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IR DeVices

Ultra-high-Resolution, Label-Free Hyperlens Imaging in the Mid-IR

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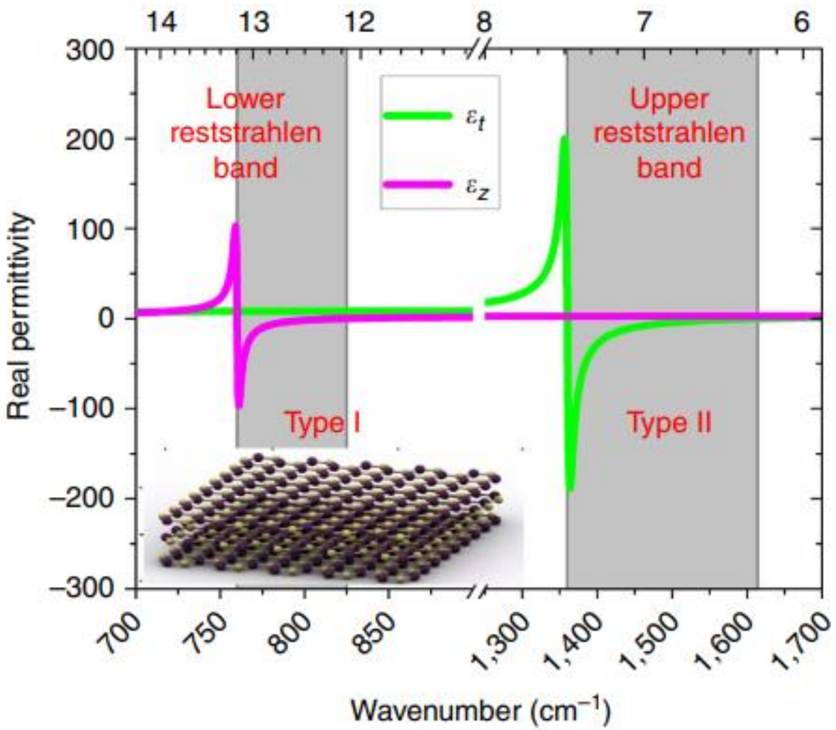
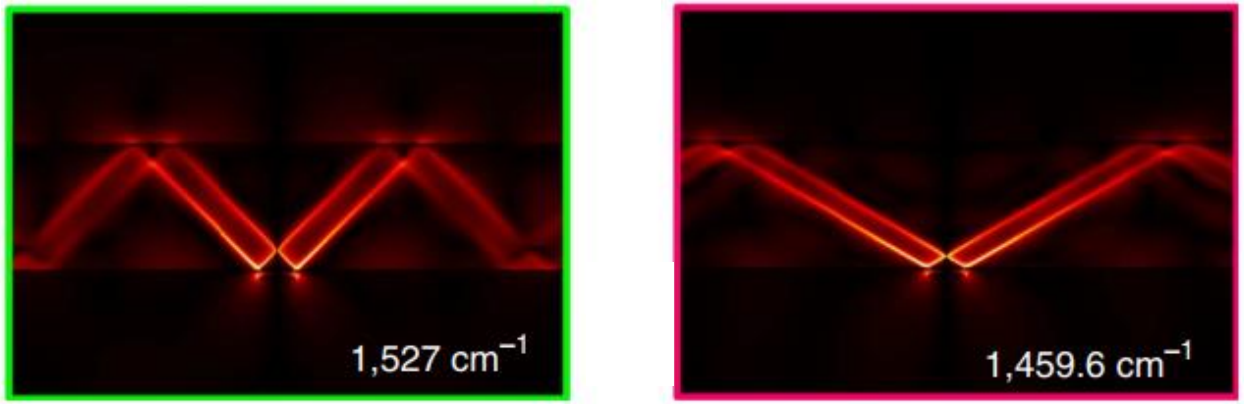
Hyperbolic phonon polaritons



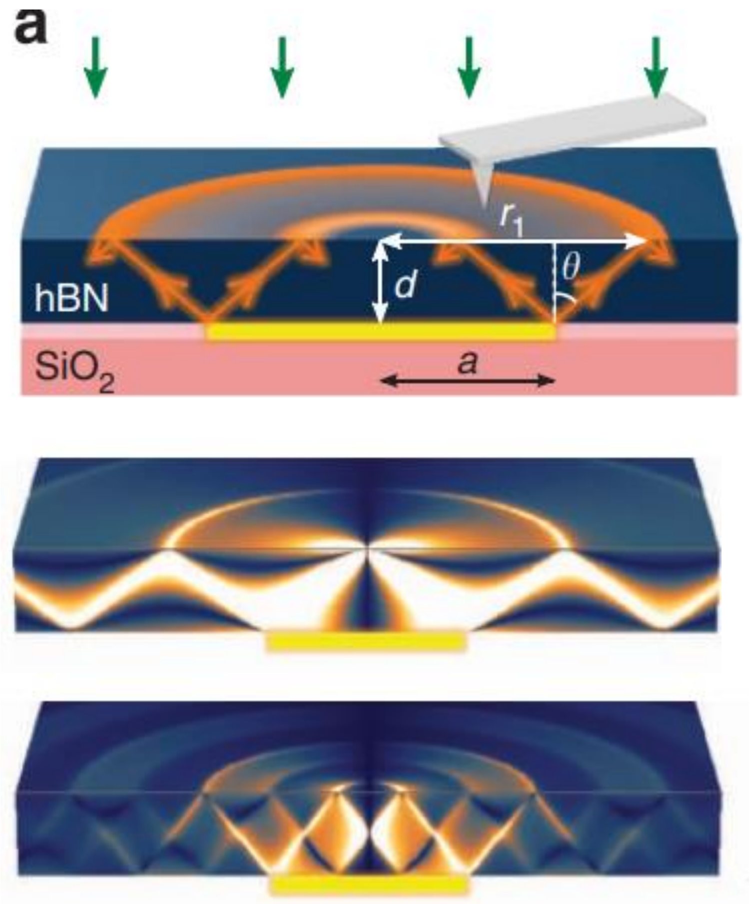


$$\frac{\mathbf{k}_z^2}{\varepsilon_t(\omega)} + \frac{\mathbf{k}_t^2}{\varepsilon_z(\omega)} = 0, \ \frac{\omega}{c} \ll \mathbf{k}_t, \mathbf{k}_z \ll \frac{1}{a}. \qquad (1)$$

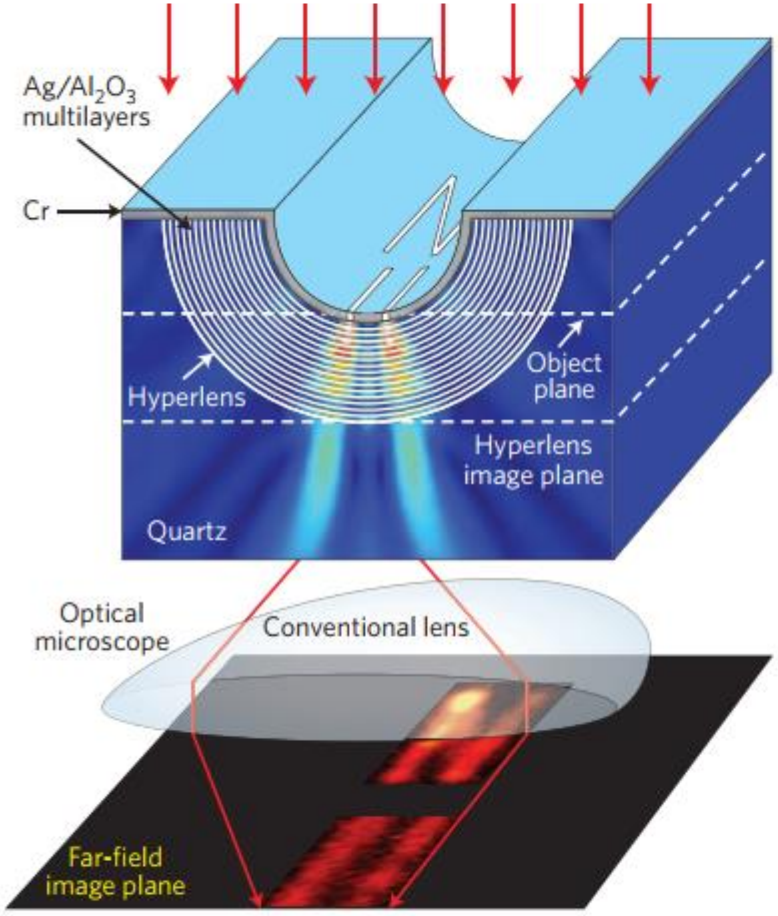
The angle of hyperbolic polaritons within the material is fixed

Caldwell J D, et al. Nature communications, 2014, 5: 5221.
Dai, Siyuan, et al. *Science* 343.6175 (2014): 1125-1129.

