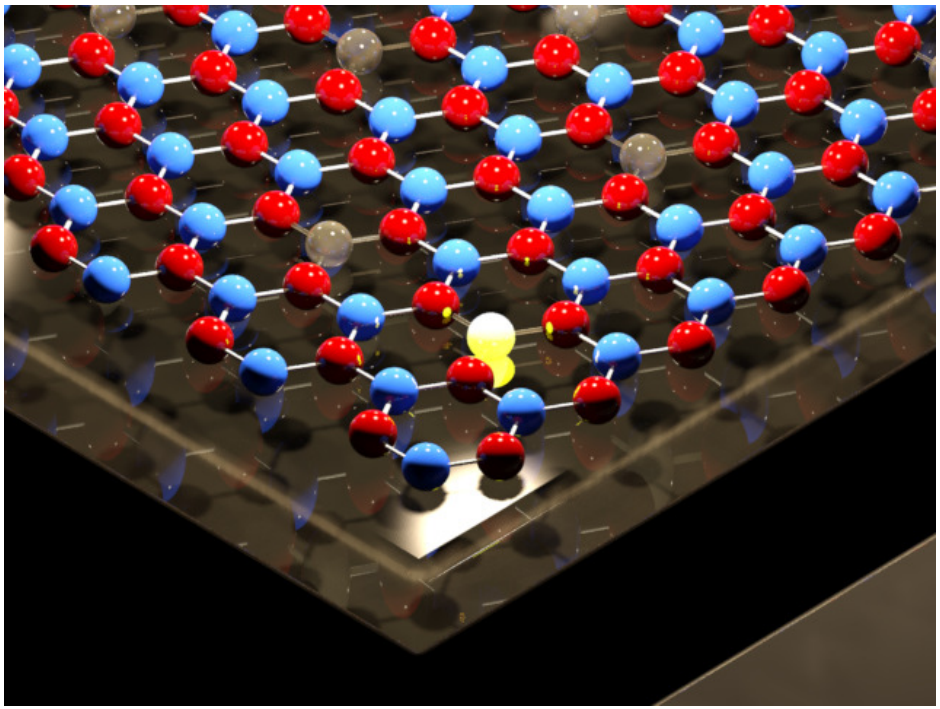
# Quantum Emitters in 2D Materials

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*Institute of Bio-Medical Materials and Devices, University of Technology Sydney*


*Nanolight 2018, Benasque*

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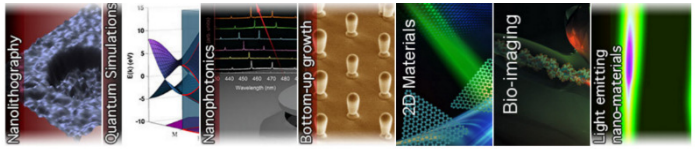
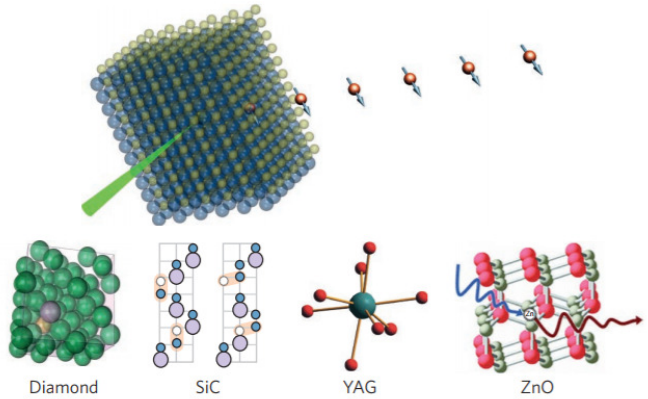



www.sydneynano.com

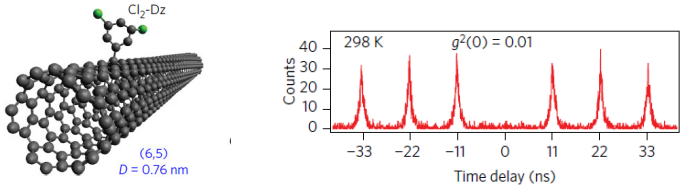
# *Do we actually need more single photon sources?*

## Colour centres in solids

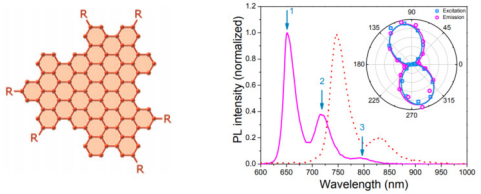



I. Aharonovich et al., Nat. Photonics (2016)

## Defects in CNTs and Graphene QDs

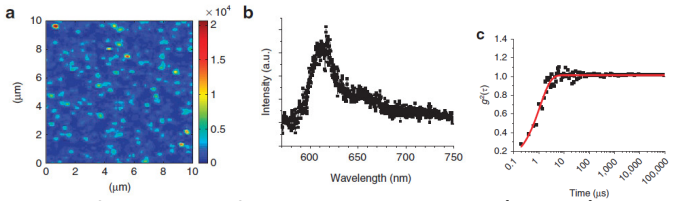



X. He et al., Nat. Photonics (2017)

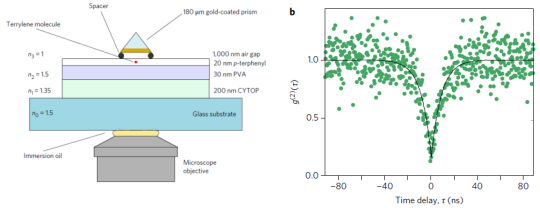



S. Zhao, J Lauret et al., arXiv:1802.09870

## Single molecules

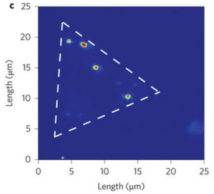



L. Zhang et al., Nat. Commun. (2017)

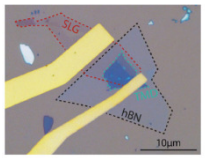



X.-L. Chu et al., Nat. Photonics (2017)

## 2D materials



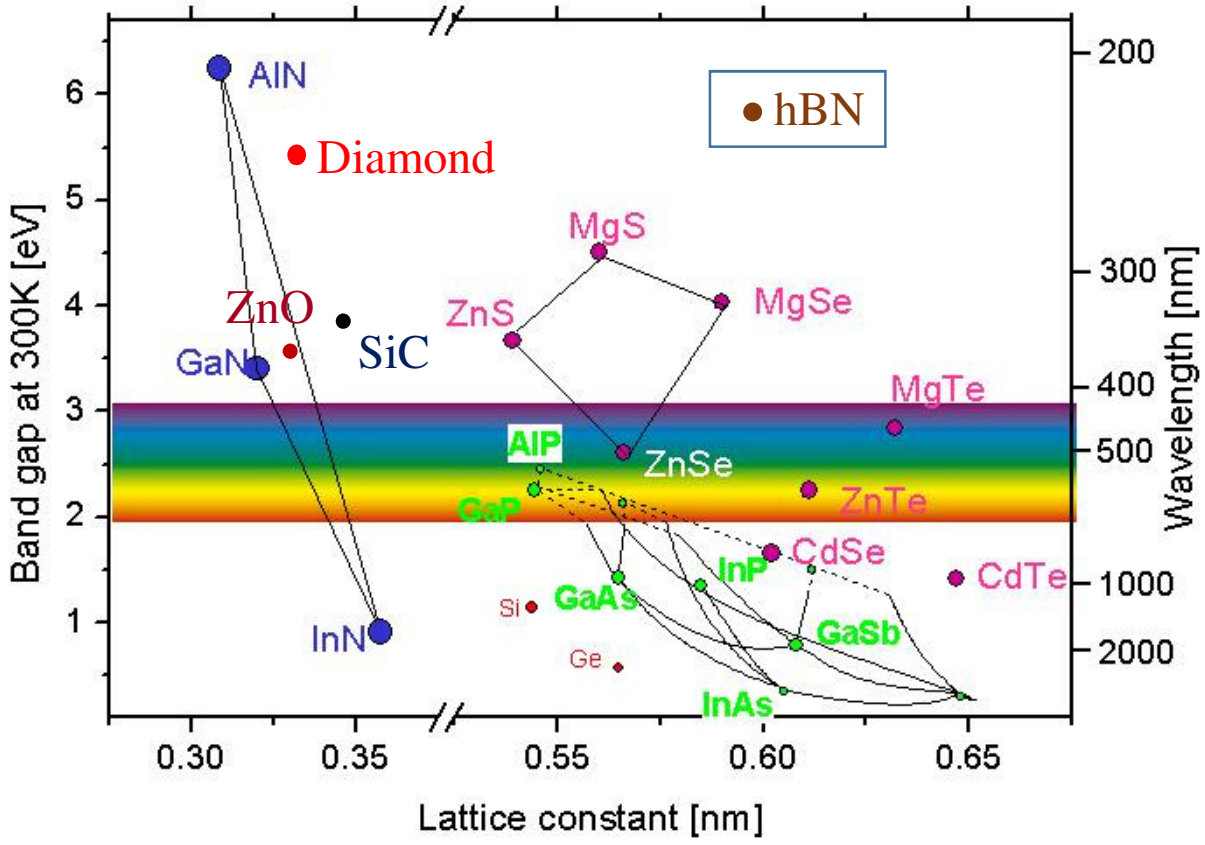
C. Chakraborty et al., nature nano (2015)
A. Srivastava et al., nature nano (2015)
Y. M. He et al., nature nano (2015)
M. Koperski et al., nature nano (2015)
P. Tonndorf et al., , Optica (2015)

