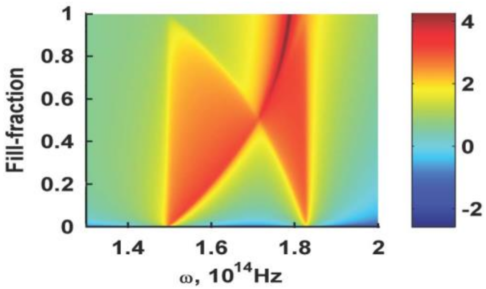
Zubin Jacob Research Group
University of Alberta, Canada



Controlling Field Fluctuations with metamaterials

- Vacuum fluctuations
- Thermal fluctuations

Y. Guo et. al. Appl. Phys. Lett. 101, 131106 (2012)

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Expelling vacuum fluctuations

Birth of Photonic Crystals

VOLUME 58, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1987

Inhibited Spontaneous Emission in Solid-State Physics and Electronics

Eli Yablonovitch
Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701
(Received 23 December 1986)

It has been recognized for some time that the spontaneous emission by atoms is not necessarily a fixed and immutable property of the coupling between matter and space, but that it can be controlled by modification of the properties of the radiation field. This is equally true in the solid state, where spontaneous emission plays a fundamental role in limiting the performance of semiconductor lasers, heterojunction bipolar transistors, and solar cells. If a three-dimensionally periodic dielectric structure has an electromagnetic *band gap* which overlaps the electronic *band edge*, then spontaneous emission can be rigorously forbidden.

PACS numbers: 42.50.−p, 42.55.Bi, 78.45.+h

See also: S. John, same issue of PRL, “Strong Localization in Certain Disordered Dielectric Superlattices”

Can metamaterials help us to do the exact opposite?

Giant Zero Point and Thermal Energy

$$\left\langle E(r,\omega)\otimes E^{*}(r',\omega)\right\rangle = \coth(\hbar\omega/2k_BT)\frac{\hbar\mu_0\omega^2}{4\pi}\operatorname{Im}\overleftrightarrow{G}(r,r';\omega)$$

$$=\left[\frac{\hbar\omega}{\exp(\hbar\omega/k_BT)-1}+\frac{\hbar\omega}{2}\right]\frac{\mu_0\omega}{2\pi}\operatorname{Im}\overleftrightarrow{G}(r,r';\omega)$$

Spectrum of
Field fluctuations

Thermal
distribution

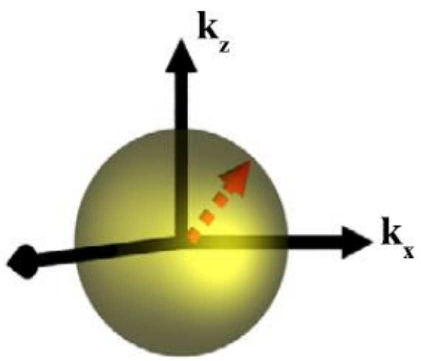
Zero point
energy

Related to
Density of states

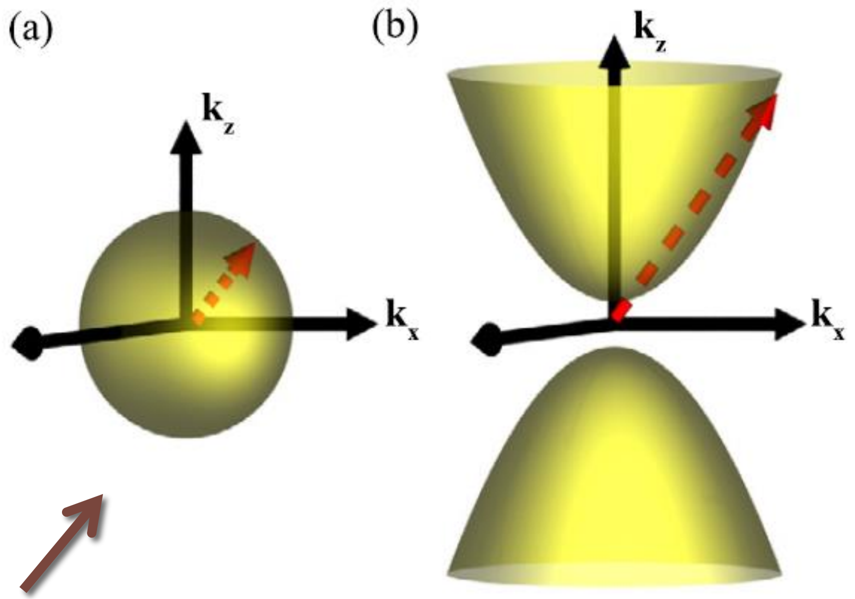
Broadband enhancement in Density of States ?