What does that profile mean?



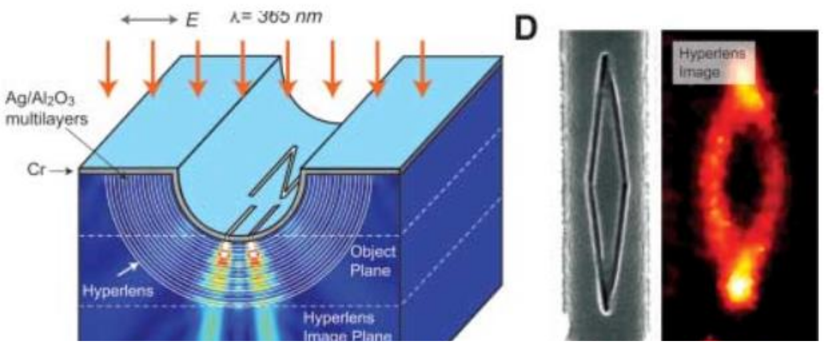
Dai, S., et al. *Nature communications* 6.1 (2015): 1-7.

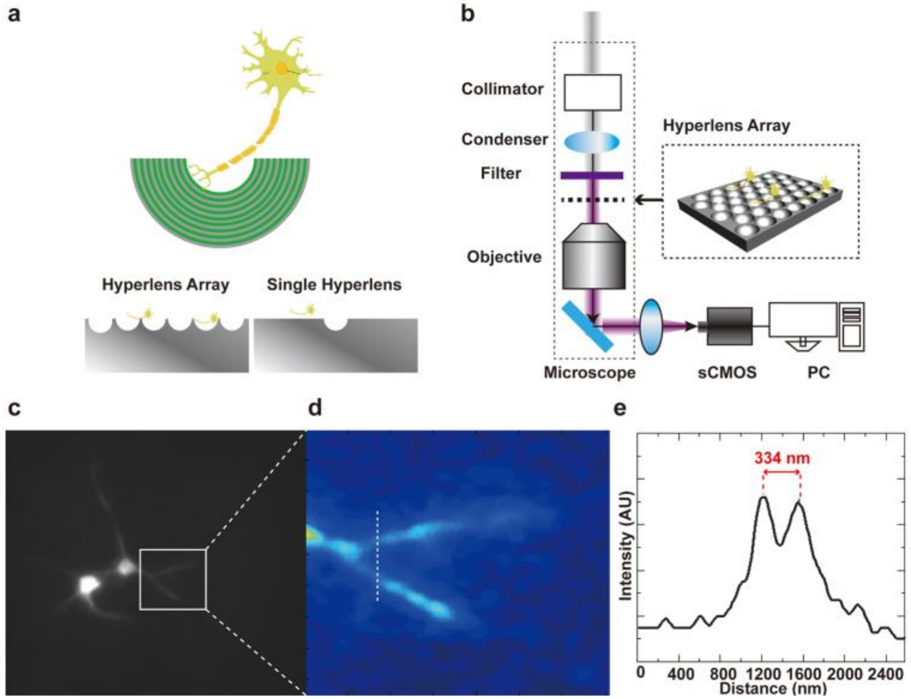


Liu, Z., et al, X. *Science* **315,** 1686 (2007).

Objects under hyperbolic media can be magnified

Early demonstrations of super-resolution imaging





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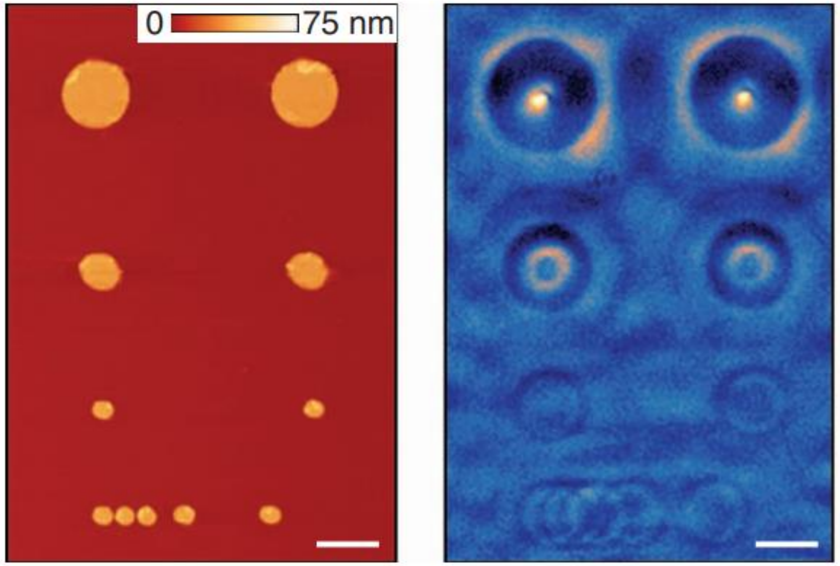
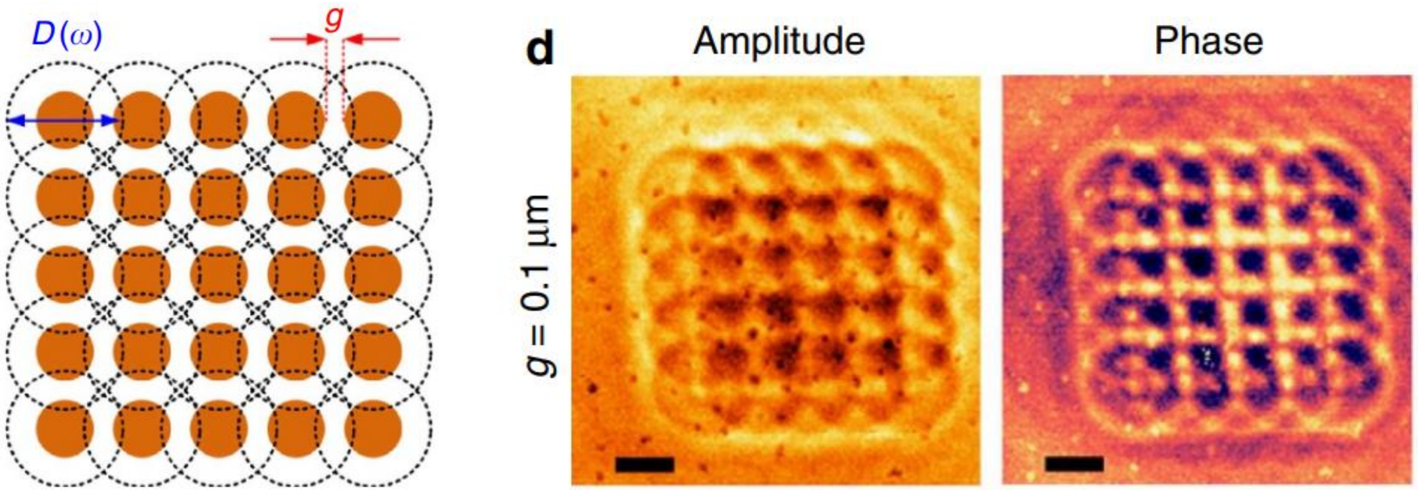
Lee, Dasol, et al. *ACS Photonics* 5.7 (2017): 2549-2554.



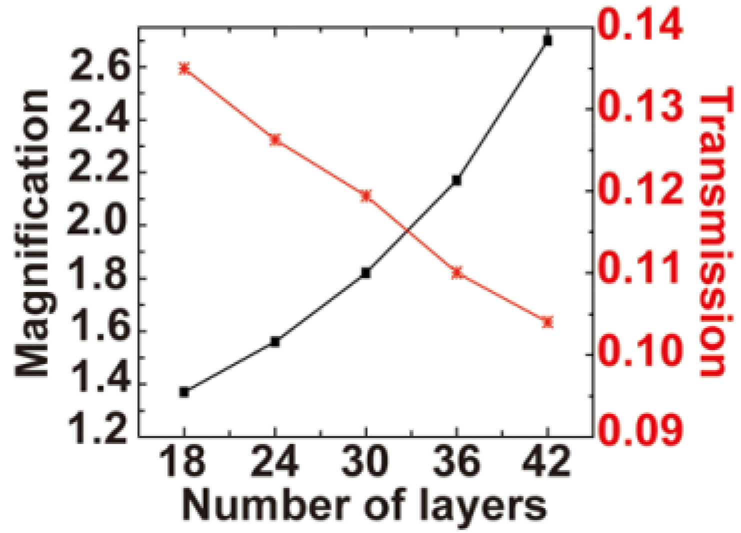
Dai, S., et al. *Nature communications* 6.1 (2015): 1-7.



