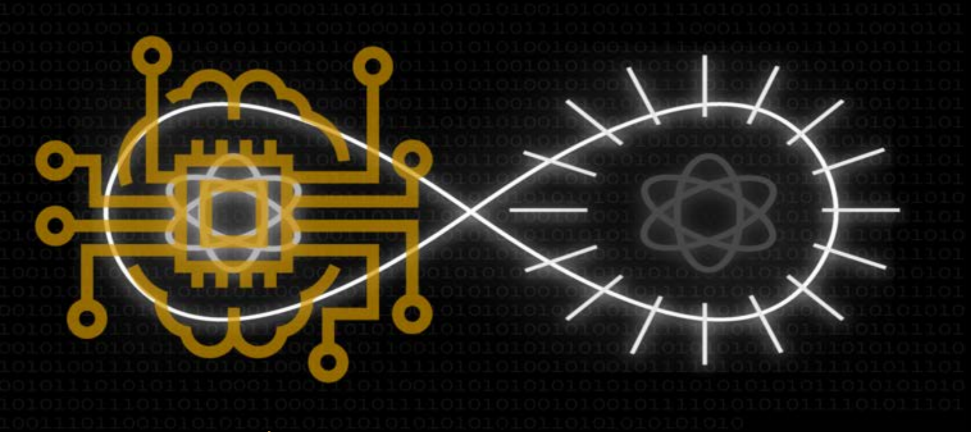


PURDUE UNIVERSITY | School of Electrical and Computer Engineering

ADVANCING PHOTONICS WITH MACHINE LEARNING

From Photonic Meta-Device Design to Quantum Measurements

Alexandra (Sasha) Boltasseva

Ron And Dotty Garvin Tonjes Professor of Electrical and Computer Engineering, Purdue University

WHY MERGING AI AND PHOTONICS?

- Optical and Quantum Photonic Technologies
- How Machine Learning/AI Can Empower Photonics?
- Advanced Optimization for Plasmonic Metasurfaces
- Machine Learning Algorithms for Energy: Thermophotovoltaics
- Materials Database for AI-Assisted Photonics
- Machine Learning for Quantum Photonic Measurements
- Summary and Outlook

OPTICAL TECHNOLOGIES

IT/Communication

https://www.mpoptical.com

Health

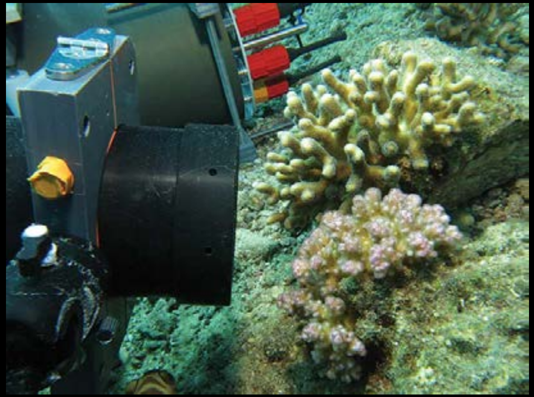
www.universalmedicalinc.com

Energy

https://www.bam.de

Economy

Environment



Scripps Inst. of Oceanography

Agriculture

Consumer Physics

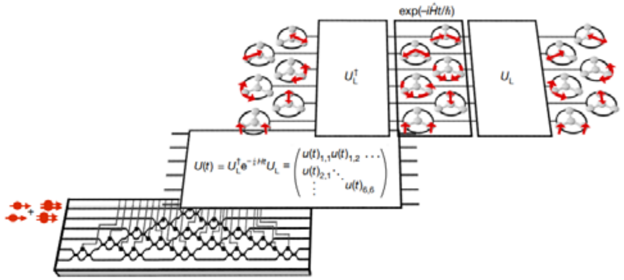
Social

Yui Mok/Zuma Press

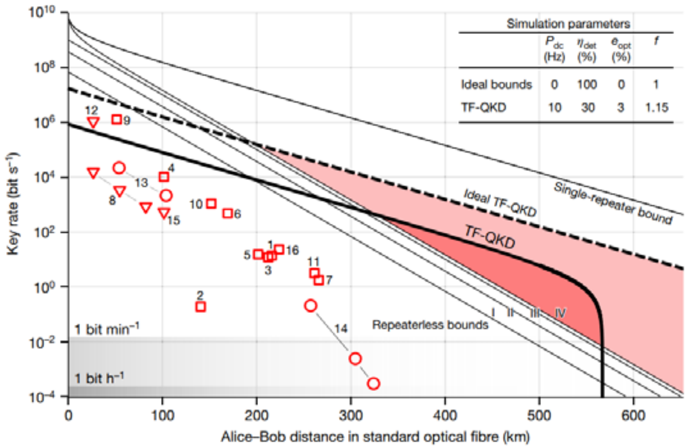
PROMISE OF QUANTUM PHOTONIC TECHNOLOGIES

- Speed of light!
- Exceptionally immune to decoherence!
  - Quantum Secure Communication
  - Photonic Quantum Simulation
  - Quantum Sensors

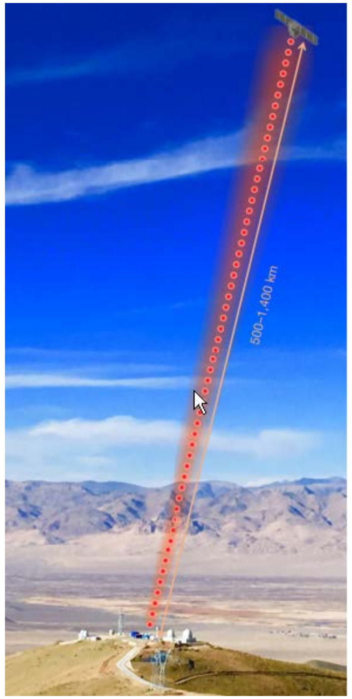
Photonic Quantum Simulation

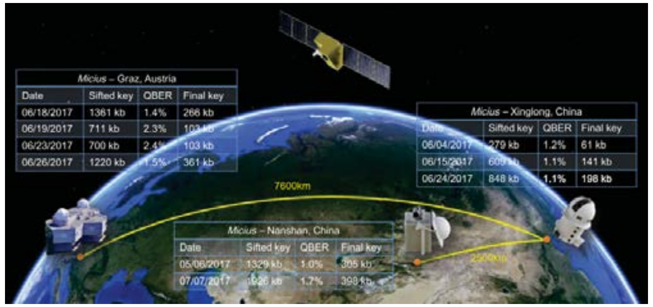


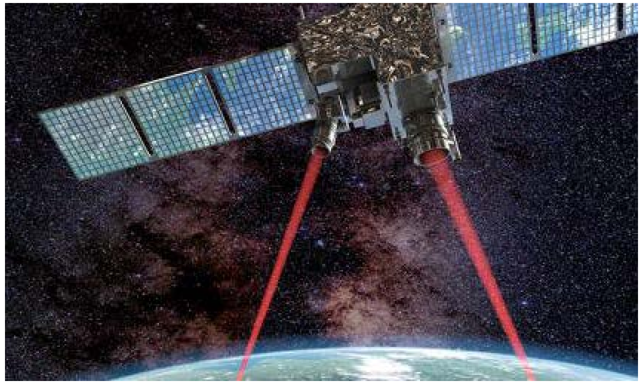
Sparrow et al. Nature (2018)



Lucamarini et al. Nature (2018)







Satellite-mediated QKD, WCS
1-10 kbps, QBER 1%; trusted satellite. Liao et al. PRL (2018)

Ground-to-satellite quantum teleportation
8 Hz, Fidelity 80%. Ren et al. Nature (2017)

Satellite-based entanglement distribution
1 Hz, Fidelity 87%. Yin et al. Science (2017)

nature photonics FOCUS | REVIEW ARTICLES
PUBLISHED ONLINE: 30 DECEMBER 2009 | DOI: 10.1038/NPHOTON.2009.229

Photonic quantum technologies

Jeremy L. O'Brien[1]*, Akira Furusawa[2] and Jelena Vučković[3]

NATURE|Vol 453|19 June 2008|doi:10.1038/nature07127 INSIGHT REVIEW

The quantum internet

H. J. Kimble[1]

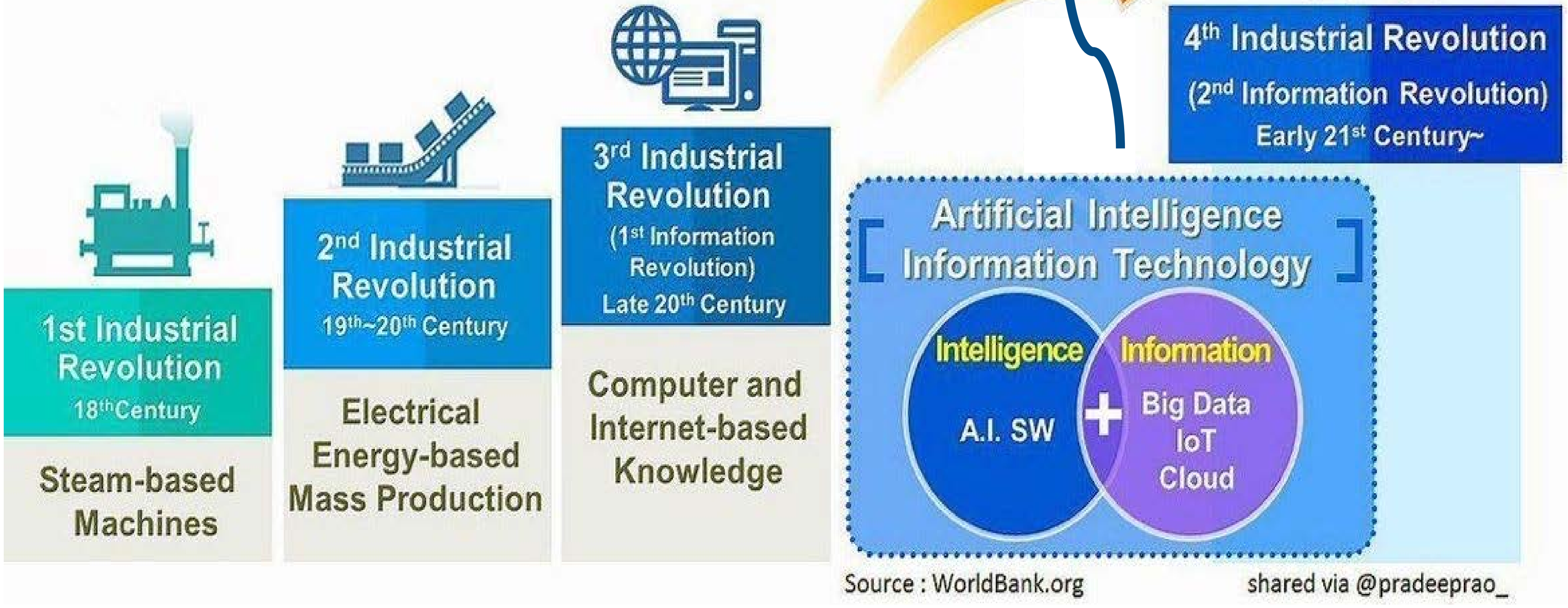
FAST YET SLOW!

4th INDUSTRIAL AND INFORMATION REVOLUTION

Quantum Information Science and Technology

- In the heart of modern technologies
- Harness full power of quantum world for ultimate control of matter (2000,2001,2005, 2012 Nobel prizes)

AI + QIST

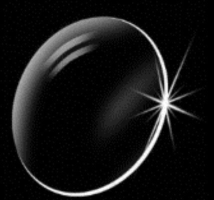


Major breakthroughs are MATERIALS related: Stone Age, Iron Age, Si Age, … METAMATERIALS

ALL ABOUT (META)MATERIALS

0 | 1 | ∞

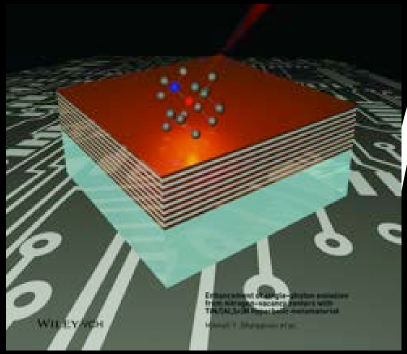
OBJECT SIZE/WAVELENGTH

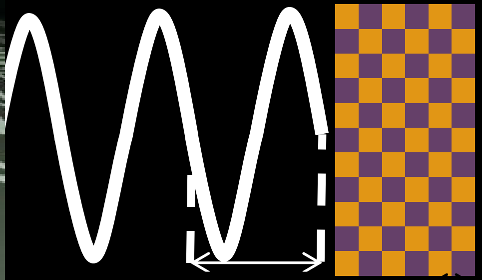


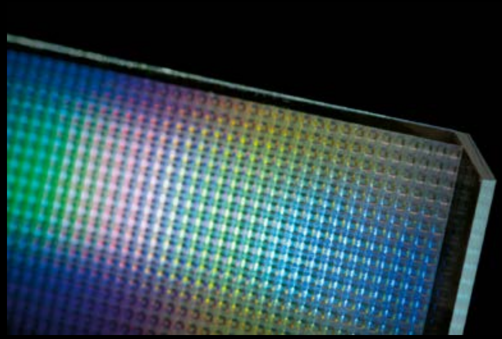
size << λ
METAMATERIALS
QUANTUM
NANOPHOTONICS

size ~ λ
Diffraction
Interference
Gratings

size >> λ
Geometrical Optics
Lenses
Shadows





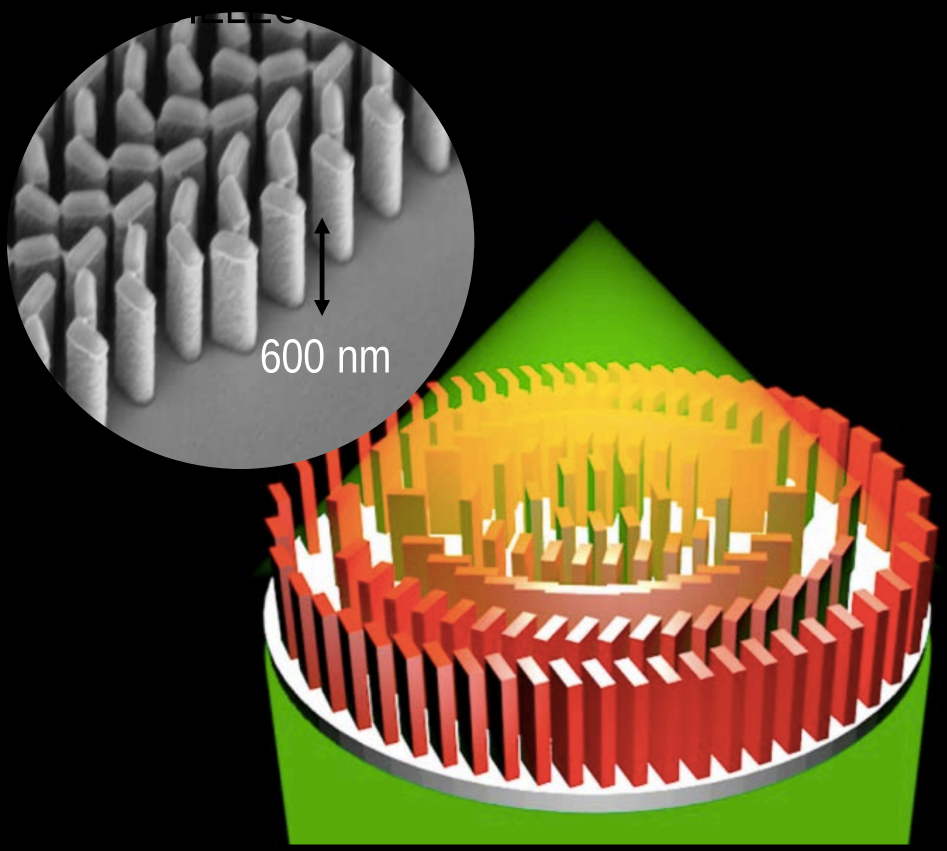


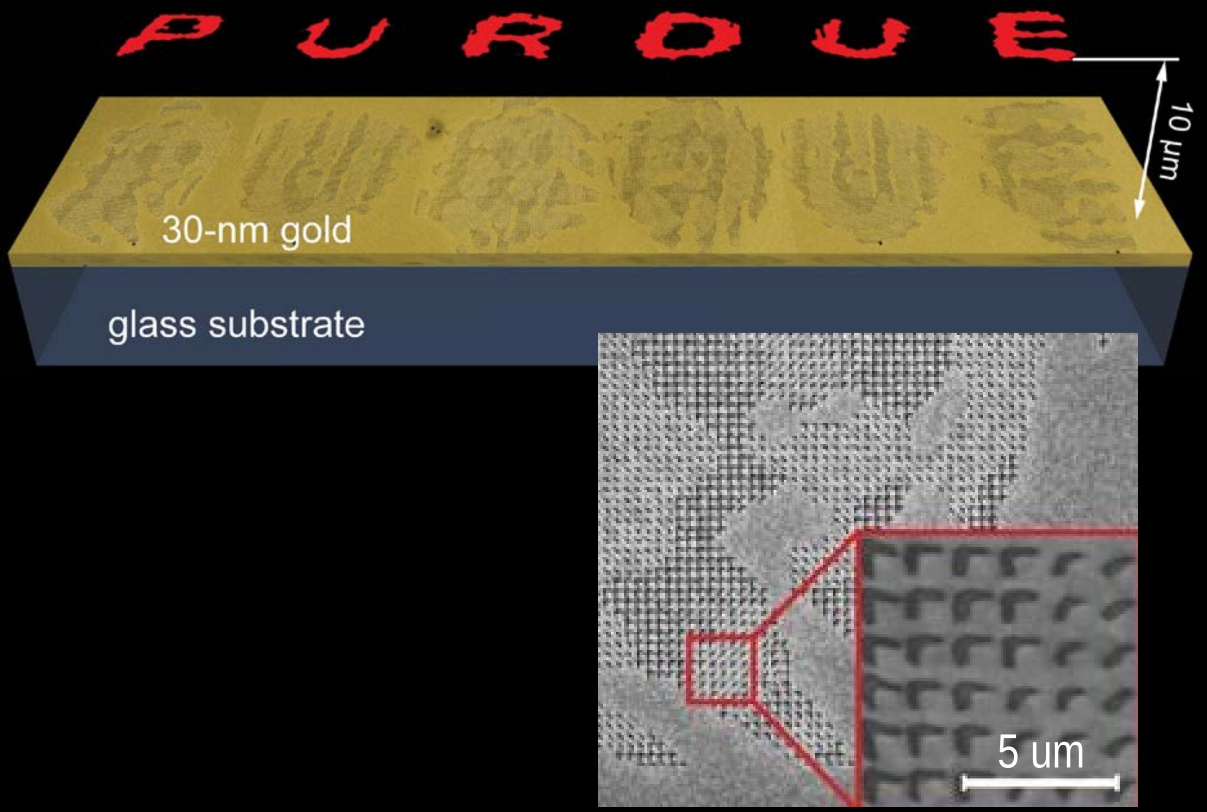
Jenoptik

Wikipedia

Scientists have gone from BIG LENSES, to OPTICAL FIBERS, to ULTRA-SMALL/THIN DEVICES with unique functionalities using METAMATERIALS

METASURFACES





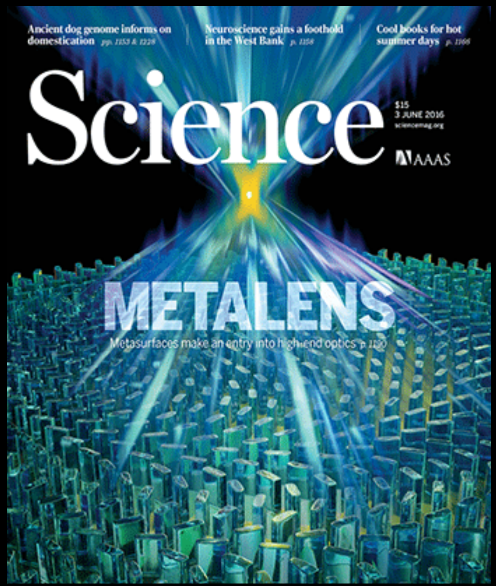
M. Khorasaninejad, et al., Jour. Quantum. Electron., 23, 4700216 (2016)
X. Ni, et al., Nat. Comm., 4, 2807 (2013)

V. Shalaev, Purdue

Seminal works on metasurfaces: Hasman, Capasso, Lalanne, Shalaev, Zheludev, Bozhevolnyi, Levy, Tsai, Zhang, Smith, Kivshar, Atwater, Brongersma, Luk'yanchuk, Kuznestov, Faraon…

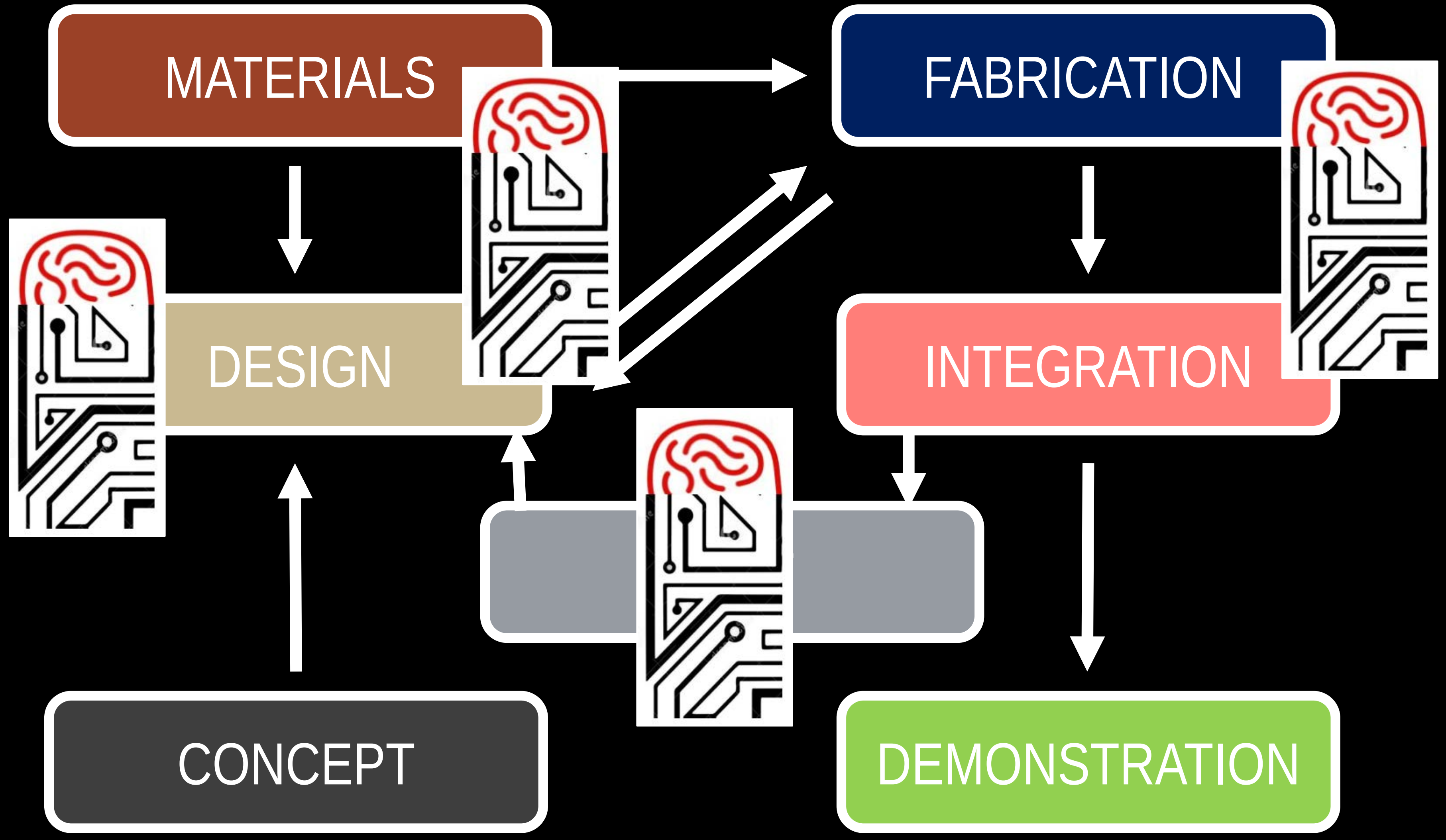
POTENTIAL IMPACT

- Flat optics
- Hybrid photon./electronic circuits
- Sub-λ photodetectors
- Data recording/storage
- Single molecule sensors
- Medical/Drug delivery/Therapy
- Sub-λ imaging
- Optical nanolithography
- Optical nanotweezers
- Solar cells/PV
- Photo-catalysis
- Novel energy conversion schemes
- LIDARs&Security
- Quantum information technology



MIT NEWS

AI-AIDED PHOTONICS: FLOW CHART



PHOTONIC DESIGN

DESIGN

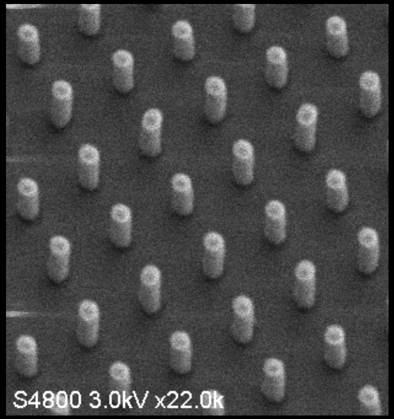
NUMERICAL SIMULATIONS

SIMPLE SHAPE VARIATION

TOPOLOGY OPTIMIZATION

DEEP/MACHINE LEARNING/AI

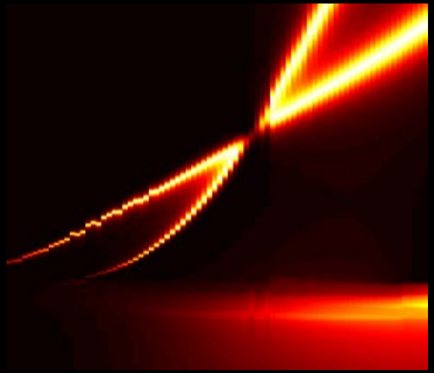
PHOTONIC DESIGN



DESIGN

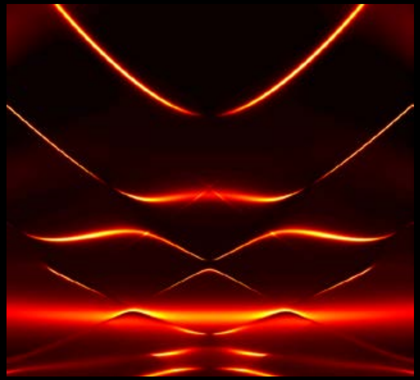
SIMPLE SHAPE VARIATION

Beautiful physics!