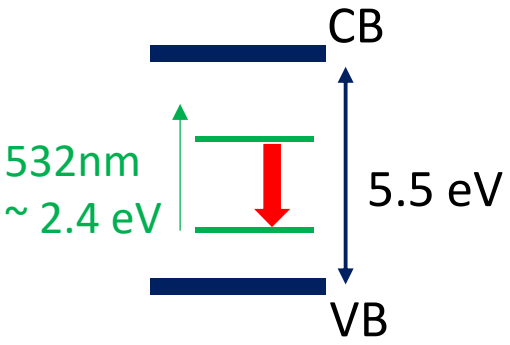


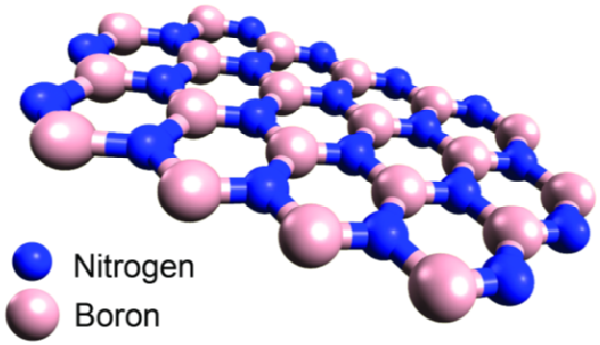

### Electrically driven 2D sources

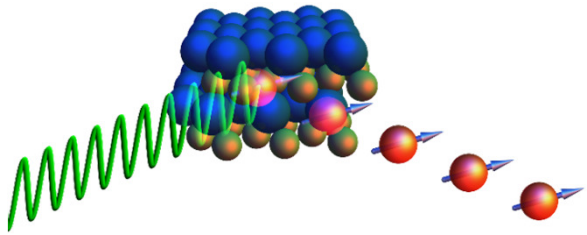
C. P. Berraquero et al., nature comms (2016)
G. Clark et al., nanoletters (2016)

# *Wide band gap semiconductors*

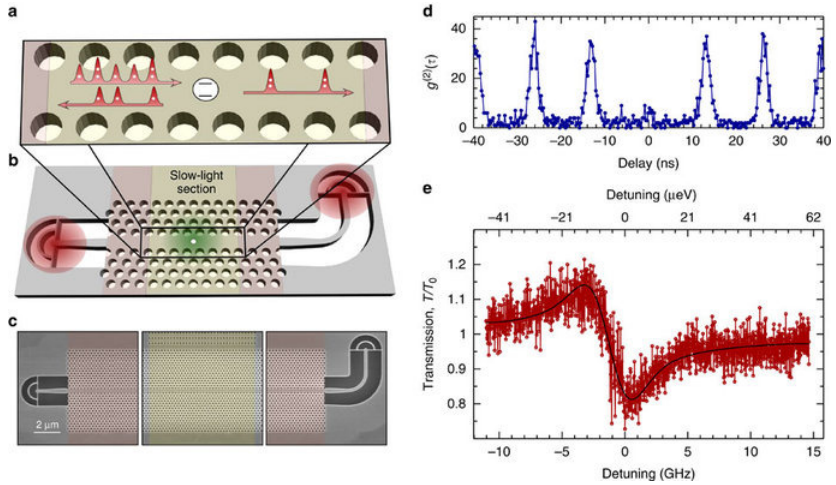


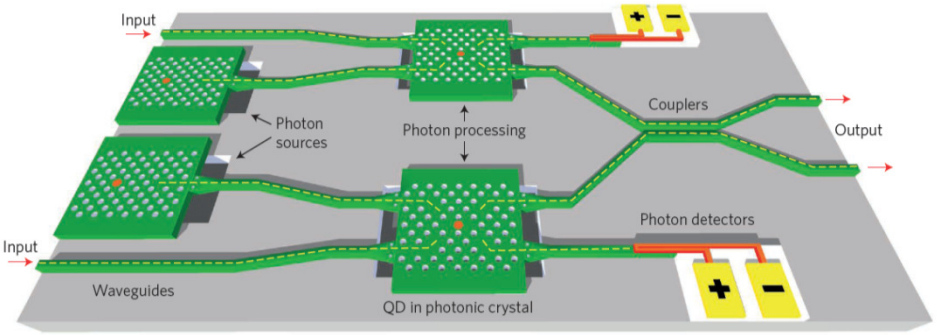



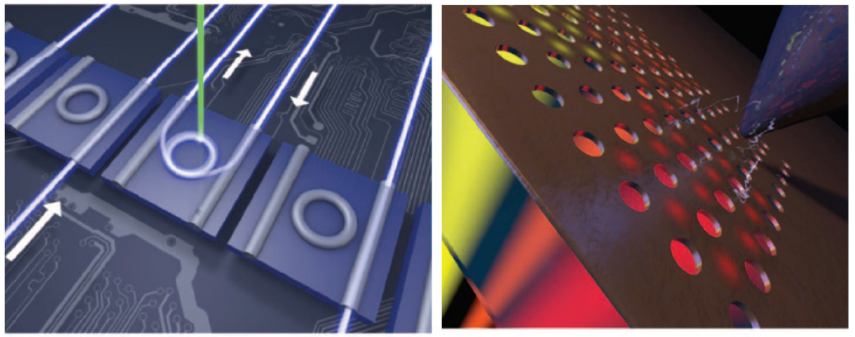



# *Quantum Nanophotonics on a single chip*

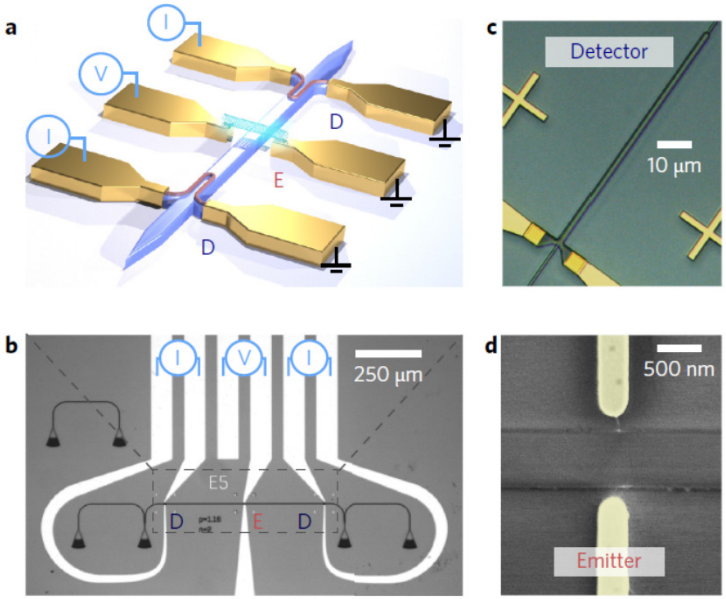



A. Javadi, P Lodahl et al., nature comms (2015)



Koenderink et al., Science (2016)
Kimble et al., Nature (2008)