Li, Peining, et al. *Nature communications* 6.1 (2015): 1-9.

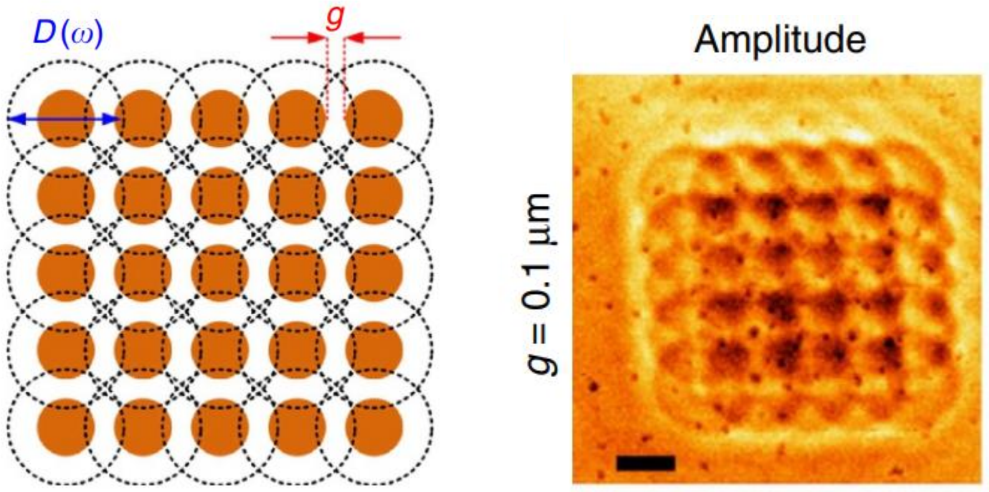
Challenges remaining

- Signal strength
  - (transmission rate, signal noise ratio, etc)
- Spatial resolution
- **Solution:**
- ***Decreased loss from hyperbolic material***



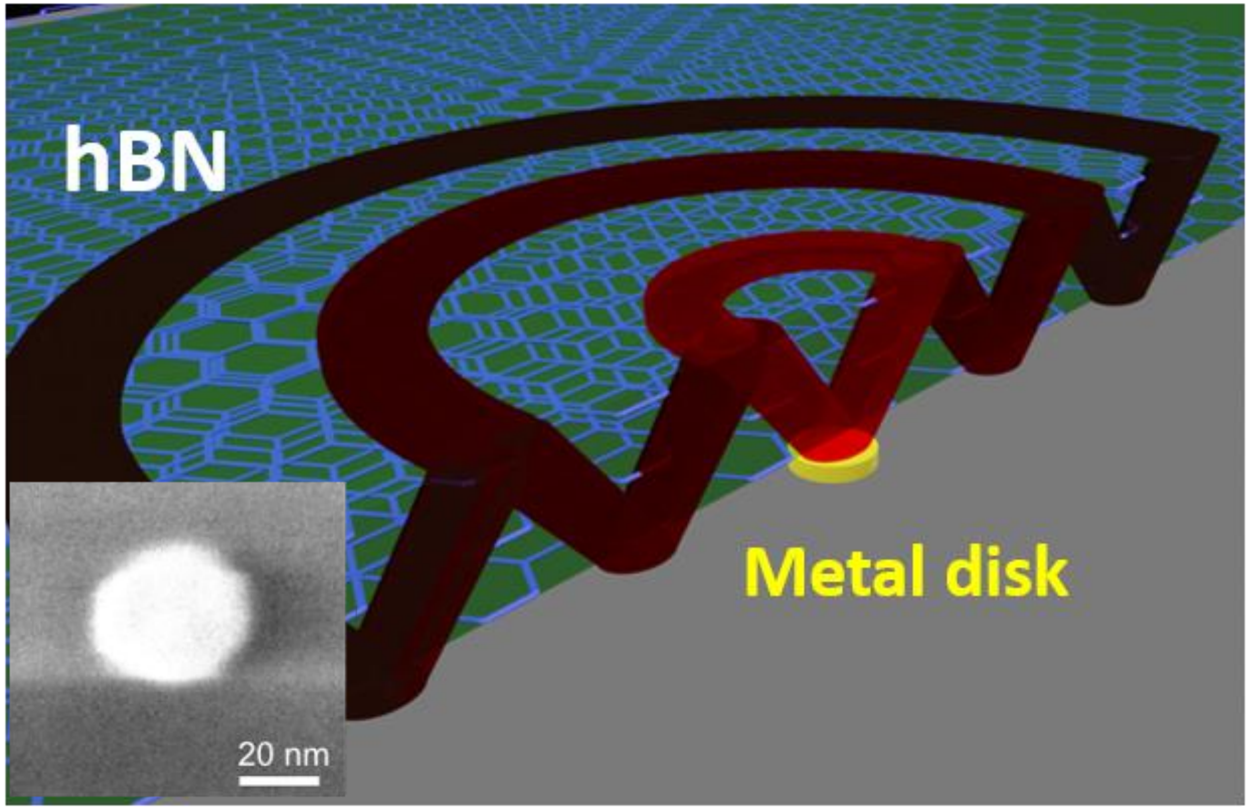
Lee, Dasol, et al. *ACS Photonics* 5.7 (2017): 2549-2554.

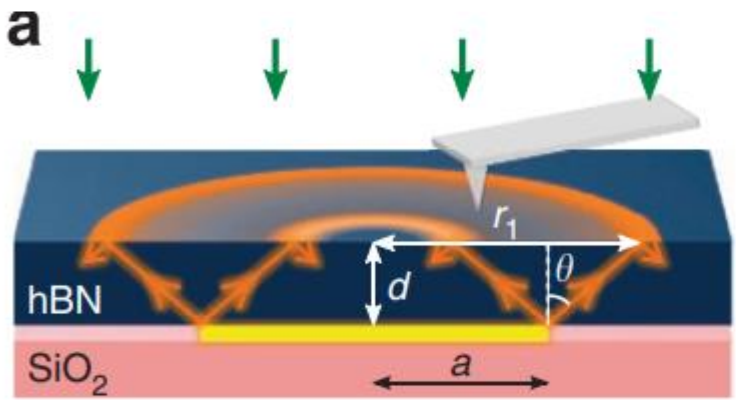
- Convoluted hyperlens field
- **Solution:**
- ***Algorithm reconstruction***



Li, Peining, et al. *Nature communications* 6.1 (2015): 1-9.

