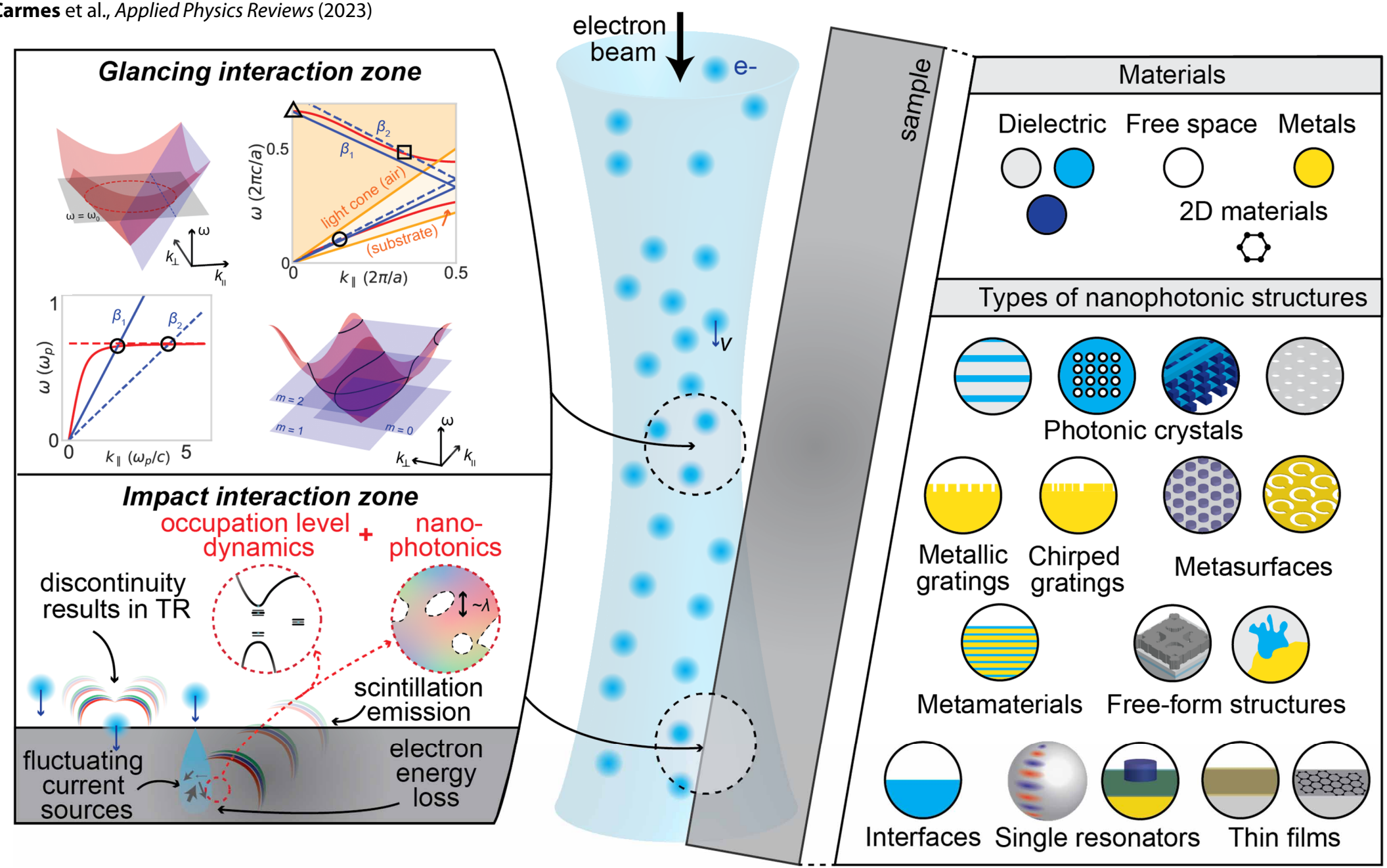
- Green's Function expansion over eigenmodes $\mathbf{F_m}(r_{\parallel}, \mathbf{r}_{\perp}, \omega)$
- Phase-matching relation $\omega = \mathbf{v} \cdot \mathbf{k}$
- **3D structure, periodic:**

$$\frac{dU}{d\omega dl} = \frac{q^2}{8\pi^2 \varepsilon_0} \sum_{m,\mathbf{G}} \int_{\partial S} dk \frac{|\mathbf{c}^{\mathbf{G}}_{m,\mathbf{k}}(\omega) \cdot \hat{r}_{\parallel}|^2}{|\nabla_{\mathbf{k}_{\perp}} \omega_{m,\mathbf{k}}|}$$

Band structure engineering to enhance emission

Roques-Carmes et al., Applied Physics Reviews (2023)

Roques-Carmes et al., *Applied Physics Reviews* (2023)



Talk overview

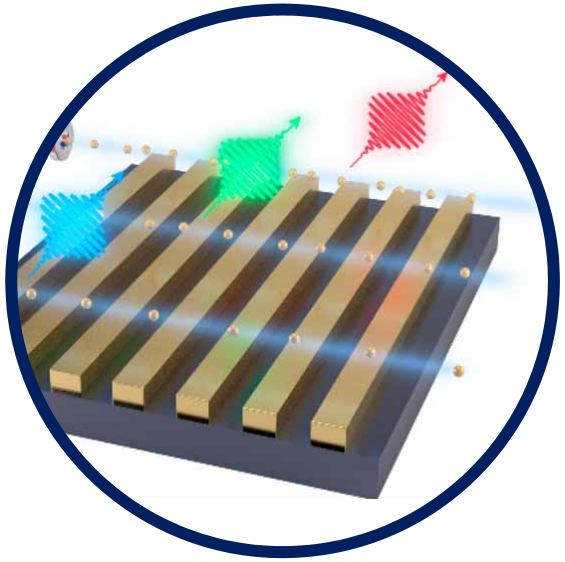
Free-electron-light interactions

Roques-Carmes et al., Applied Physics Reviews (2023)

Yang, Massuda, **Roques-Carmes**, et al., *Nature Physics* (2018)

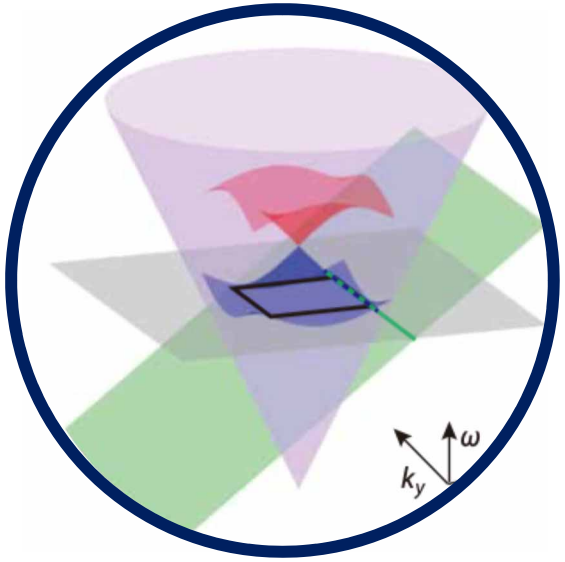
Roques-Carmes, et al. *Nature Communications* (2019)

Massuda, **Roques-Carmes**, et al., *ACS Photonics* (2018)