Conventional Media

(a)



Hyperbolic Metamaterials



$$\varepsilon_{xx} = \varepsilon_{yy} > 0$$

$$\varepsilon_{zz} < 0$$

Conventional media

Hyperbolic Isofrequency Curve (single negative component in the dielectric tensor)

Reviews:

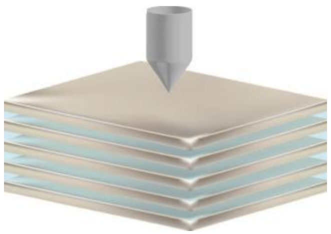
1. **C. Cortes et. al. J. Opt. 14, 063001 (2012)**
2. **Y. Guo et. al. , Advanced in Optoelectronics (2012)**

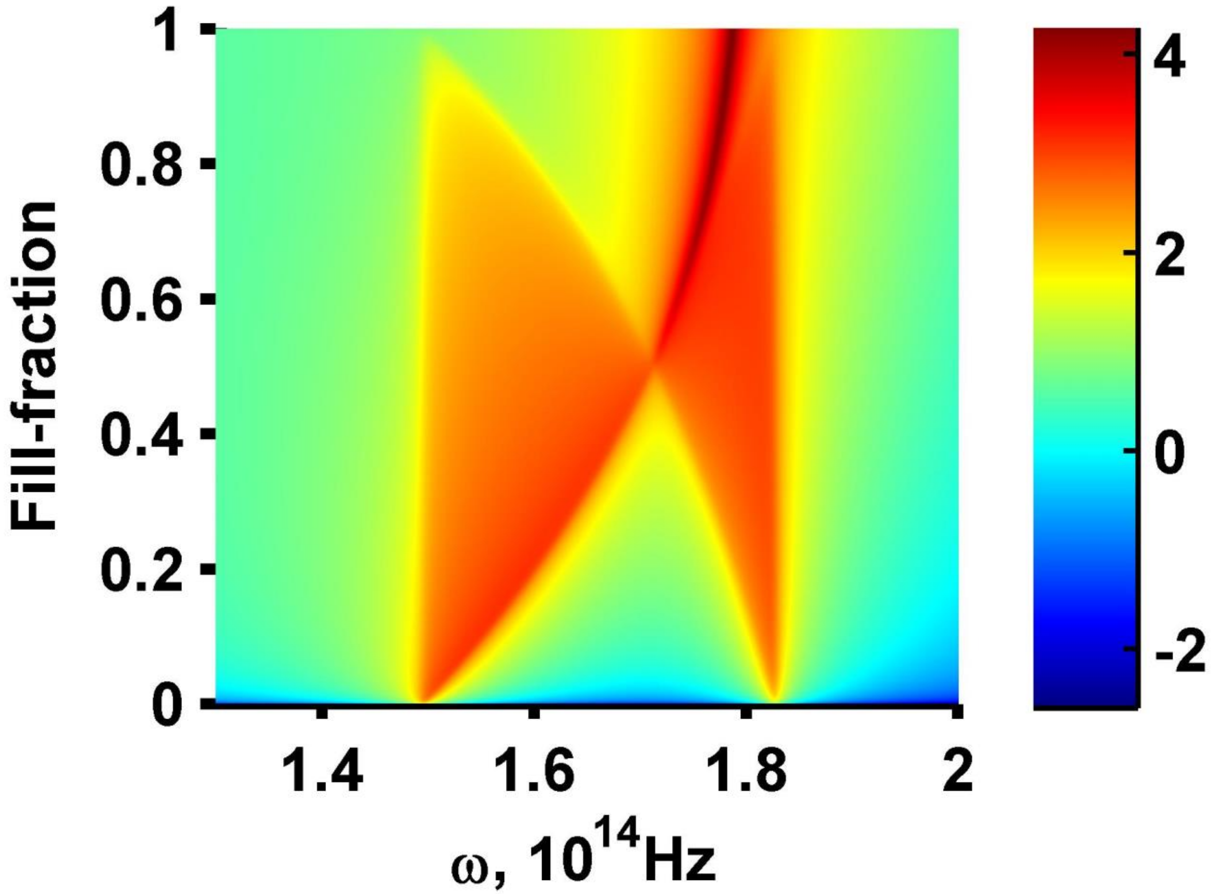
Early Work

Microwave : Keith Balmain, David Smith, Pavel Belov
Optics: E. Narimanov, V. Podolskiy