Schematics of our hyperlens



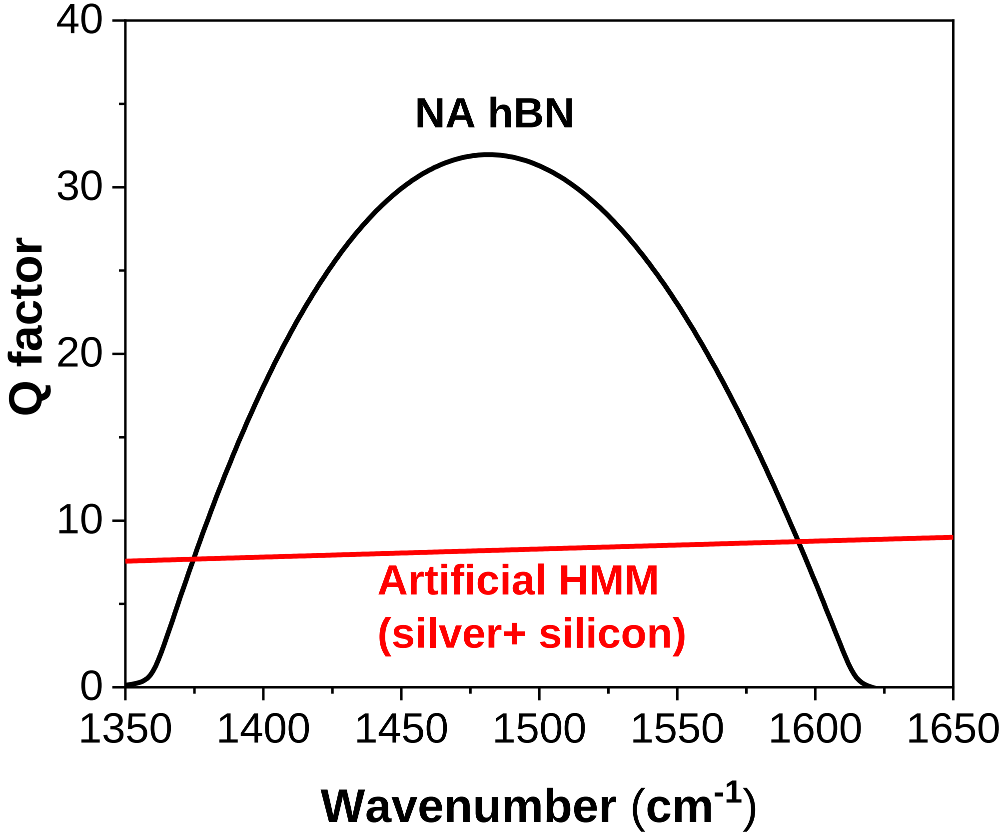


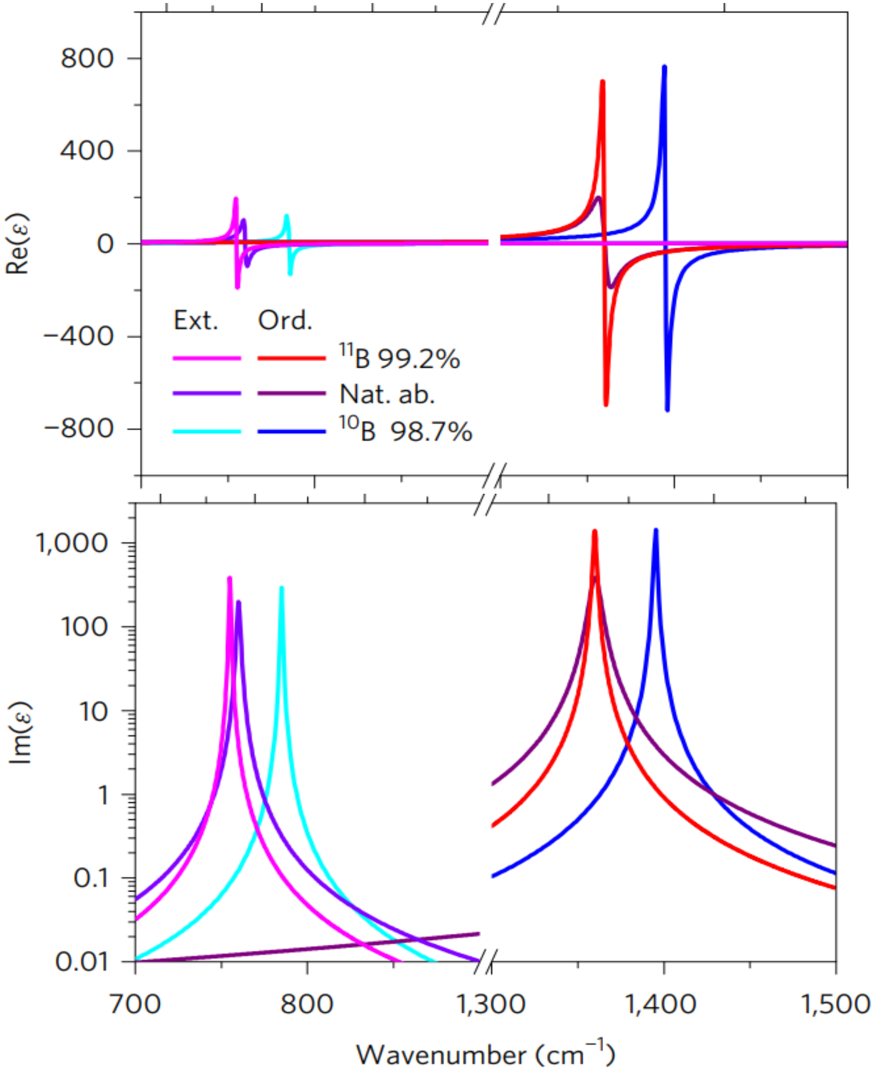
Dai, S., et al. *Nature communications* 6.1 (2015): 1-7.

1. **High momentum polaritons launched by the objects**
2. **Propagating and magnified through the hyperbolic material**
3. **Probed in the near-field at the top surface**

Mingze He, Ganjigunte R. S. Iyer, Shaurya Aarav, et al. *Nano Letters* **2021** *21* (19), 7921-7928