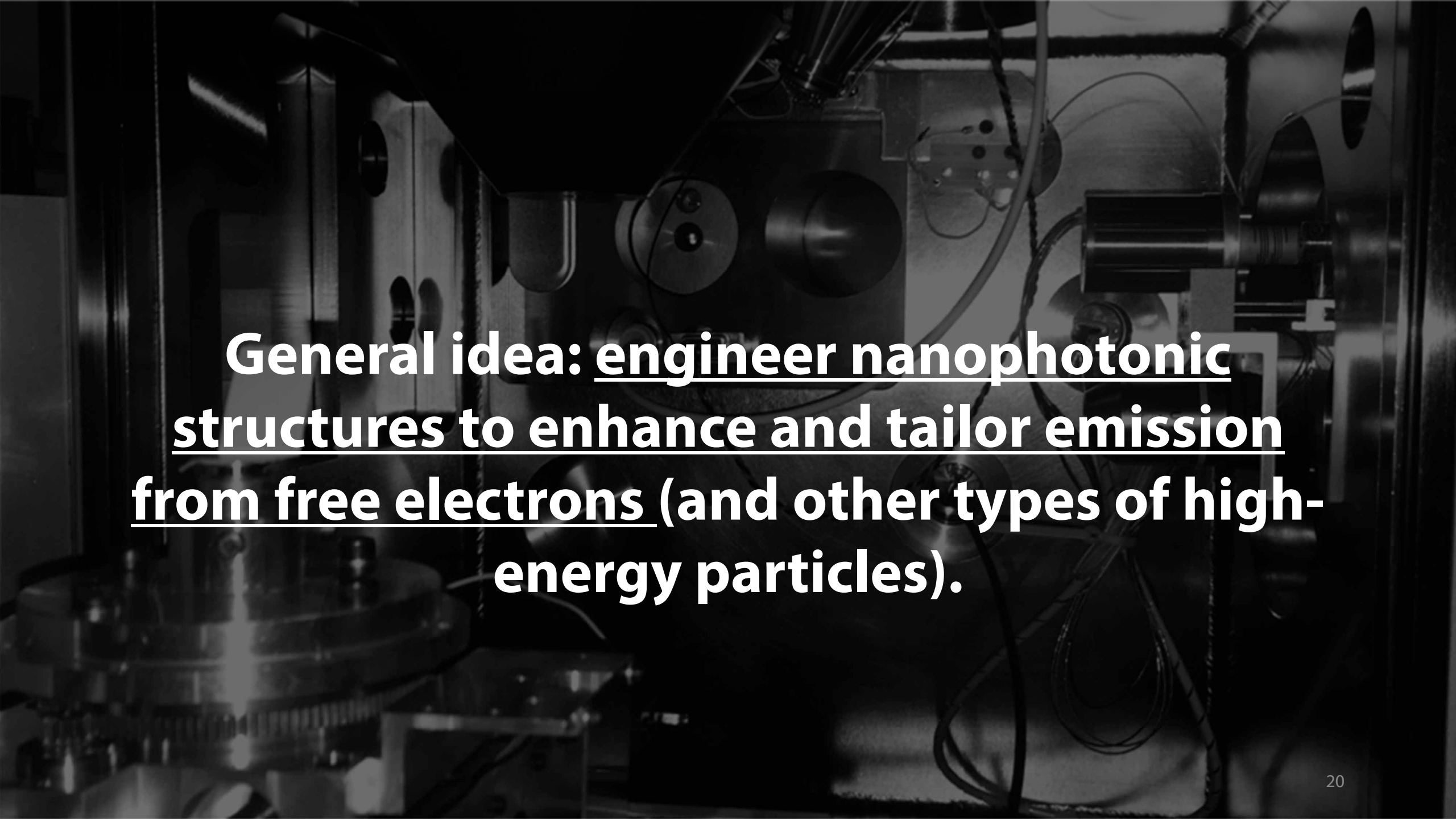


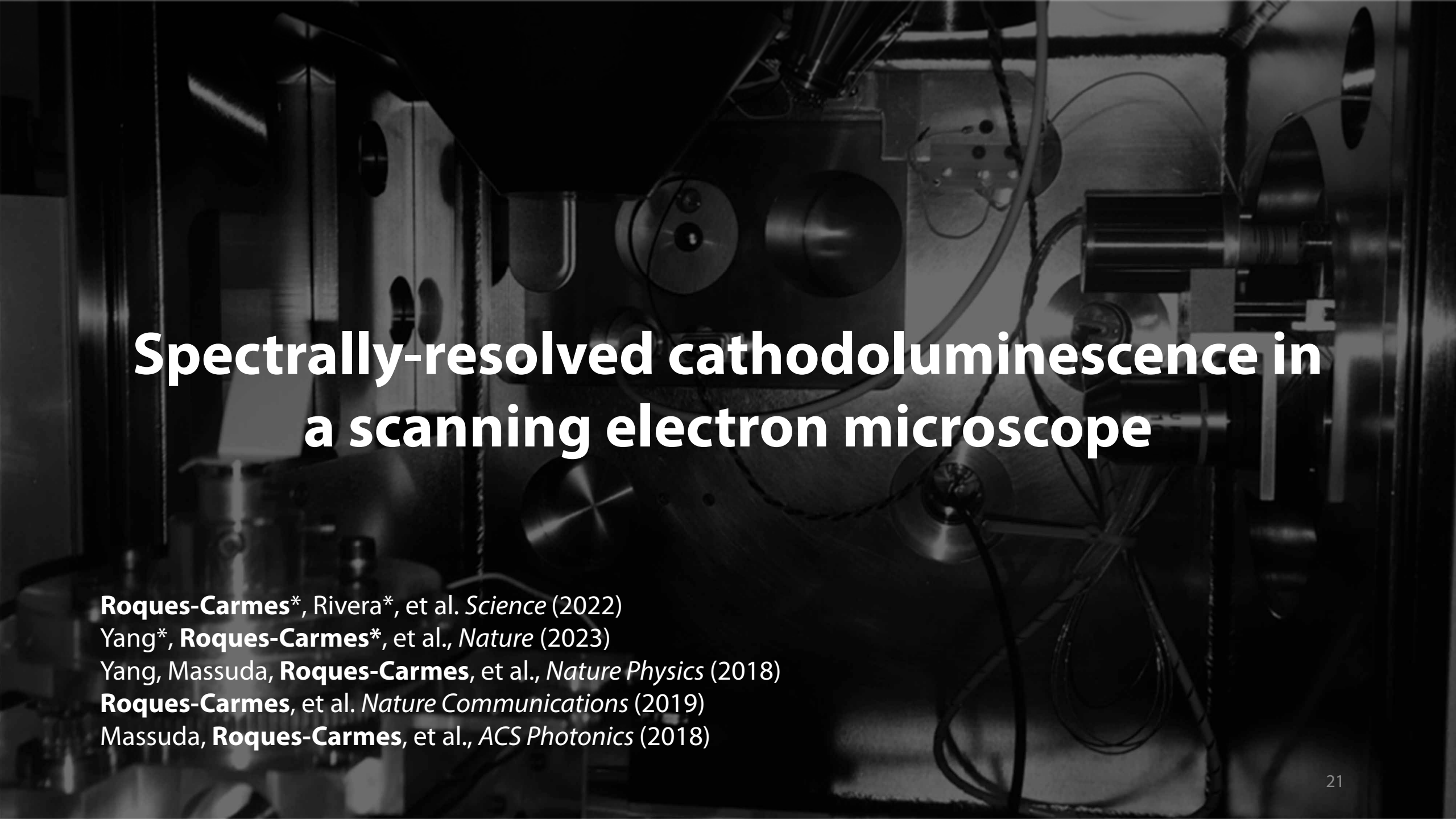
Controlling electron-beam radiation with nanophotonics

Enhancing electron-beam radiation with photonic flatbands



Yang*, **Roques-Carmes***, *Nature* (2023)

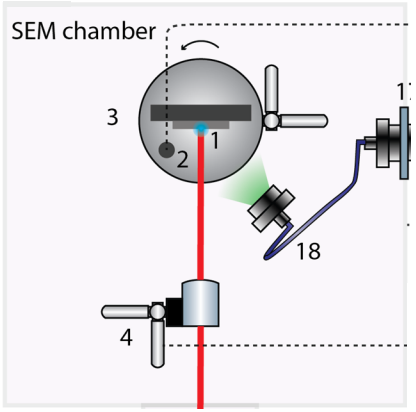

General idea: engineer nanophotonic structures to enhance and tailor emission from free electrons (and other types of high-energy particles).