Experiment: Gmachl Group, Zhang Group, Zayats Group, Noginov Group, Shalaev Group, Boltasseva Group,

Broadband Super-Planckian thermal emission





Y. Guo et. al. Appl. Phys. Lett. 101, 131106 (2012)

Multilayer structure SiC/SiO2

See also: 1. E. Narimanov and I.I. Smolyaninov, arXiv:1109.5444
2. S. A. Biehs Phys. Rev. Lett. 109, 104301 (2012)
3. Nefodotov and Simovski, Phys. Rev. B 84, 195459 (2011)

HIGH TEMPERATURE PLASMONICS AND METAMATERIALS

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High Temperature Plasmonics, Y. Guo et. al., arXiv:1304.6769, 2013

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Engineering the poles and zeros

$$H(s) = \frac{Y(s)}{X(s)}$$

← Zeros

← Poles

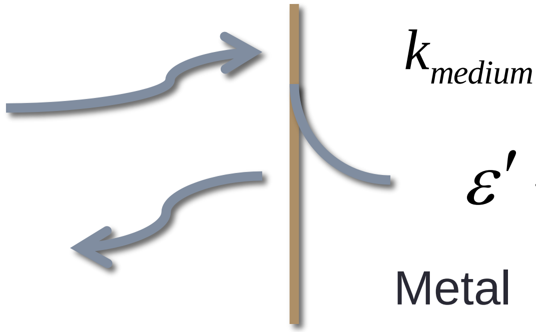
Control Systems, Stability, Designing filters ……..

What about engineering the poles and zeros of the dielectric response function?

Epsilon-Near-Zero : ENZ
Epsilon-Near-Pole: ENP

ENZ: A. Alu and N. Engheta

Natural ENZ and ENP



$$k_{medium} = \sqrt{\varepsilon'}(\omega / c)$$

$$\varepsilon' < 0$$

Naturally occuring **ENZ**:

- *Bulk Plasma Frequency* $$\varepsilon'\left(\omega_p\right) \approx 0$$
- *Longitudinal Optical Phonon* $$\varepsilon'\left(\omega_{LO}\right) \approx 0$$

Naturally occuring **ENP**:

- *Transverse Optical Phonon* $$\left|\varepsilon'\left(\omega_{TO}\right)\right| \to \infty$$

Natural ENZ and ENP

$$\omega_p \propto \frac{1}{\sqrt{m_e}}$$

↓

Low electron mass:
Ultraviolet
Frequencies
(Ag,Au,Cu ….)

$$\omega_{LO}, \omega_{TO} \propto \frac{1}{\sqrt{M_{ion}}}$$

↓

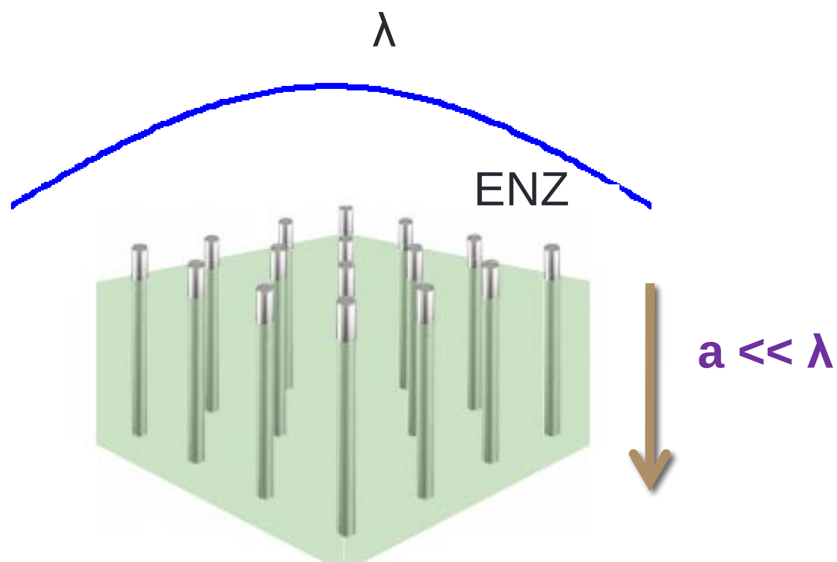
Large ion reduced-mass:
Mid-IR wavelengths
(SiC, SiO2,SrTiO2…)