Bound States in the Continuum

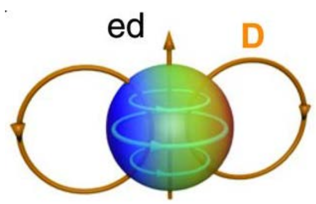
Photonic Crystals

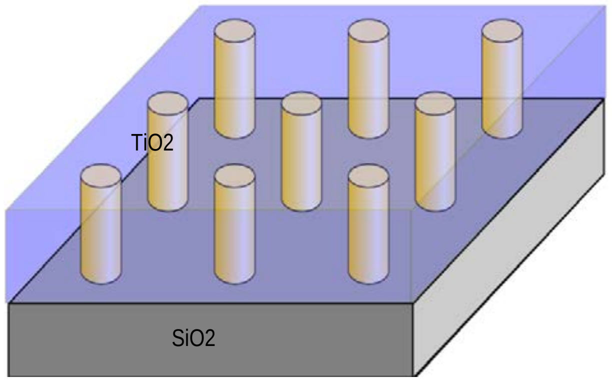


Bound States in Continuum–BIC METASURFACES

ALL-DIELECTRIC METASURFACE at BIC regime:

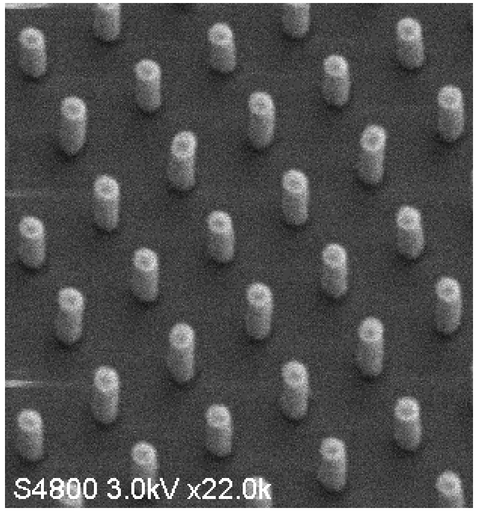
- High-Q resonances in the visible spectral range
- Single unit-cell design metasurfaces
- Polarization-insensitive high-Q response in the visible



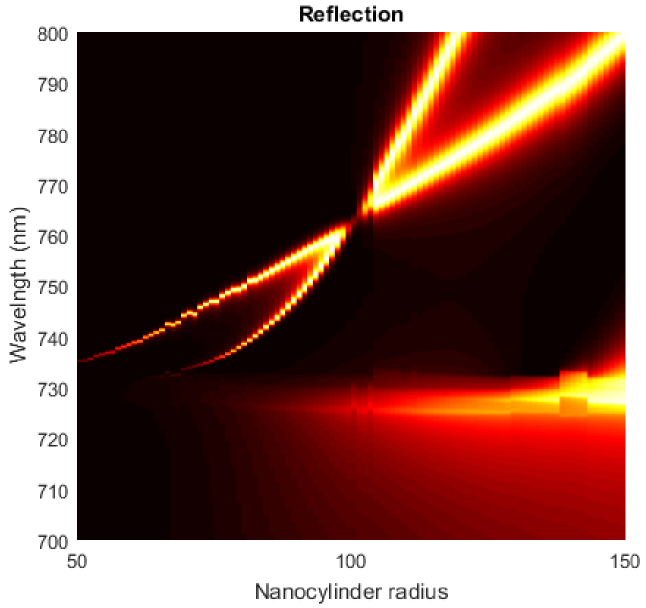


Resonance can be adjusted by simple design modification

Polarization independent due to symmetry



TiO_2 nanopillars on a silica

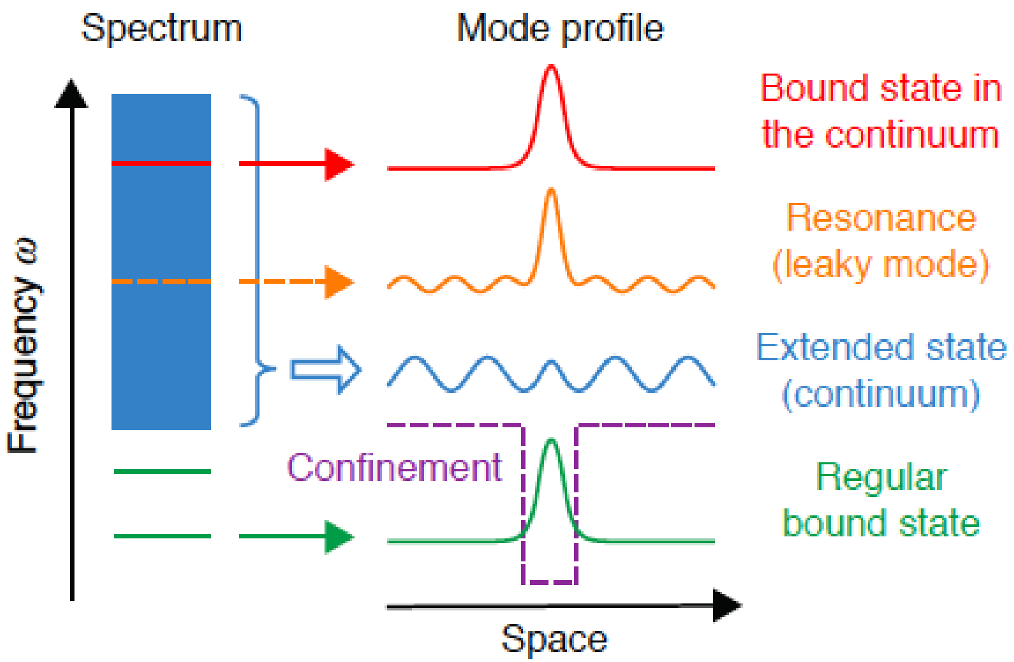


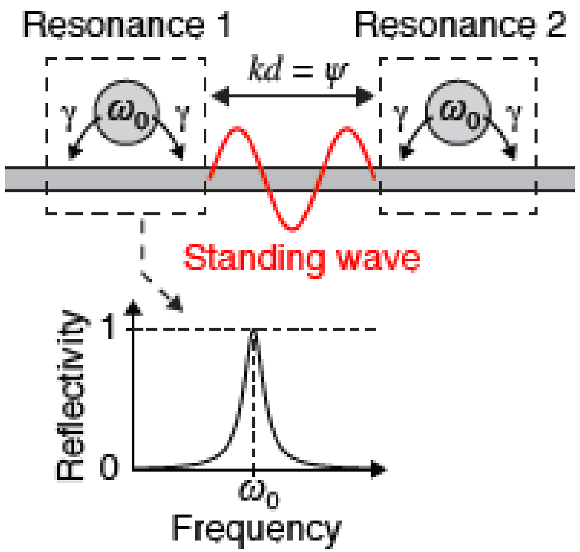
Near the BIC point

High Q-factor

S. Azzam, K. Chaudhuri, V. M. Shalaev, A. Boltasseva, A. Kildishev, CLEO, 2019

Bound States in Continuum–BIC REGIME



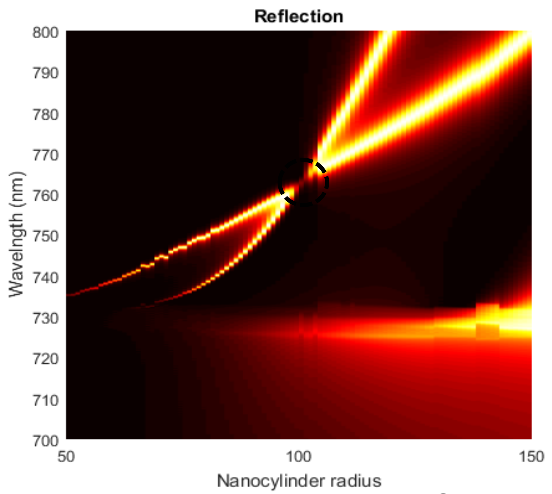


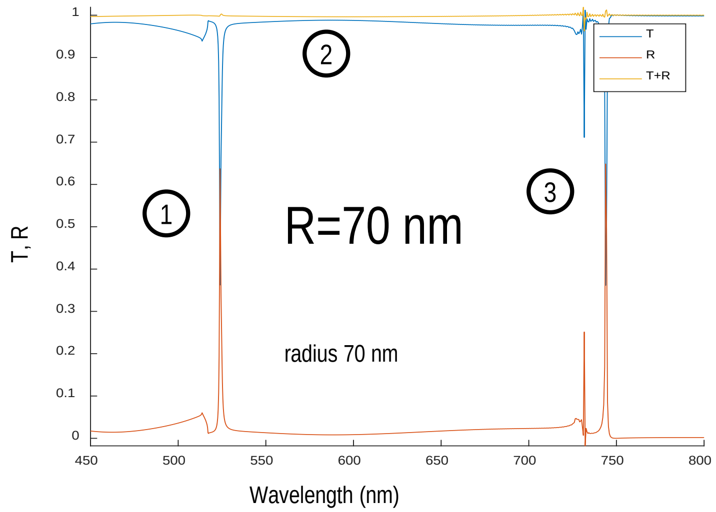
- Conventional confinement: bound states away from continuum (discrete levels)
- Bound states in the continuum (BICs) (no radiation): states remain localized and have infinite lifetimes while residing inside the continuum
- Fabry-Pérot BIC: two resonances coupled to one radiation channel, and act as perfect reflectors near the resonance frequency, so the two can trap waves in between

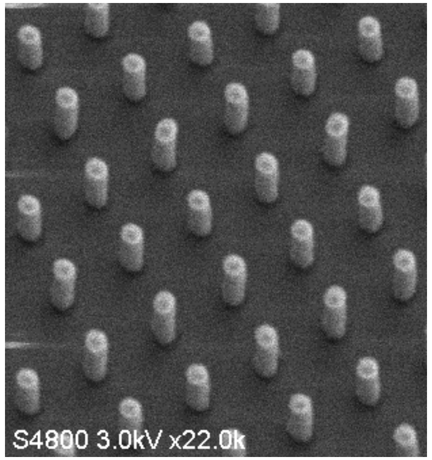
Hsu, Zhen, Stone, Joannopoulos, Soljačić, Nature Reviews Materials 1, 16048 (2016)

ALL-DIELECTRIC METASURFACES AT BIC

Reflection as a function of nanopillars radius

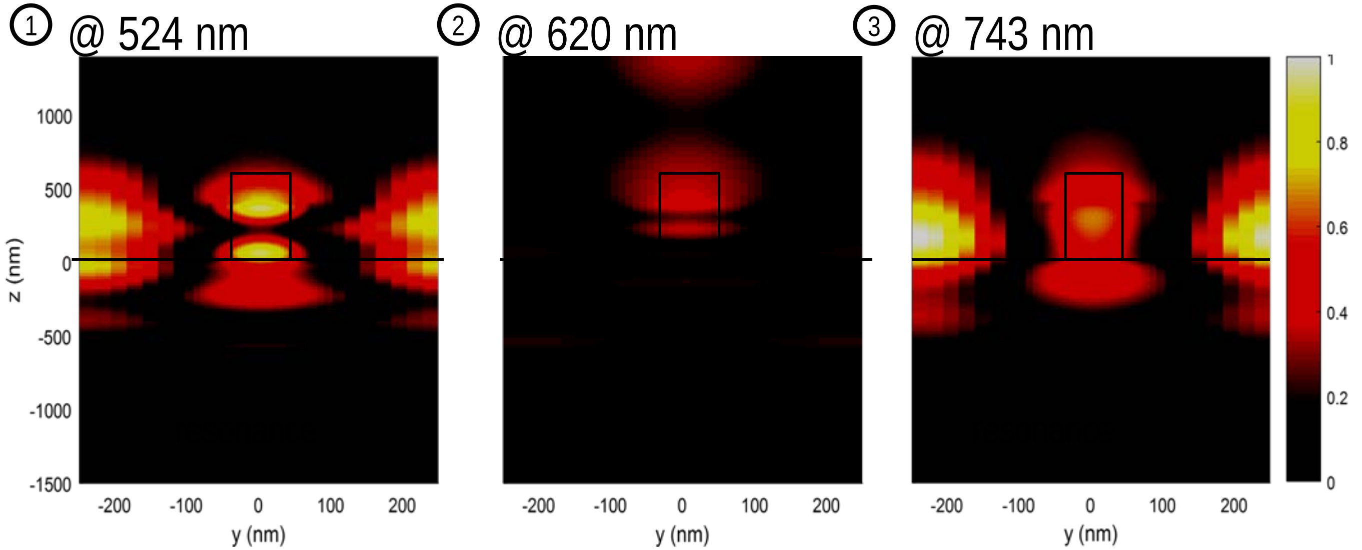




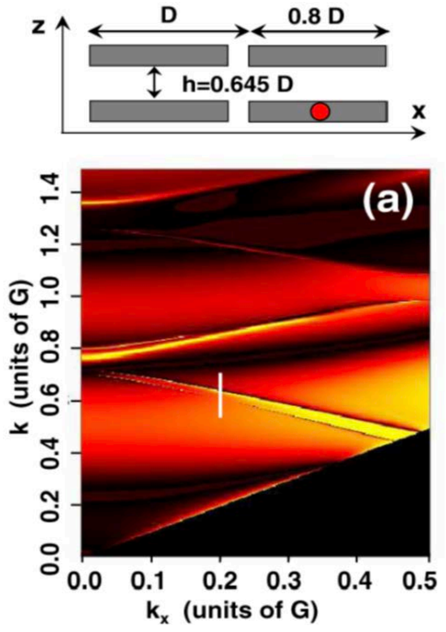


- Q ~ 2000
- Resonance in VIS
- Easily adjusted
- Polar. insensitive
- Single unit cell
- Tight confinement :

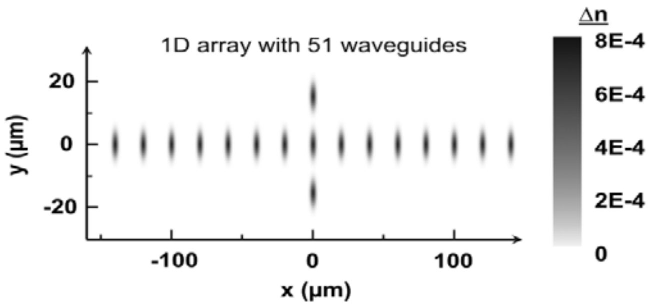
Enhanced Nonlinearities



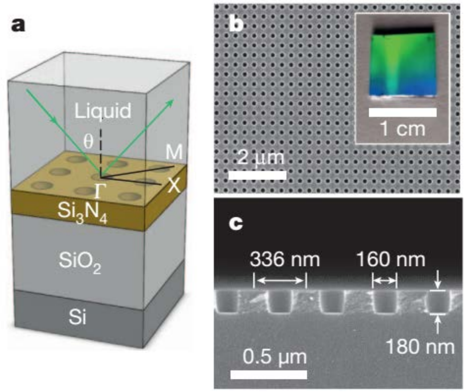
PHOTONIC BIC



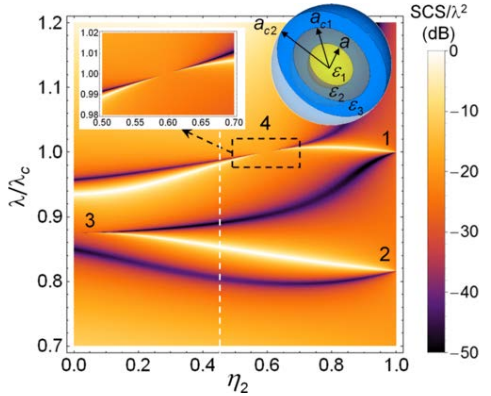
DC Marinica et al. PRL 100, 183902 (2008)



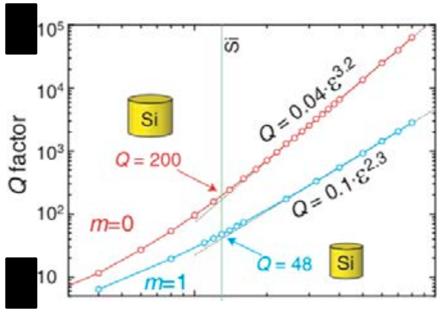
Y Plotnik et al. PRL 107, 183901 (2011)



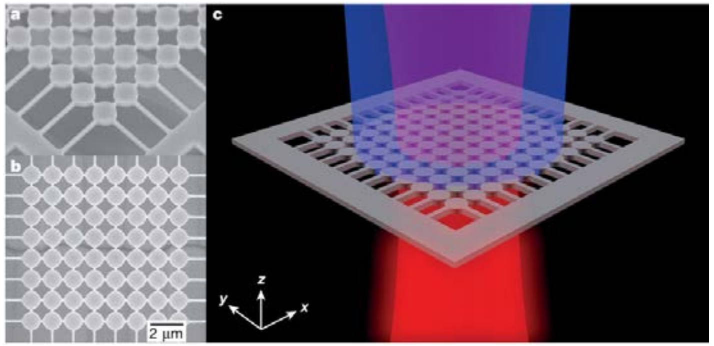
CW Hsu et al. Nature 499, 188 (2013)



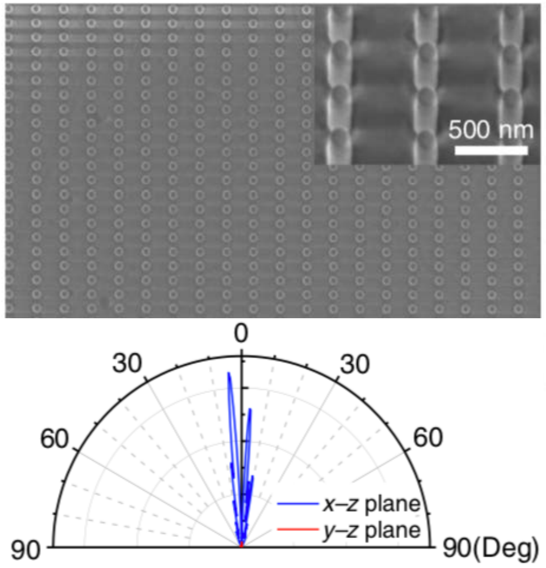
F Monticone et al. PRL 112, 213903 (2014)



MV Rybin et al. PRL 119, 243901 (2017)



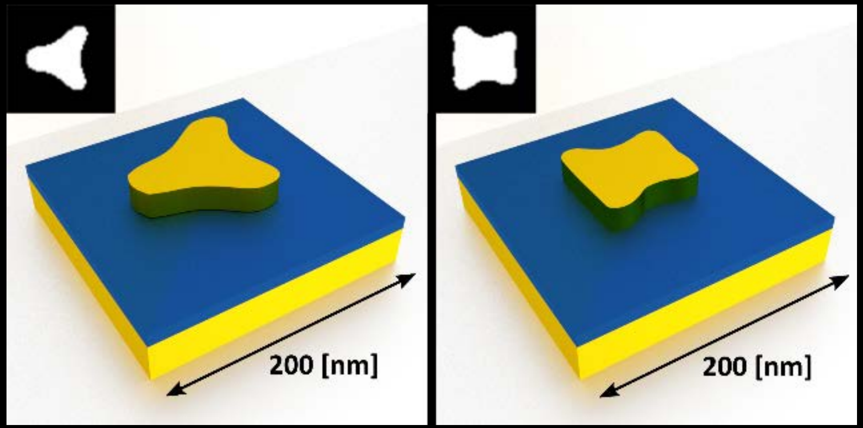
A Kodigala et al. Nature 541, 196 (2017)



ST Ha et al. Nature Nano 13, 1042 (2018)