Spectrally-resolved cathodoluminescence in a scanning electron microscope

Roques-Carmes*, Rivera*, et al. *Science* (2022)
Yang*, **Roques-Carmes***, et al., *Nature* (2023)
Yang, Massuda, **Roques-Carmes**, et al., *Nature Physics* (2018)
Roques-Carmes, et al. *Nature Communications* (2019)
Massuda, **Roques-Carmes**, et al., *ACS Photonics* (2018)

Our experimental setup

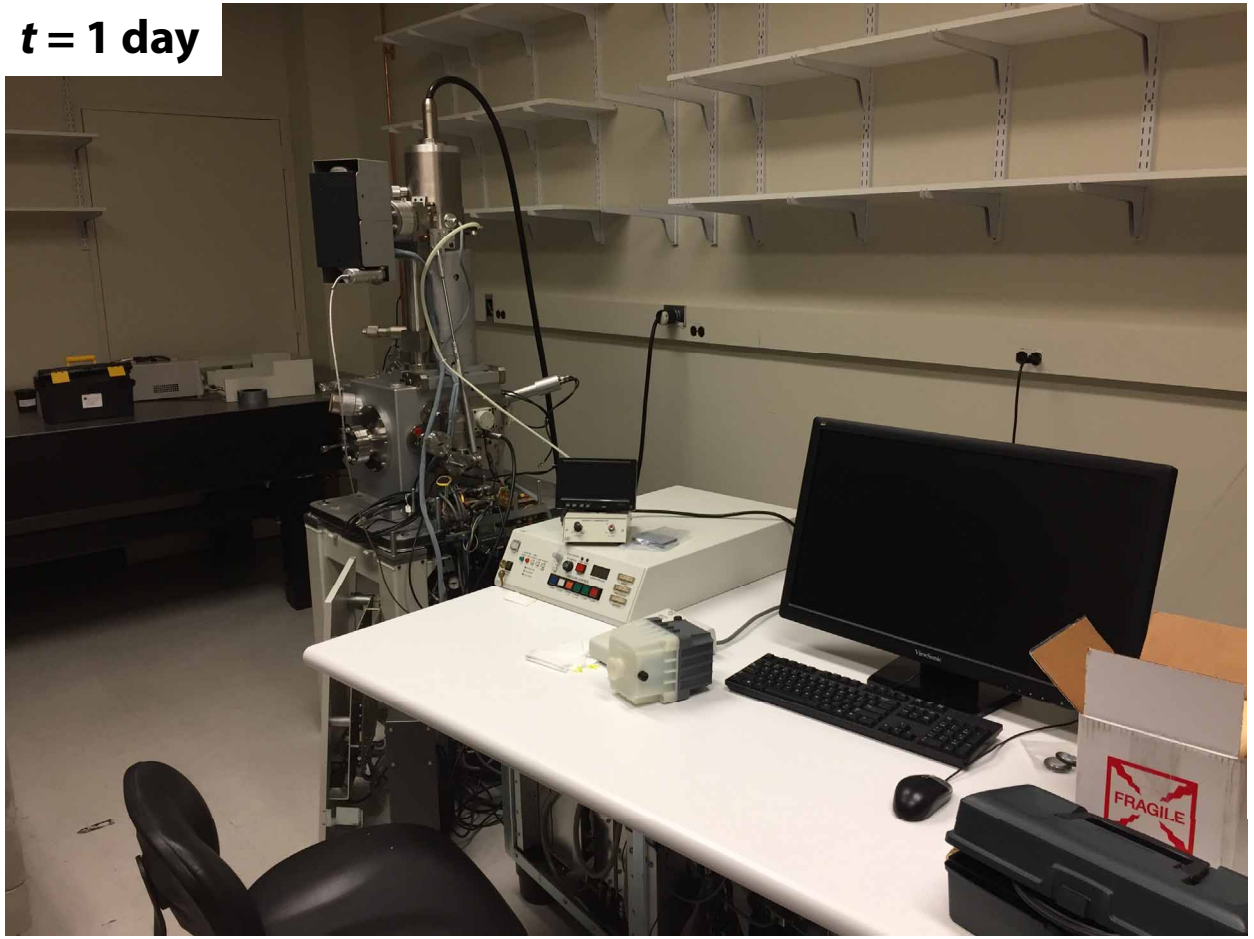


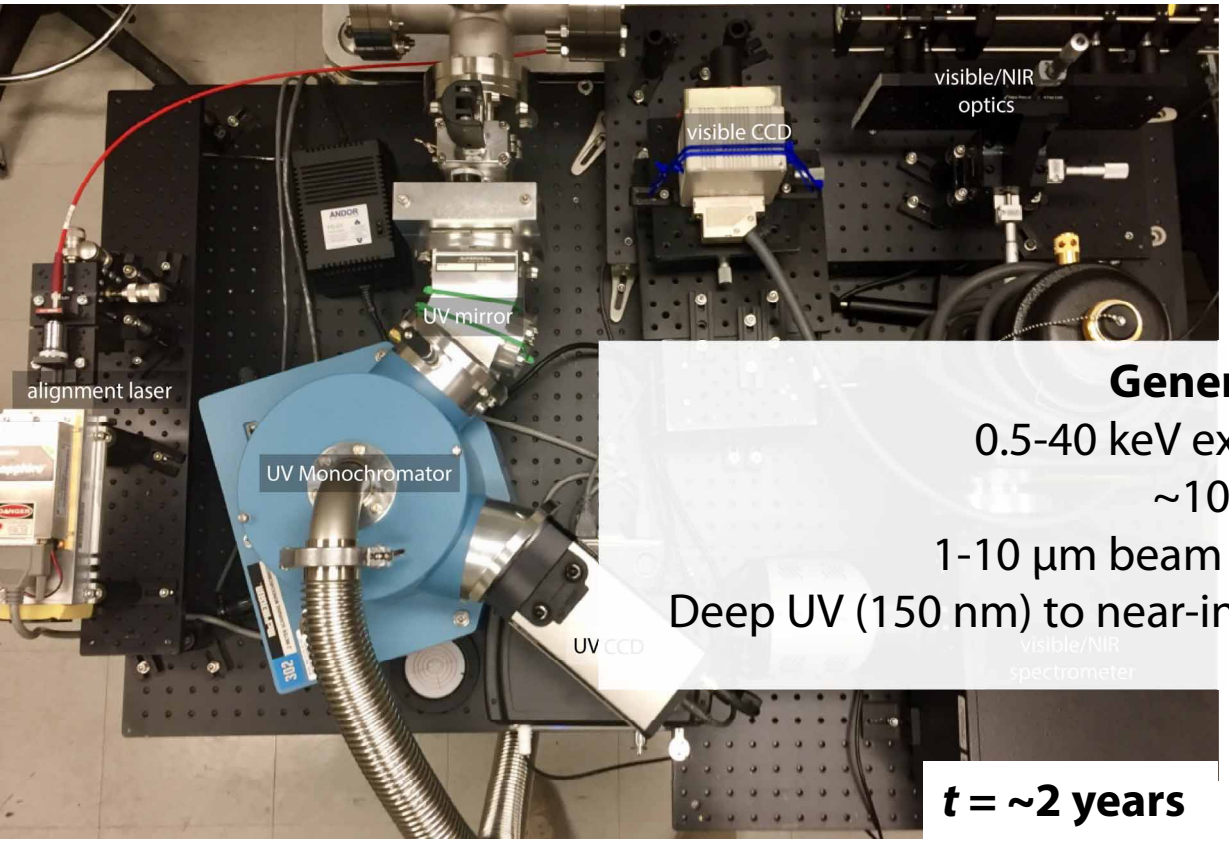
See also the works from (among others)

Fabrizio Carbone (TEM)
Ido Kaminer (TEM)
Claus Ropers/Tobias Kippenberg (TEM)
Ady Arie (TEM)
Peter Hommelhoff (TEM)
ACHIP collaboration (TEM)
Michael Krueger (TEM)
Giovanni Vanacore (TEM)
June Lau (TEM)
Jo Verbeeck (TEM)
Attolight (TEM)
Mathieu Kociak (SEM/TEM)
Sophie Meuret (SEM/TEM)

Albert Polman/Toon Coenen/DELMIC (SEM)
Karl Berggren/Donnie Keathley (SEM)
Nikolai Zheludev (SEM)
Yidong Huang (SEM)
Jennifer Dionne (SEM)
Nahid Talebi (SEM)