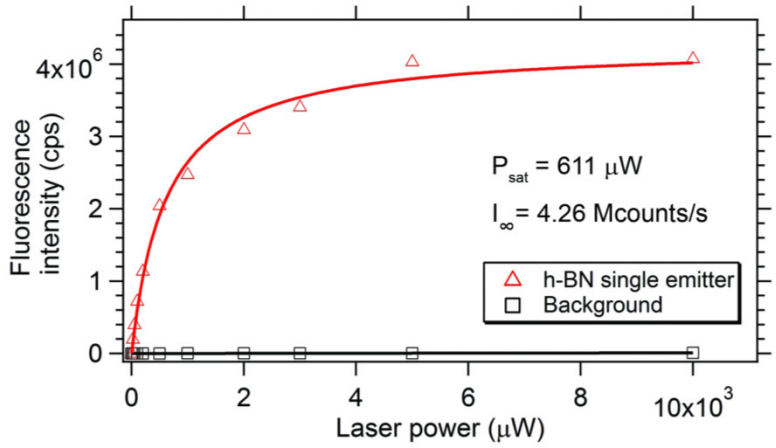


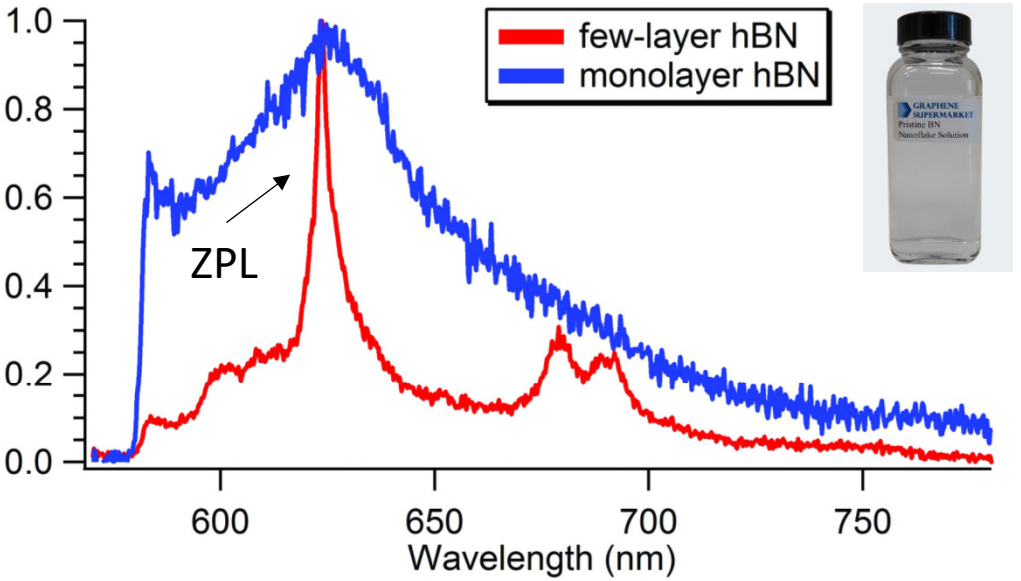

S. Khasminskaya, W Pernice et al., nature photon (2016)

"Fundamental" – e.g. single photon nonlinearity

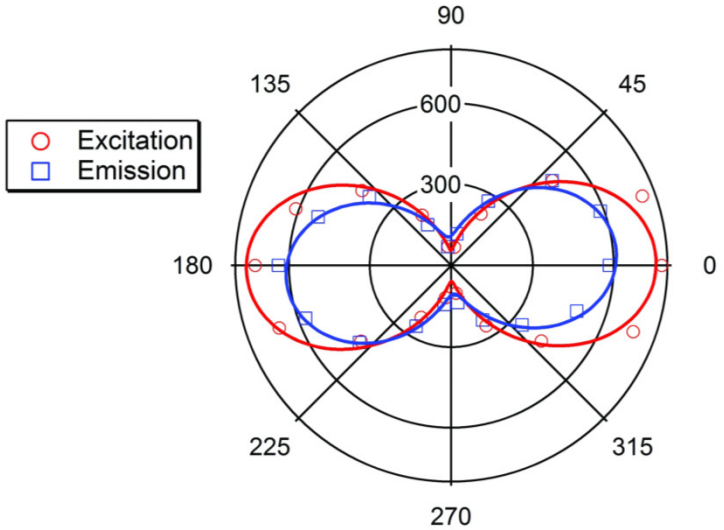
"Practical" – e.g. electrically driven SPS on a chip