PHOTONIC DESIGN

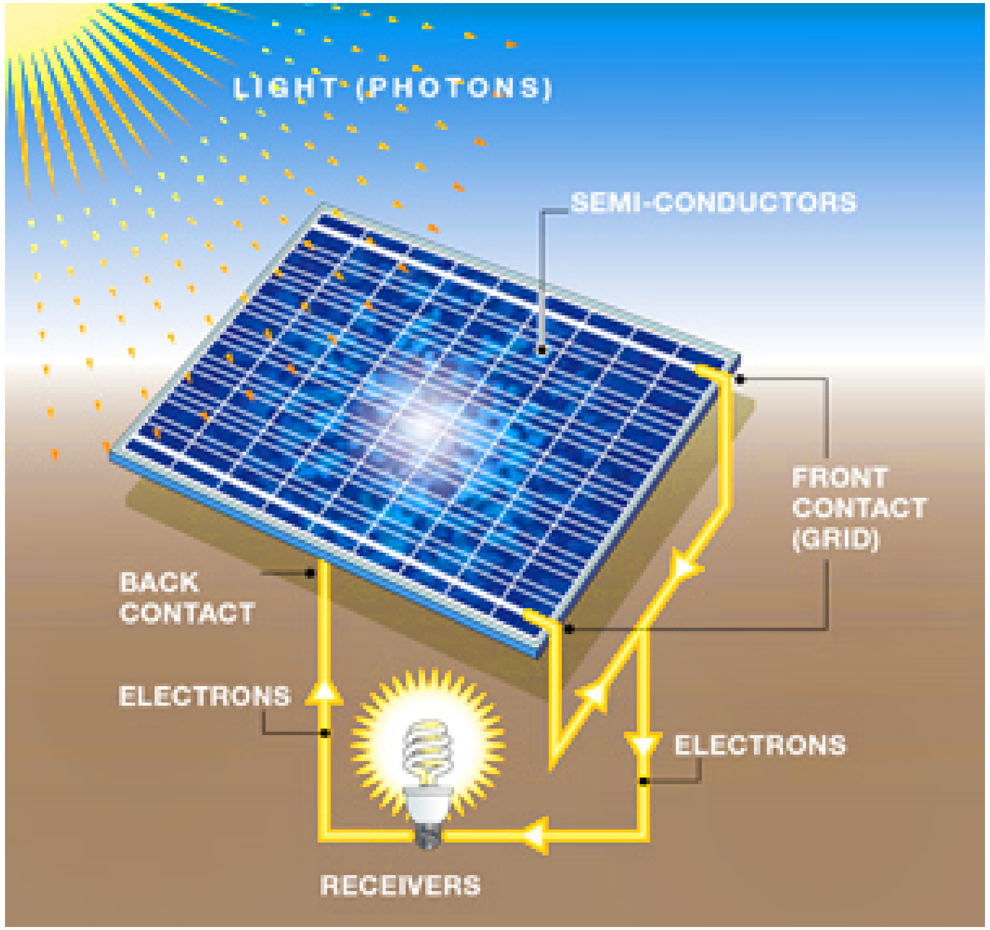
DESIGN



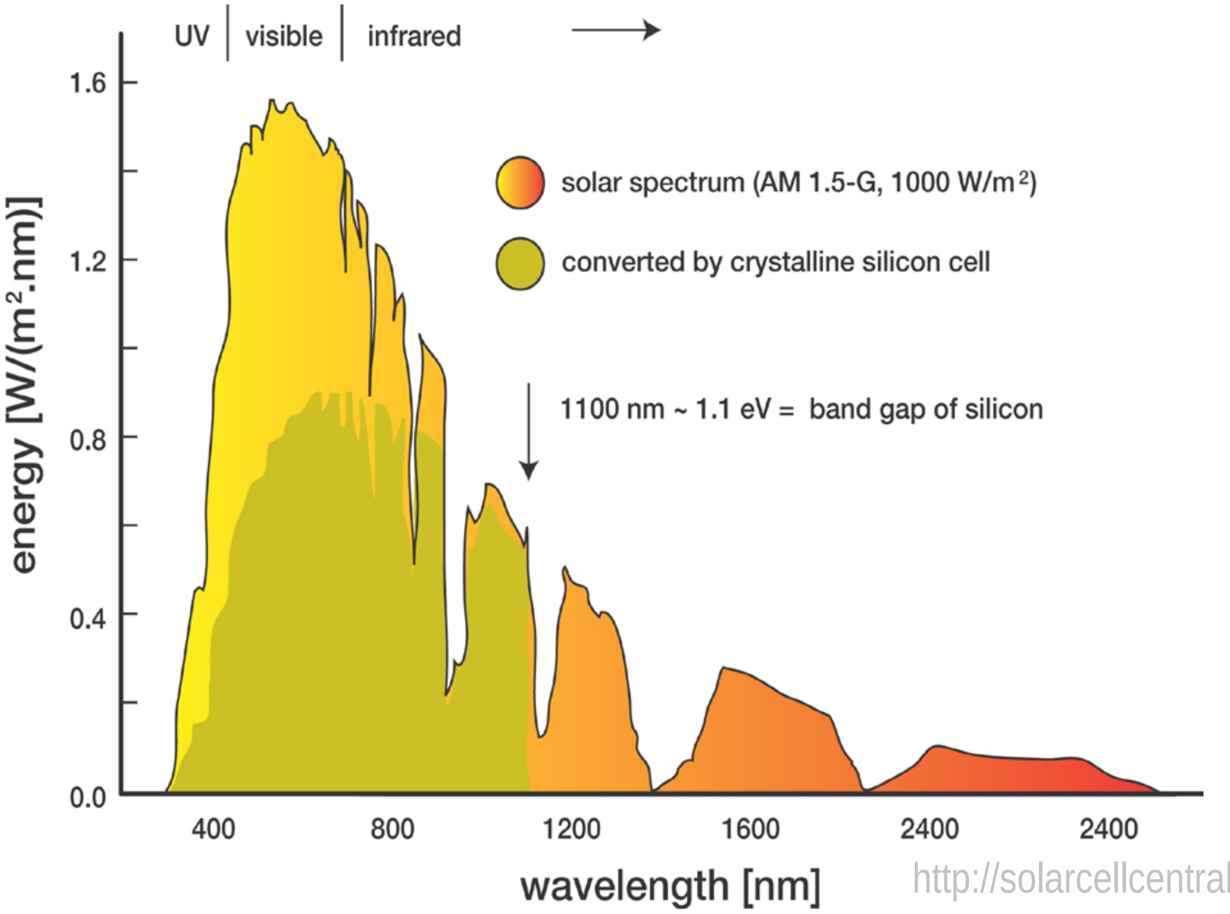
TOPOLOGY OPTIMIZATION

PHOTOVOLTAICS (PV)

Single Junction Photovoltaic Cell:



CSI Sun

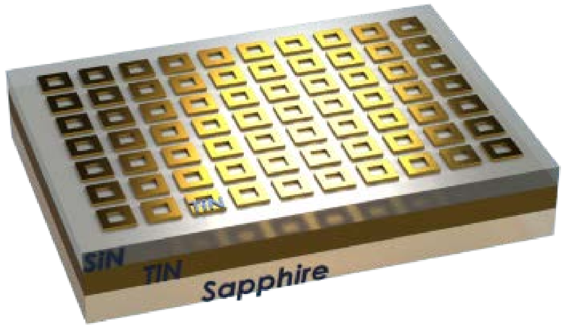


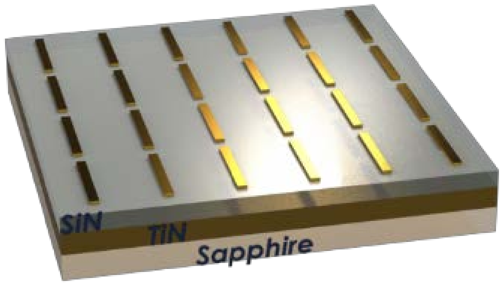
http://solarcellcentral.com

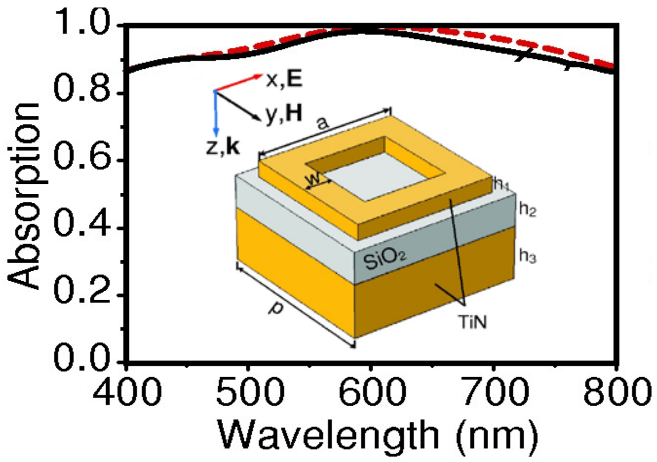
Spectrum Losses

- Lower energy photons: LOST 19%
- Higher energy photons: partly LOST 33%

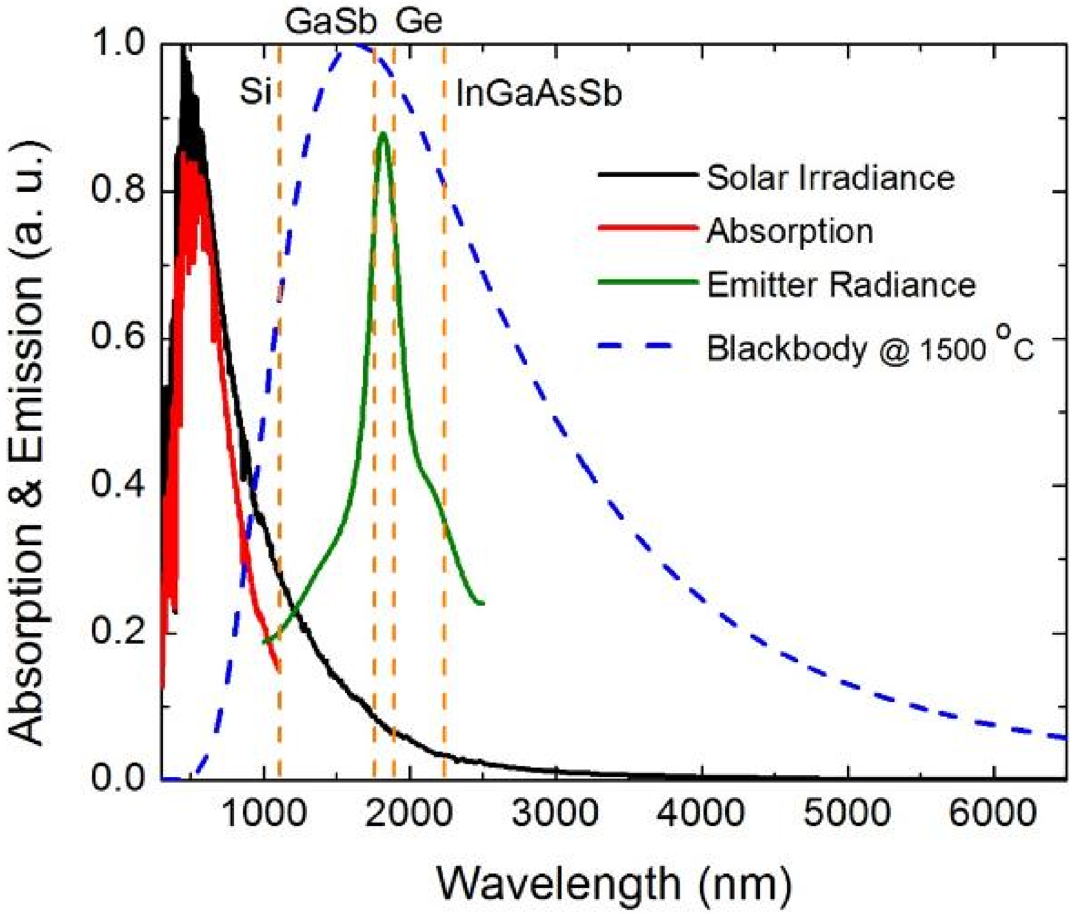
REFRACTORY BROADBAND ABSORBER

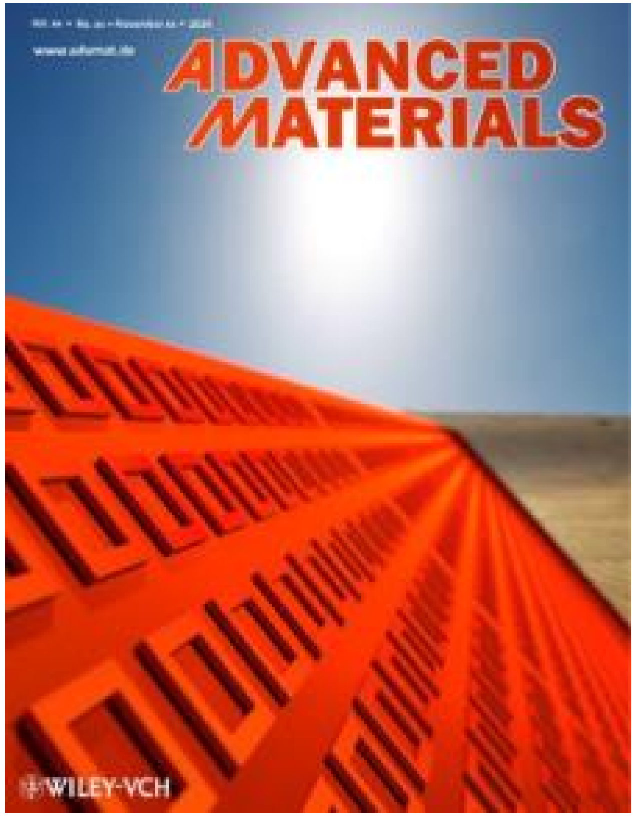






HIGH-T STABLE METASURFACE





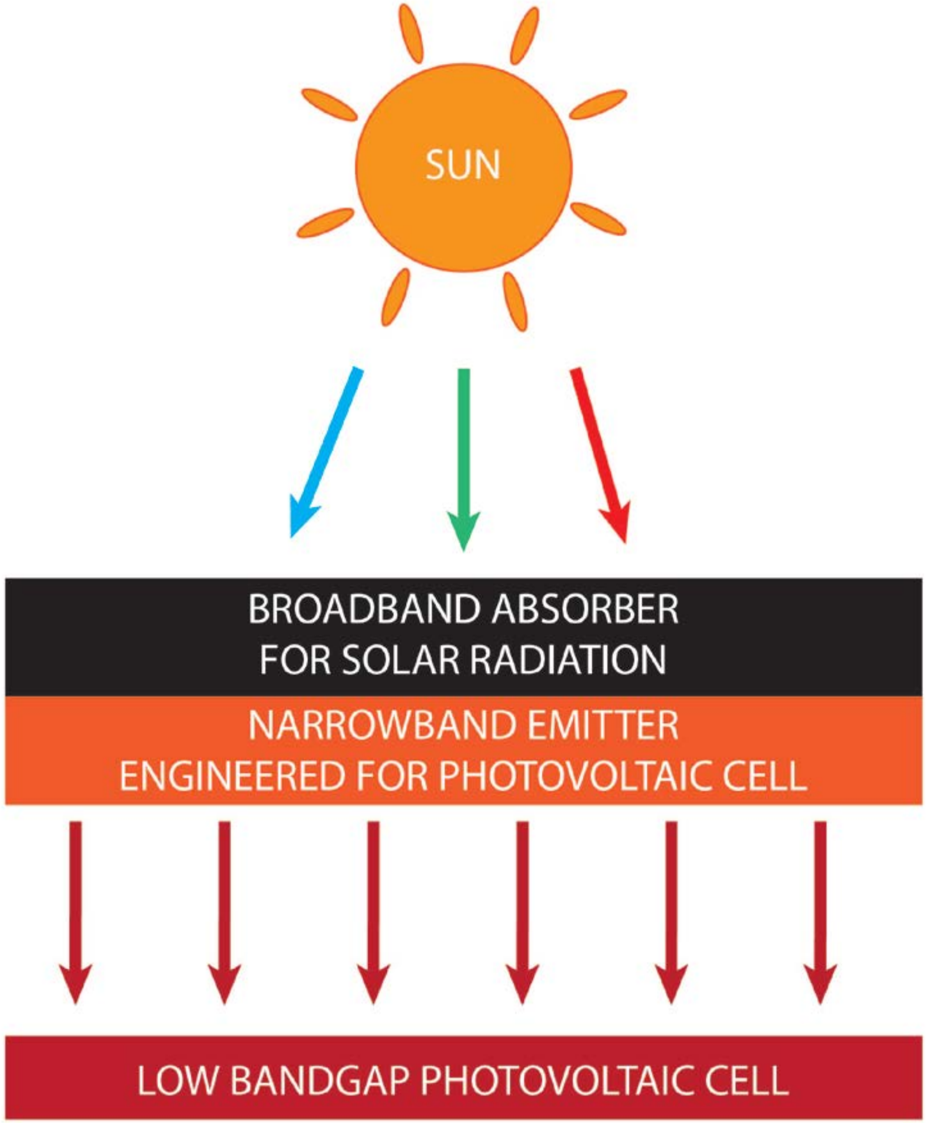
W. Li et al., Adv. Mater. (2014)

SOLAR/THERMOPHOTOVOLTAICS (S/TPV)

SOLAR/TPV

- BROAD light ABSORPTION
- SELECTIVE “in-band” EMISSION
- “Human-made sun”

85%



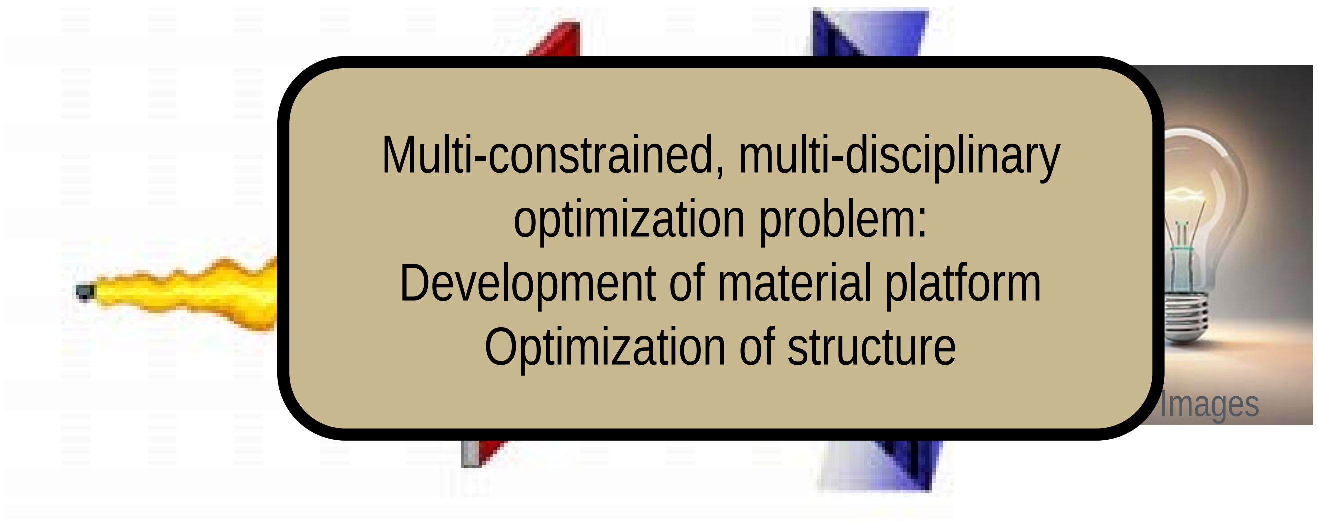
High operation temperatures:
Above 1000^{o}C
CERAMICS IS NEEDED!

A. Lenert et al., Nat. Nano. 9, 126 (2014)
D. M. Bierman et al., Nat. Energy 1, 16068 (2016)

S/TPV CONCEPT: METASURFACE

Broad absorption of sunlight/Heat - Selective "in-band" emission - Hybrid operation - "Human-made sun"

EMITTER TPV CELL

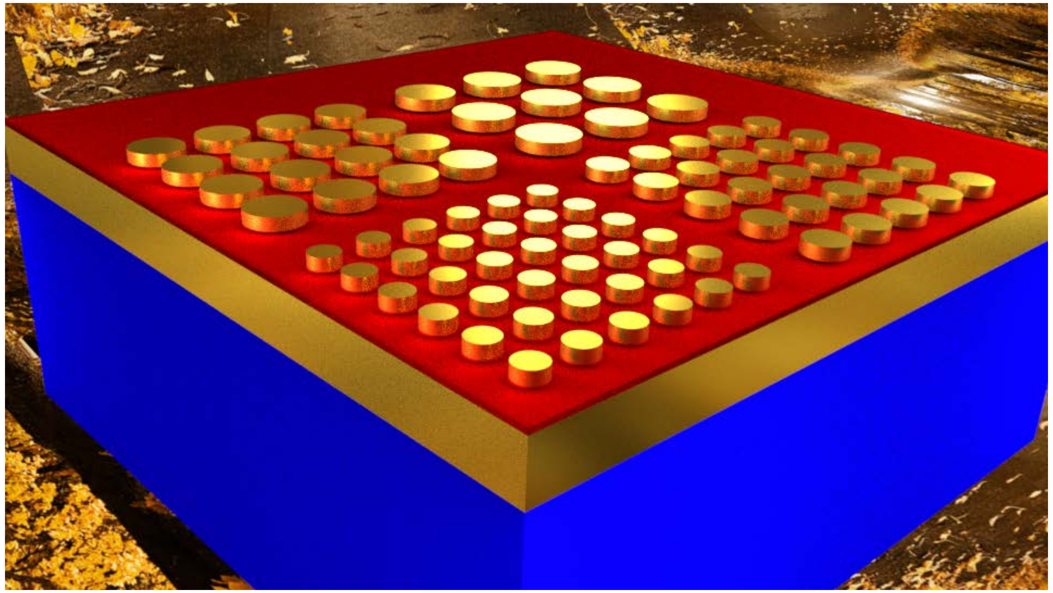


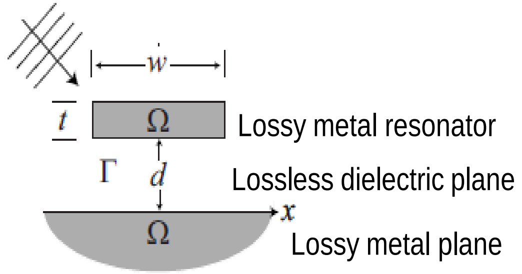
Multi-constrained, multi-disciplinary optimization problem:
Development of material platform
Optimization of structure

SUN/HEAT → RADIATION → ELECTRICITY

THERMO- PHOTO- VOLTAICS

High-T Stable METASURFACE

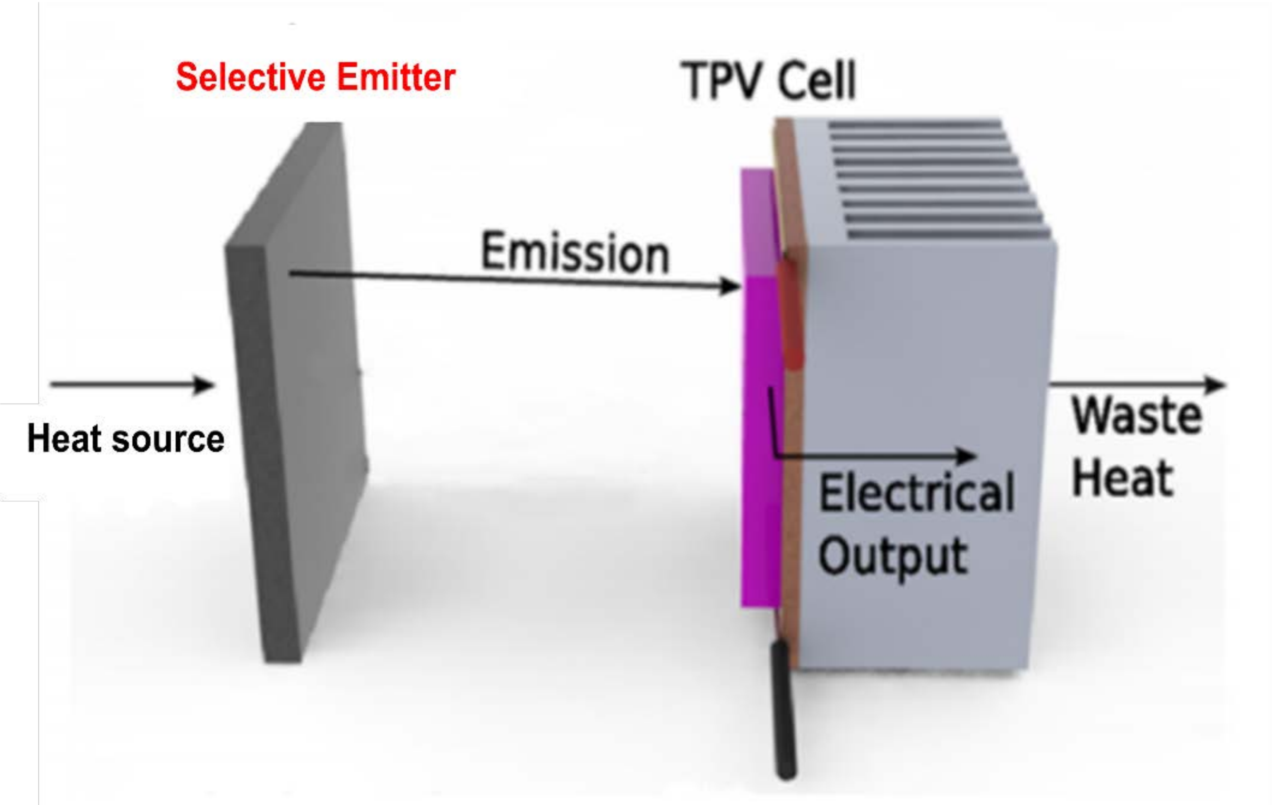




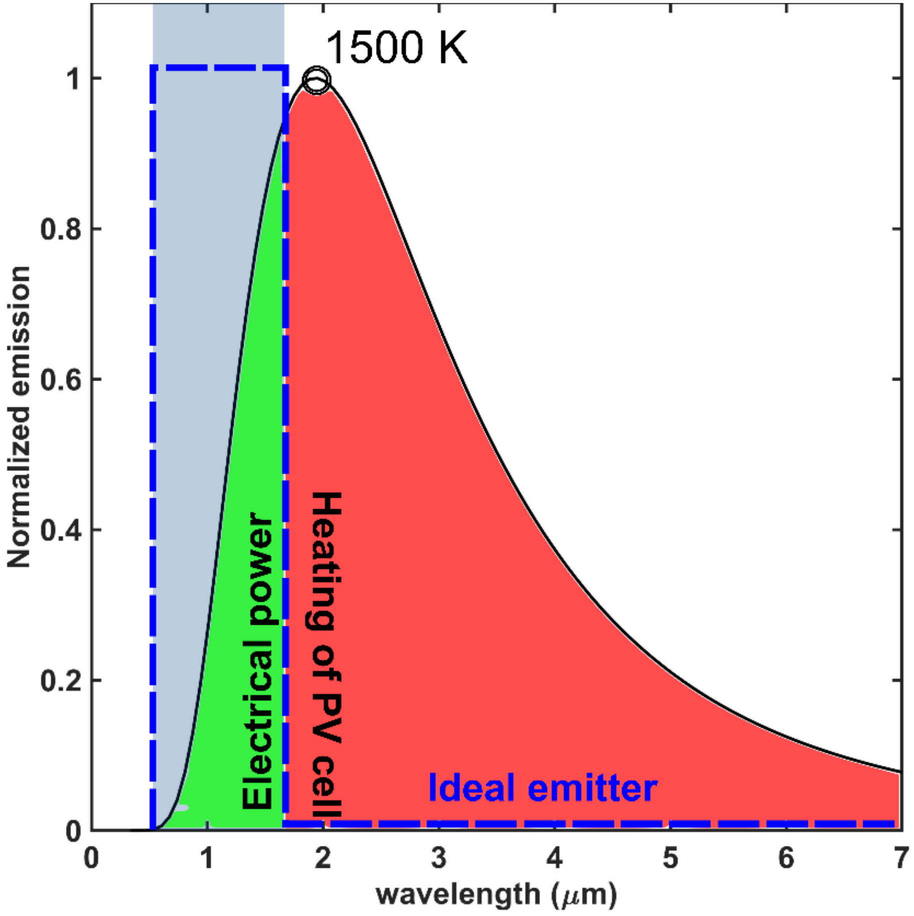
Gap surface plasmon resonator

Gap plasmon metasurface absorbers: S. Bozhevolnyi, H. Atwater, D.P. Tsai,, K. Aydin, W. Padilla and other