Optical and Near-IR ENZ and ENP:
Clear need for Metamaterials

Isotropic ENZ and ENP is difficult!

Control ENZ

Dilute metal with a dielectric



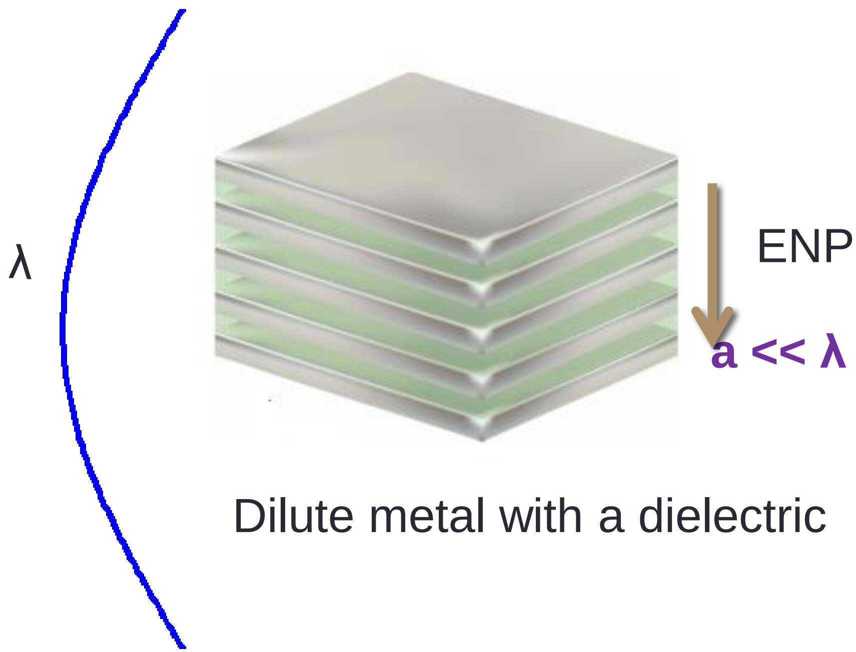
Dilute dielectric with a metal

EMT: Effective Medium Theory (Homogenized medium/ Metamaterial)

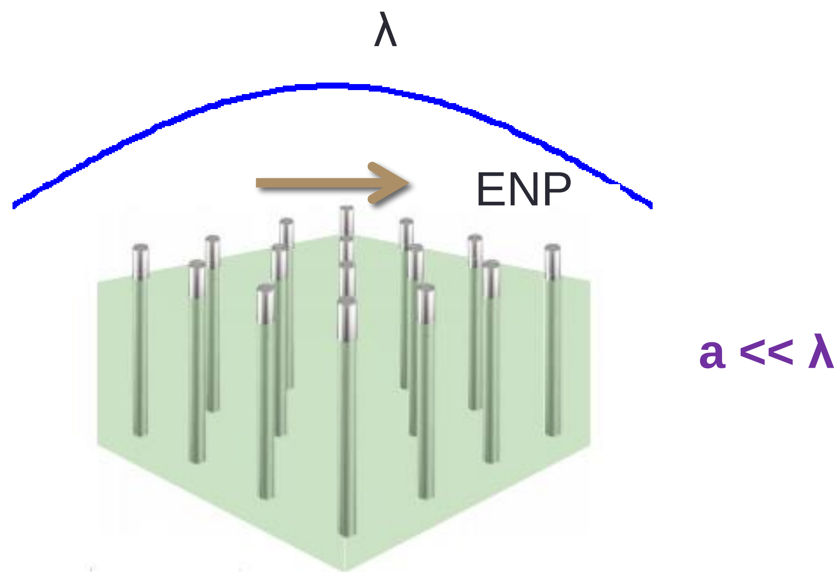
S. Molesky, C. Dewalt, Z. Jacob
Opt. Exp., V.21, Issue S1 pp. A96-A110, 2013