Our experimental setup





***t* = ~2 years**

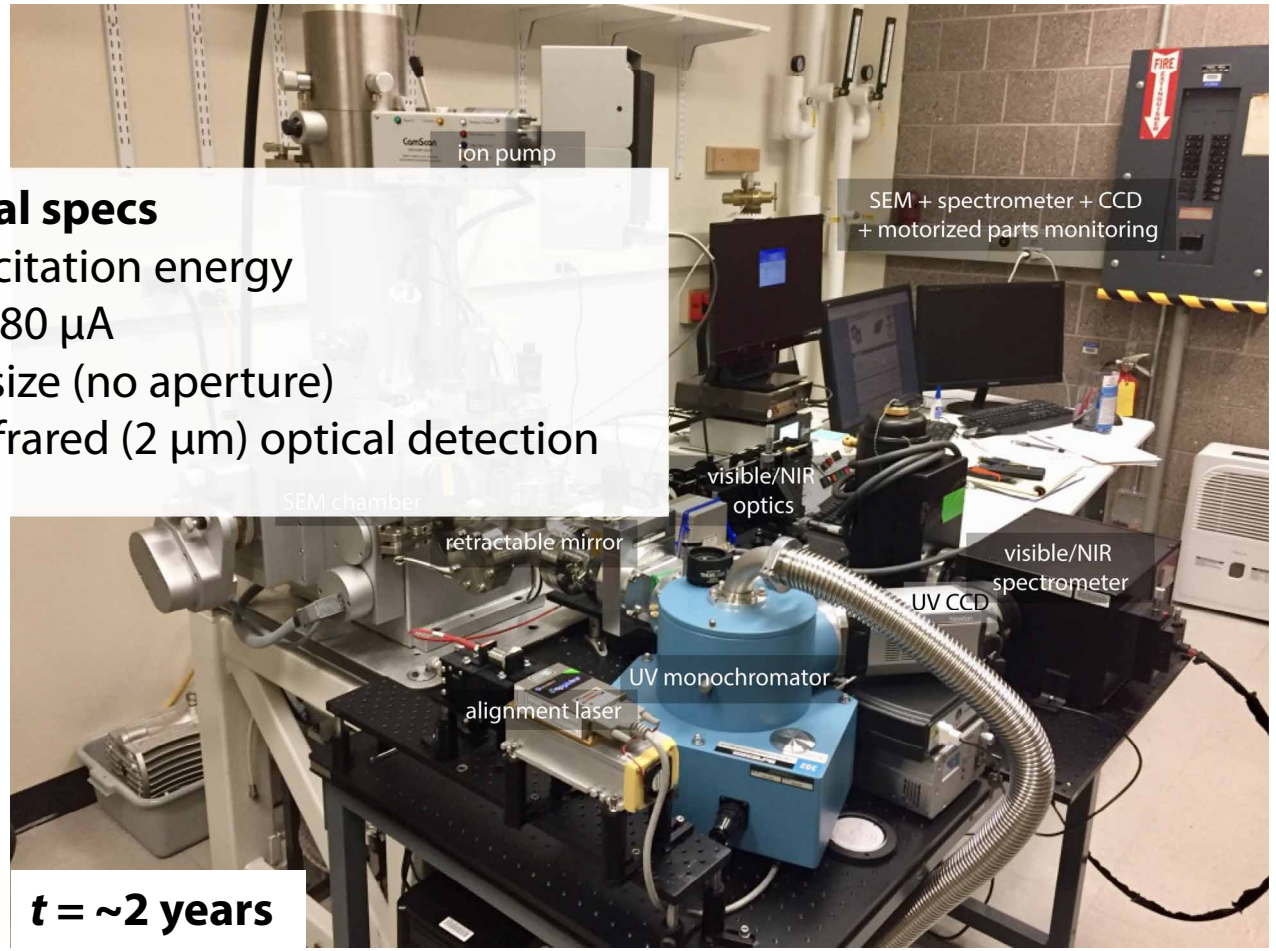
General specs

0.5-40 keV excitation energy

~10-80 μA

1-10 μm beam size (no aperture)

Deep UV (150 nm) to near-infrared (2 μm) optical detection



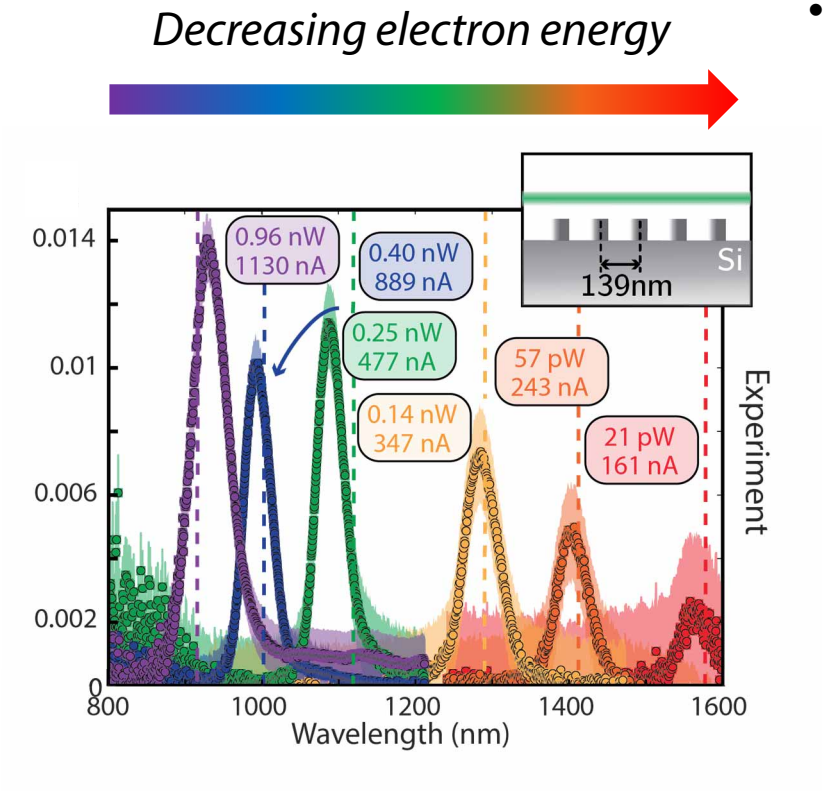
***t* = ~2 years**

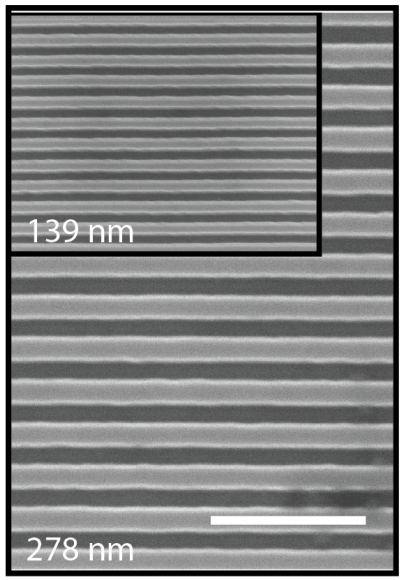
In vacuum:

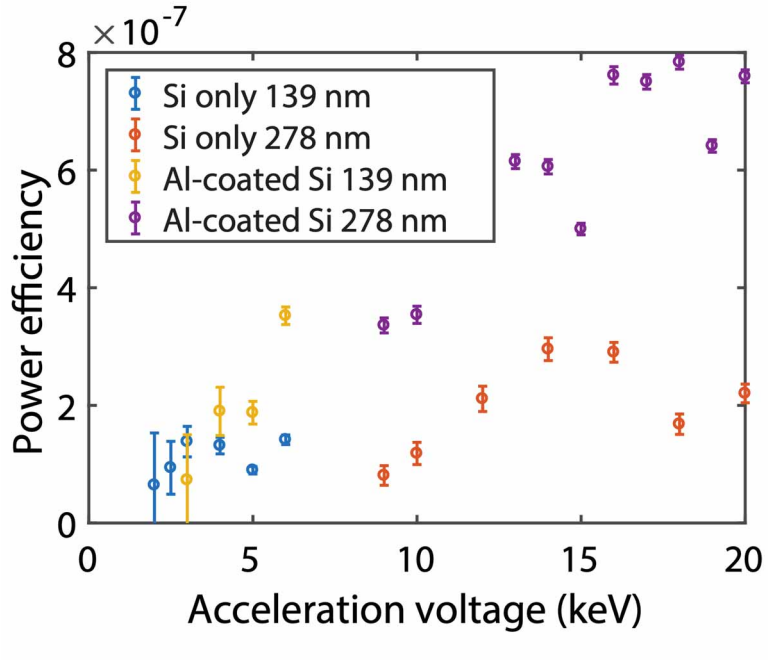
- Relocated SEI detector
- XYZ motorized objective stage
- Sample tilt stage
- Optical in/out coupling