TPV CHALLENGES



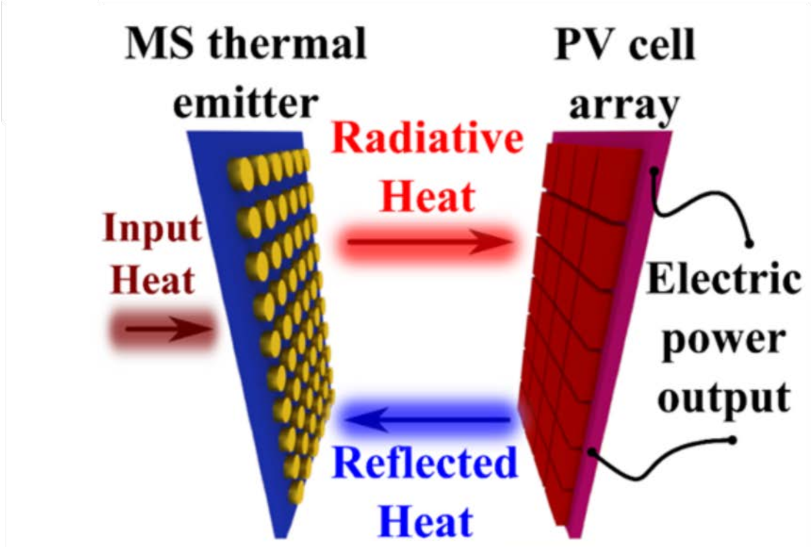
Schematics from Y. Yeng et.al., Opt. Exp. V. 21, (2013)



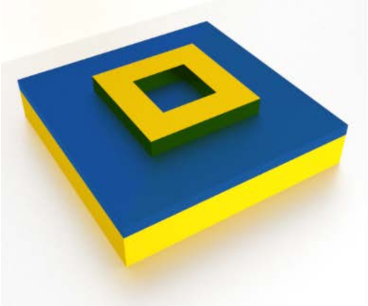
Main challenges of TPV system realization:

- High efficiency thermal emitters
- High temperature stable, tailorable material platform

DESIGN OF TPV EMITTER



Metasurface based emitter with trivial shapes



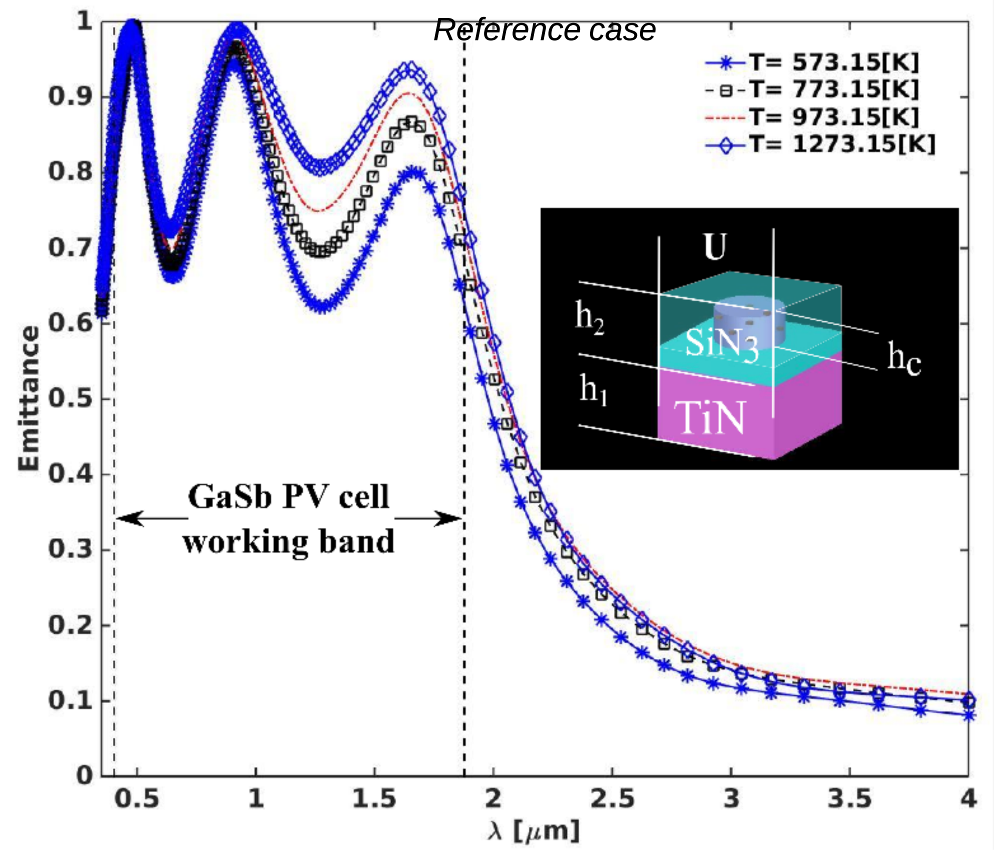
Photonic crystal based emitters

Wei Li et al., *Adv. Mater.*, 26, **2014**

Andrej Lenart et al., *Nat. Nano.*, 9, **2014**

Optimized cylindrical structure

Particle Swarm Optimization (PSO)



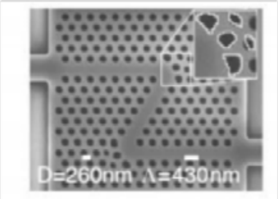
Maximizing the emittance/absorption in band, while suppressing out-of-band emittance

How to achieve more efficient emitter design with topology optimization technique?

TOPOLOGY OPTIMIZATION IN PHOTONICS

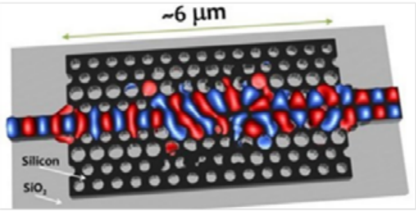
Photonic crystals	Waveguide Components	Metasurface structures	Topological Photonics

Photonic crystals



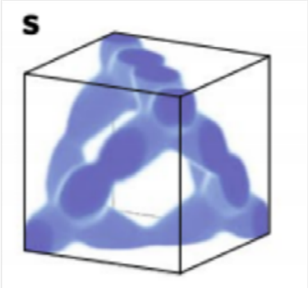
Topologically optimized Z waveguide band

P. Borel et al., Opt. Exp., 2004



Mode converter

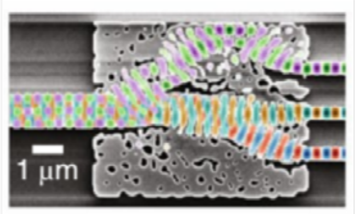
L. Fardsen et al., Opt. Exp., 2014



Band-structure optimized 3D photonic crystal

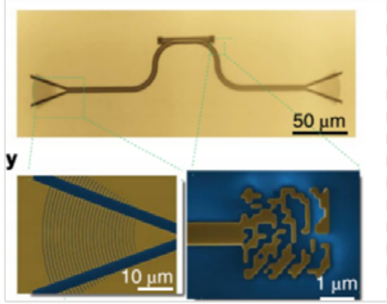
H. Men et al., Opt. Exp., 2014

Waveguide Components



Two port demultiplexer and power splitter

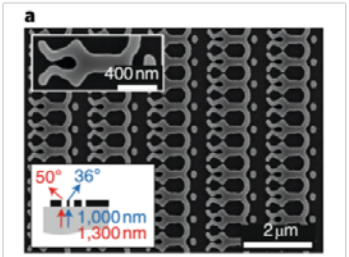
A.Y. Piggot et al., Nat. Photon, 2015



Compact on-chip Fabry-Perot resonator

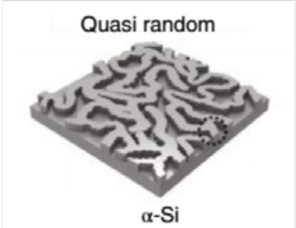
D. Sell et al., Nano Lett., 2017

Metasurface structures



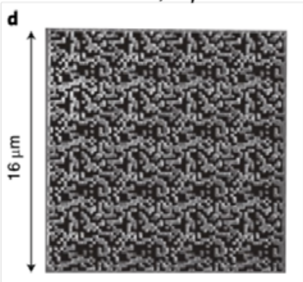
Diffrective metagrating with ~95% efficiency

D. Sell et al., Nano Lett., 2017



Enhanced light trapping

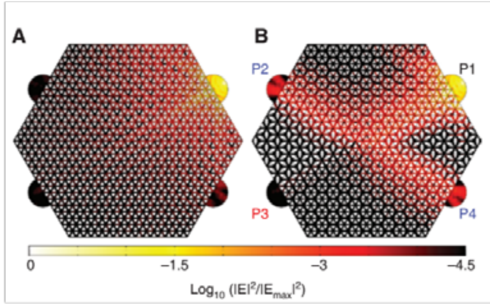
B. Shen et al., Optica 2014

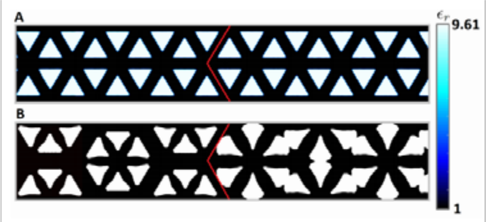


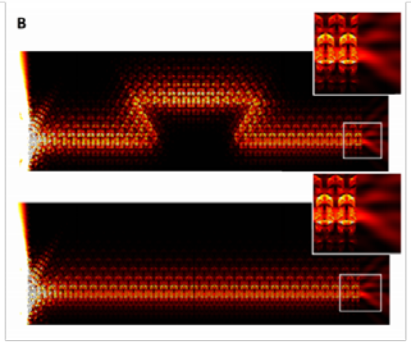
Polarizer with ~90% efficiency

Lee, W.-K. et al. Proc. Natl Acad. Sci. 2017

Topological Photonics





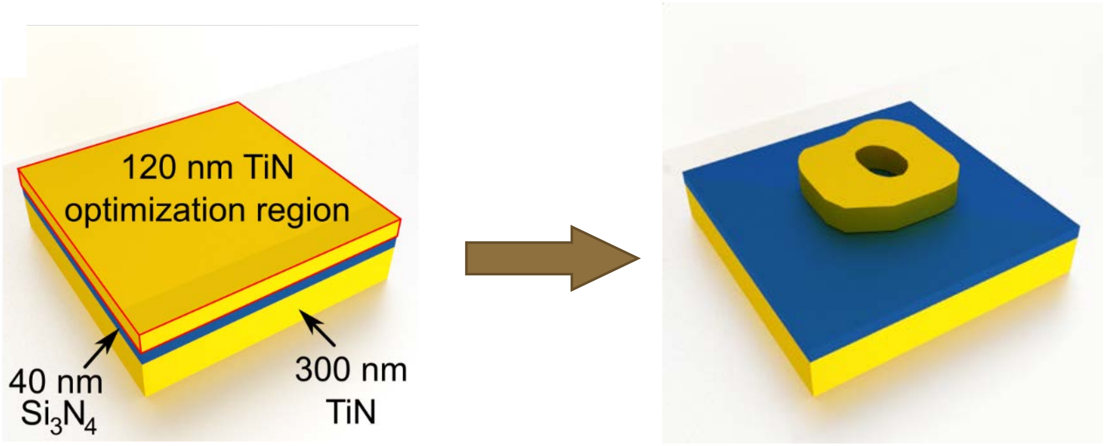


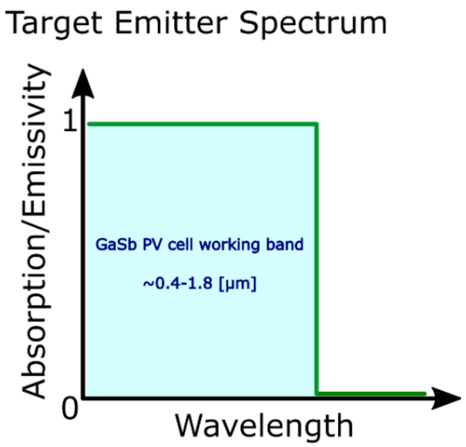
Topologically optimized photonic topological insulator

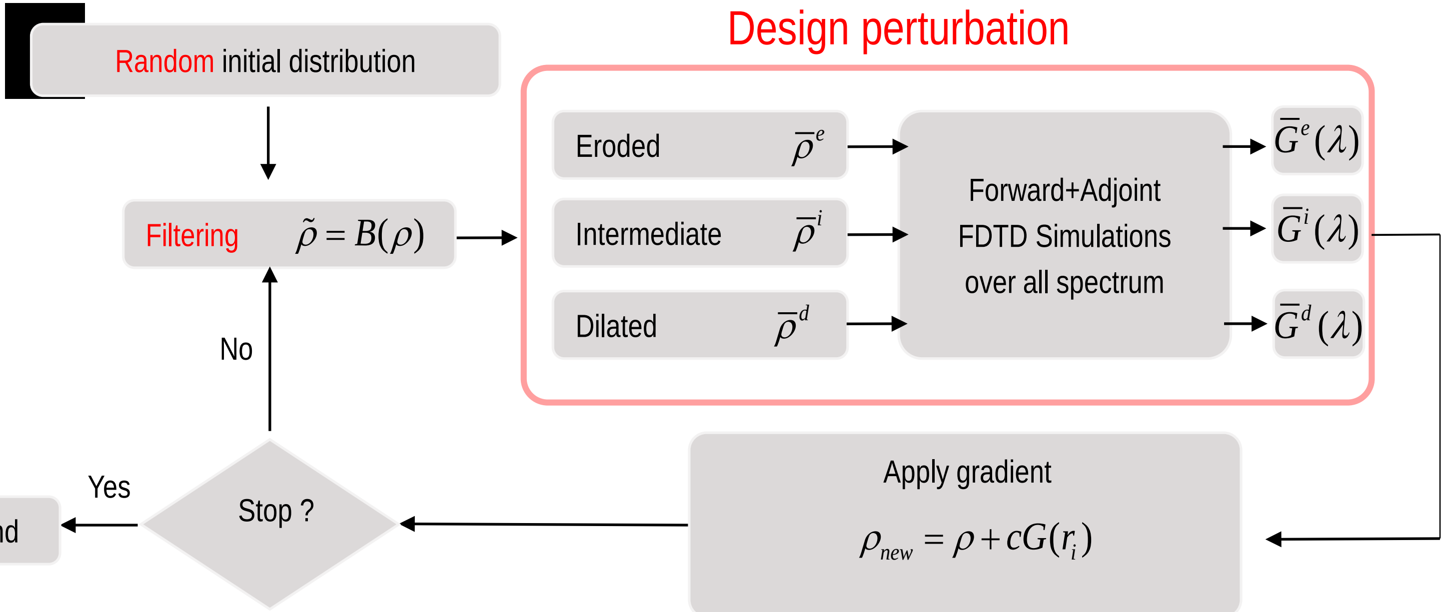
R. Christiansen et al., Nanophotonics 2019

E. Yablonovitch, O. Sigmund, S. Fan, J. Vučković, S. Johnson, J. Fan, and other

TOPOLOGY OPTIMIZATION

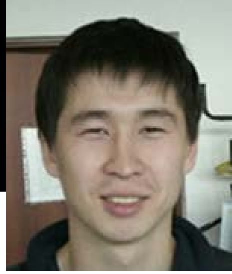






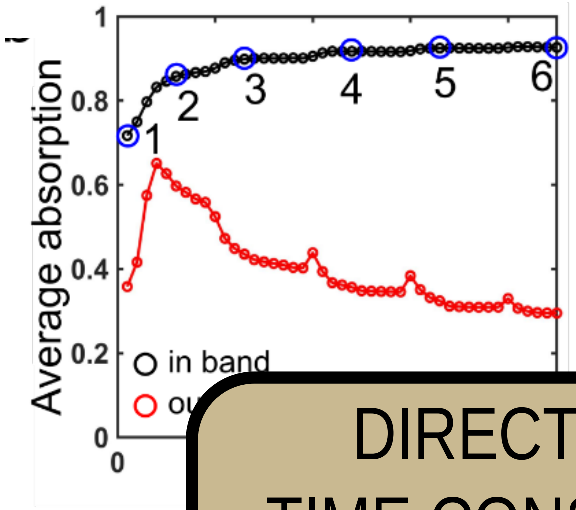
F. Wang et.al. JOSA B 2011; D.Sell et. al., Nano. Lett. 2017

TO for TiN THERMAL EMITTERS

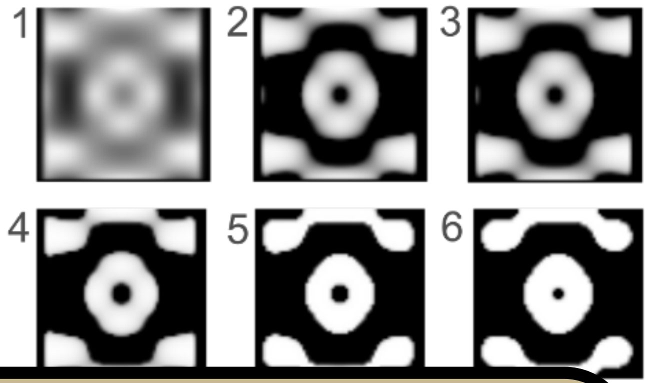


Z. Kudyshev

weighted average of in-band absorption and out-of-band reflectivity

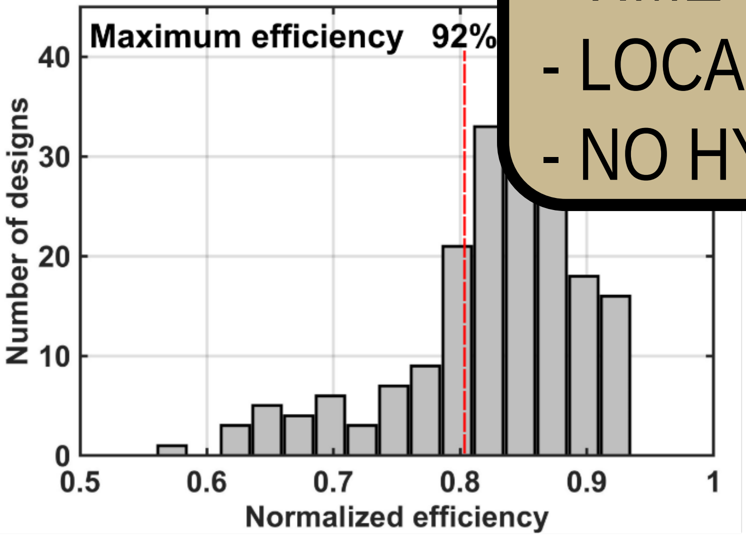


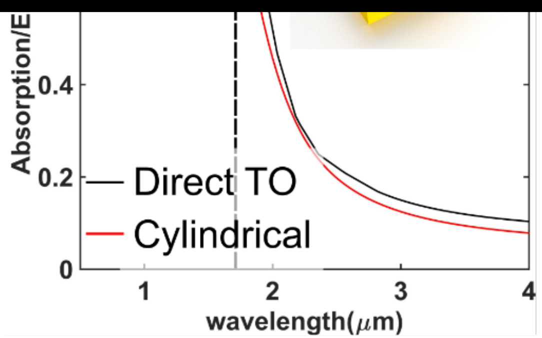
continuous material distribution

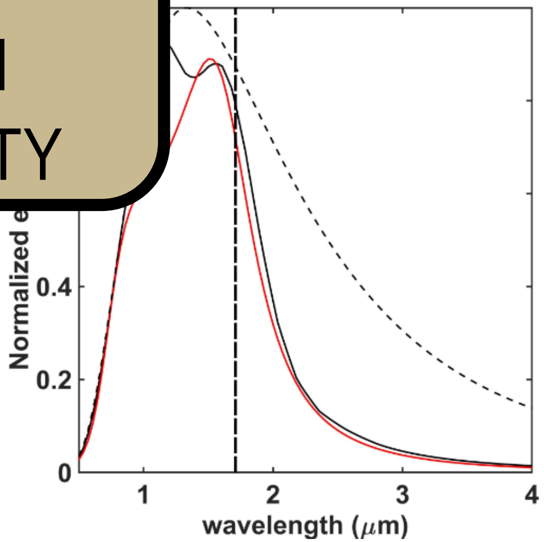


binary air/TiN mixer

DIRECT OPTIMIZATION:
- TIME CONSUMING
- LOCAL MAXIMUM SEARCH
- NO HYPERDIMENSIONALITY







PHOTONIC DESIGN

DESIGN

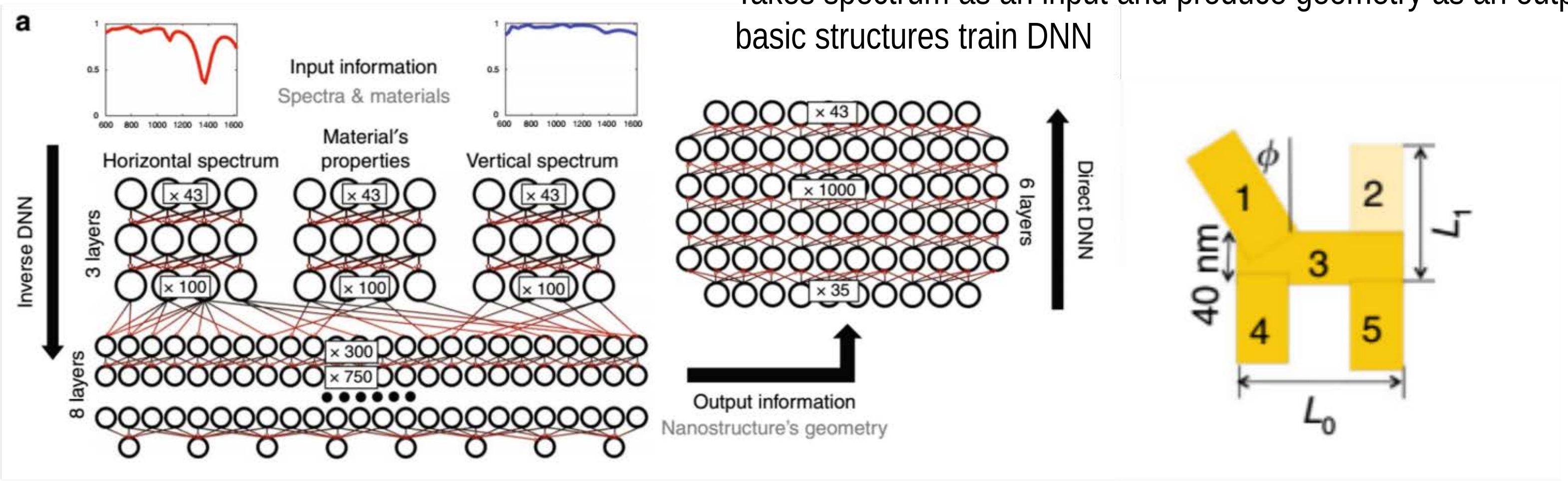
DEEP/MACHINE LEARNING/AI

MACHINE LEARNING IN PHOTONICS

Inverse problem solution requires substantial computational power and time

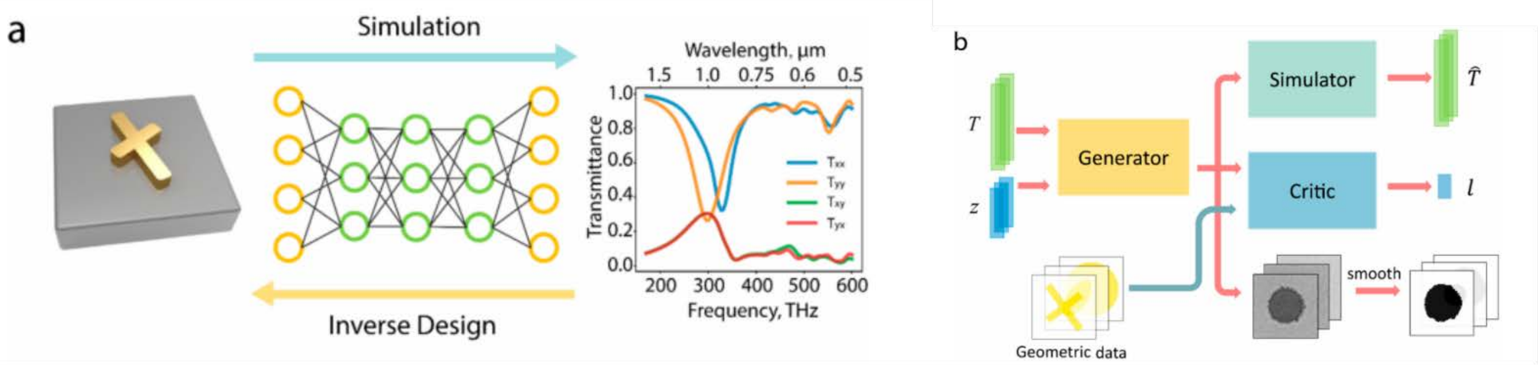
Deep neural network based

Takes spectrum as an input and produce geometry as an output - basic structures train DNN