Control ENP

Recall: Drude dispersion has no pole => Free electrons
Lorentzian dispersion has a pole => Bound electrons



Dilute metal with a dielectric

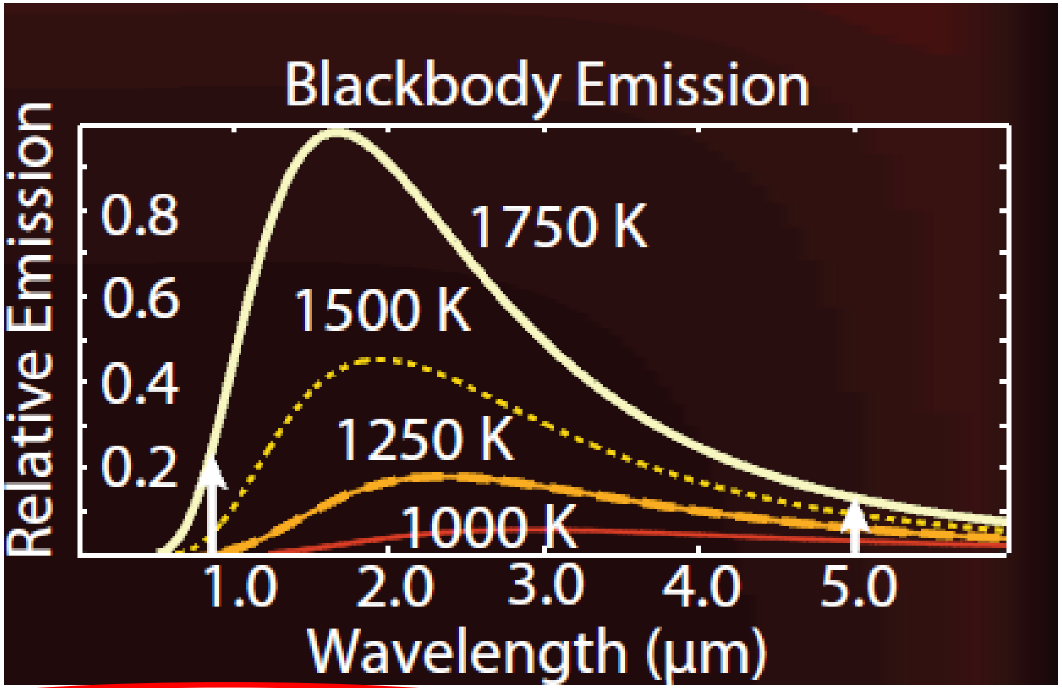


Dilute dielectric with a metal

Electron motion is confined to the films/wires (“bound electrons”)

Roadblock!