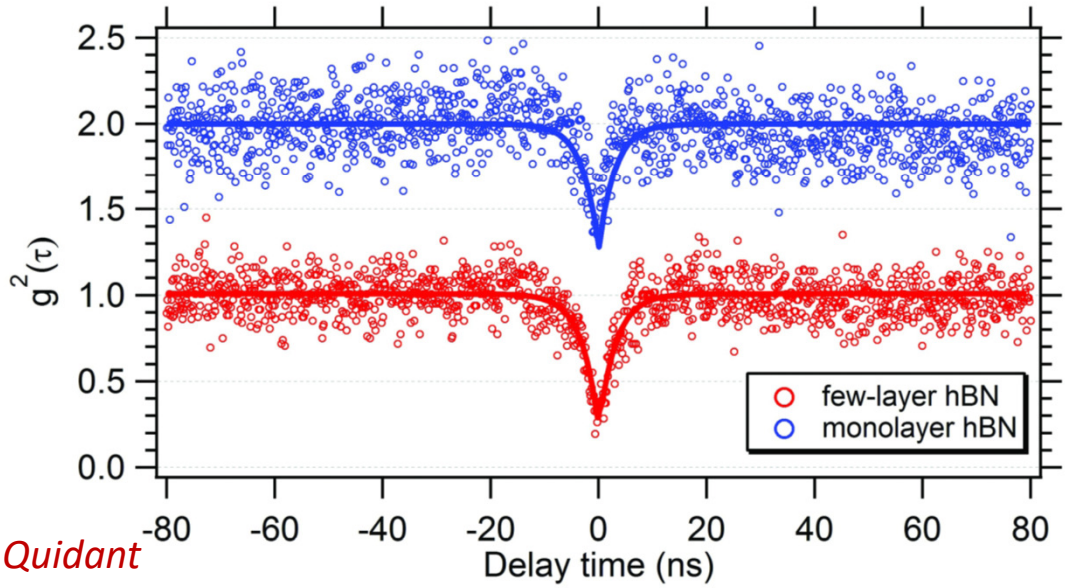
# *hBN – initial characterization*





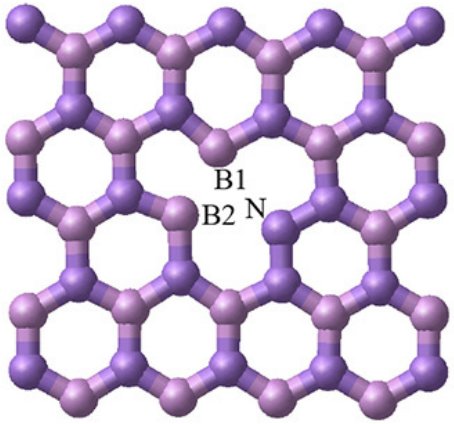




T. Tran et al., Nature Nanotech (2016)

*See also @Fuchs, Wrachtrup, Meriles, Bassett, Quidant*

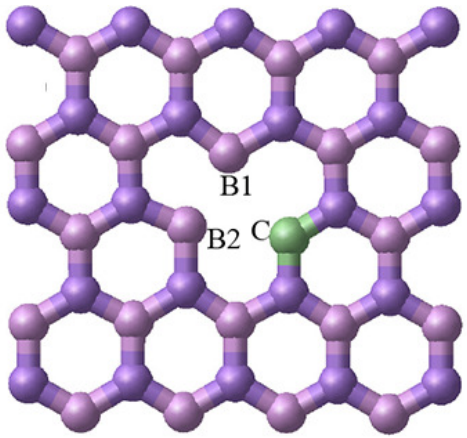
# *hBN – defect structure*

$N_BV_N$



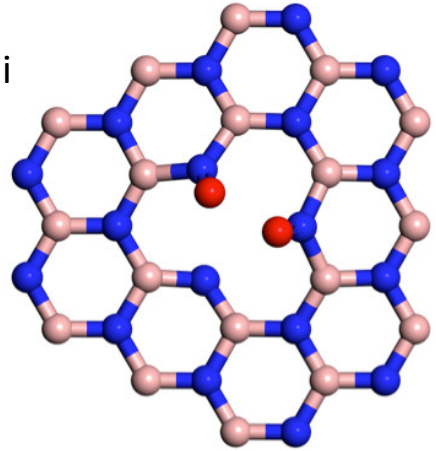

ZPL ~ 2.1 eV

$C_BV_N$

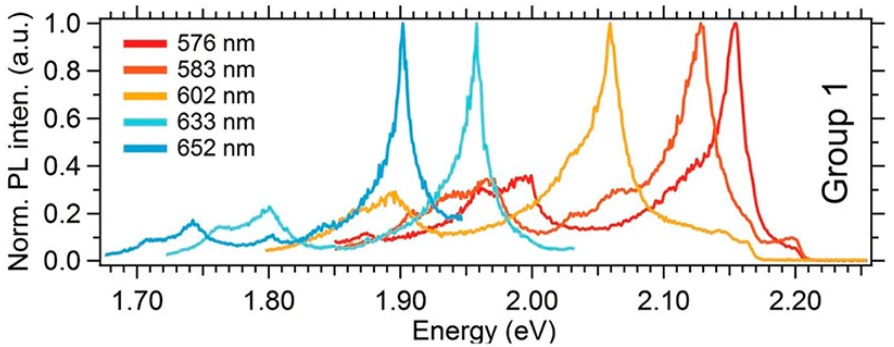


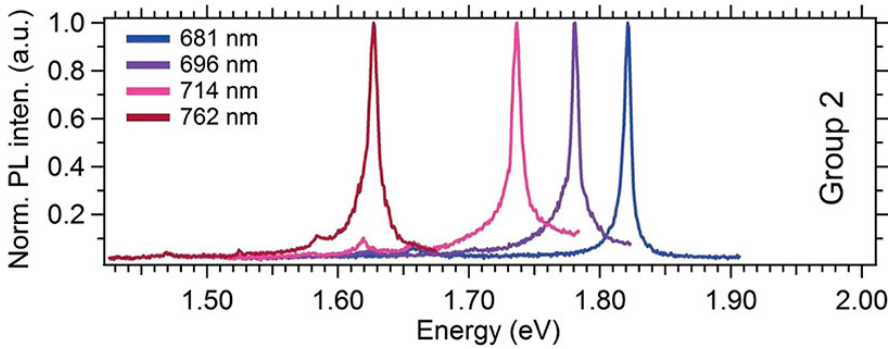

ZPL ~ 1.4 eV

$O_iV_BO_i$



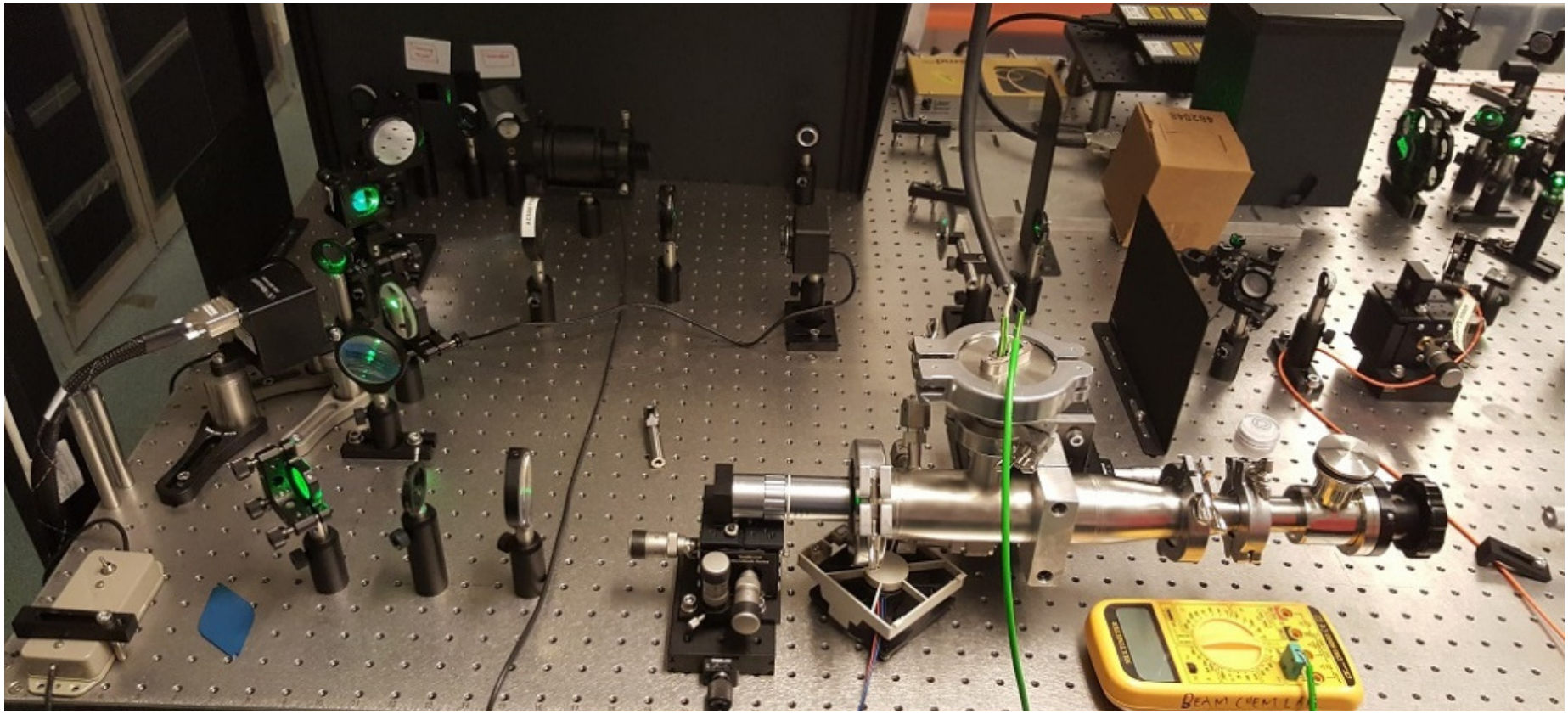
ZPL ~ 1.9 eV



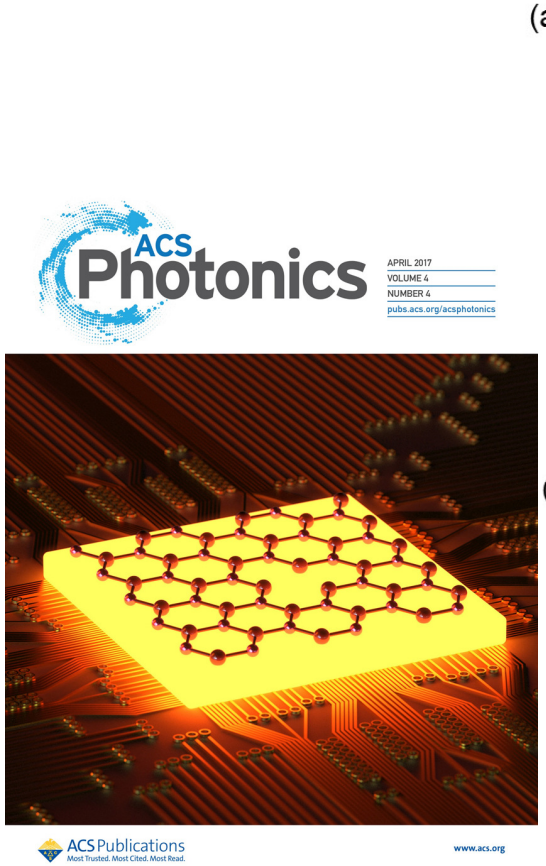

Tran et al., ACS Nano 10 (2016) 7331
Tawfik et al Nanoscale (2017)
Ford, Reimers PRB (2018)

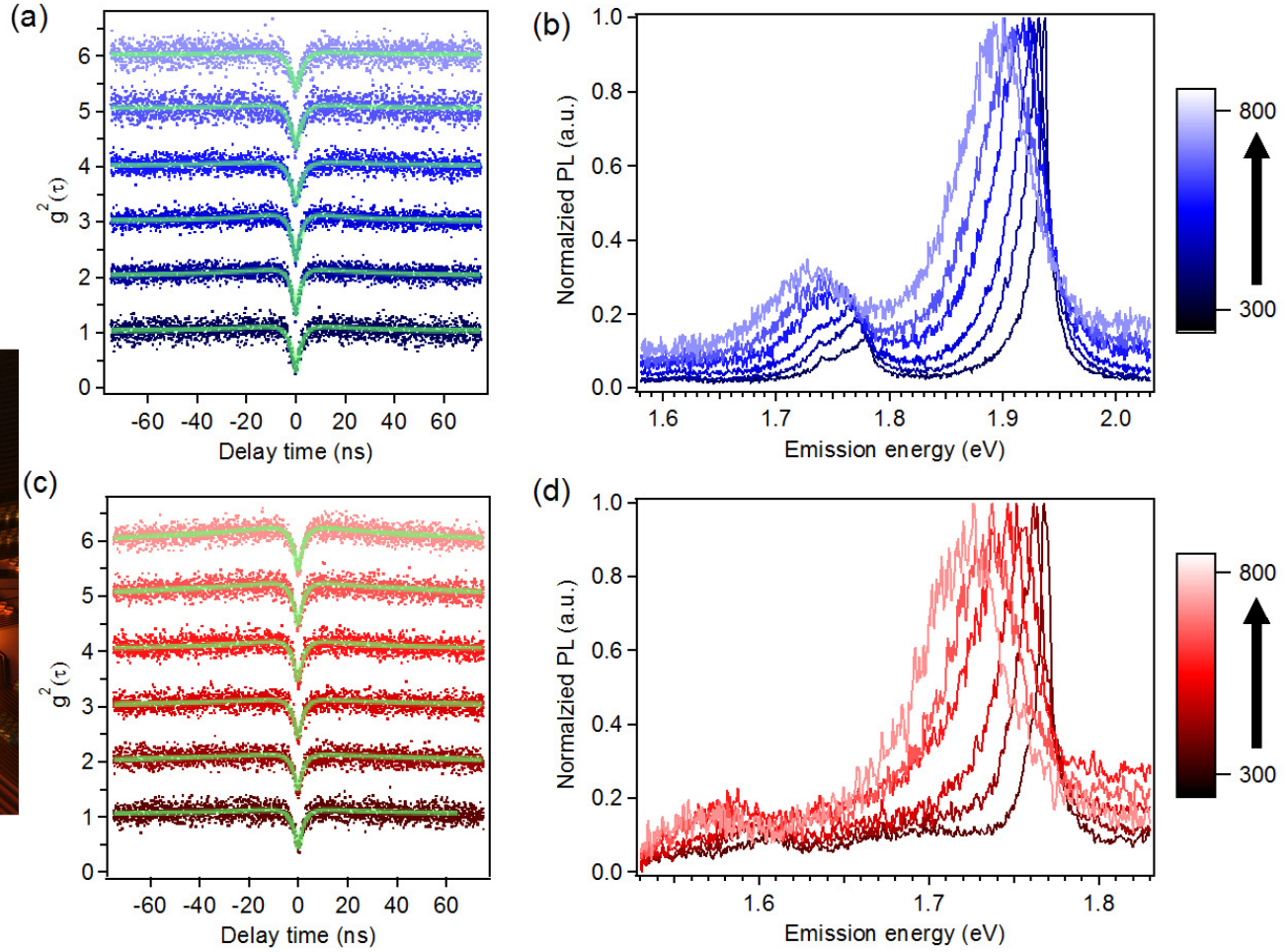
# *Emerging experiments – high Temp PL*



Kianinia et al., ACS Photon (2017)