Tunable emission from silicon nanogratings

- Low-energy electrons (→ 2keV)
- Tunable radiation spanning silicon's transparency window

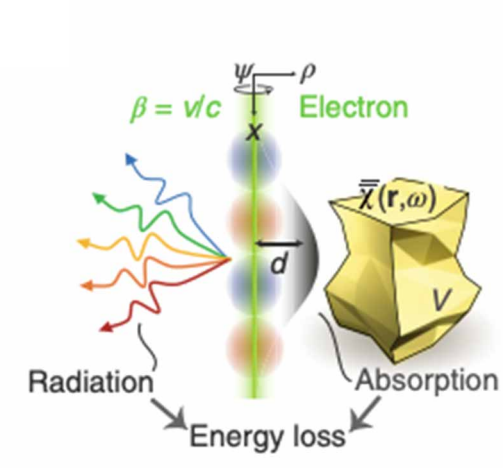






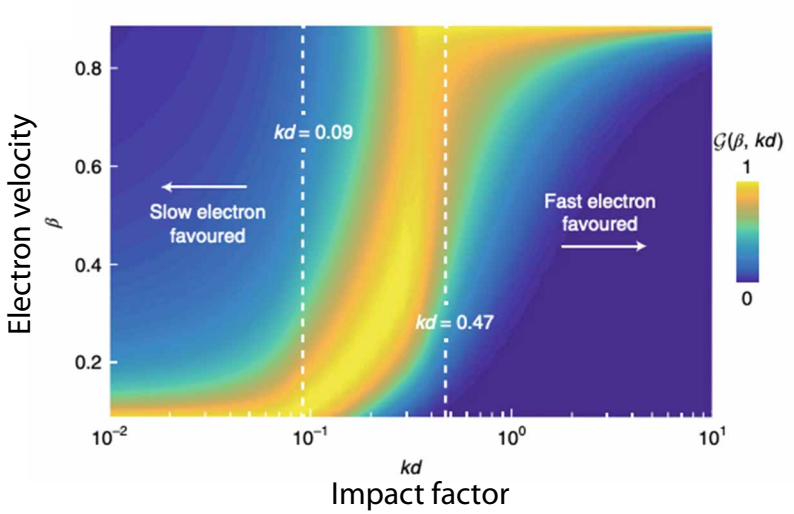
Roques-Carmes, et al., *Nature Communications* (2019)

Maximal emission from electron-light interactions?

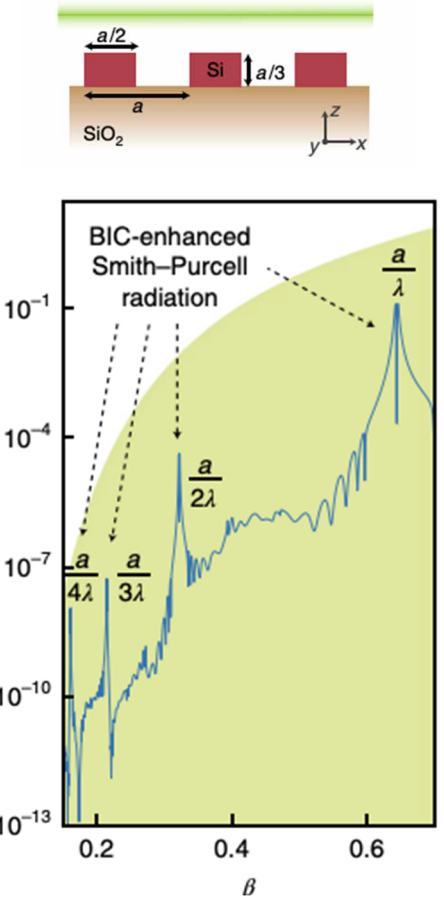


Generalizing fundamental bounds in electromagnetism to free-electron radiation.
[See work by Owen Miller's group]

Revealing counter-intuitive regimes where slow electrons are more efficient than fast ones



Bound states in the continuum to boost free-electron emission



Yang, Massuda, **Roques-Carmes**, et al., *Nature Physics* (2018)
Roques-Carmes, et al., Nature Communications (2019)

Talk overview

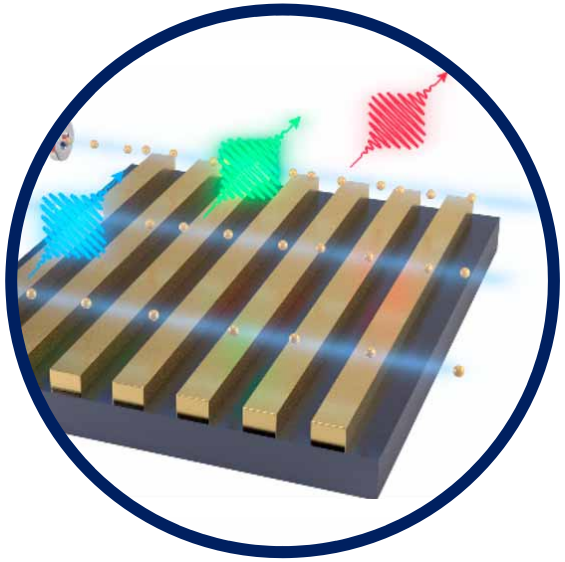
Free-electron-light interactions

Roques-Carmes et al., Applied Physics Reviews (2023)

Yang, Massuda, **Roques-Carmes**, et al., *Nature Physics* (2018)

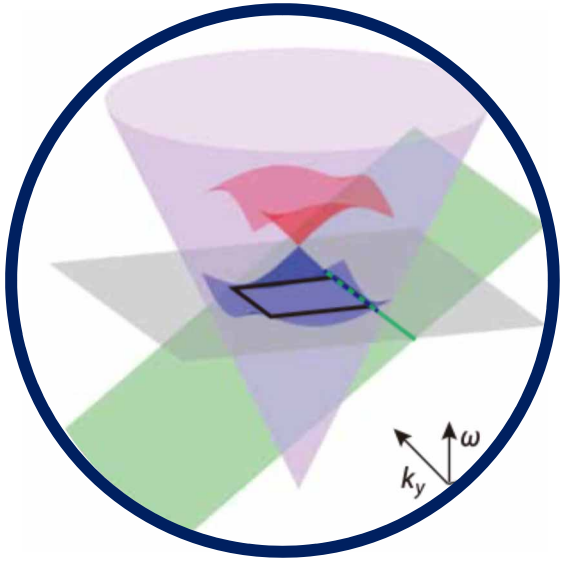
Roques-Carmes, et al. *Nature Communications* (2019)

Massuda, **Roques-Carmes**, et al., *ACS Photonics* (2018)



Controlling electron-beam radiation with nanophotonics

Enhancing electron-beam radiation with photonic flatbands

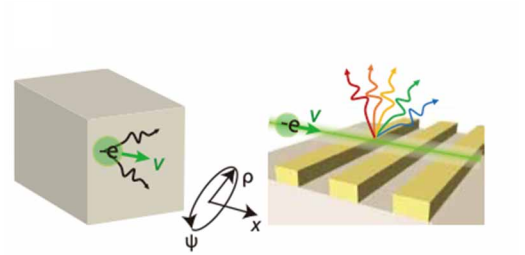


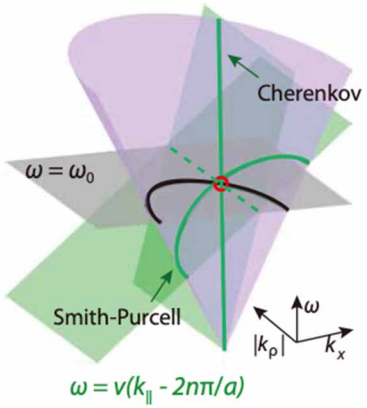
Yang*, **Roques-Carmes***, *Nature* (2023)