I. Malkiel et al., Light Sci. Appl. 2018

Generative networks for design optimization

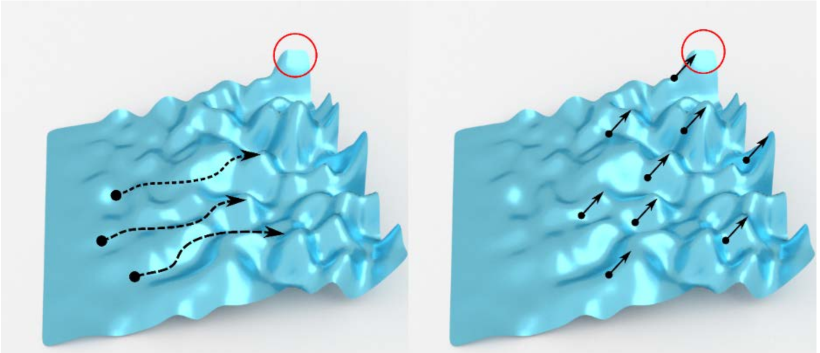


Trivial shapes train GAN - produces patterns for the desired spectrum

Z. Liu, Nano Lett. 2018

J. Vučković S. Johnson
J. Fan
W. Cai
Y. Liu
N. Zheludev
and many other

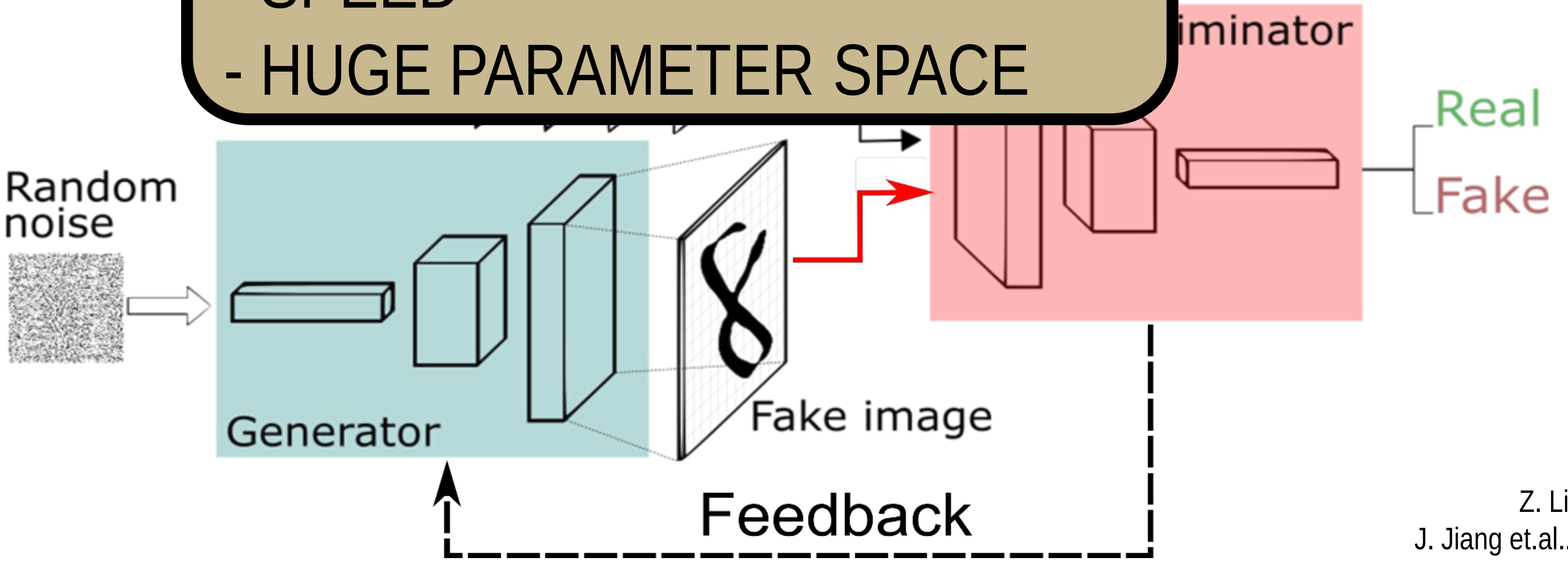
GENERATIVE ADVERSARIAL NETWORK (GAN)



ML:

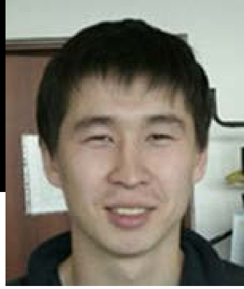
- GLOBAL MAXIMUM
- SPEED
- HUGE PARAMETER SPACE

training of GAN

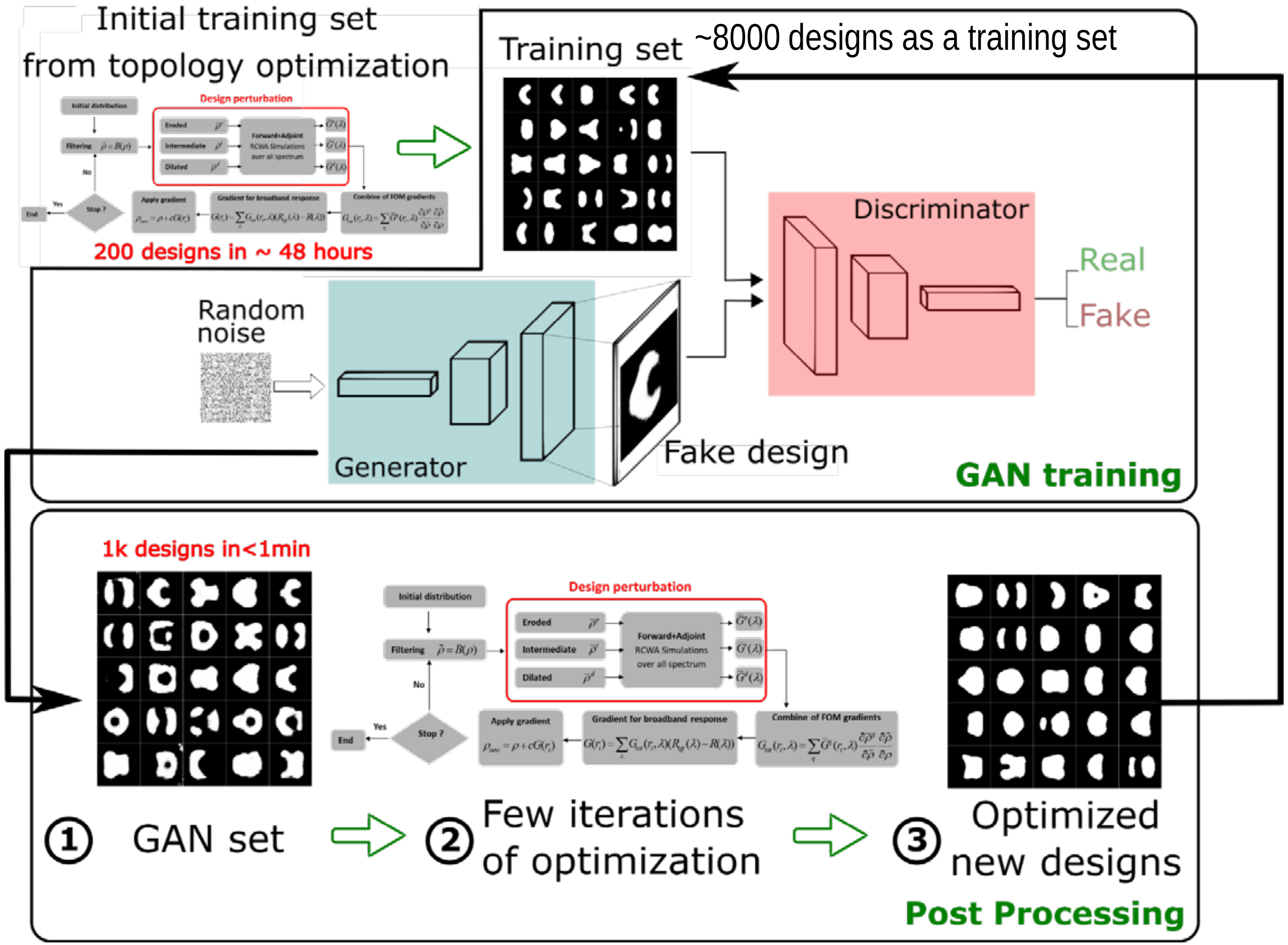


Z. Liu, et.al., Nano Lett. (2018)
J. Jiang et.al.. arXiv: 1811.12436 (2018)

GANs FOR DESIGN PRODUCTION


Dr. Z. Kudyshev

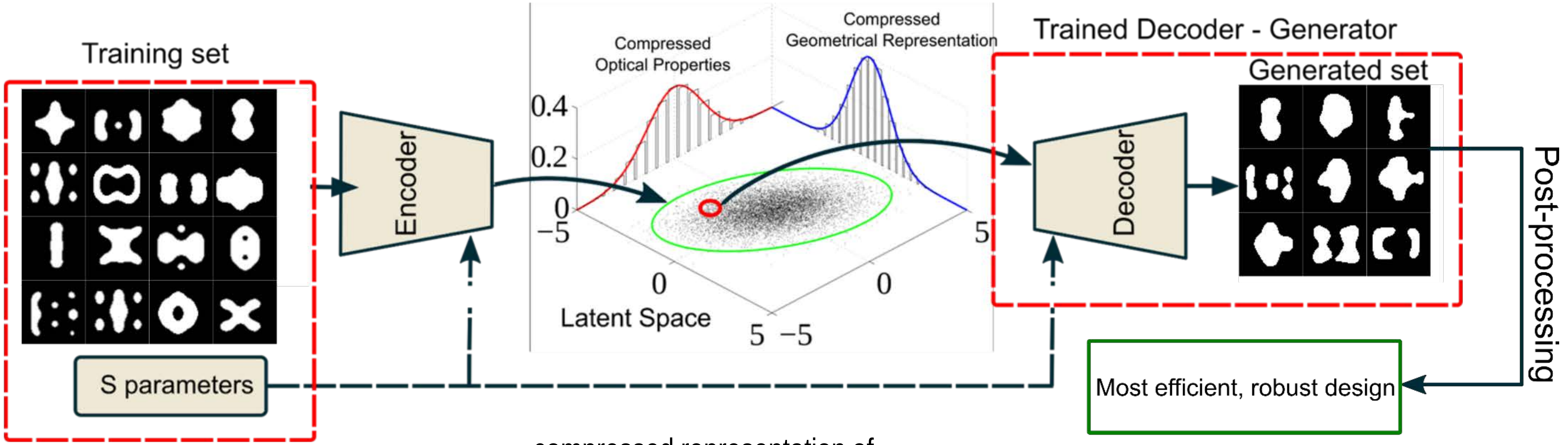
Generative Adversarial Networks



Z. Liu, et.al., Nano Lett. (2018)
J. Jiang et.al.. arXiv: 1811.12436 (2018)

See also work by Wenshan Cai

VARIATIONAL AUTOENCODER (VAE)



Topologically optimized designs
200 designs ~48 hours

compressed representation of geometrical and optical features

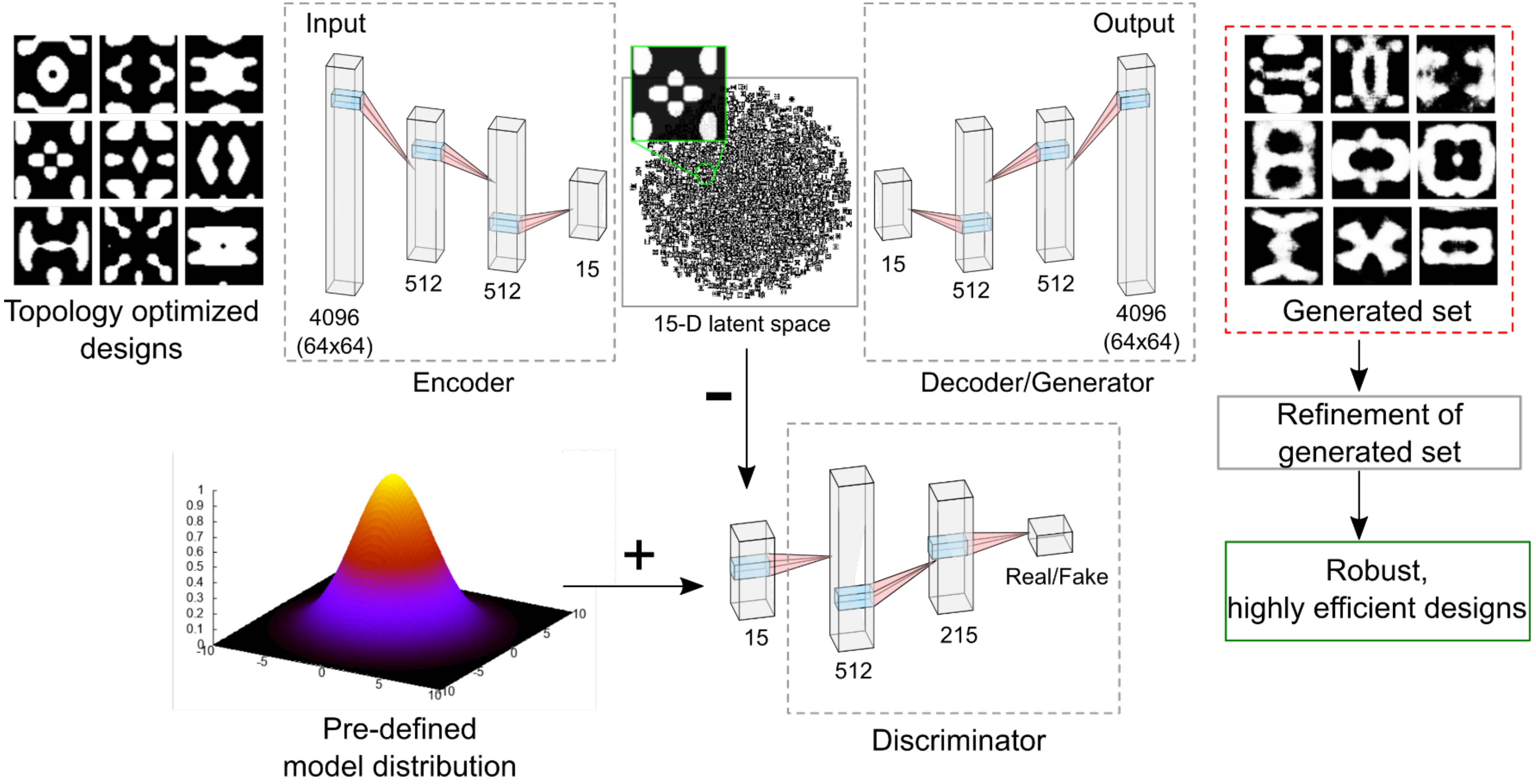
VAE generated design set
1000 designs <1 min

E: determine main feature of the training patterns and compress them into compact representation (latent space)
D: read out the state from compact representation and reconstruct it

Z. A. Kudyshev, A. V. Kildishev, V. M. Shalaev, and A. Boltasseva, Applied Physics Reviews 7(2) 021407 (2020)

AAE BASED DESIGN EFFICIENCY

Adversarial autoencoder (AAE)

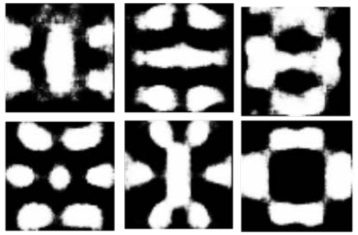


AAE performs adversarial learning (like in GANs) by applying discriminator to force latent space to pre-defined model distribution – dense latent space - hyperdimensional; more generated designs

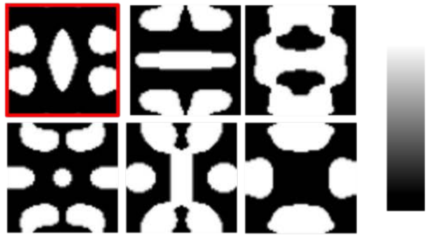
Z. A. Kudyshev, A. V. Kildishev, V. M. Shalaev, and A. Boltasseva, Applied Physics Reviews 7(2) 021407 (2020)

AAE BASED DESIGN EFFICIENCY

Generated by AAE



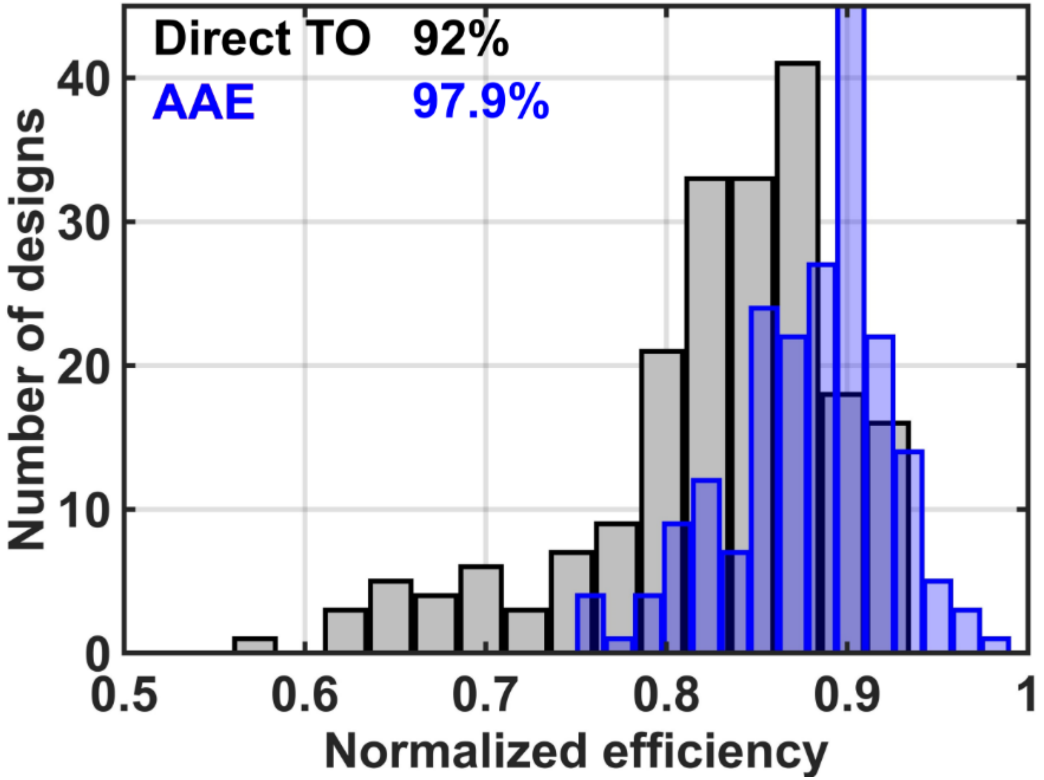
After refinement

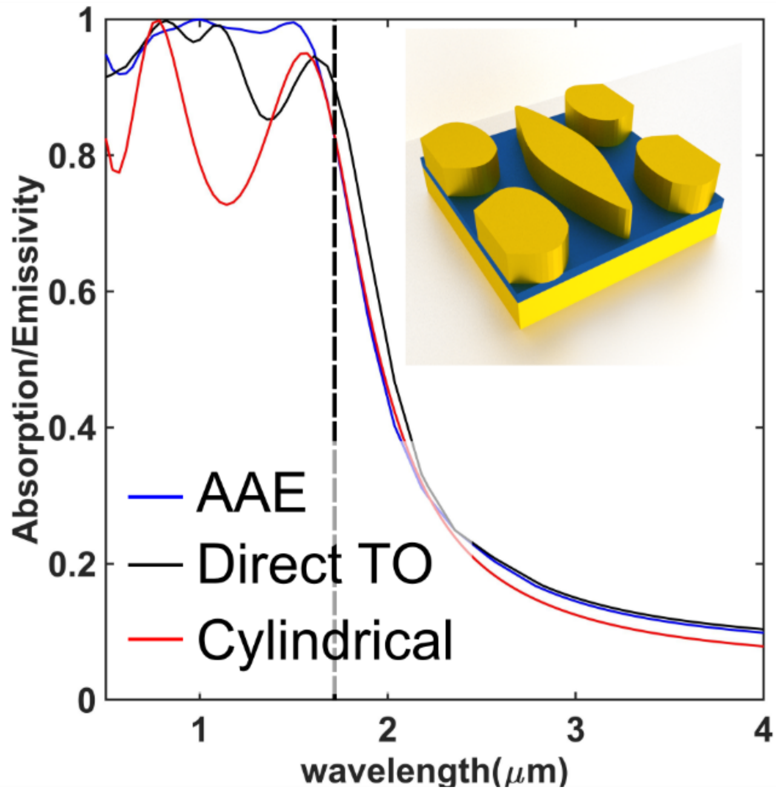


TiN

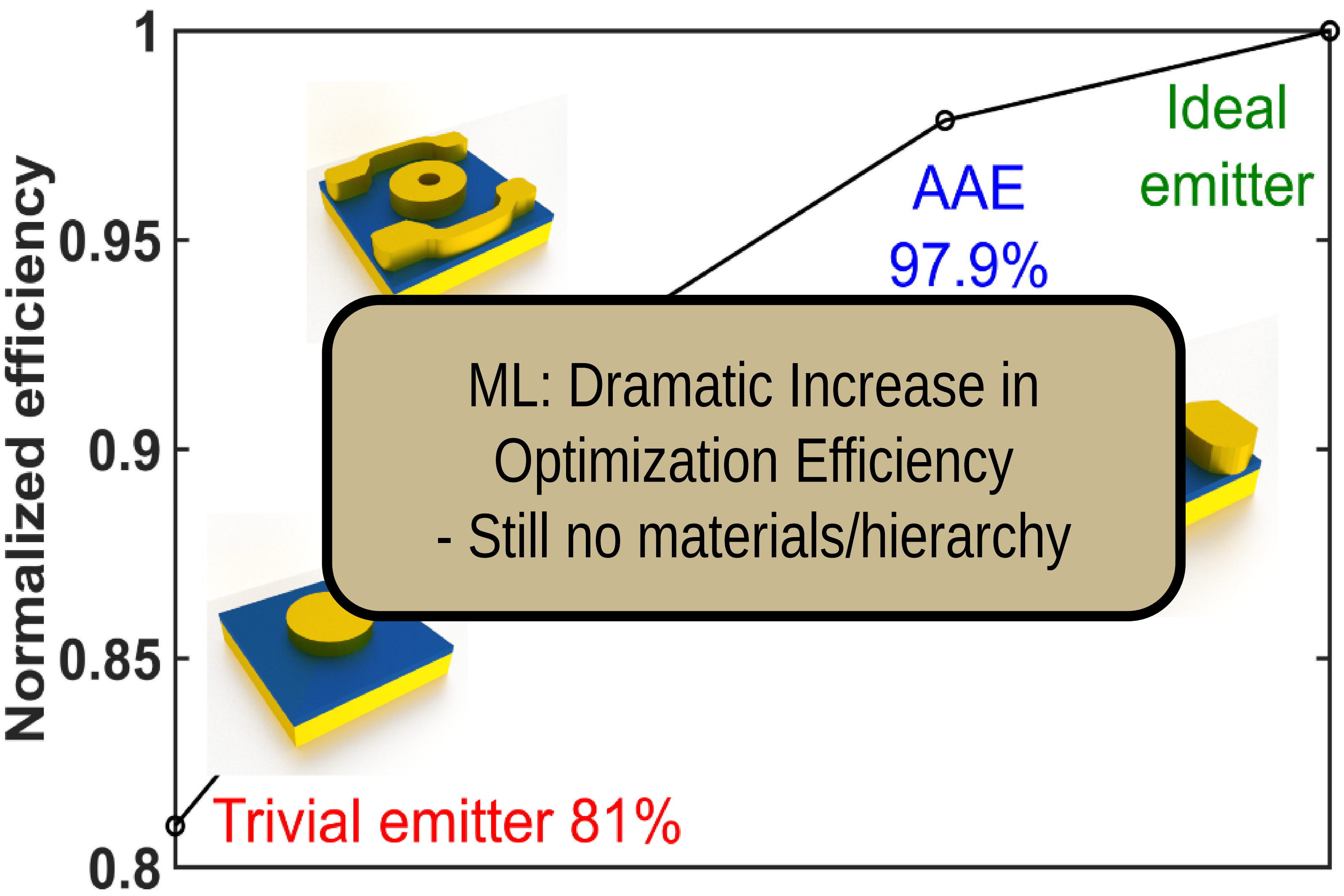
stability of the designs
Remove sub 30 nm features