# *Emerging experiments – high Temp PL*

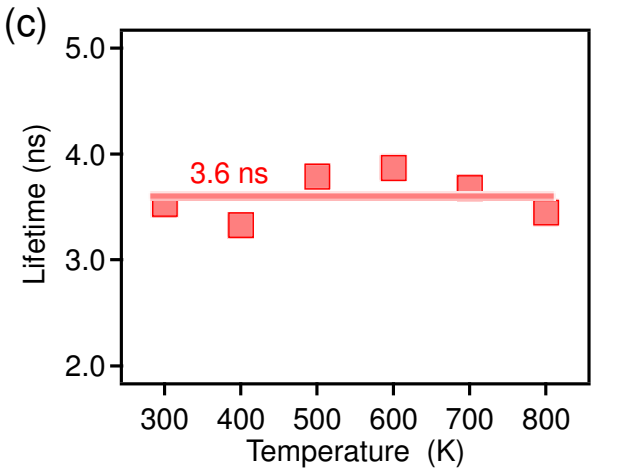


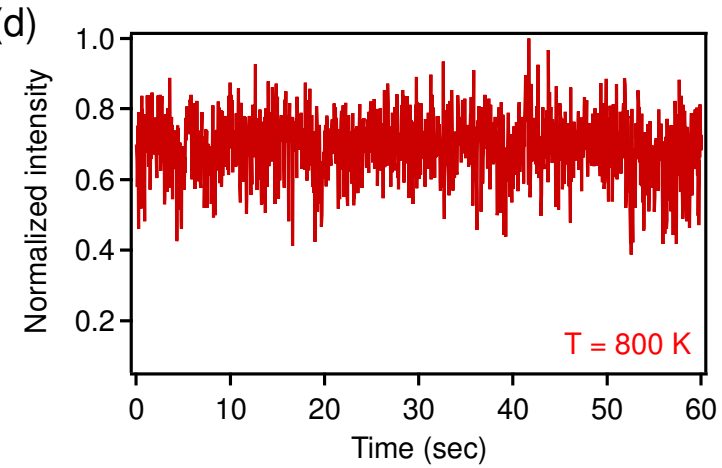



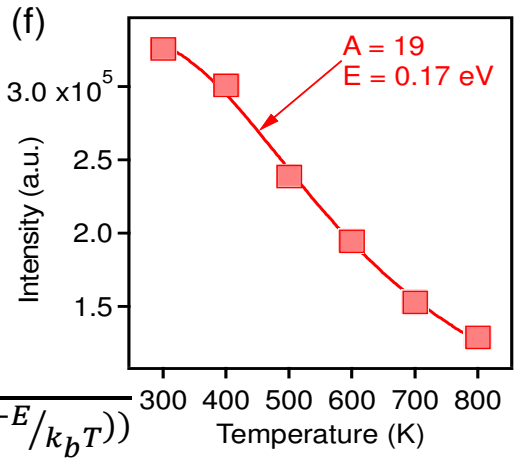

Kianinia et al., ACS Photon (2017)

- Stability up to 800K during heating and cooling
- 'Hottest' single photon source

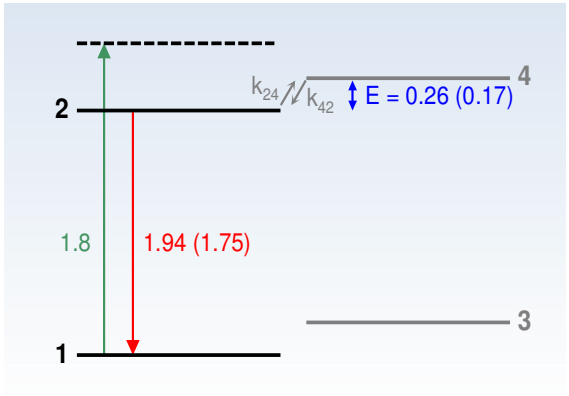
# Emerging experiments – high Temp PL



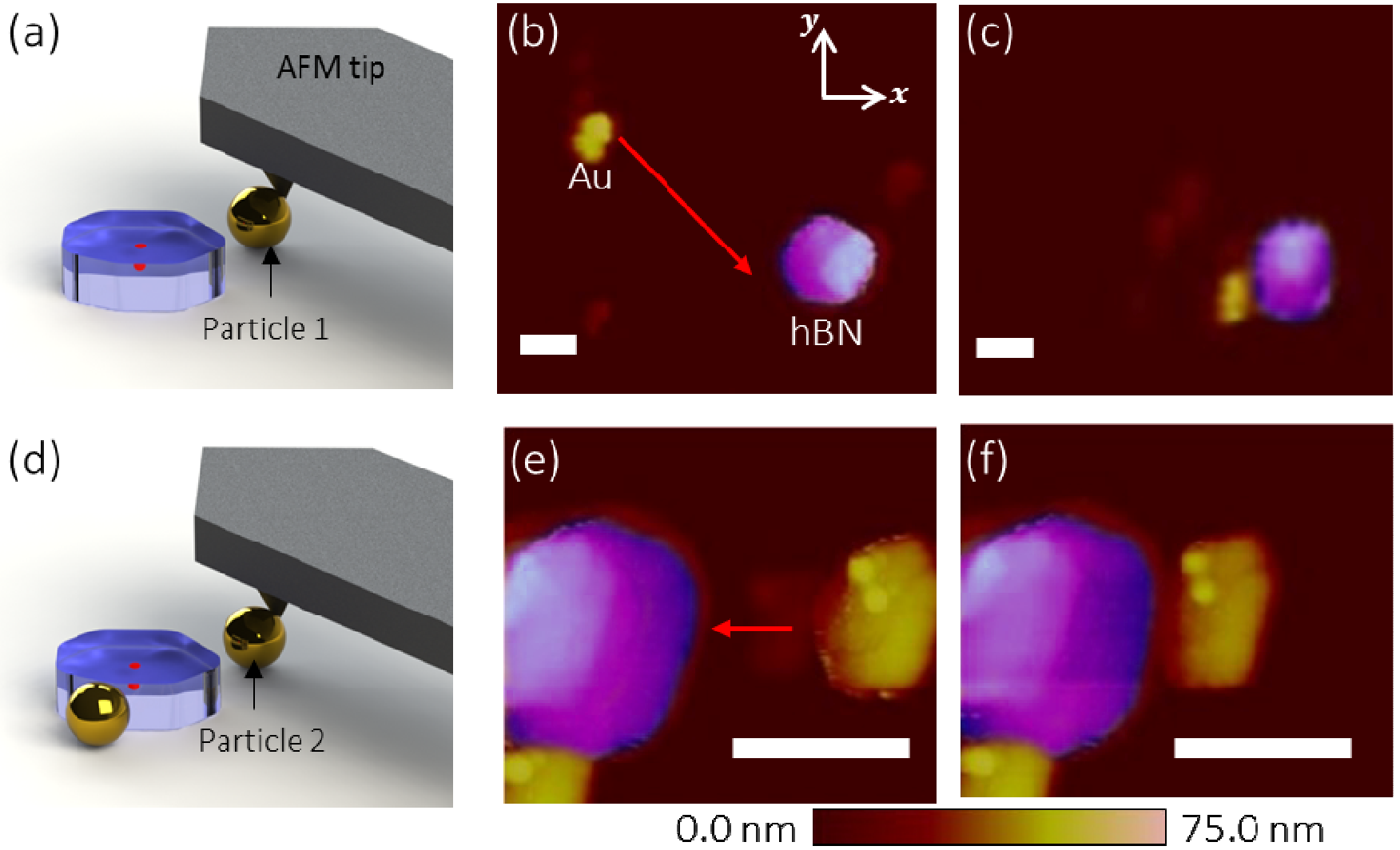

$$I = \frac{I_0}{(1+A\exp(^{-E}/_{k_bT}))}$$




- Lifetime is constant → no new relaxation channels
- Stability to 800 K (probably higher but we can't measure)