Material advancements via isotopic engineering

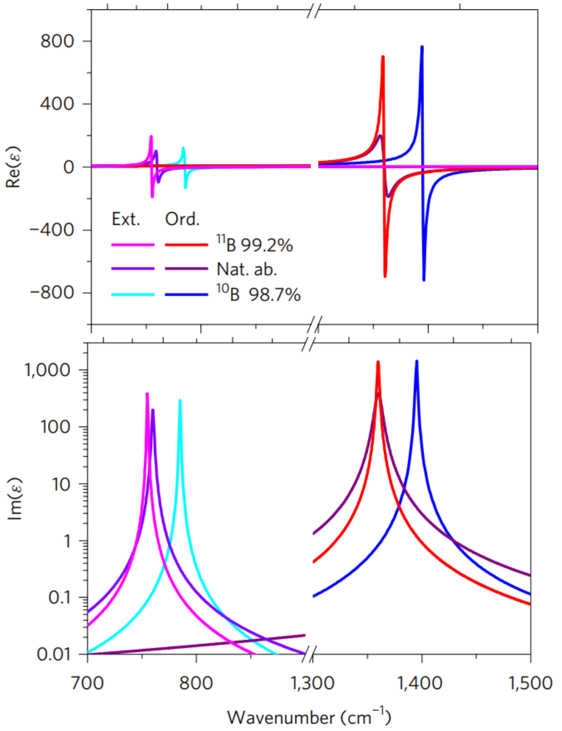


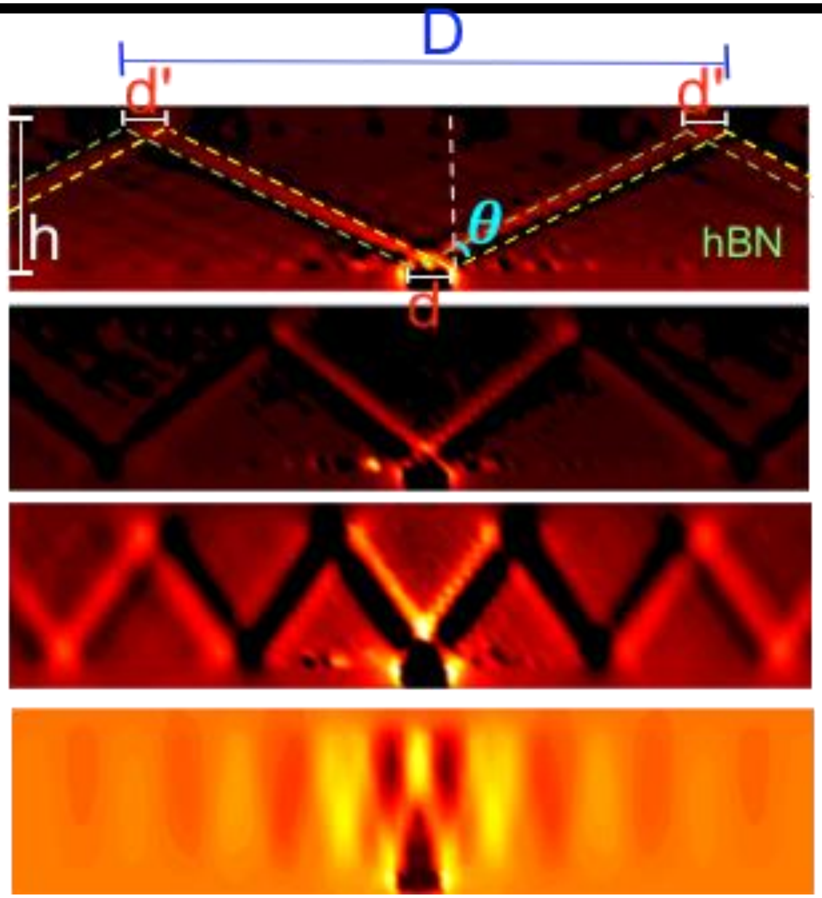


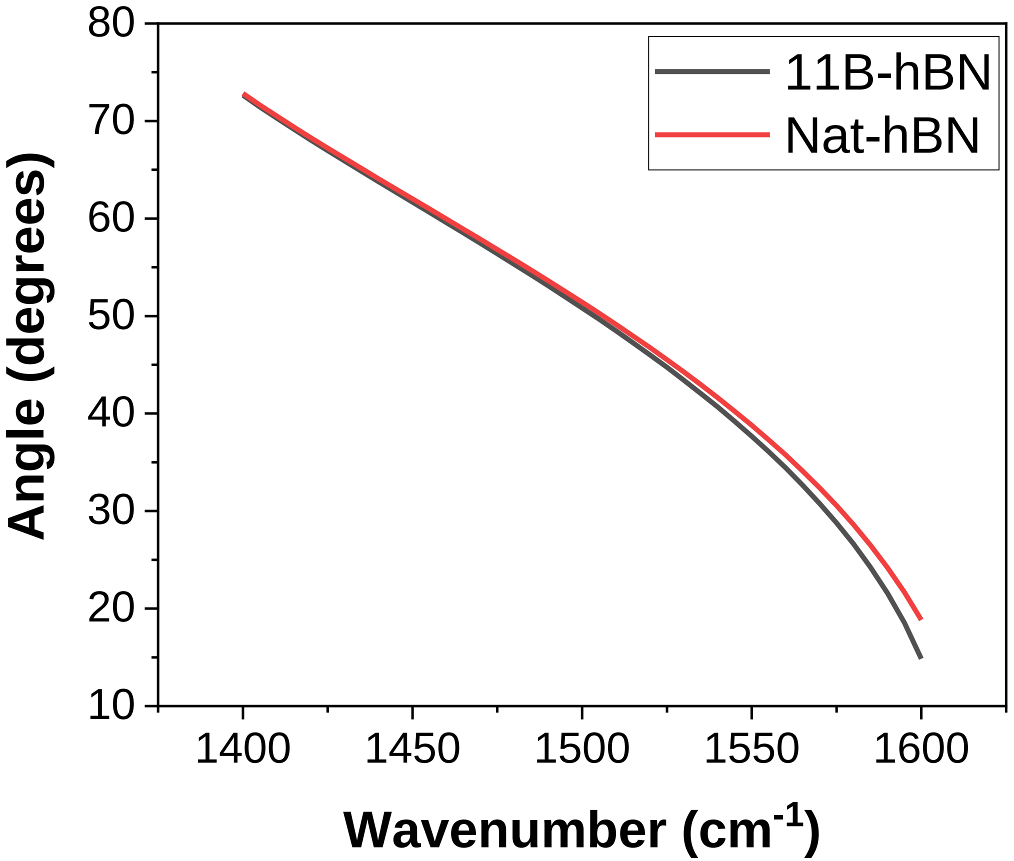
With isotopic enrichment, the loss can be further reduced

Giles, A., *et al.* *Nature Mater* **2017,** 134–139 (2018).

Material advancements via isotopic engineering



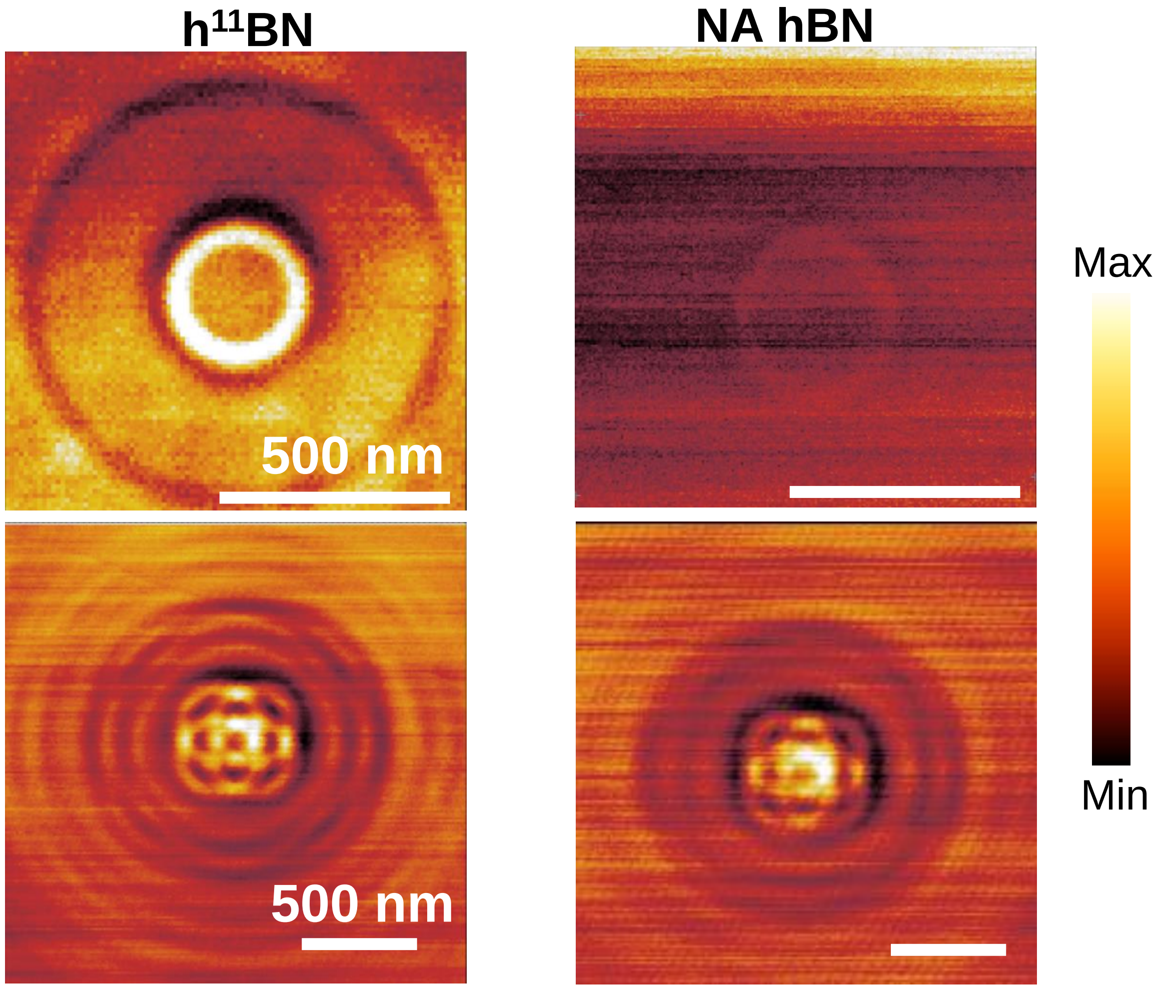


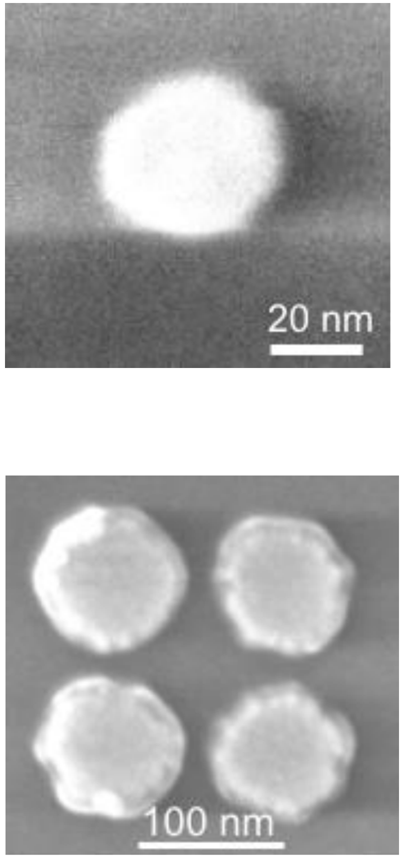


Same phonon frequency, reduced imaginary part of permittivity
Comparable real part (magnification times)

Giles, A., *et al.* *Nature Mater* **2017,** 134–139 (2018).
Mingze He, Ganjigunte R. S. Iyer, Shaurya Aarav, et al. .*Nano Letters* **2021** *21* (19), 7921-7928

Experimental demonstration of reduced loss





44 nm diameter disk

1500 cm^{-1} (6.67 μm)

100 nm diameter disk

125 nm pitch

25 nm spacing

1480 cm^{-1} (6.76 μm)