High Temperature Metamaterials

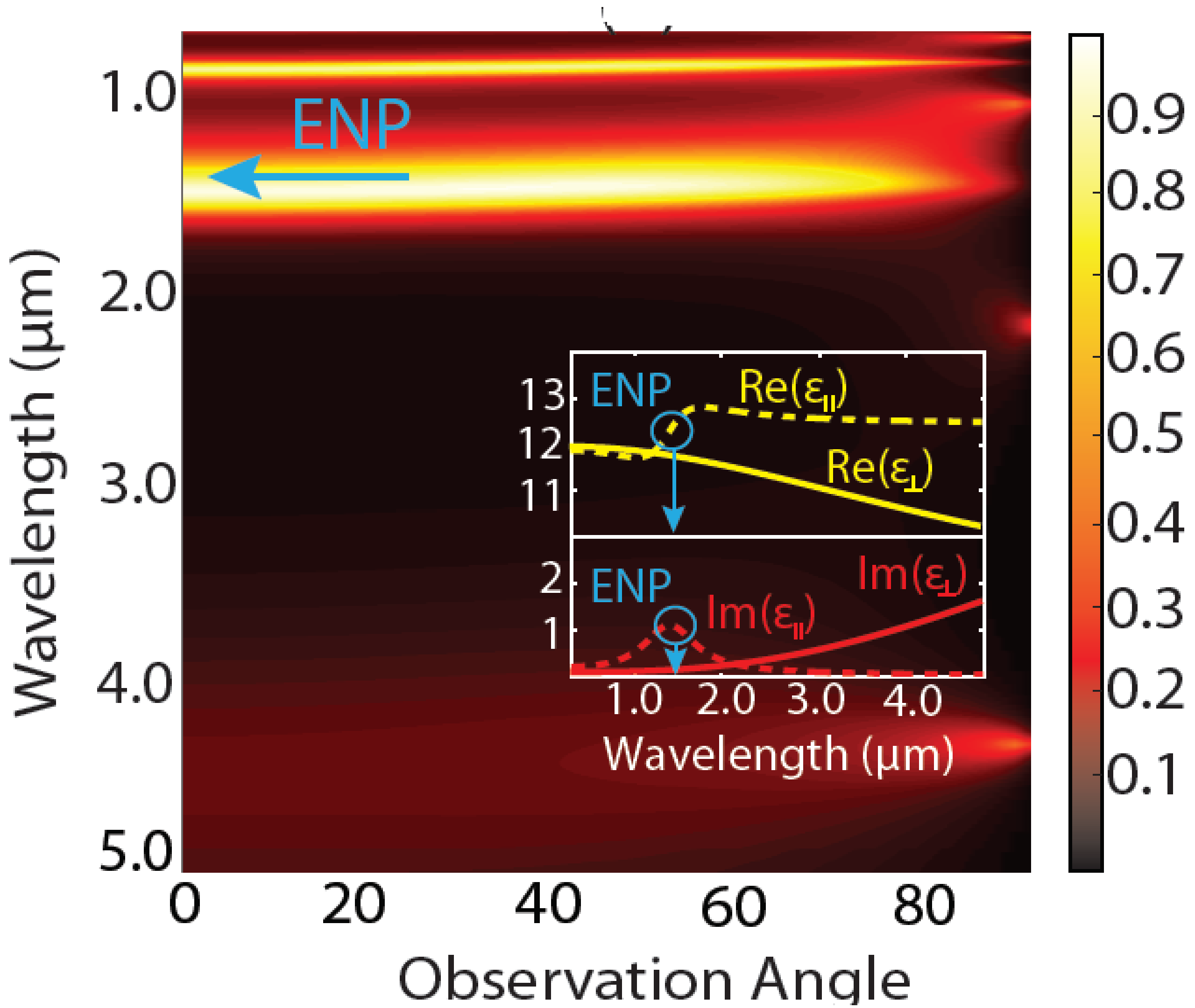


Silver, Gold melting point ~ 1000 C, Titanium Nitride ~ 3000 C

Recent work : G. V. Naik, T. Sands and A. Boltasseva
Optics Materials Express (2010)

S. Molesky, C. Dewalt, Z. Jacob Opt. Exp., V.21, Issue S1 pp. A96-A110, 2013

ENP Nanowire Narrowband Thermal Emitter



Titanium Nitride Nanowires (high melting point)

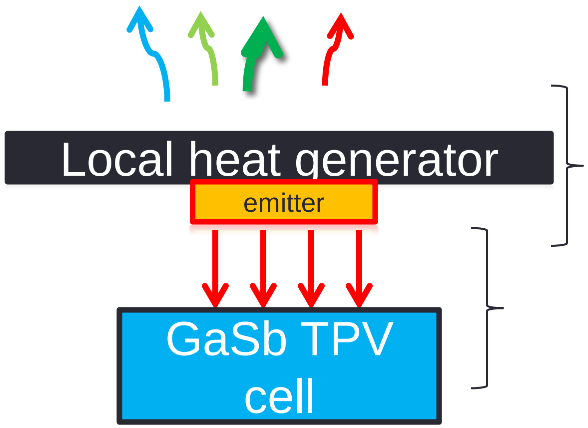
High Figure of Merit

-Parallel component Interactions with both S and p polarized

- Near Omnidirectional

Thermophotovoltaics System

Energy from waste heat or local heat generator



Major expected application:

Cogeneration of
Heat and electricity for remote locations

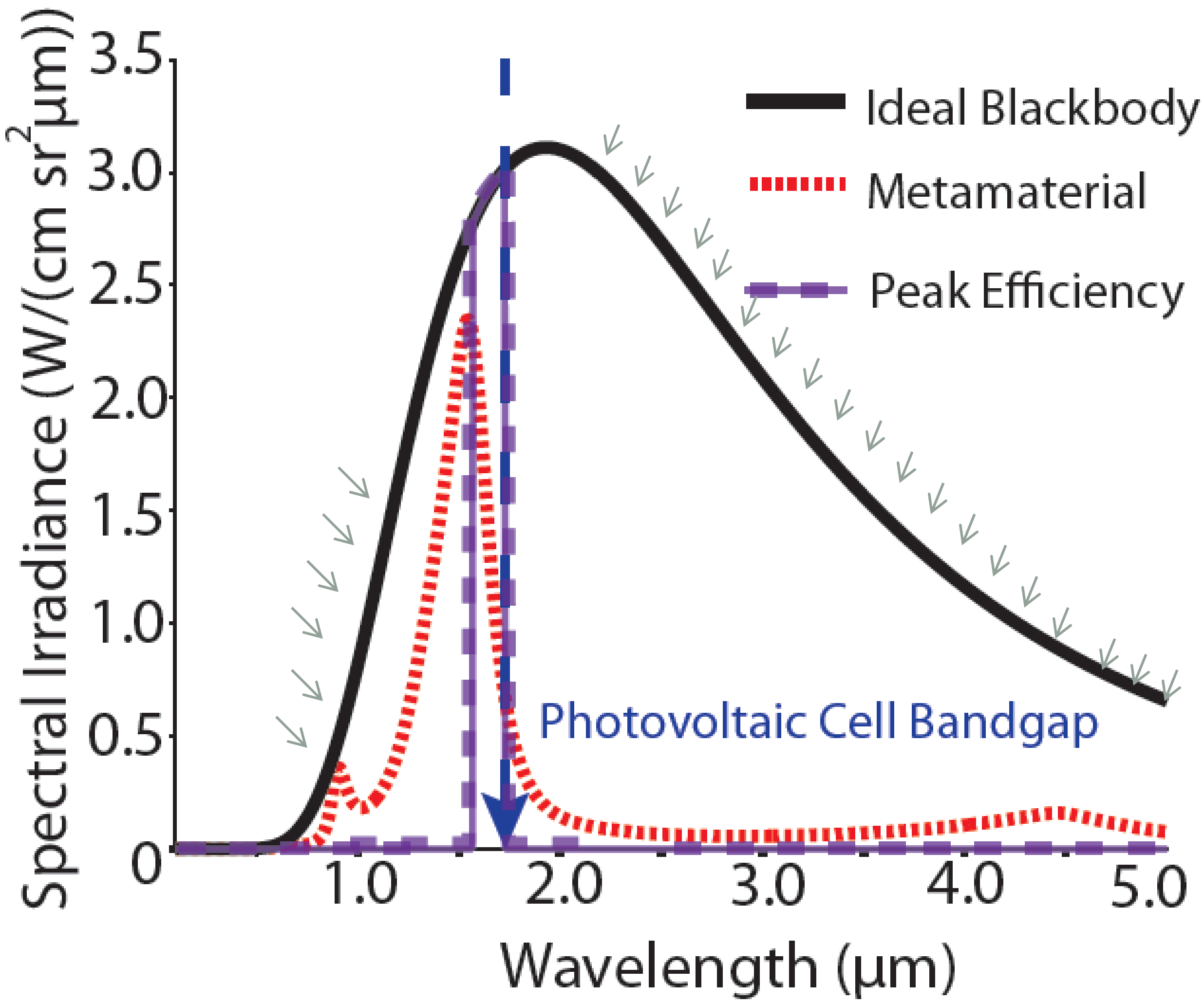
Materials
D. Norris Group (ETH Zurich)
A. Boltasseva Group (Purdue)
M. Noginov Group (NSU)

Nanophotonic approaches
Fan Group (Stanford)
Solijacic Group (MIT)
Shvets Group (U T Austin)

Refractory metal: Tungsten (too lossy)
Possible alternatives: Nitrides and Oxides

High efficiency heat and electricity cogeneration for remote locations

Prospects for thermophotovoltaics



ENP metamaterial Emitter

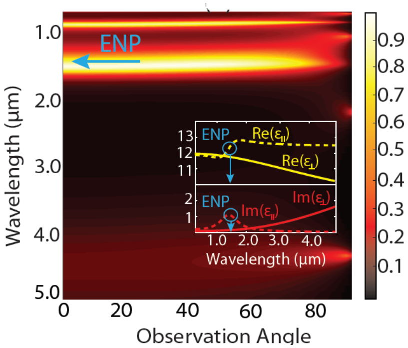
TiN nanowires

S. Molesky, C. Dewalt, Z. Jacob
Opt. Exp., V.21, Issue S1 pp. A96-A110, 2013 (Nature Photonics highlight, OSA Spotlight on optics, Laser Focus World spotlight)