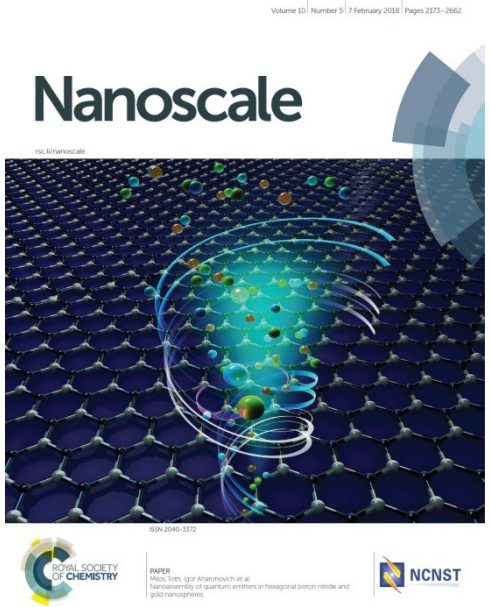
Kianinia et al., ACS Photon (2017)

# *Deterministic plasmonic enhancement*

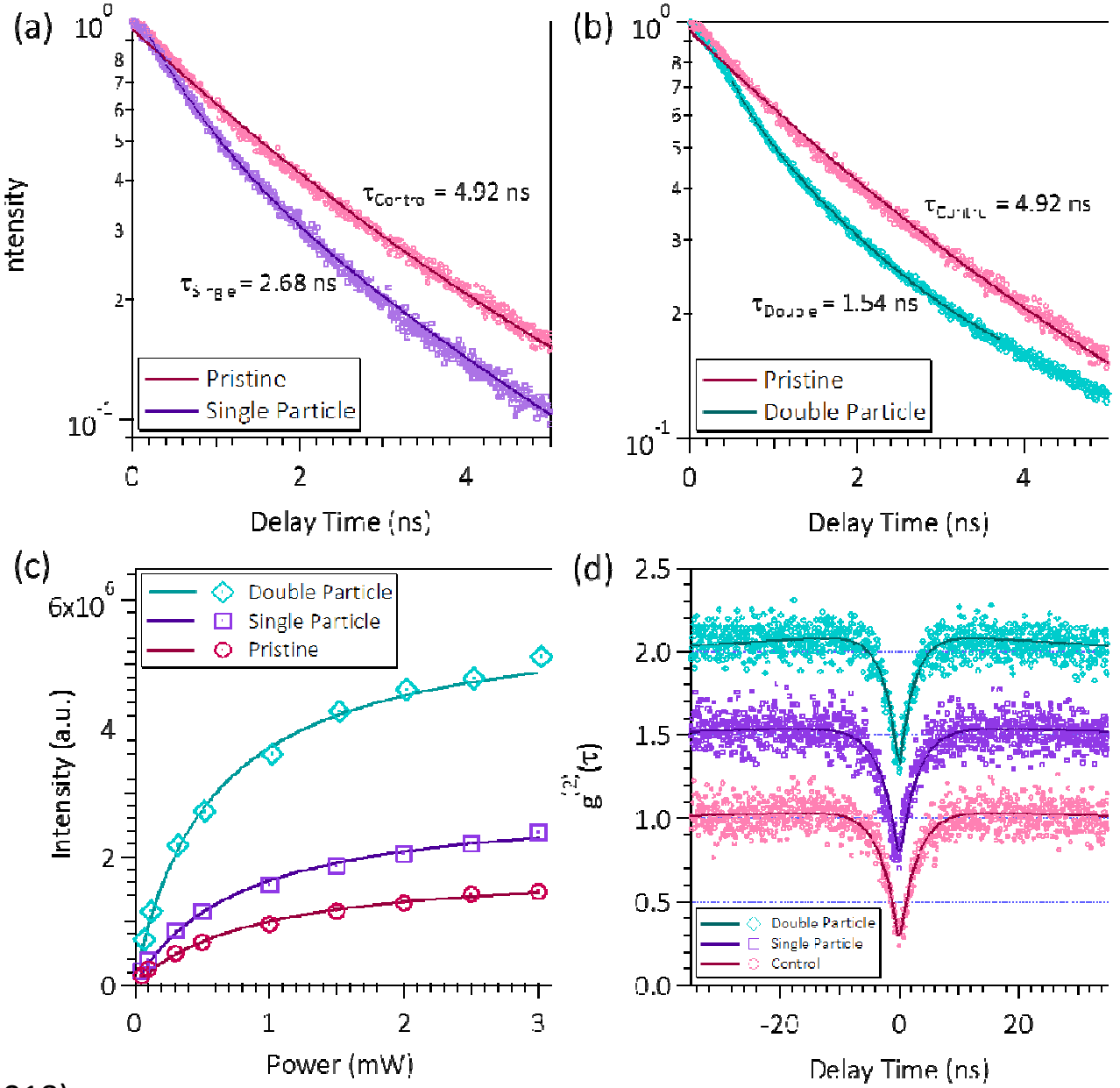



Nguyen, Kim et al., nanoscale (2018)

# *Deterministic plasmonic enhancement*

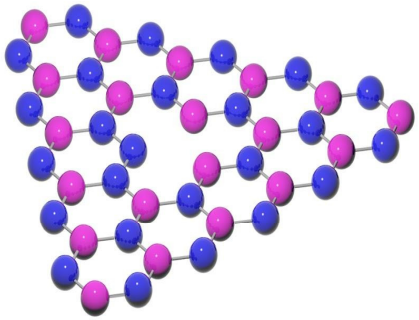


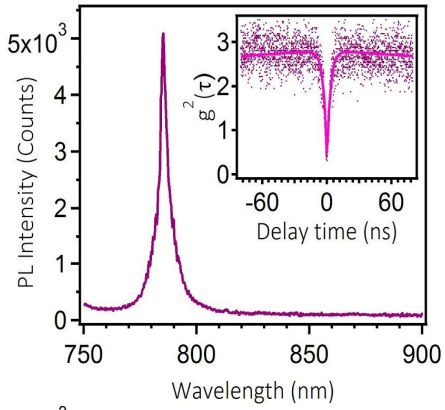

➢ Brightest RT SPE*

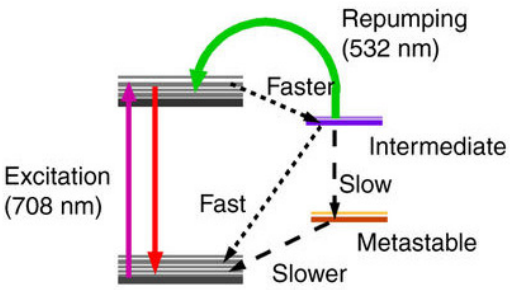


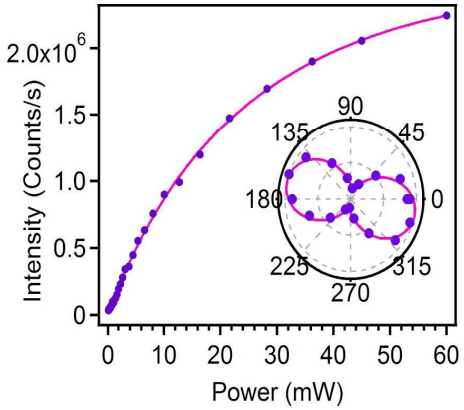

Nguyen, Kim et al., nanoscale (2018)