Improved image quality from h^{11}BN

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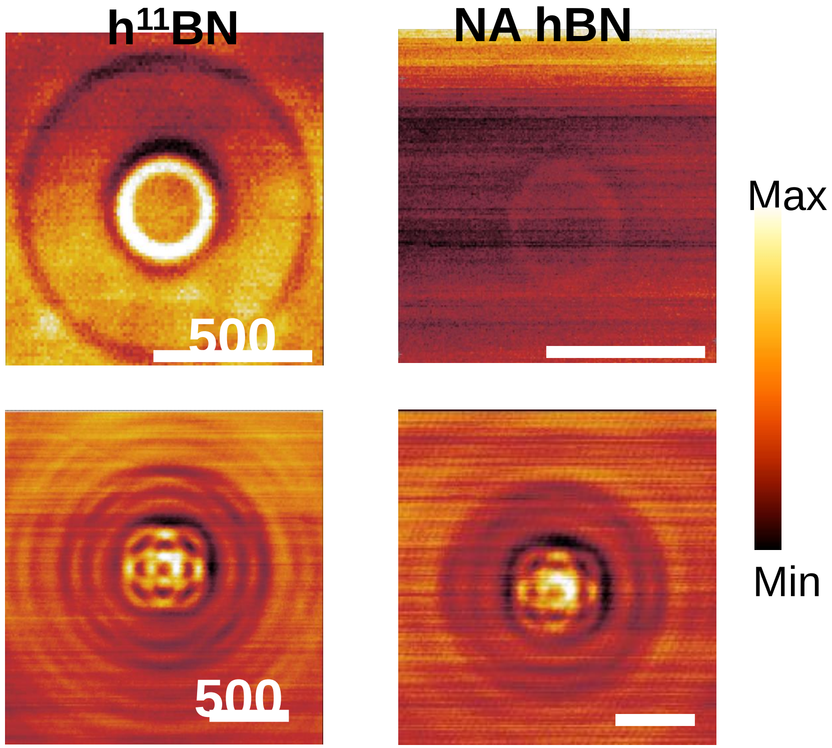
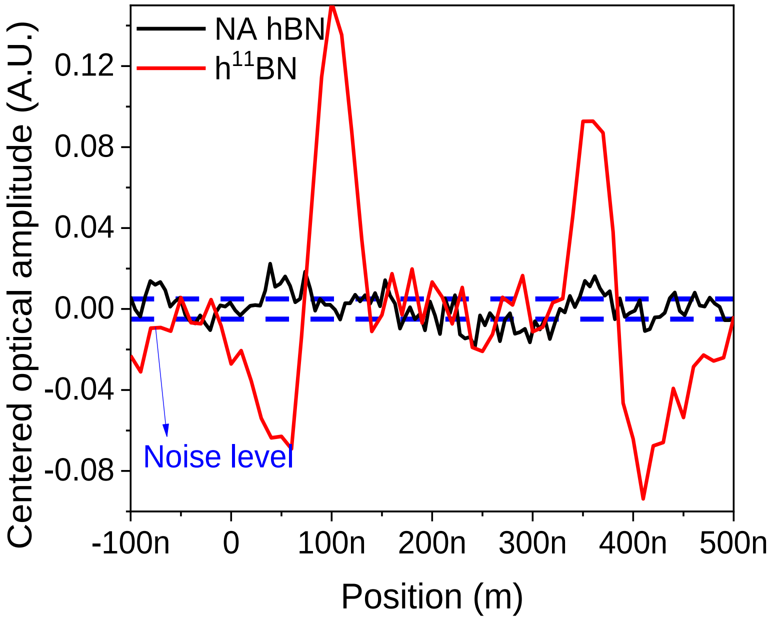
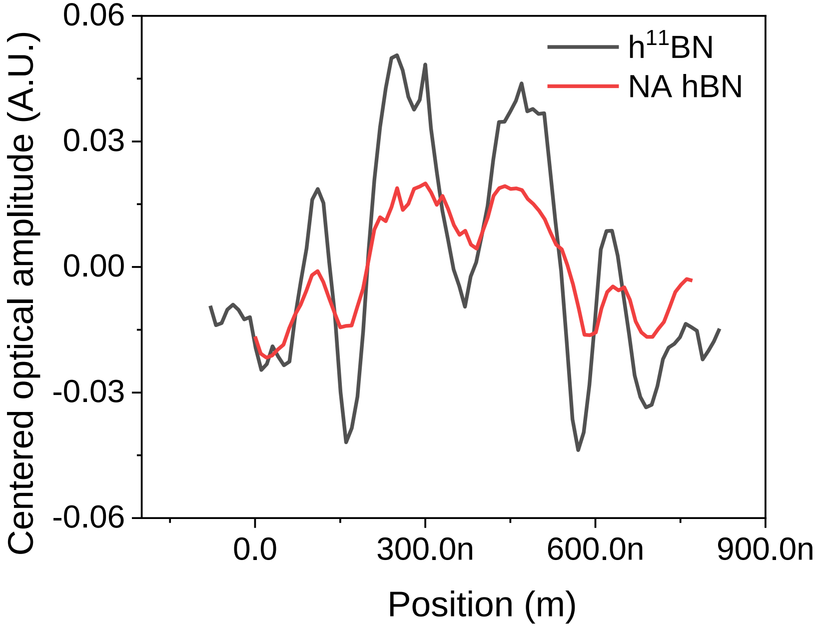
Quantifying the improvements







Comparable noise level
Enhanced signal strength
Improved signal noise ratio (SNR)

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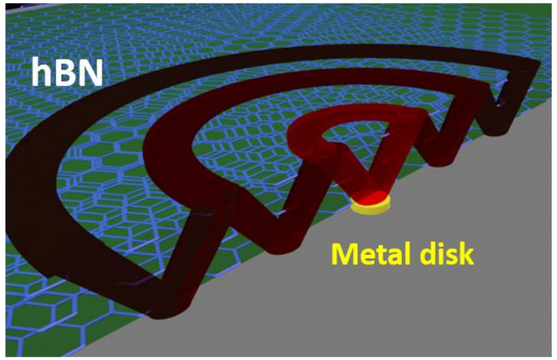
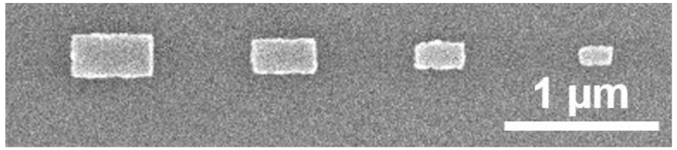
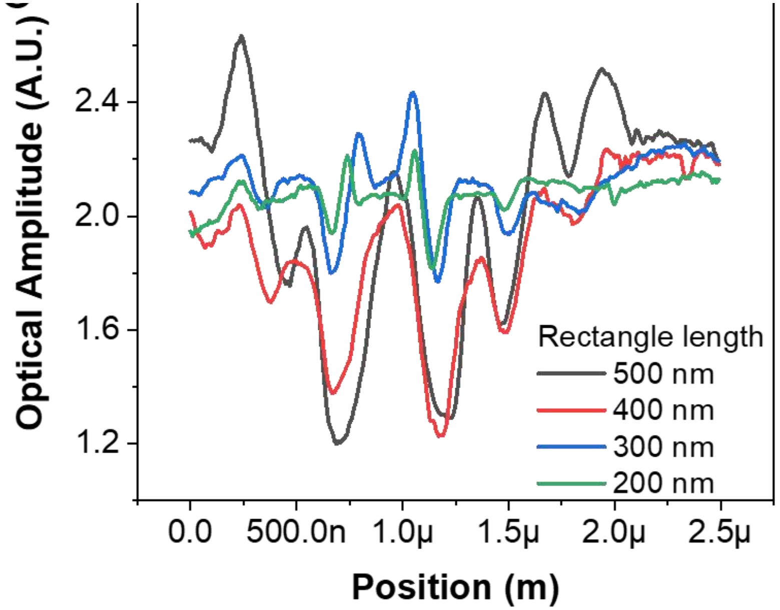
The relationship between loss and resolution

$$E_{top\ surface} = E_{bottom}\frac{circumference_{disk}}{circumference_{top\ ring}}\frac{1}{Loss}$$

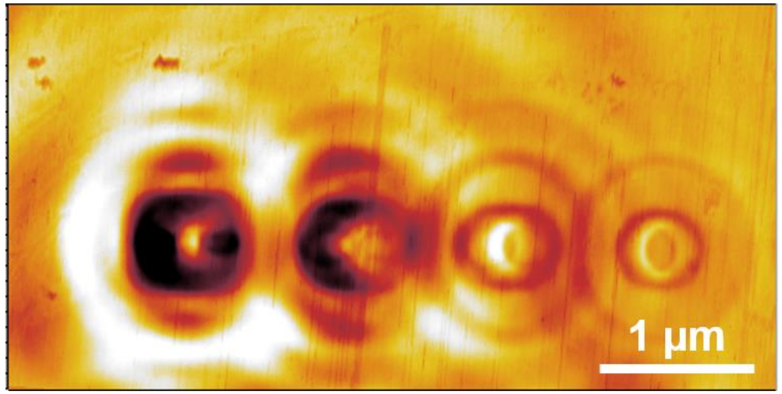


$$= \frac{E_{bottom}}{Loss \cdot Magnification}$$





b



The **measurable** $E_{top\ surface}$ is defined as noise-equivalent power, which is a **constant** dictated by detector, s-SNOM…