Air





DESIGN EFFICIENCY



ML: Dramatic Increase in Optimization Efficiency
- Still no materials/hierarchy

Z. A. Kudyshev, A. V. Kildishev, V. M. Shalaev, A. Boltasseva, arXiv:1910.12741 (2019)

OPTICAL MATERIALS

MATERIALS

TAILORABLE/ADJUSTABLE

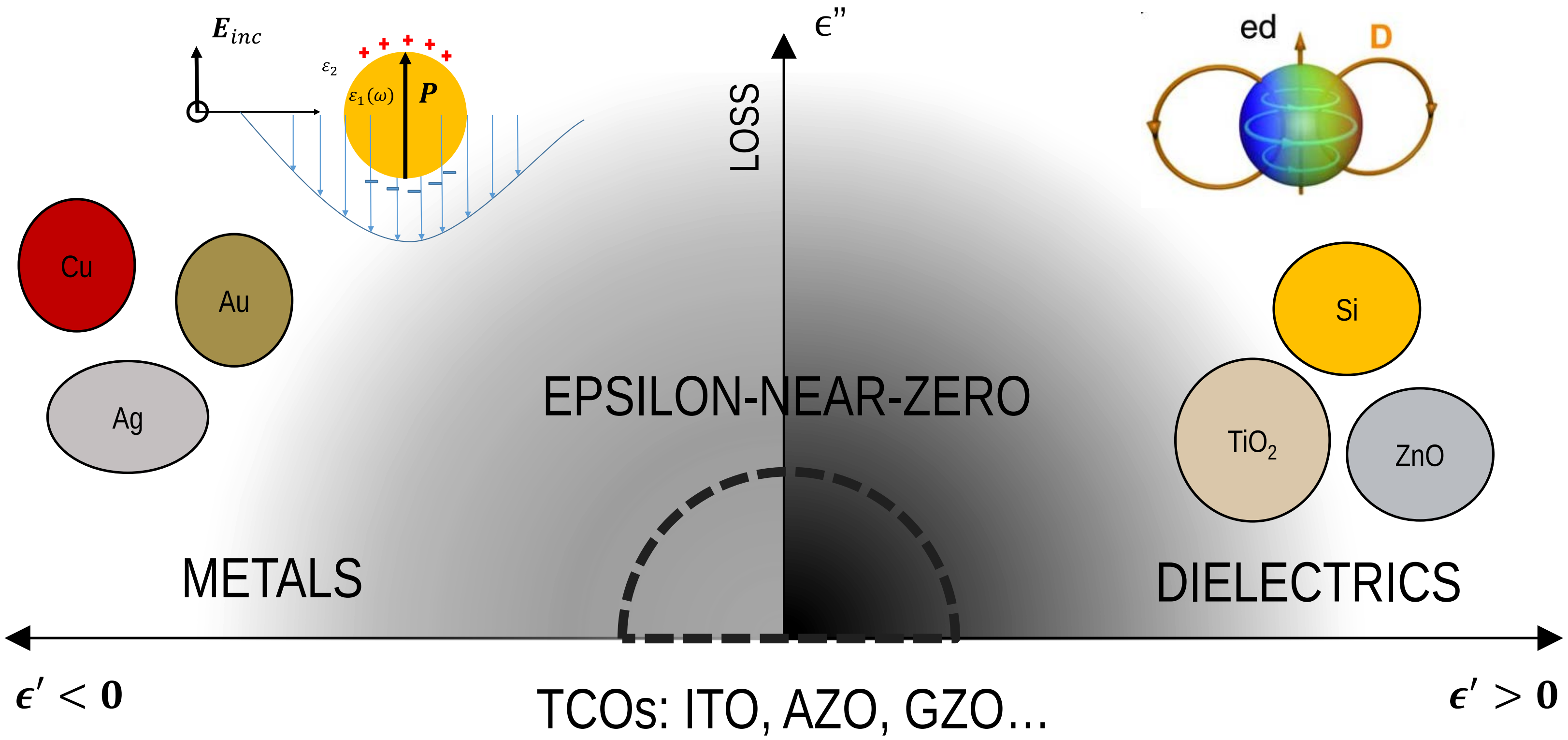
DYNAMICALLY TUNABLE

REFRACTIVE INDEX NEAR ZERO

REFRACTORY

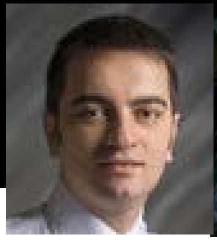
MATERIALS OPTICAL RESPONCE

$$\boldsymbol{D}(\omega) = (\epsilon' + i\epsilon'')\mathbf{E}(\omega)$$



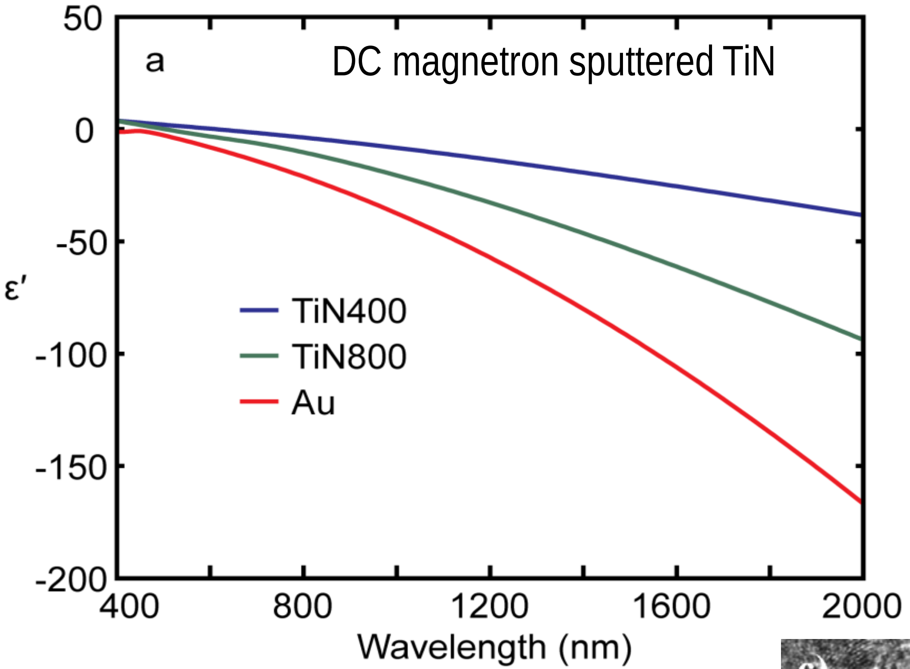
A. Kuznetsov, et al. Science 18, 354 (2016) || Nanophotonics 7 (6), 959-987 (2018)

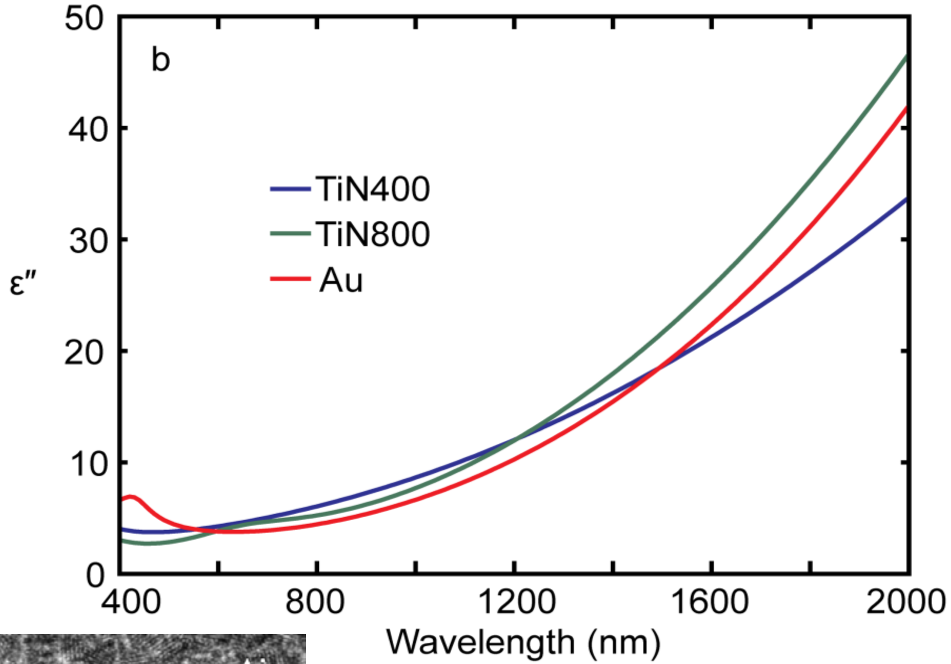
TAILORING OPTICAL RESPONSE



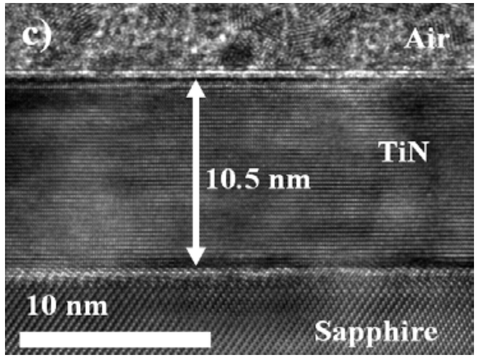
Dr. U. Guler D. Shah

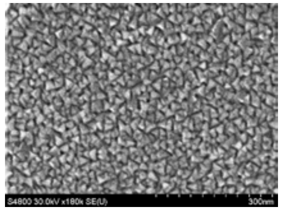
TIN: Plasmonic, Refractory, Tailorable





Ultra-thin/Smooth
Epitaxial growth





Crystalline TiN on c-Sapphire
(rms roughness 0.5 nm)

See also work by H. Atwater, L. Dal Negro, H. Giessen, J. Dionne, G. Naik, E. Hu, S. Ishii and other

G.V. Naik et al., OMEx 2, 478 (2012), U. Guler et al., Nano Letters 13, 6078 (2013)

TCO: ENZ MATERIAL

CONCEPT:

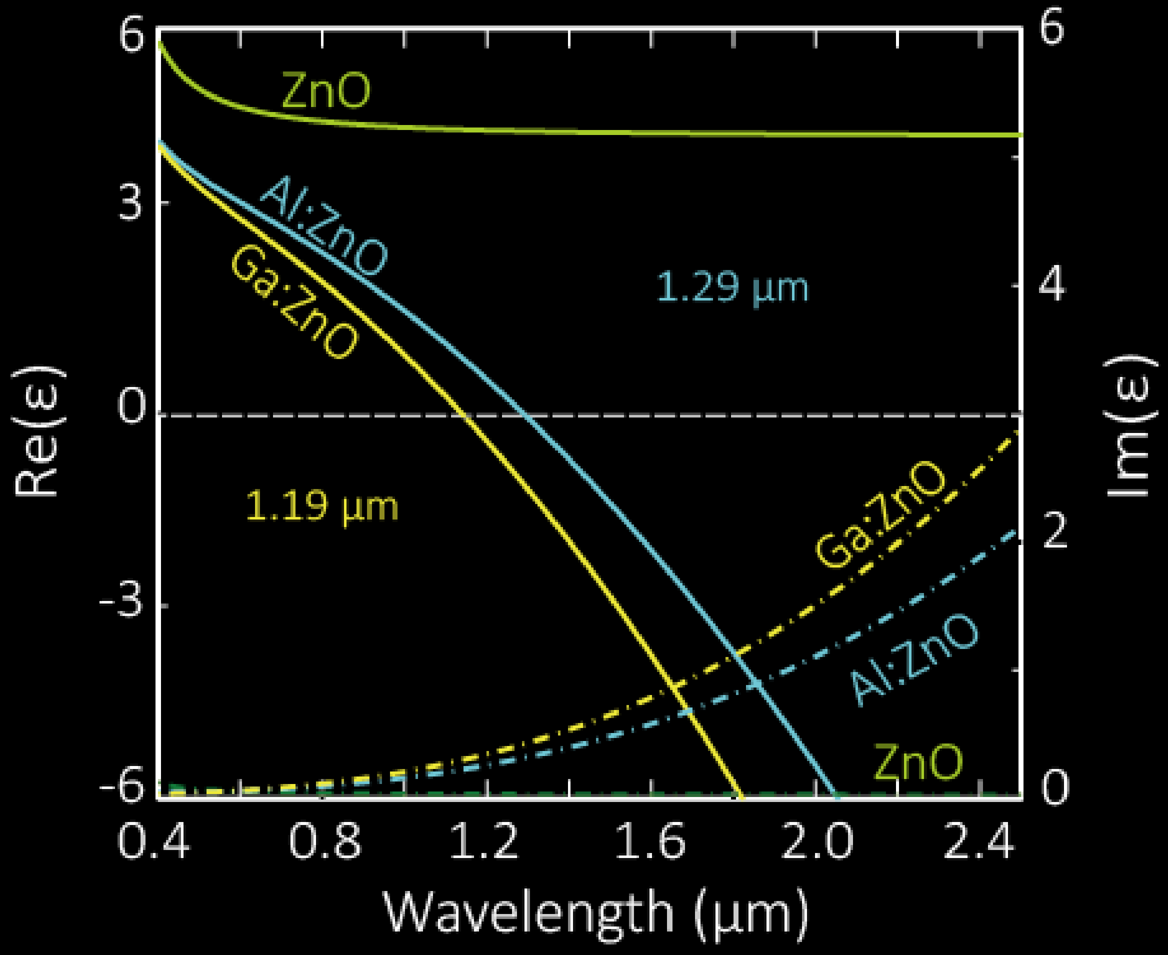
Light propagates with almost no phase advance! (a very small phase variation over a physically long distance!)

Region of space with

→ provides the possibility for

- Directive radiation or beaming
- Transmission enhancement
- Wavefront shaping
- Controlled spontaneous emission
- Enhanced nonlinearities
- Superradiance
- Singular optics: enhanced fields

N. Litchintser et al, OL (2008); Kinsey, et al Optica, (2020)]



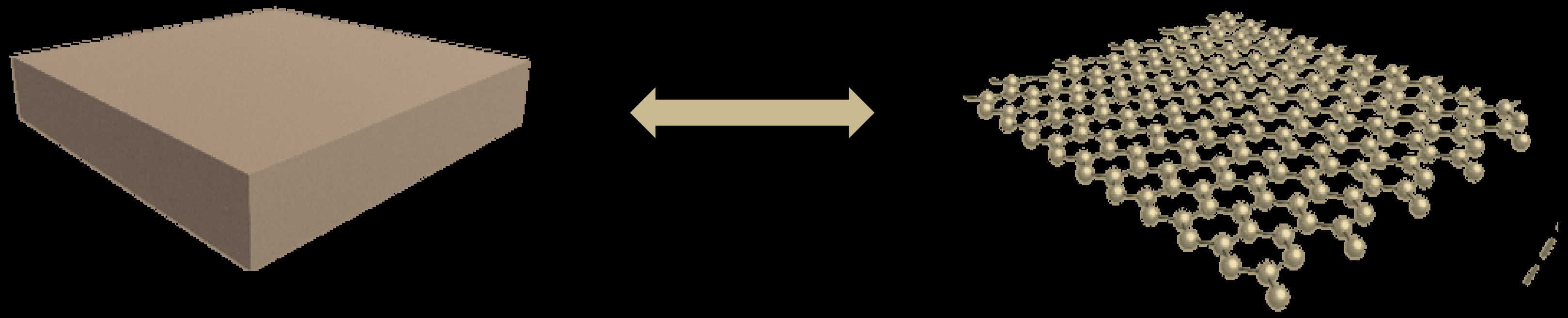
Impact of ENZ media upon the local antenna Resonance condition, Radiation behavior

A. Alu, Physical Review B 75, 155410, 2007

Work by N. Engheta, A. Alu, A. Zayats and O. Muskens

TRANSDIMENSIONAL MATERIALS

- Between 2D and 3D
- STRONG CONFINEMENT: novel phenomena, forbidden transitions
- New optics: Strong nonlinearities, Quantum effects
- Extraordinary TAILORABILITY and electrical/optical TUNABILITY/SWITCHING



New properties
New phenomena
New applications

FUNDAMENTAL SCIENCE
TUNABLE FLAT OPTICS
QUANTUM SCIENCE/TECH

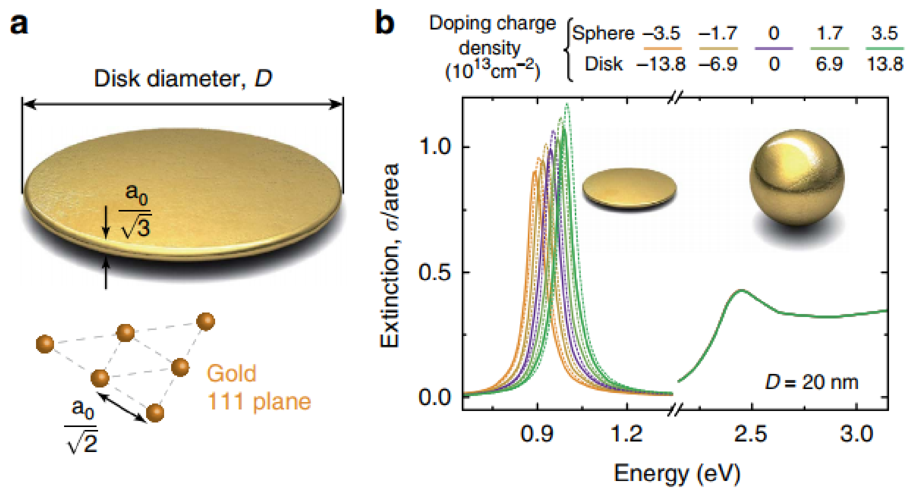
Au, Ag: Tunable plasmons in ultrathin metal films
F J. García de Abajo, ArXiv, ACS Nano 2019 J. Garcia de Abajo, Nat. Comm. (2014)

A. Boltasseva & V. M. Shalaev, ACS Photonics, Editorial, 2019

ULTRA-THIN PLASMONIC FILMS

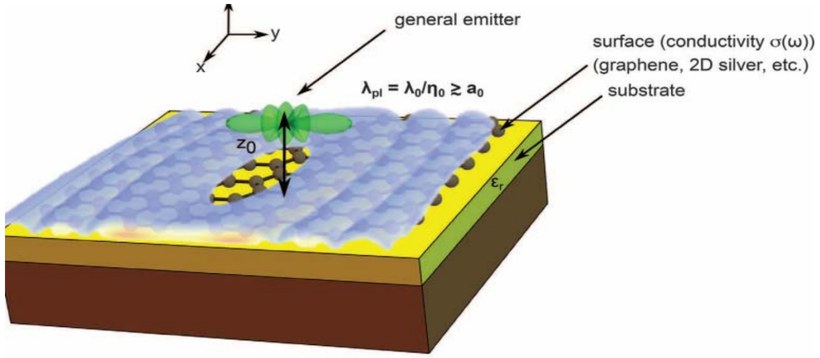
- Electrical (optical) control over the properties

J. Garcia de Abajo's group
Nature Communications, 2014



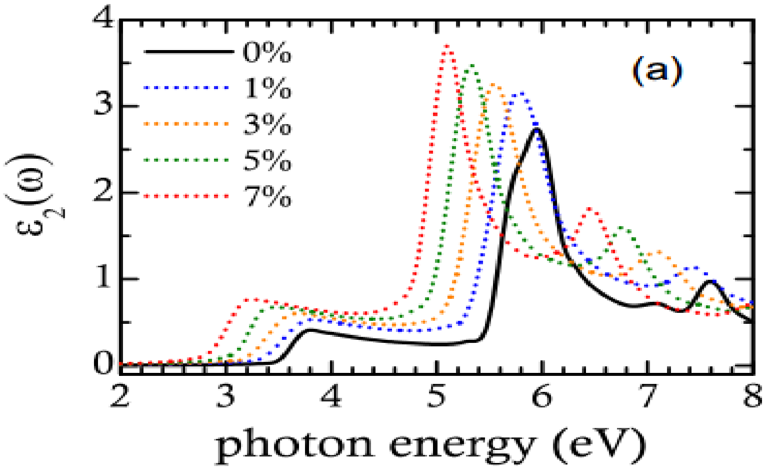
- Unique light-matter interactions in highly confined light regime