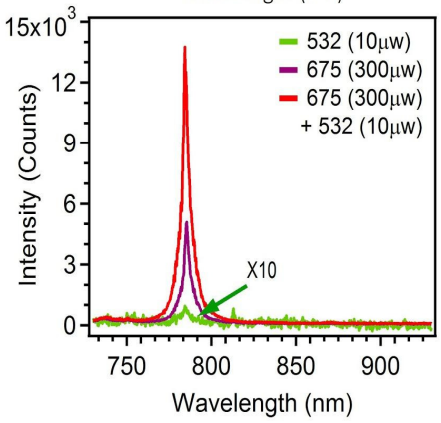
# *Nonlinear behavior of hBN*

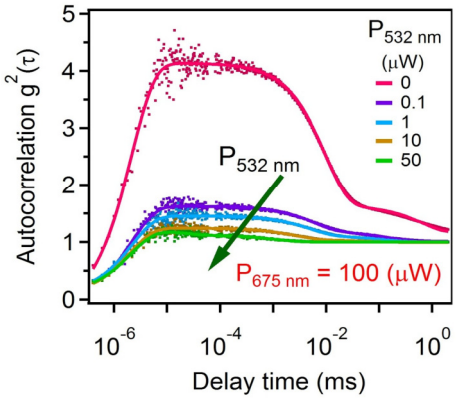




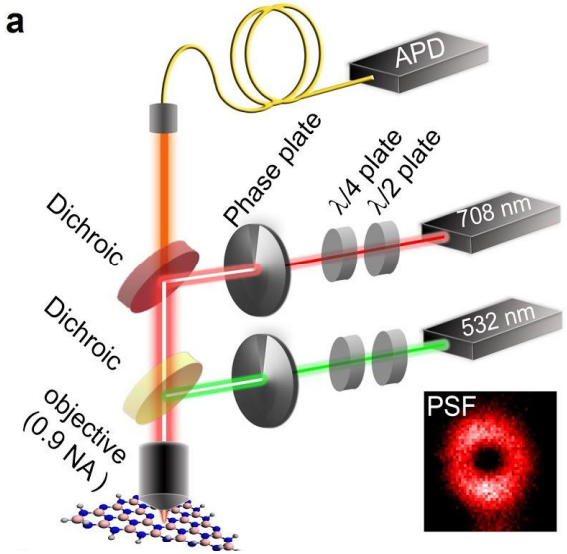



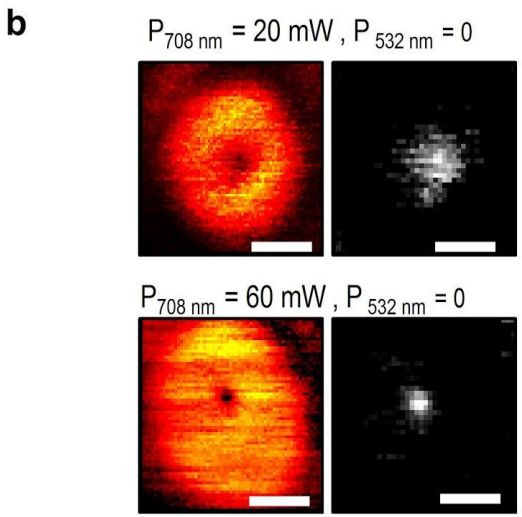



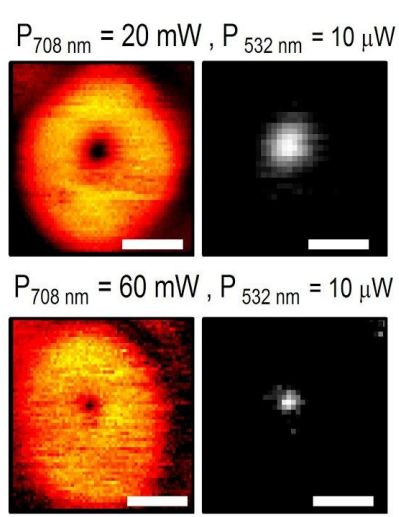

- Non linear behaviour
- Repumping mechanism

Kianinia, Bradac et al., nature comms (2018)

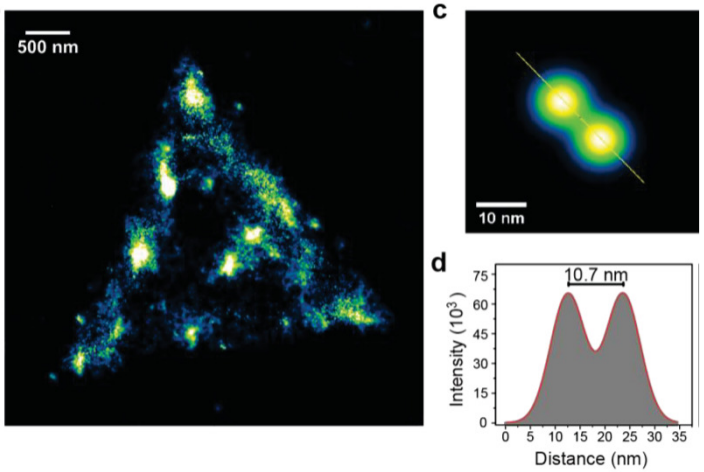
# *Super-resolution with defects in hBN*



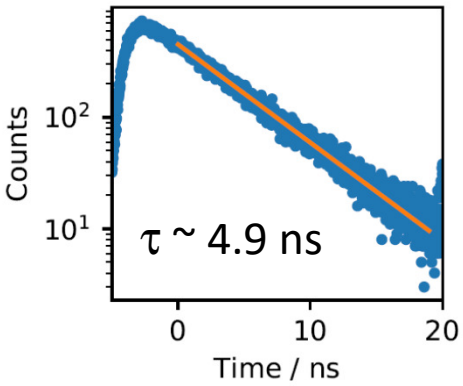



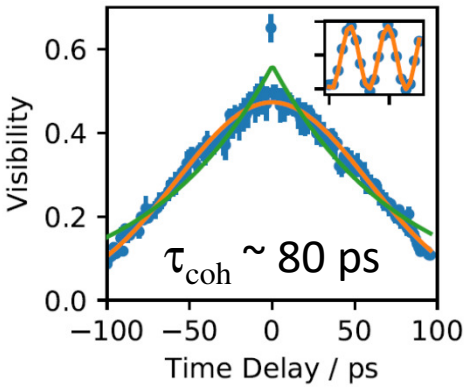

Kianinia, Bradac et al., nature comms (2018)