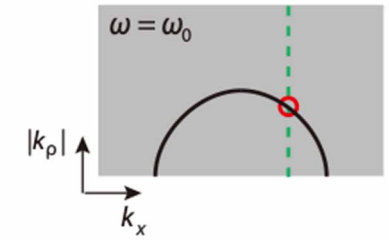
“Total” phase-matching

Setup | **Band structure** | **Iso-frequency contour**

Conventional Smith-Purcell

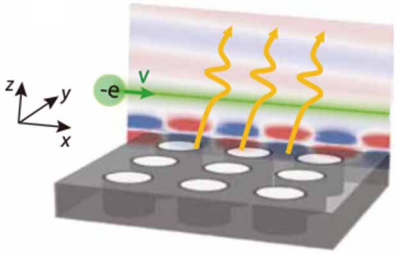


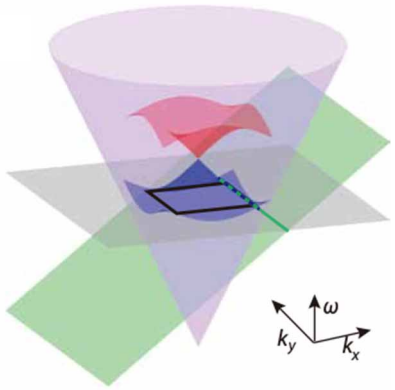


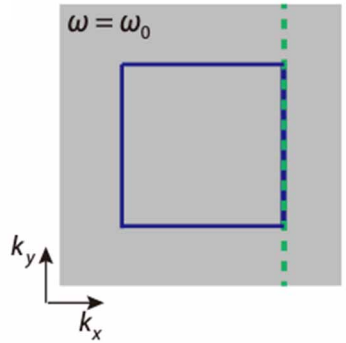


$$\frac{dU}{d\omega dl} = \frac{q^2}{8\pi^2\varepsilon_0}\sum_{m,\mathbf{G}}\int_{\partial S} dk \frac{|\mathbf{c}^{\mathbf{G}}_{m,\mathbf{k}}(\omega)\cdot\hat{r}_{||}|^2}{|\nabla_{\mathbf{k}_\perp}\omega_{m,\mathbf{k}}|}$$

Flatband Smith-Purcell



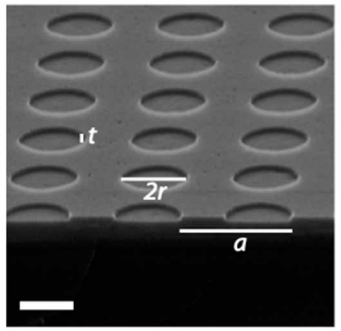


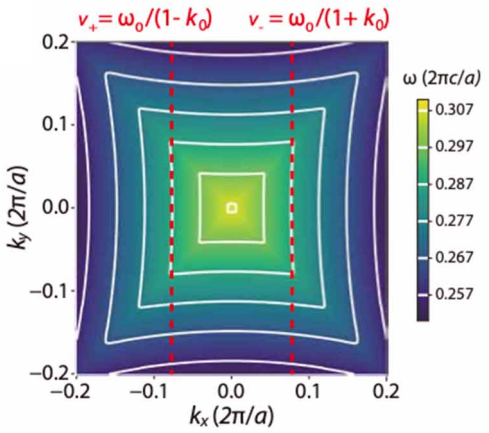


Yang*, **Roques-Carmes***, et al., *Nature* (2023)

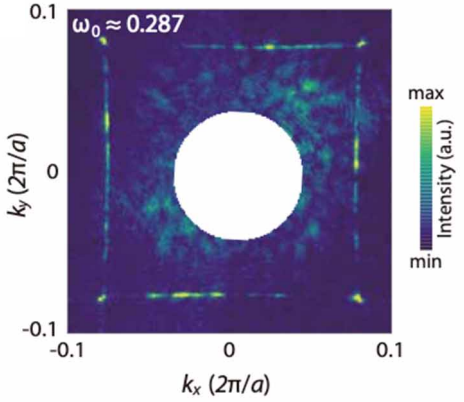
Design + optical measurements

Sample (2D PhC)



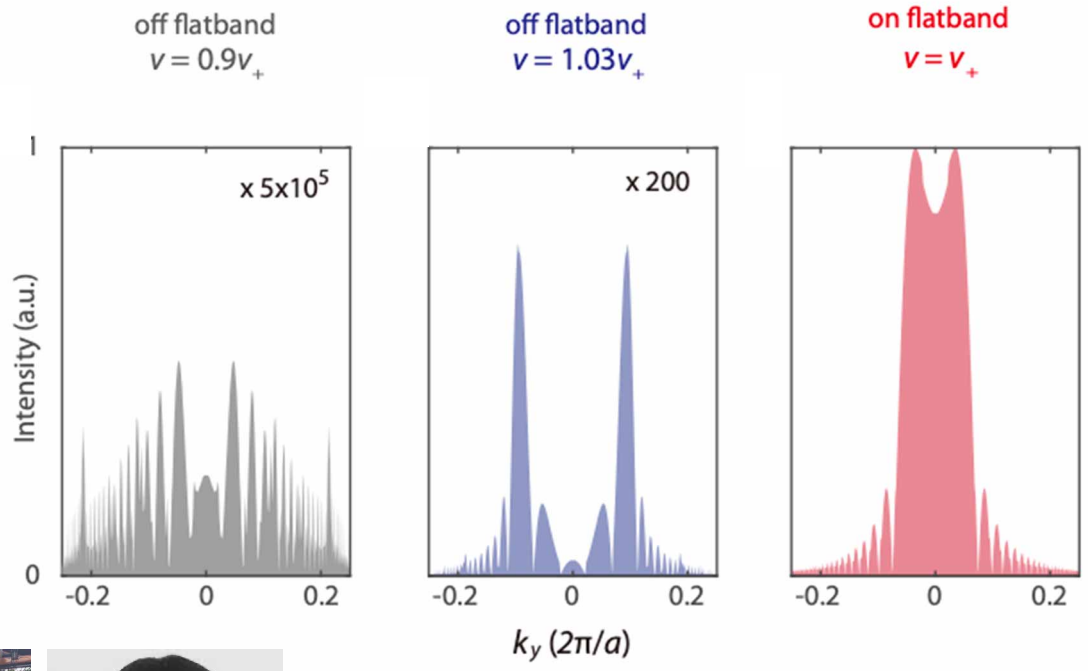


Simulation

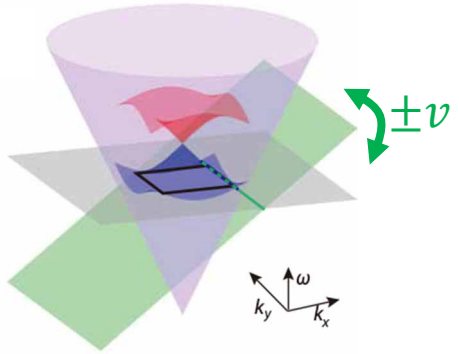


Experiment (optical)

Free-electron radiation enhancement (simulation)