With reduced loss, we can get higher $Magnification$**.**

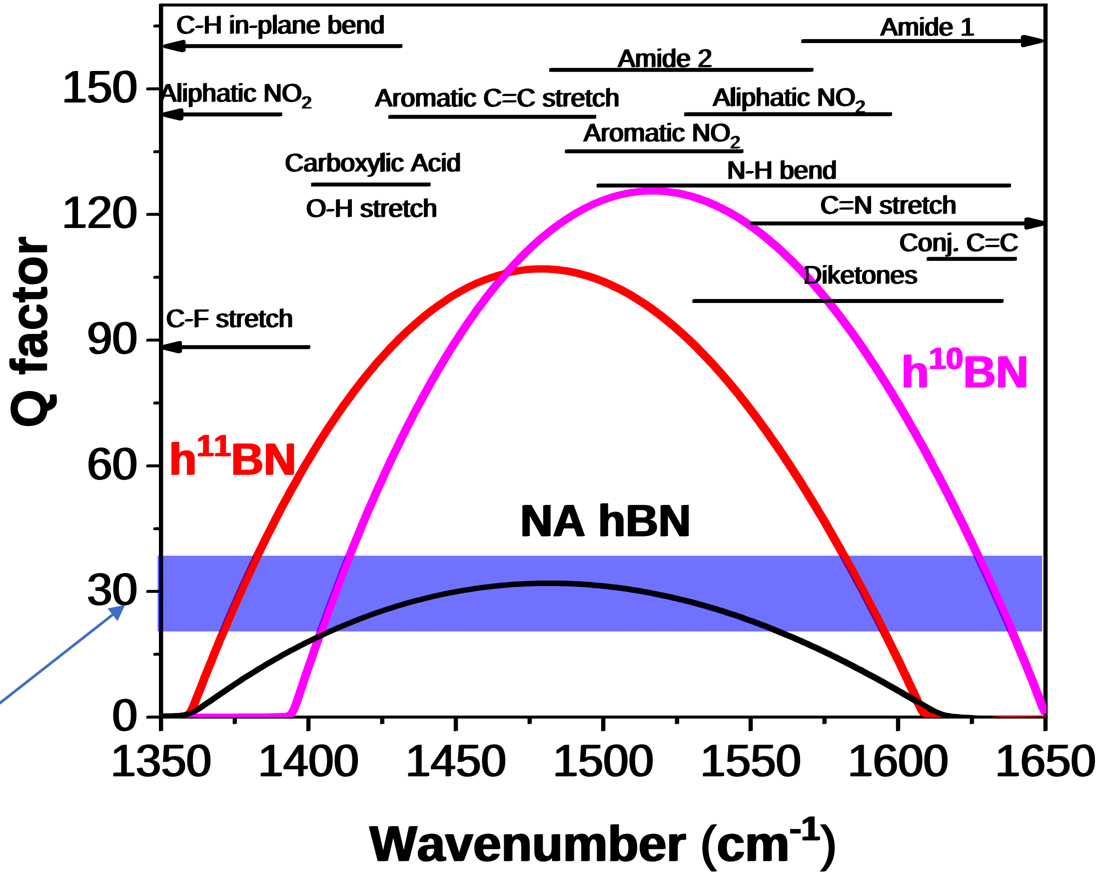
Material advancements

$$k(w) = k' + ik'' = -\frac{\psi}{t}\left[a\tan\left(\frac{\varepsilon_o}{\varepsilon_t\psi}\right) + a\tan\left(\frac{\varepsilon_s}{\varepsilon_t\psi}\right) + \pi l\right]$$

$$\psi = -i\sqrt{\frac{\varepsilon_z}{\varepsilon_t}} \quad (3)$$

Dai, S. *et al. Nano letters* **19**, 1009-1014 (2018).

$$Q = \frac{k'}{k''} = 4\pi N$$

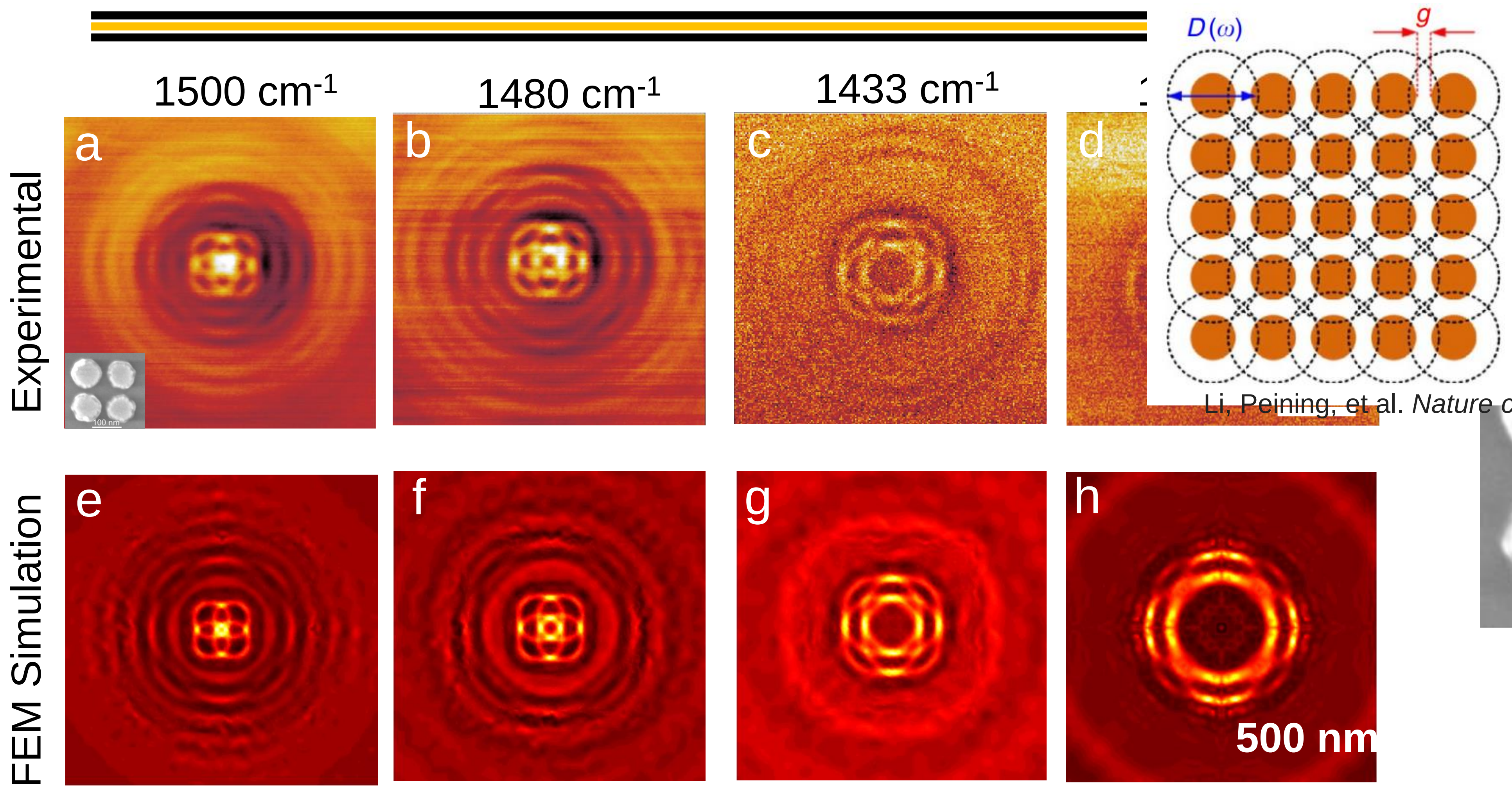


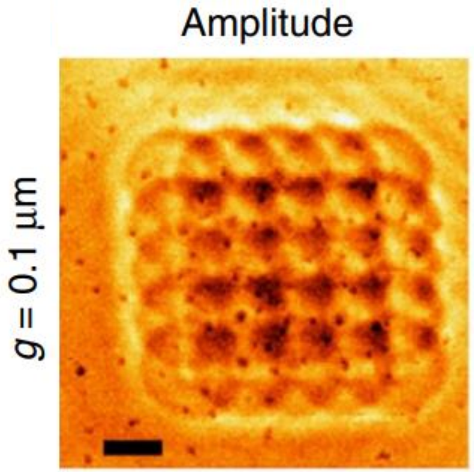
Assuming sodium/silicon HMM

Wang, Yang, et al. Nature 581.7809 (2020): 401-405.