M. Soljacic's group
Science 2016

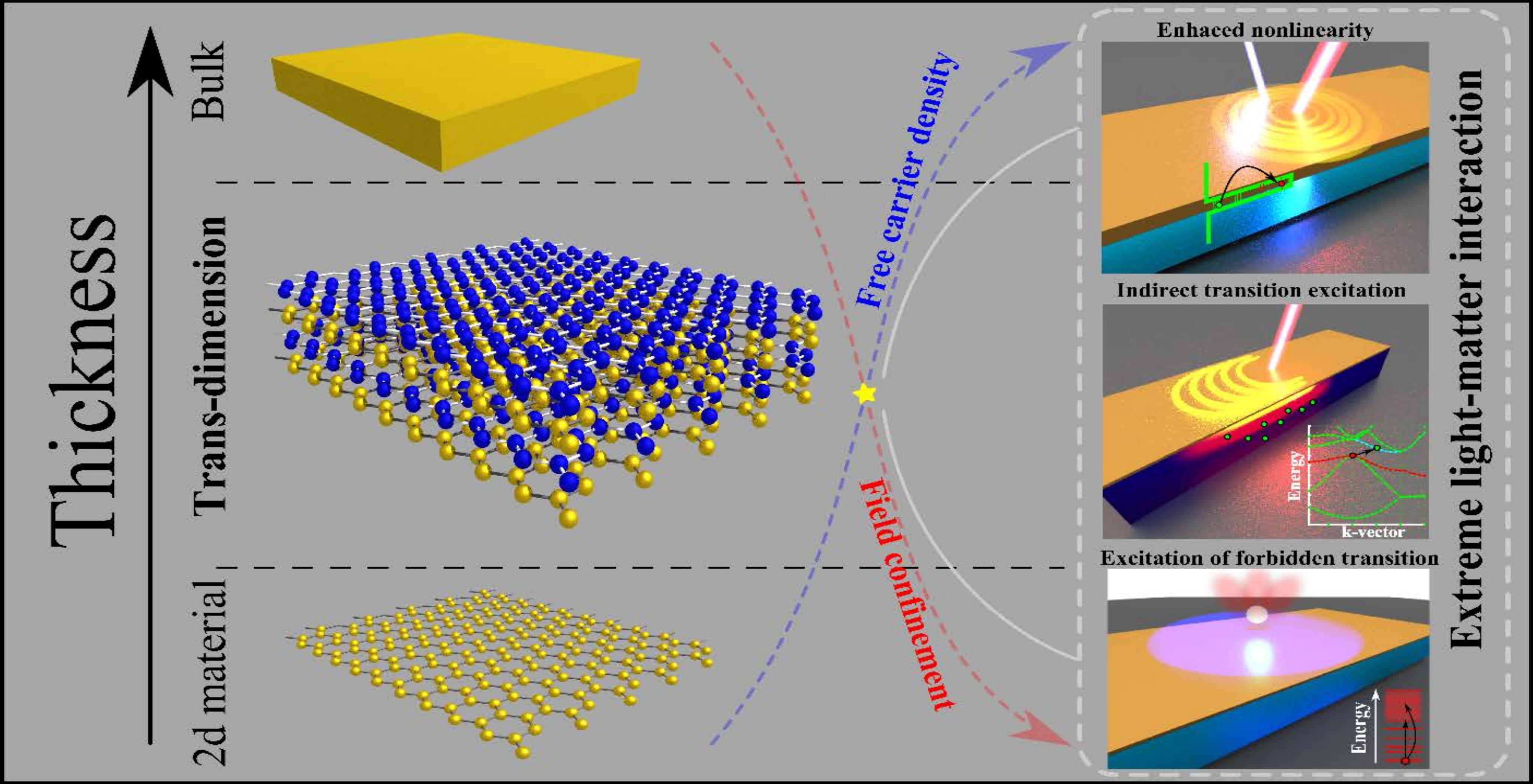


- Control the optical properties

  by adjusting strain/stress



UNIQUE PROPERTIES

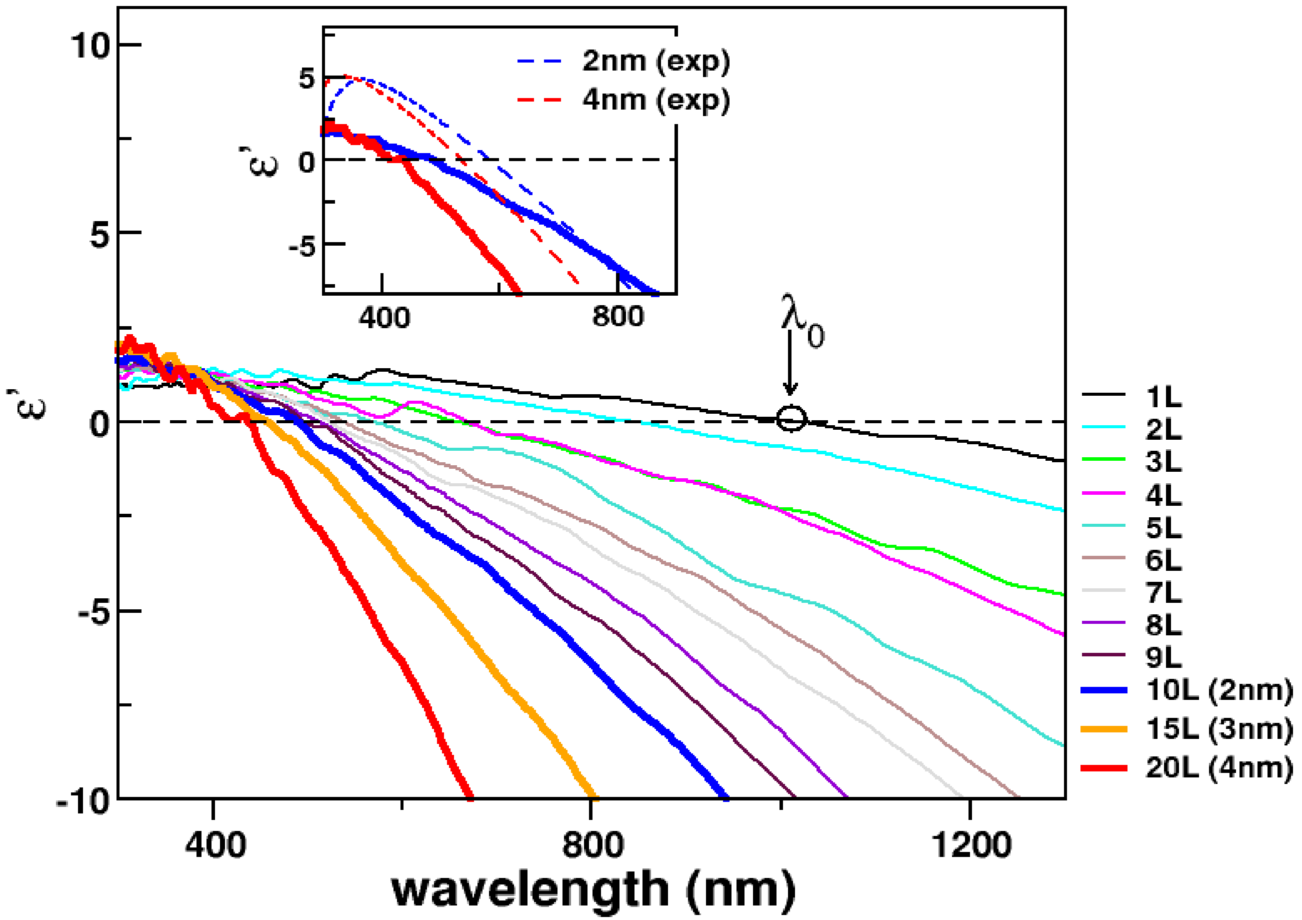


A. Boltasseva and V. M. Shalaev, “Transdimensional Photonics,” ACS Photonics 6, 1–3 (2019)

THEORETICAL MODELING OF ULTRATHIN TiN

Blue shift with increasing thickness – good agreement with experiment

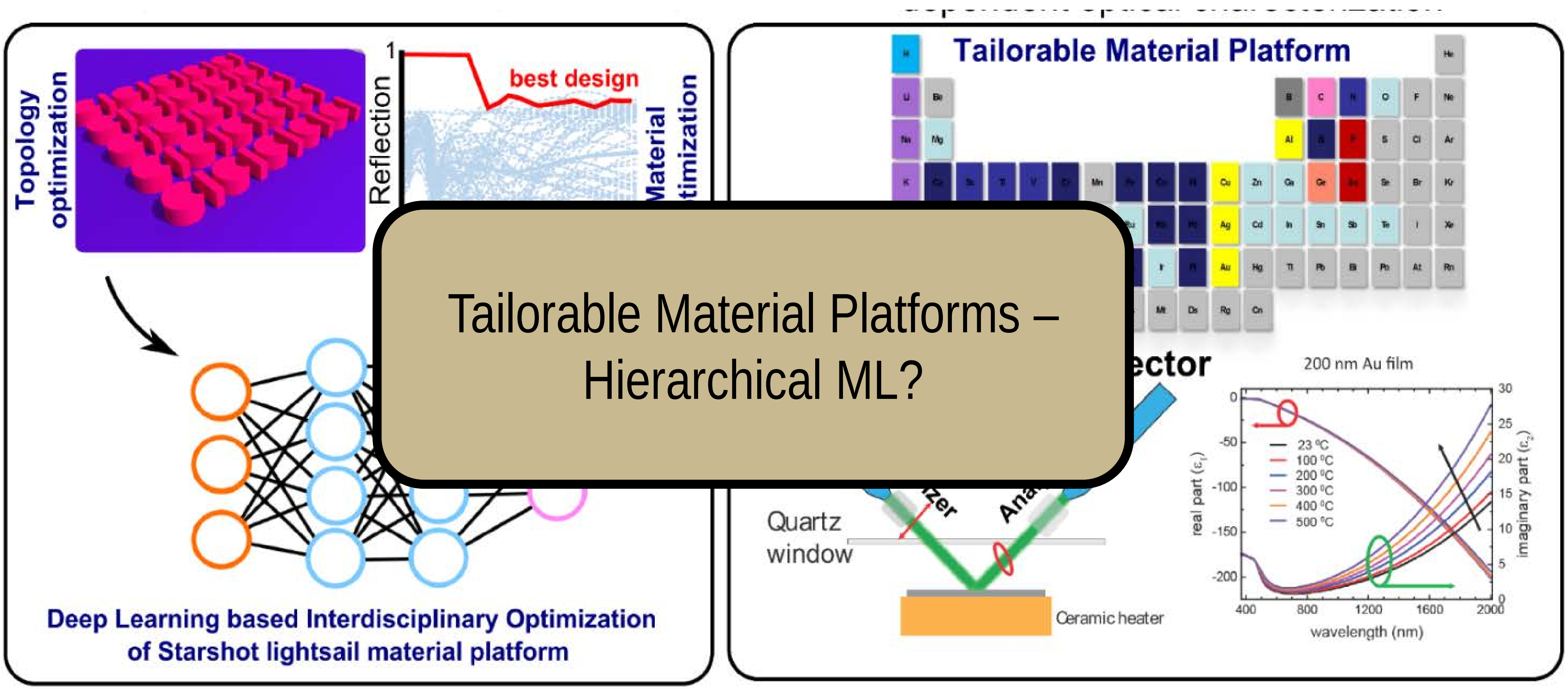
Optical properties of ultrathin TiN modeled using DFT



With A. Calzolari

D. Shah, et al, ACS Photonics 5 (6) 2816 (2018)

OPTIMIZATION + MATERIALS



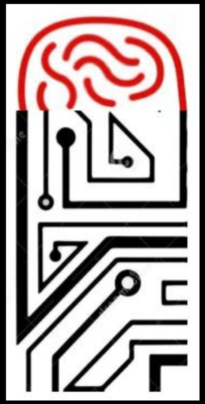
Tailorable Material Platforms – Hierarchical ML?

Include tailorable optical properties!

MEASUREMENTS

IMAGE RECONSTRUCTION/SPARSE DATA

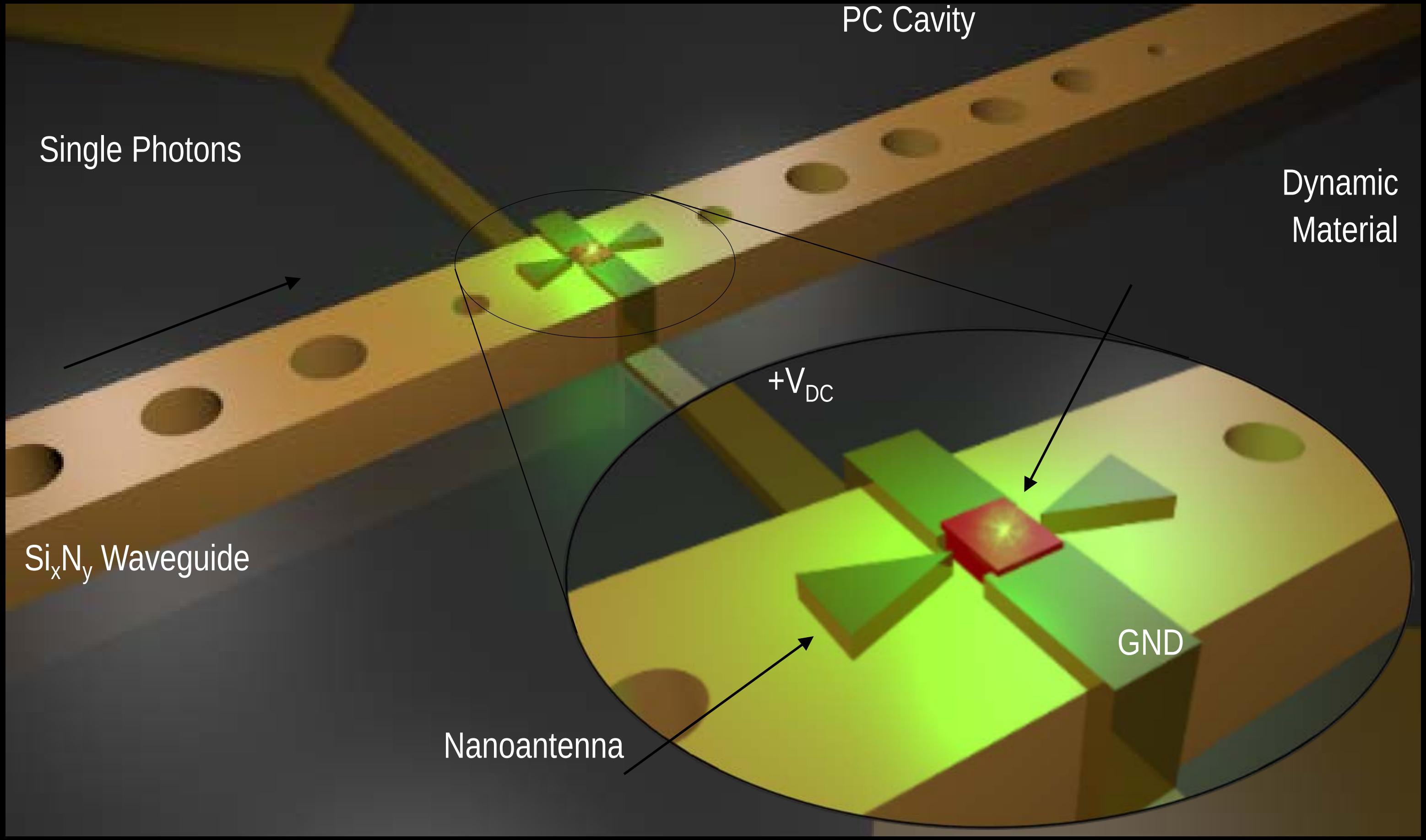
MEASUREMENT SPEED-UP/REAL TIME PROTOTYPING



TEST

N. I. Zheludev, Unlabelled Far-field Deeply Subwavelength Superoscillatory Imaging (DSSI), arXiv:1908.00946

INTEGRATED QUANTUM NANOPHOTONICS WITH HYBRID PLATFORMS

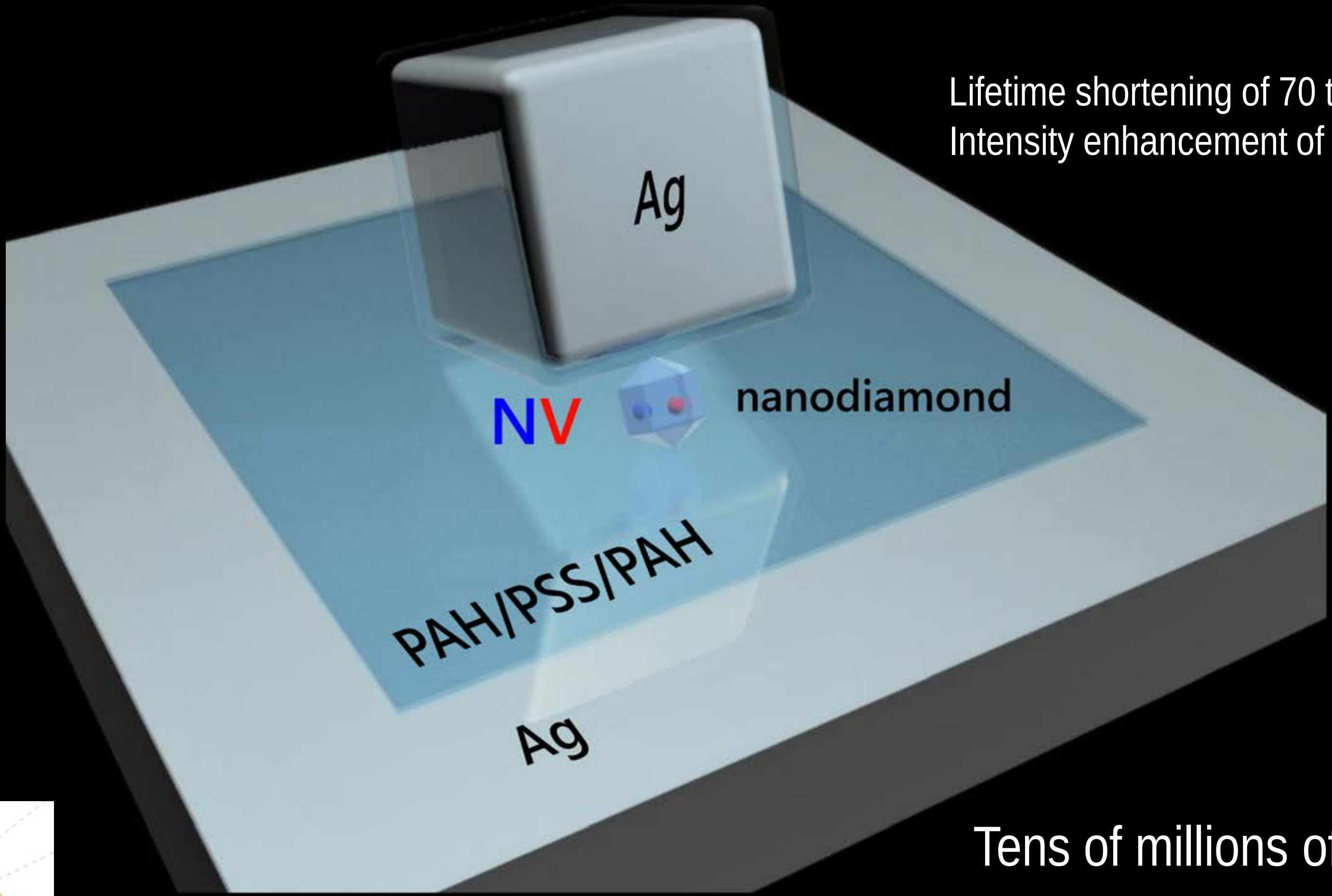


Utilize the advantages of photonics, electronics, and plasmonics to achieve high performance

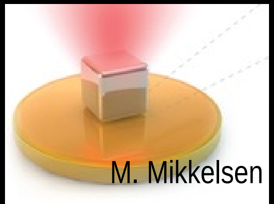
Explore new materials, new atomistic defects, and new structures to optimize performance

TOWARDS BRIGHT ROOM-T SINGLE-PHOTON SOURCE

Quantum Emitters (NV centers in nanodiamond) in Plasmonic Cavity



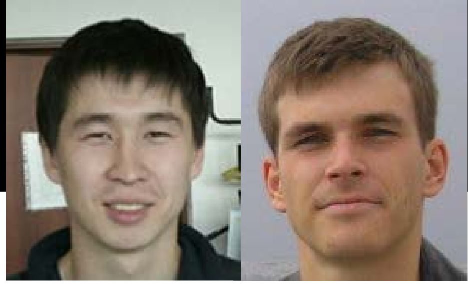
Lifetime shortening of 70 times
Intensity enhancement of 90 times



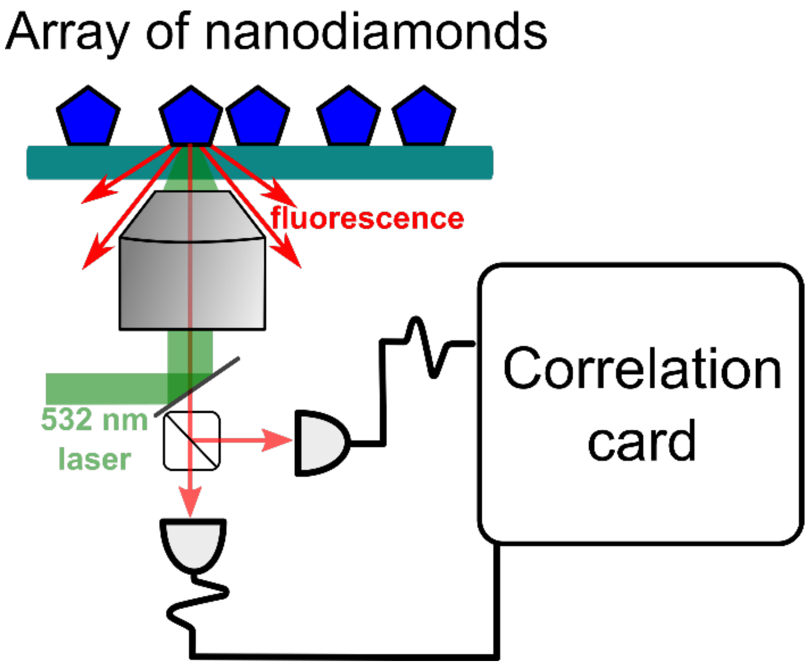
Tens of millions of photons per second!