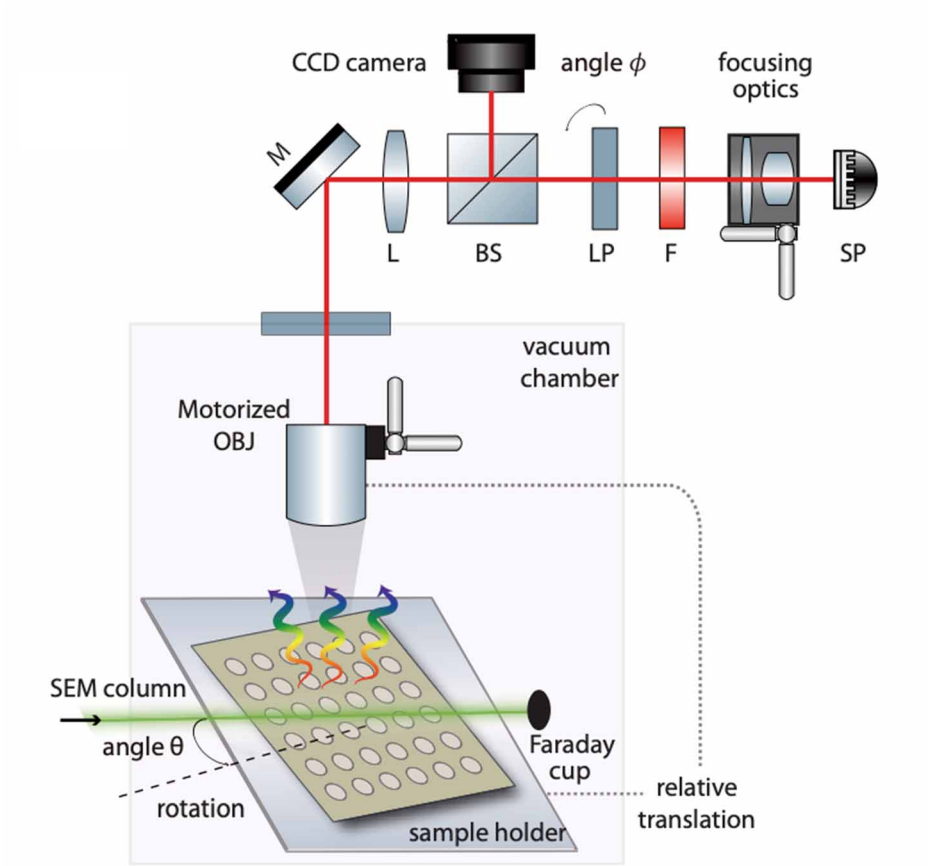


Design and optical experiment:
Yi Yang, Haoning Tang



Yang*, **Roques-Carmes***, et al., *Nature* (2023)

Electron-beam measurement confirmation



Yang*, **Roques-Carmes***, et al., *Nature* (2023)

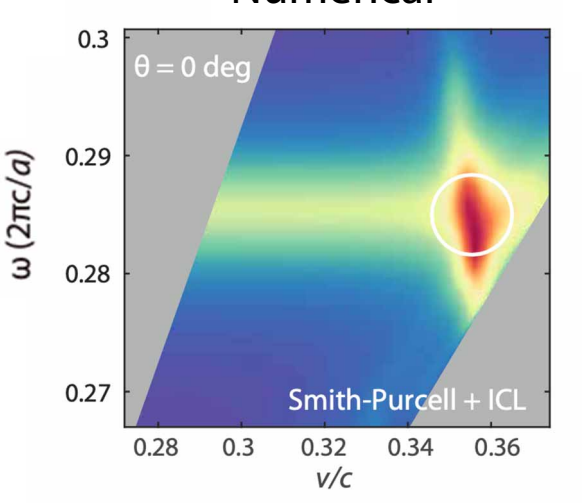
Electron-beam measurement

No tilt
(max. enhancement)

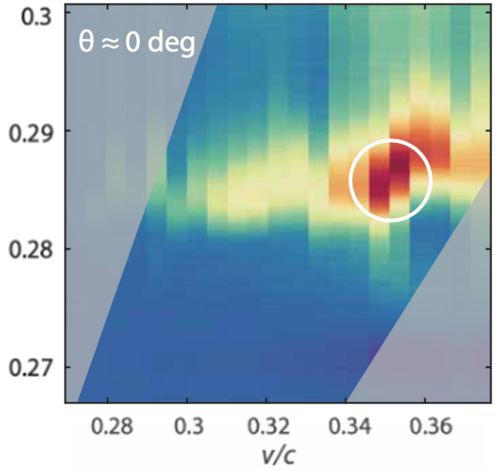
With tilt
(cancels enhancement)

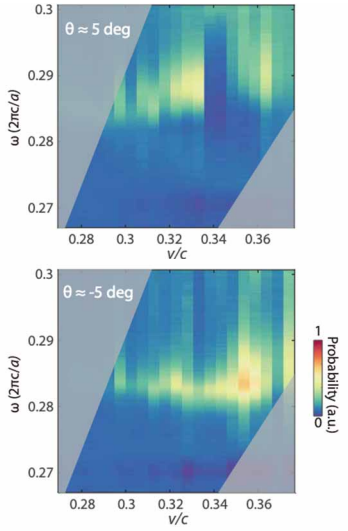
Benchmark
(silicon grating)

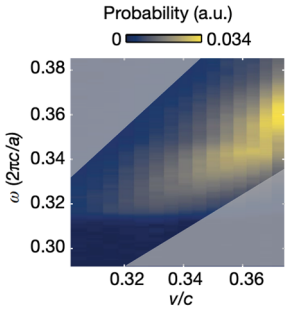
Numerical



Measurement





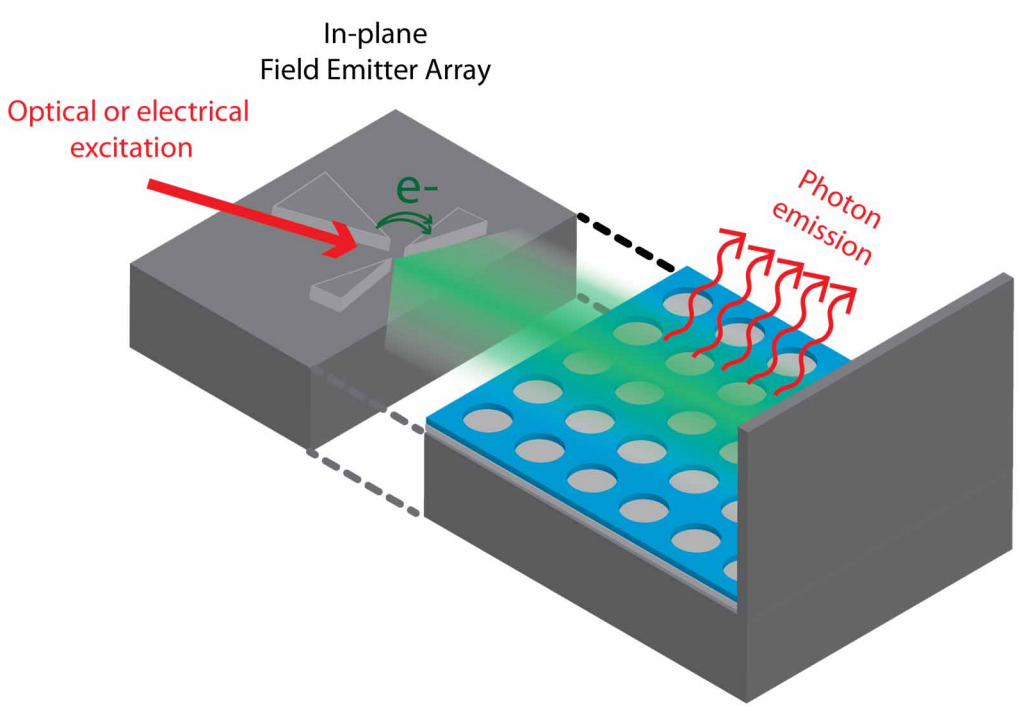


100-fold radiation enhancement on vs. off flatband [in contrast with SPR]
30x stronger than SPR from 1D grating

Yang*, **Roques-Carmes***, et al., *Nature* (2023)