In the mid IR, isotopically enriched hBN outperforms natural hBN, as well as artificial hyperbolic materials (metal/dielectric stacks)

Complicated hyperlens field





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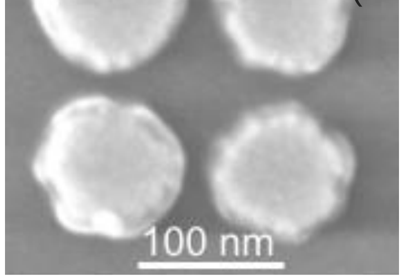

Hyperlens fields are convoluted

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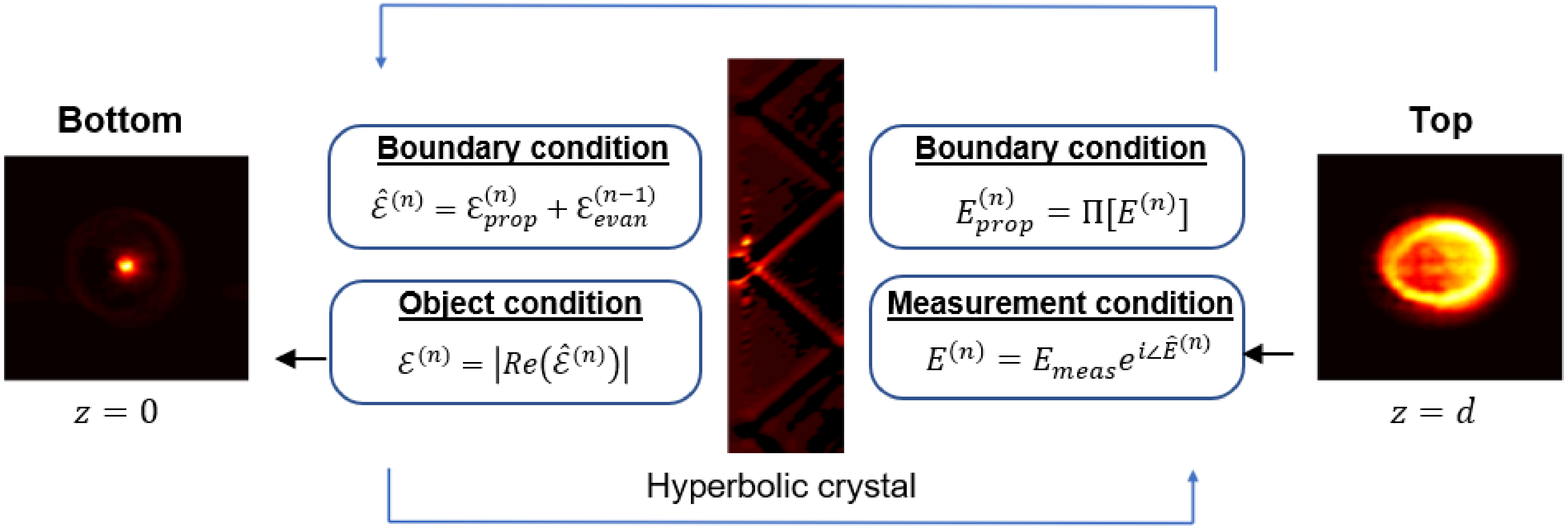
Algorithm to reconstruct hyperlens field

Back-propagation: $\mathcal{E}^{(n)}_{prop} = \mathcal{P}_{-d}\left[E^{(n)}_{prop}\right]$



Forward propagation: $\hat{E}^{(n)} = \mathcal{P}_{d}\left[\mathcal{E}^{(n)}\right]$

Field under the hyperbolic material can be reconstructed from the E-field amplitude at the top surface

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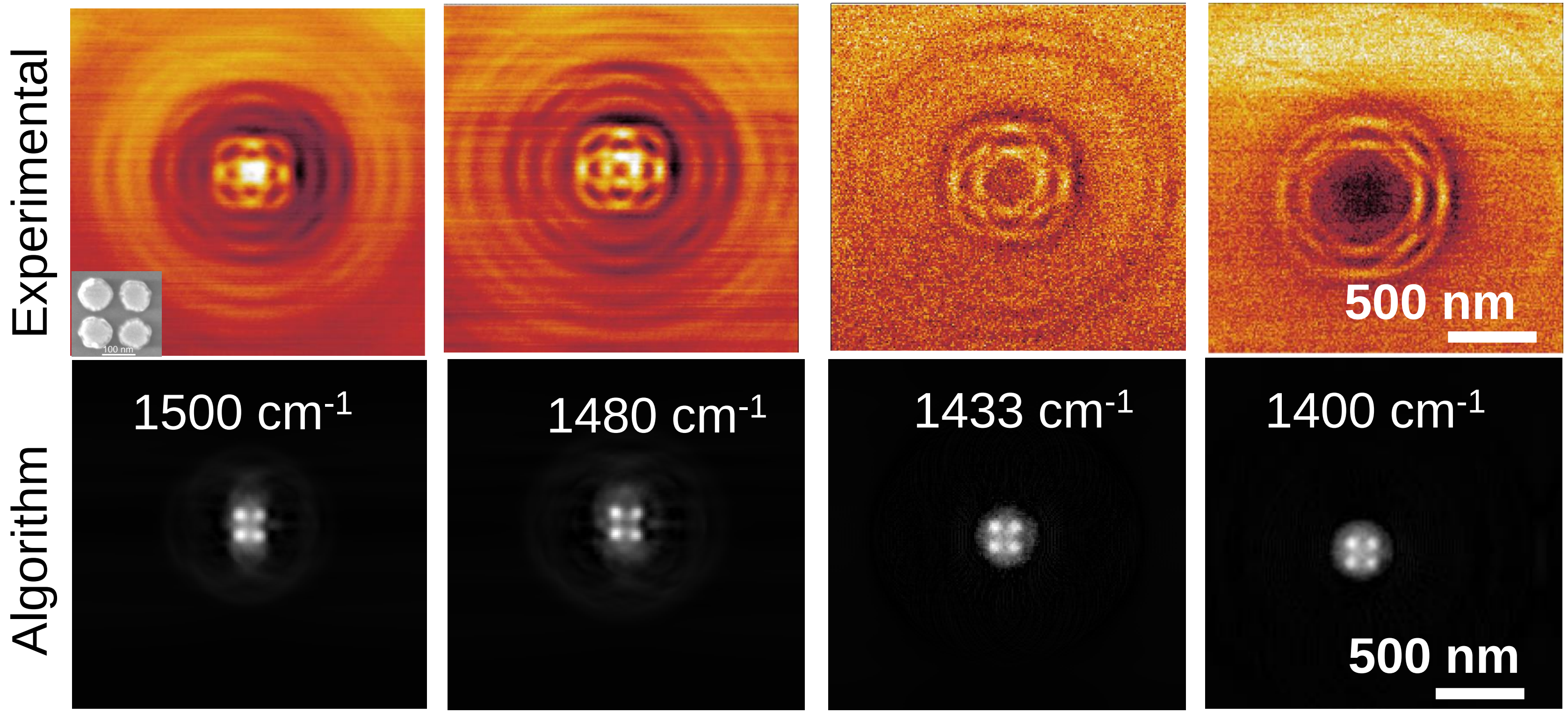
Reconstructed fields under hyperbolic media



Accurate reconstruction can be performed

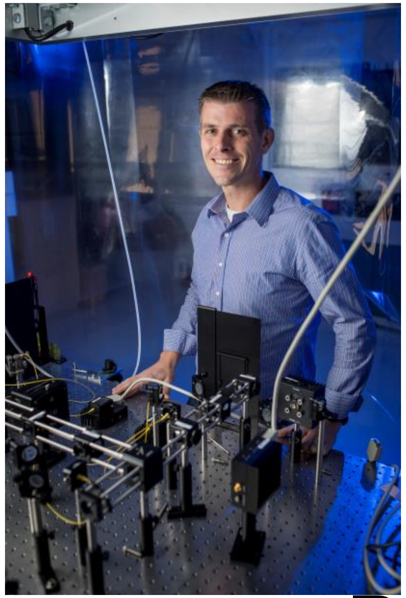
Image frequency (cm^{-1})	Disk diameters (nm)	Pitch size (nm)	Interparticle gap (nm)
1400	86 (2)	113 (2)	27 (2)
1433	88 (5)	113 (8)	25 (8)
1482	83 (6)	117 (6)	34 (8)
1500	89 (5)	112 (12)	23 (13)
SEM	100	125	25

Summary

- Material advancements enable high-resolution hyperlens imaging
  - 44 nm diameter disk imaged
  - 100 nm diameter disks with 125 nm pitch resolved
  - Outperforms natural hBN and artificial HMM significantly
- Computational technique allows accurate reconstruction of E-field from convoluted hyperlens field with only amplitude information
  - Could be used in other measurement schemes, e.g., photothermal infrared (PTIR)

The Caldwell Group

Prof. Joshua Caldwell



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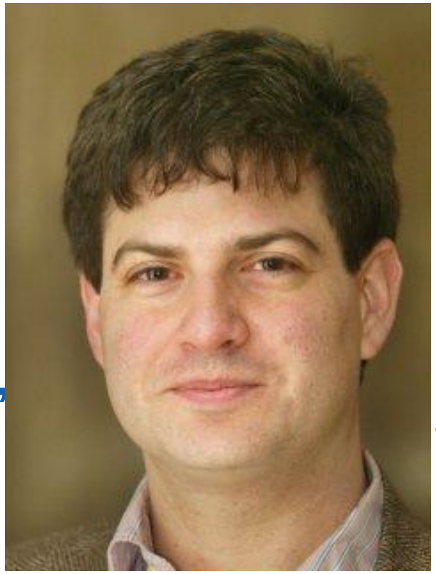

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