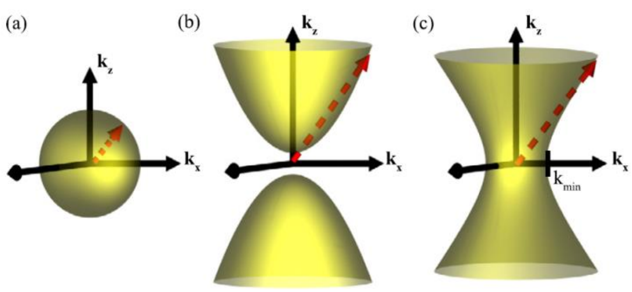
Summary

High temperature Metamaterials : Far-field narrowband thermal sources

1. Epsilon-near-pole metamaterials
2. Epsilon-near-zero metamaterials



Controlling broadband field fluctuations: Hyperbolic Metamaterials



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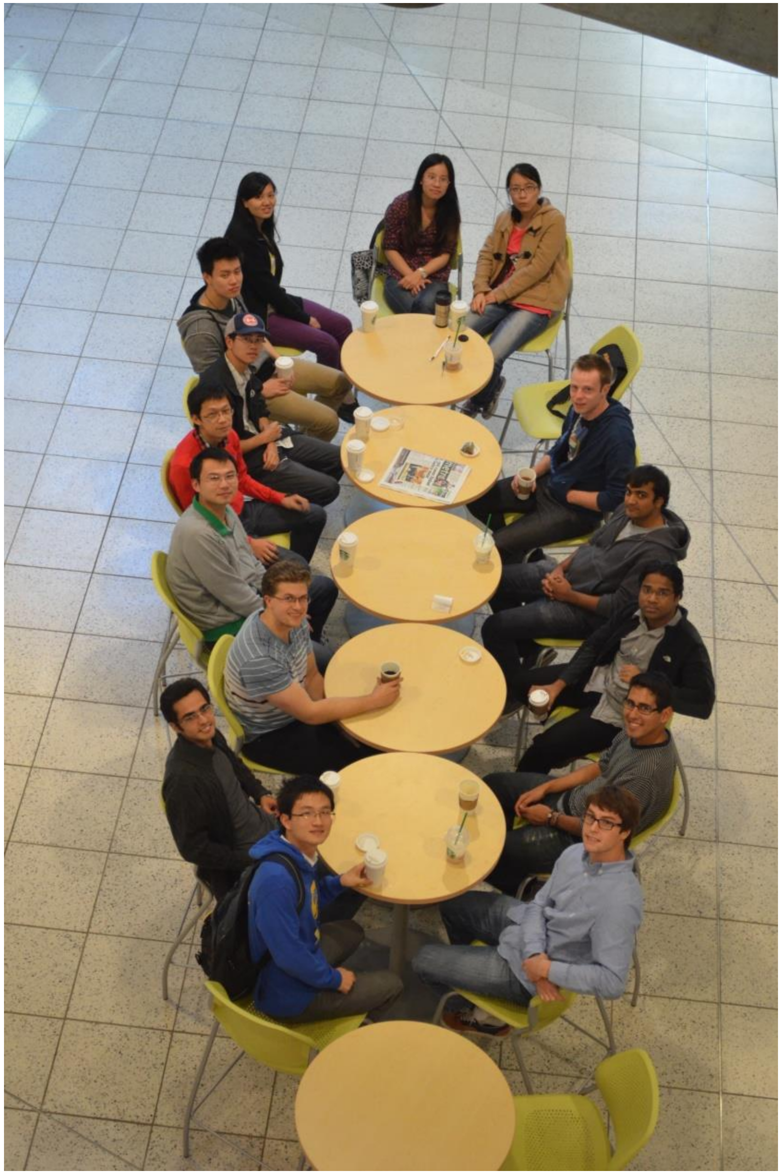
S. Jahani
S. Molesky



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