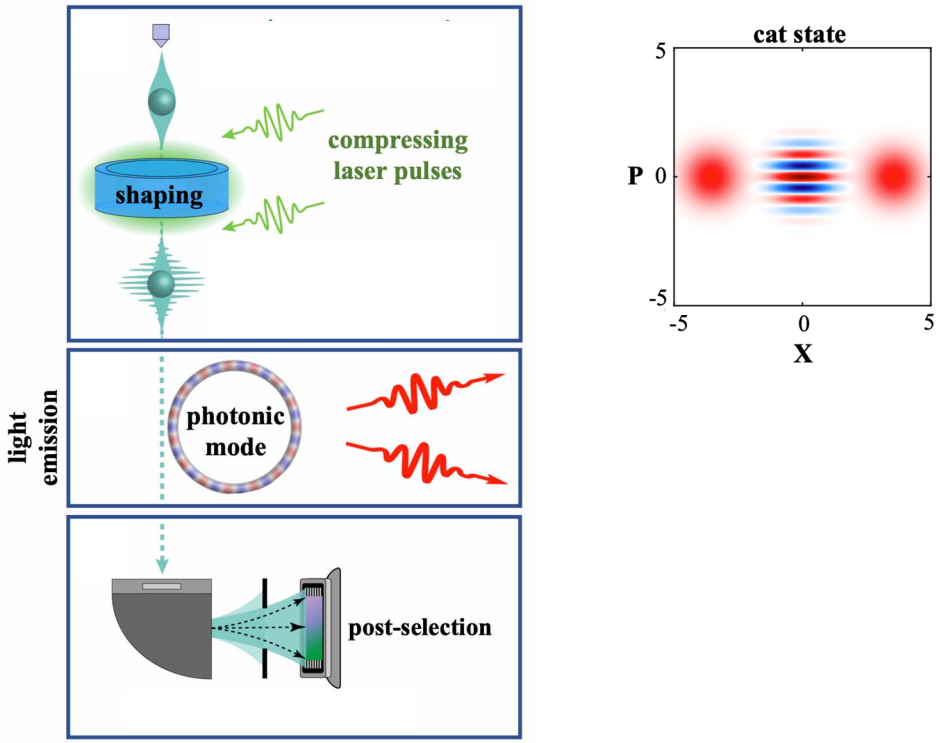
Can flatbands introduce a new regime of electron-light-matter interactions?

Fully integrated electron-beam-driven light sources



Proposal and efficiency analysis : Roques-Carmes, et al. *Nature Communications* (2019)

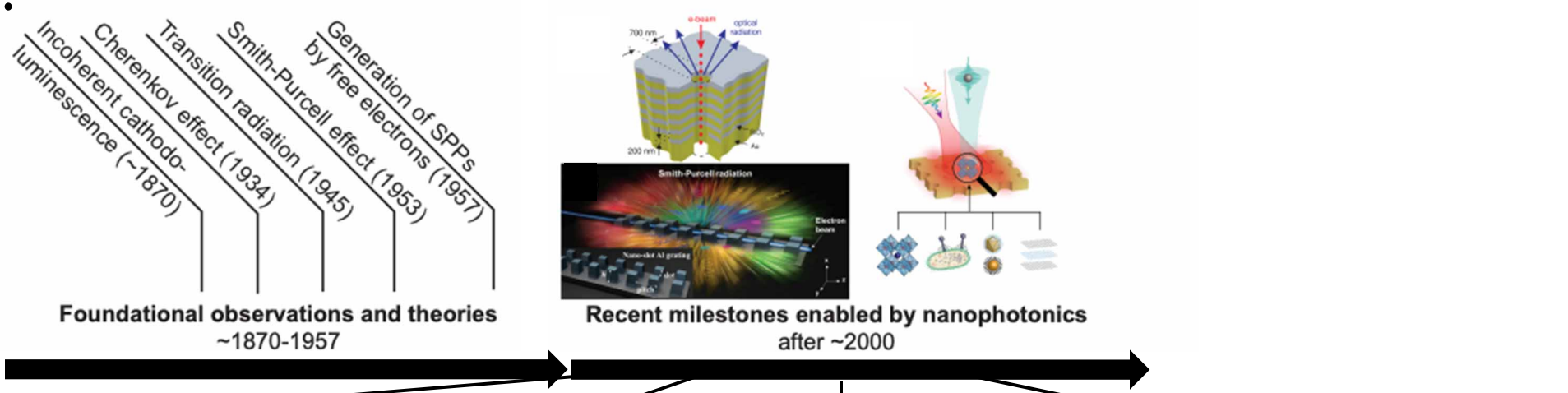
Quantum electron-light interactions



Original proposal : Dahan, Baranes, et al., Kaminer group, *PRX* (2023)

Free-electron-light interactions in nanophotonics

- **Modelling**, **tailoring**, and **enhancing** coherent electron-light interactions with nanophotonic structures
- Why now?



Nanofabrication for nanophotonics

Free-electron quantum optics (2020-)

Nanophotonic scintillators (2022-)

Single electron/x-ray cameras (Timepix, 2015-)

Acknowledgments

MIT:
Prof. Marin Soljačić
Prof. Karl Berggren
Prof. Dirk Englund
Prof. John Joannopoulos
Prof. Steven Johnson
Dr. Steven Kooi
Dr. Donnie Keathley
Dr. Nicholas Rivera
Dr. Yi Yang
Dr. Yannick Salamin

Technion:
Prof. Ido Kaminer
Prof. Y. Bekenstein
Dr. Roman Schütz
Avner Shultzman

Tel Aviv-University:
Prof. Ady Arie

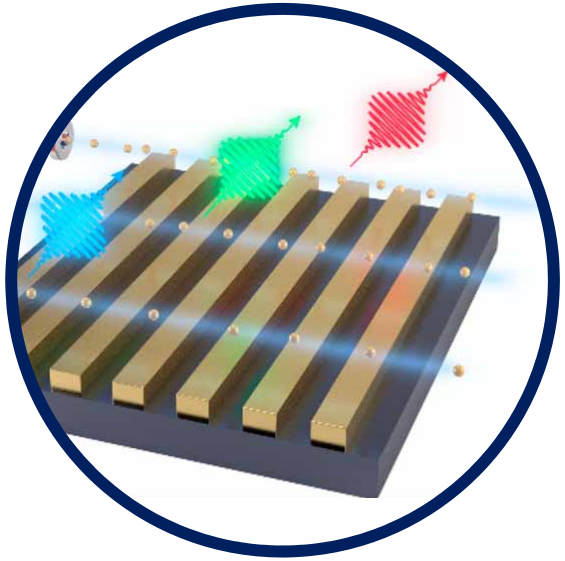
EPFL:
Dr. Jonathan Dong

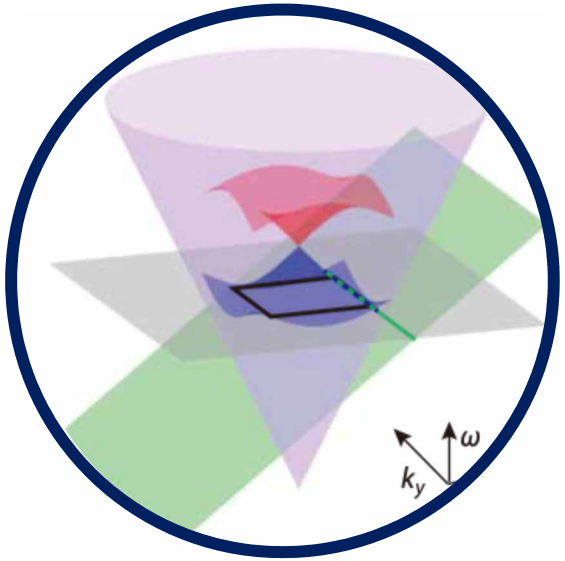
Stanford University:
Prof. Shanhui Fan
Prof. Jelena Vuckovic
Dr. Aviv Karnieli

Penn State:
Prof. Mikael Rechtsman
Marius Jürgensen

Harvard:
Prof. Eric Mazur

Free-electron-light interactions in nanophotonics





Roques-Carmes et al., Applied Physics Reviews (2023)

Yang, Massuda, **Roques-Carmes**, et al., *Nature Physics* (2018)

Roques-Carmes, et al. *Nature Communications* (2019)

Massuda, **Roques-Carmes**, et al., *ACS Photonics* (2018)

Yang*, **Roques-Carmes***, *Nature* (2023)

Charles Roques-Carmes

67th ICFA Beam Dynamics Workshop on Future Light Sources

✉ chrc@stanford.edu – 🌐 roques-carmes.com