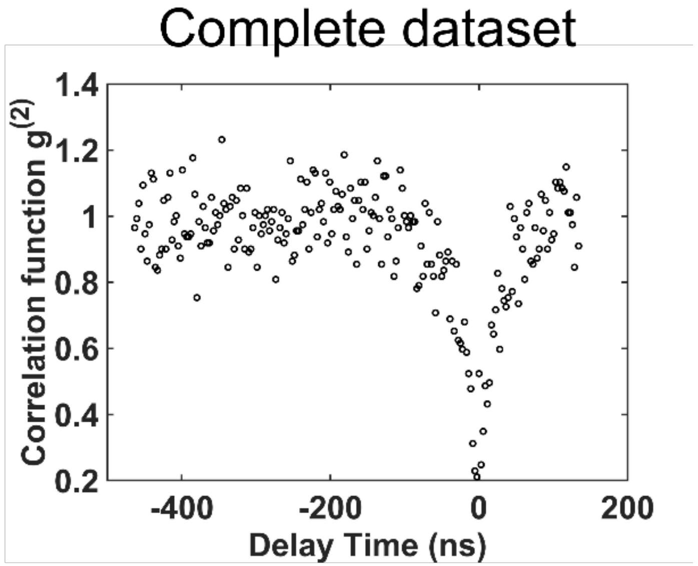
Bogdanov et al., Nano Lett. (2018)
see also Opt. Phot. News 29, 46 (2018)

CHALLENGES



Dr. Z. Kudyshev
Prof. S. Bogdanov





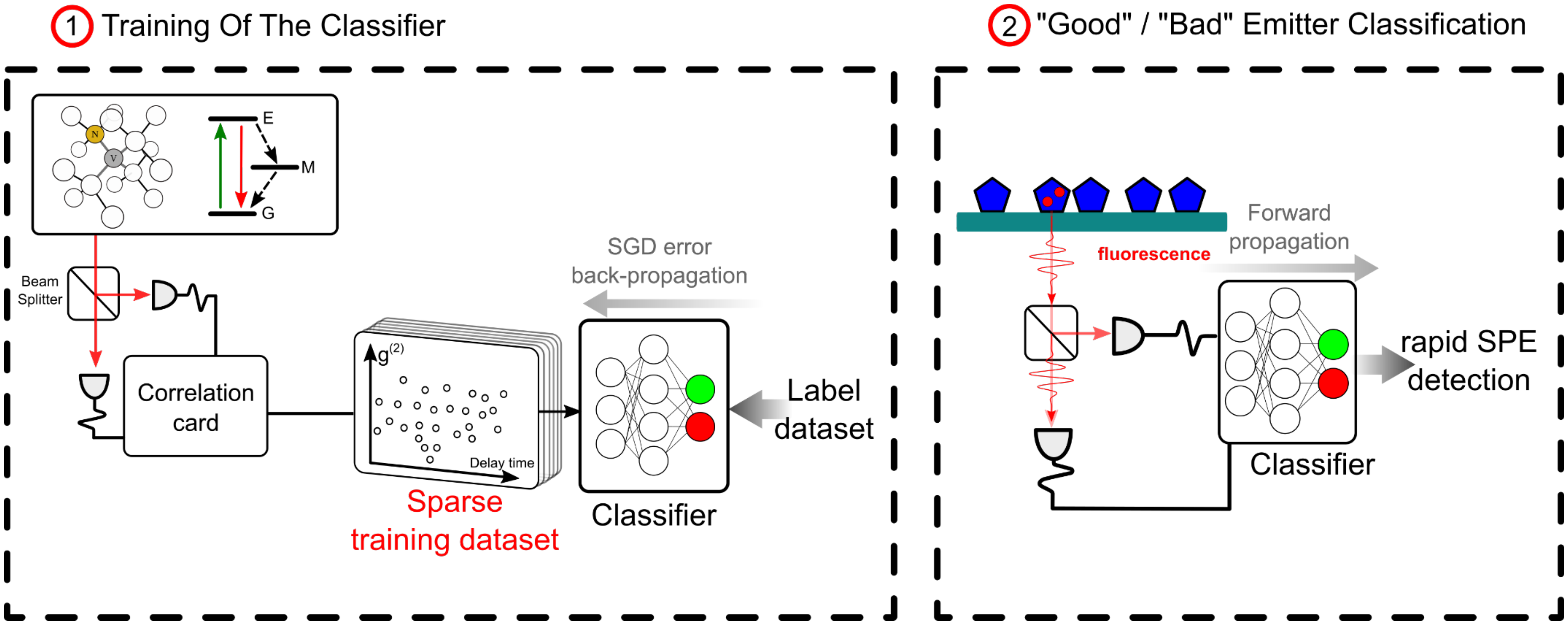
$$g^{(2)}(\tau = 0)$$

- Long characterization time spent on each emitter: complete dataset requires up to 1 min collection time for precise retrieval
- Very low density of "good" emitters: in commercial nanodiamond powders with a median particle size of ~25 nm, less than 1 out of 1,000 nanodiamonds actually hosts an NV center

N. Ares group – similar work for semiconductor quantum devices., N. Efficiently Measuring a Quantum Device Using Machine Learning. npj Quantum Inf. 2019, 5 (1), 79

Demand for fast, precise method that can identify "good" quantum emitters based on a sparse dataset (<1s)!

ML for RAPID EMITTER DETECTION



ML-based single photon source search:

(i) training of classifier based on collected sparse data and retrieved corresponding labels (“good”/”bad” emitter)

(ii) rapid SPE identification among random NV quantum emitters

Classifiers trained via error backpropagation using stochastic gradient descent (SGD) optimization

INTEGRATION

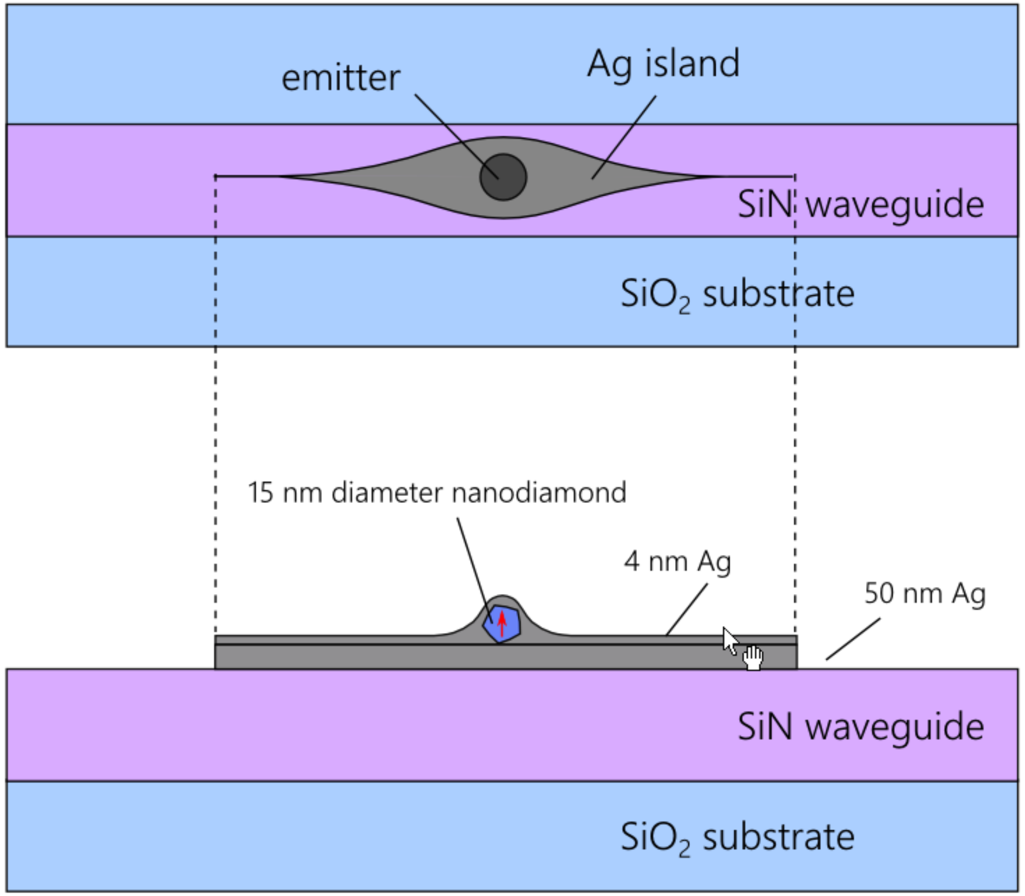
FABRICATION

INTEGRATION

SYSTEMS INTERFACING/WAVEGUIDES/CAVITIES

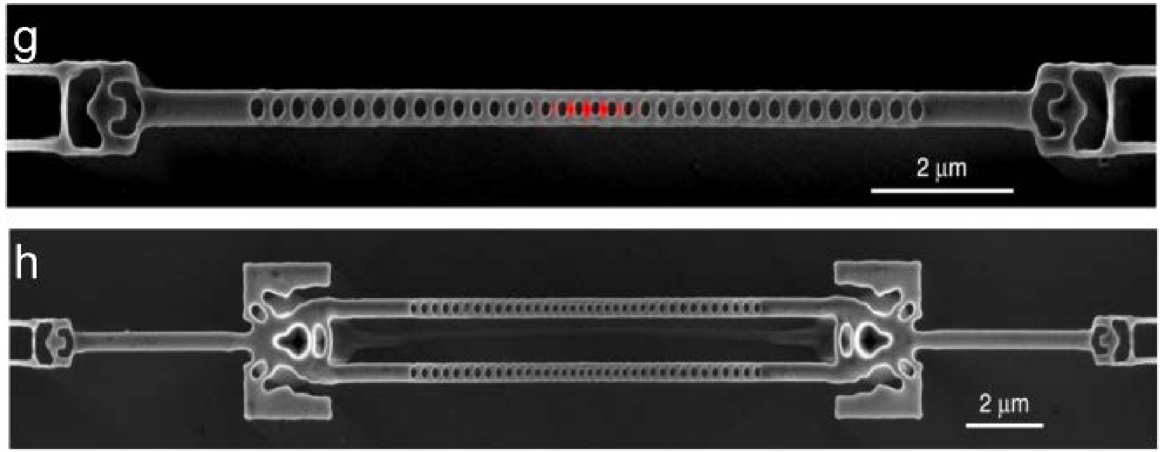
COMPLEX DESIGN FOR IN-/OUT-COUPLING

ML FOR PHOTONIC INTEGRATION



ML assisted optimization for building highly efficient antenna design for single photon source emission control:

- Cavities
- Couplers
- Guiding systems

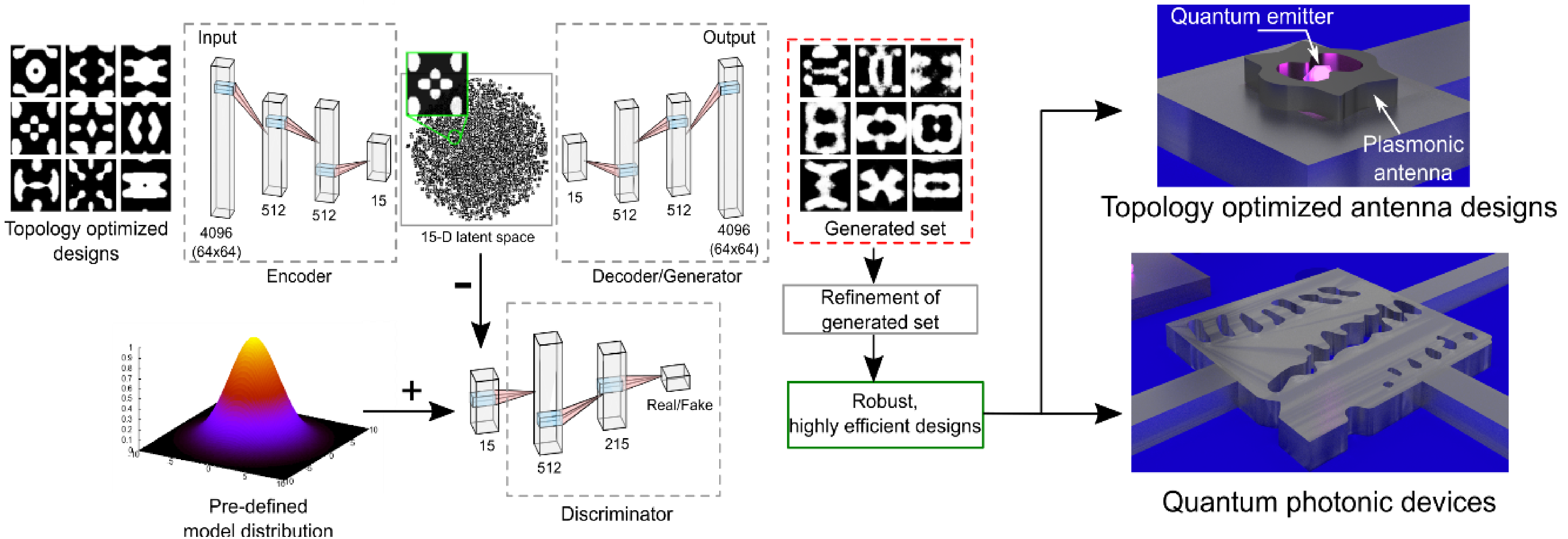


C. Dory, .; et al. J. Vučković, "Inverse-Designed Diamond Photonics". Nat. Commun. 2019, 10 (1), 3309.

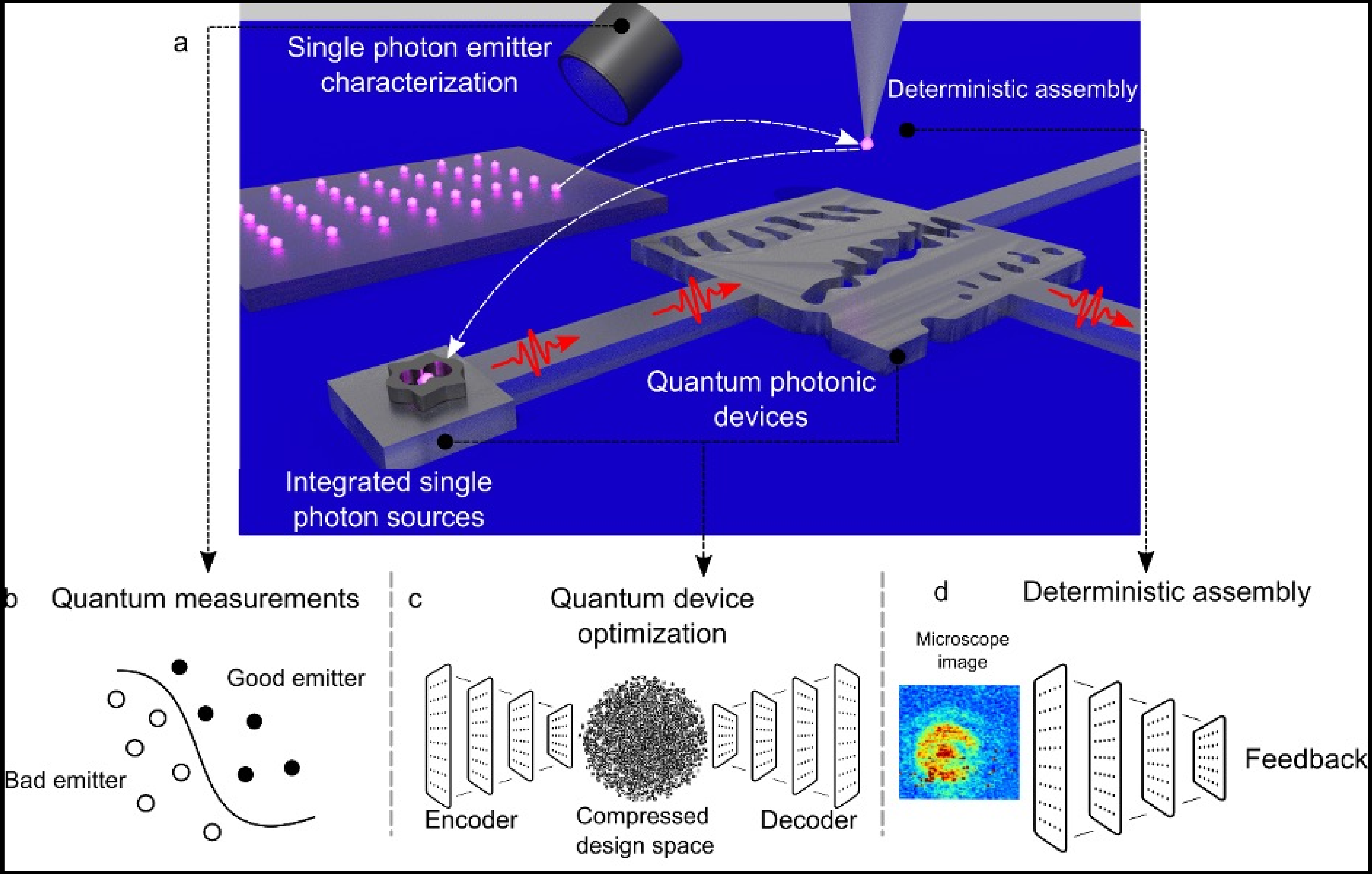
ML FOR PHOTONIC INTEGRATION

ML assisted optimization for building highly efficient antenna design for single photon source emission control:

- Cavities
- Couplers
- Guiding systems

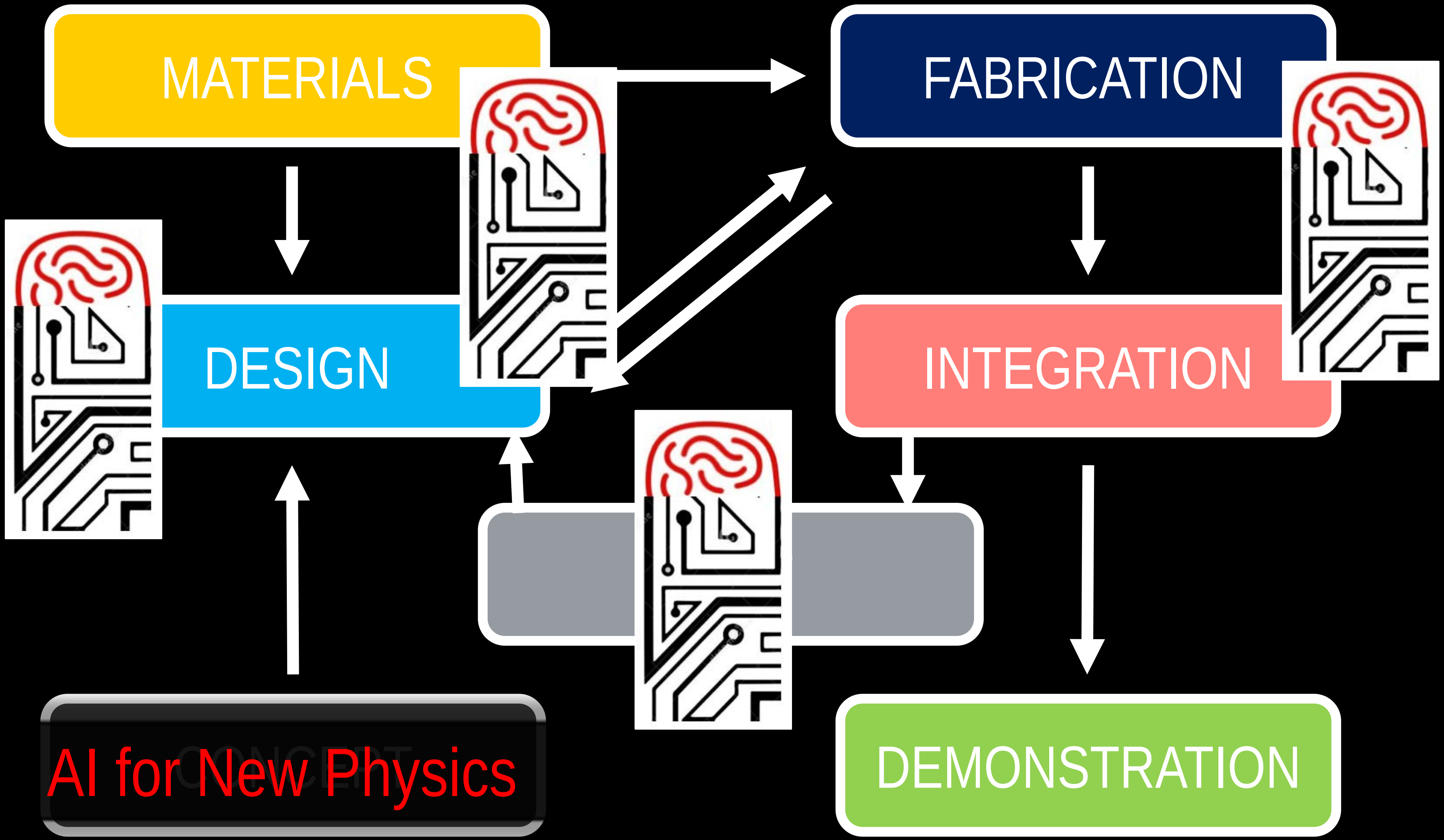


OUTLOOK



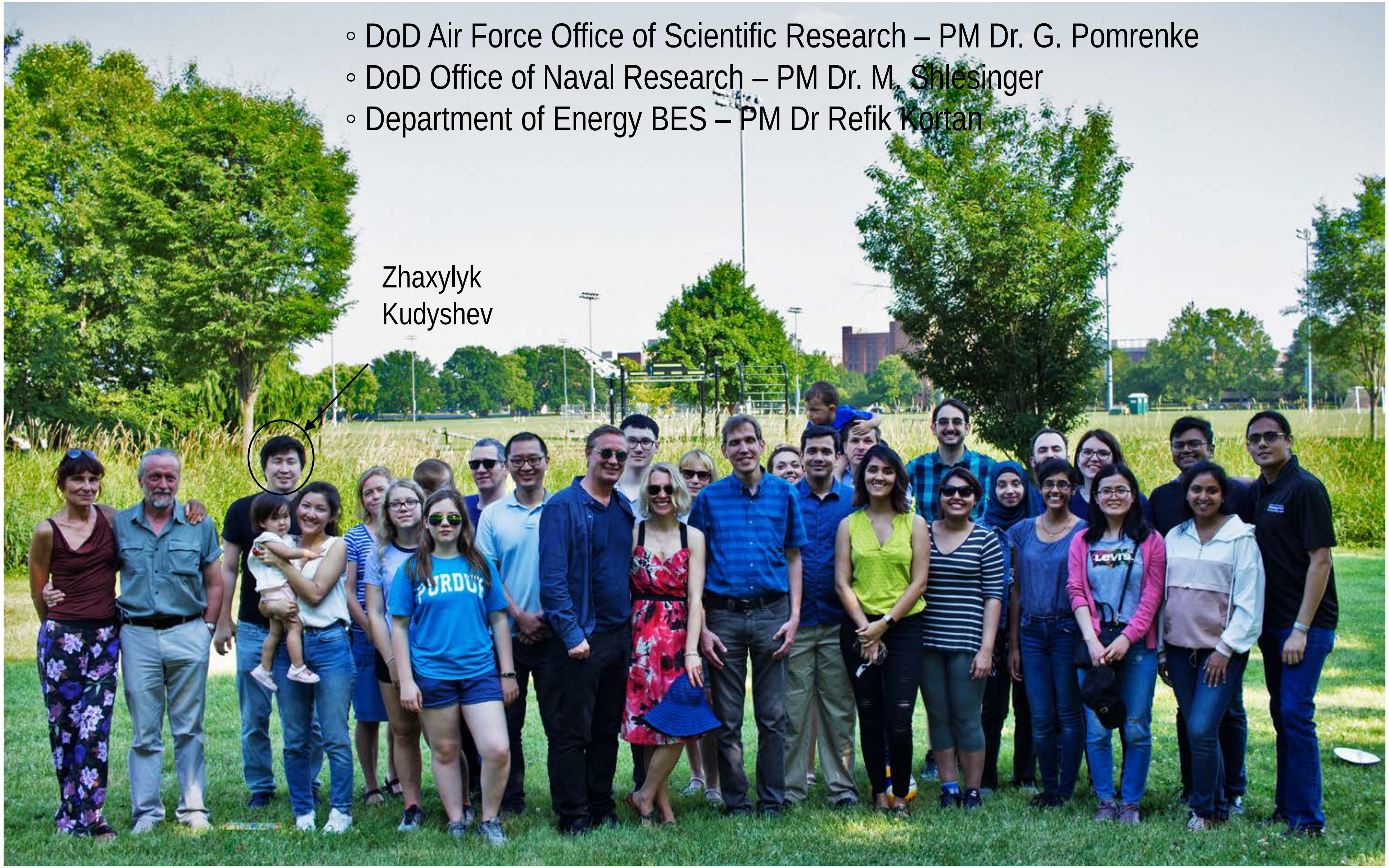
Z. Kudyshev, V. Shalaev, A. Boltasseva, ACS Photonics, Perspective, submitted

AI-AIDED PHOTONICS: FLOW CHART



TEAM AND SUPPORT

- DoD Air Force Office of Scientific Research – PM Dr. G. Pomrenke
- DoD Office of Naval Research – PM Dr. M. Shlesinger
- Department of Energy BES – PM Dr Refik Kortan



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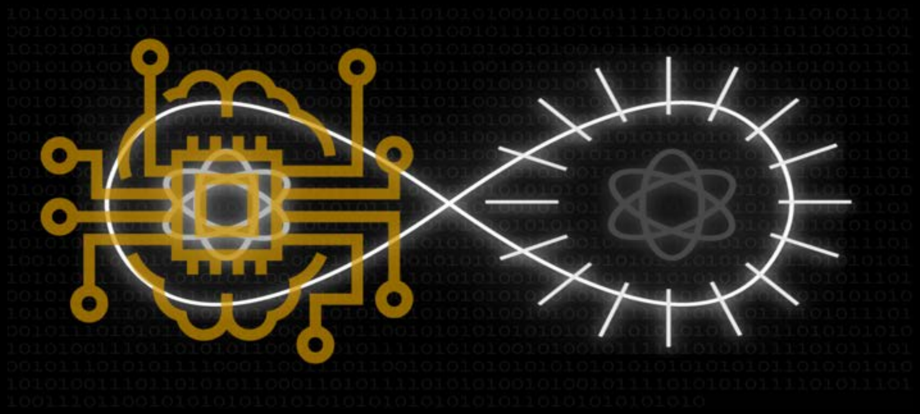
THANK YOU



ADVANCING PHOTONICS WITH MACHINE LEARNING

From Photonic Meta-Device Design to Quantum Measurements

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