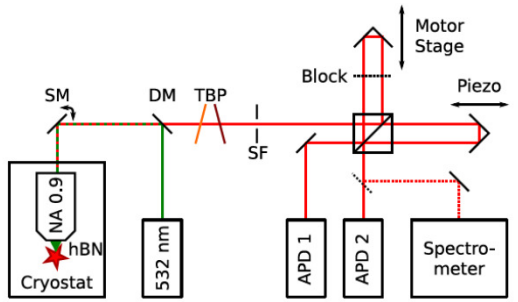


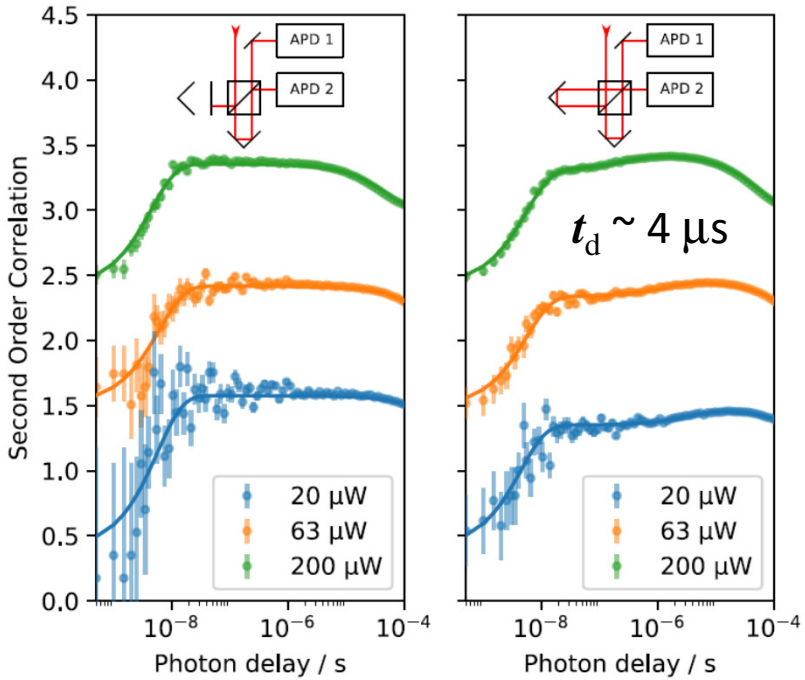

Feng et al., nanolett (2018), EPFL

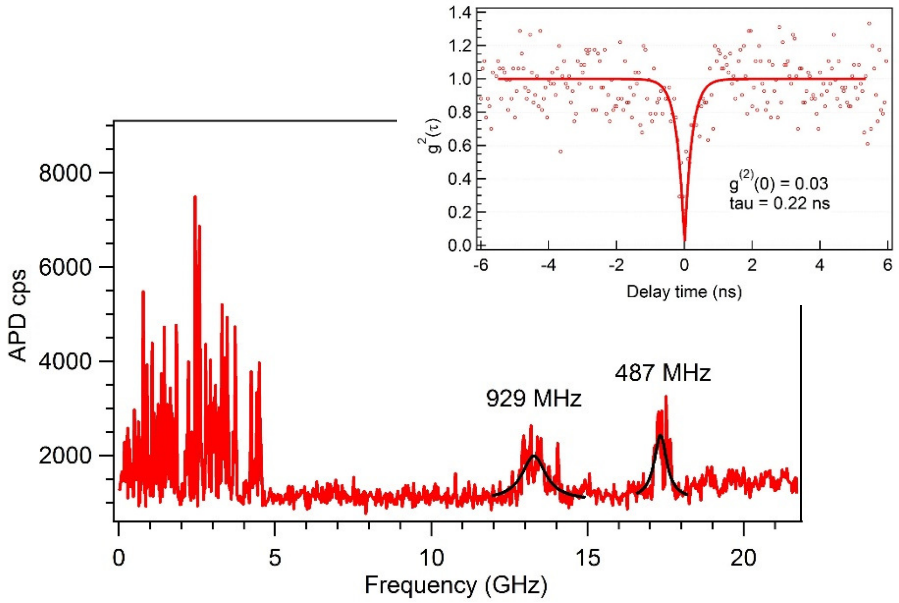
# *Cryogenic Measurements*



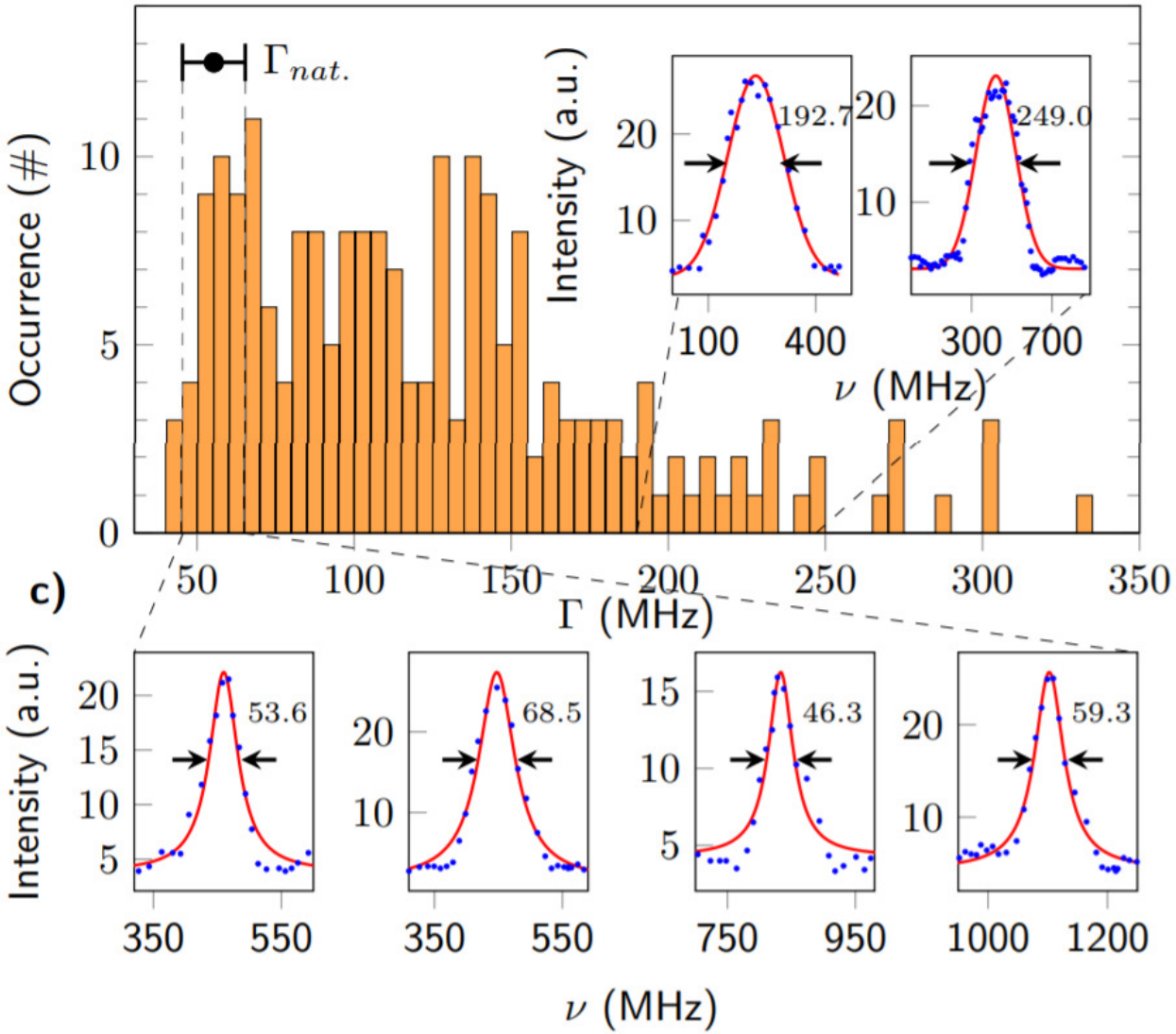




- Very Strong spectral diffusion
- PLE is possible

Sontheimer, et al., Phys Rev B (R) (2017)
Tran et al., ACS Photon (2017)

# *Cryogenic Measurements*

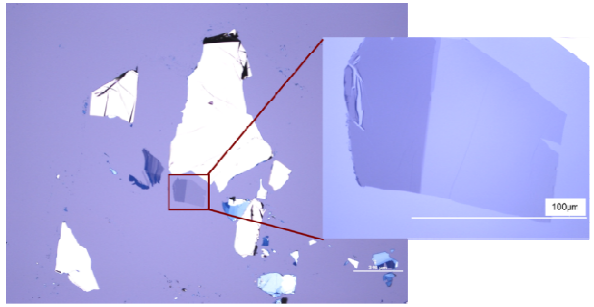



Dietrich et al., arXiv:1712.06938

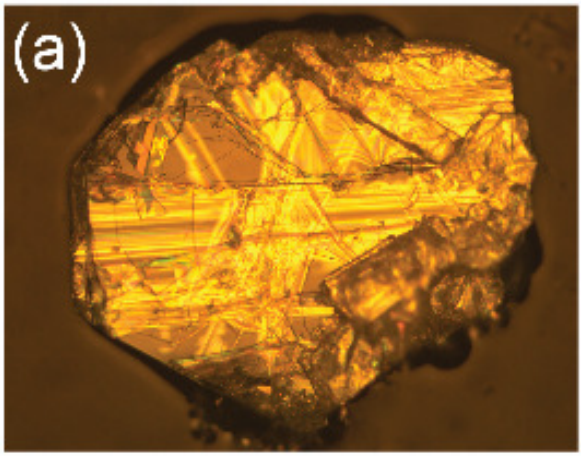
- Very Strong spectral diffusion
- PLE is possible, down to FT limited lines

# *Emitters in exfoliated flakes*

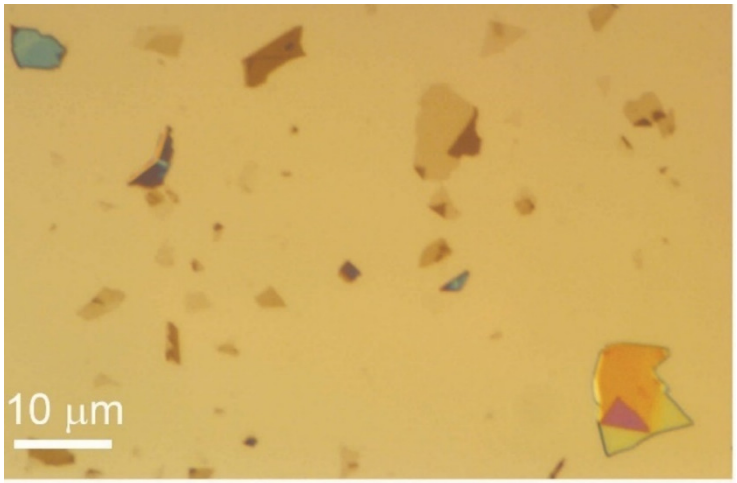
David Boyd, Caltech



Graphene tape exfoliation – easy



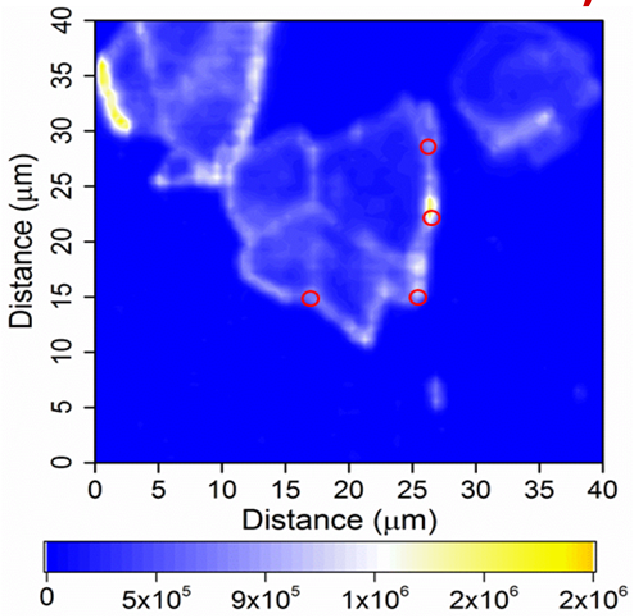

Single Crystal hBN

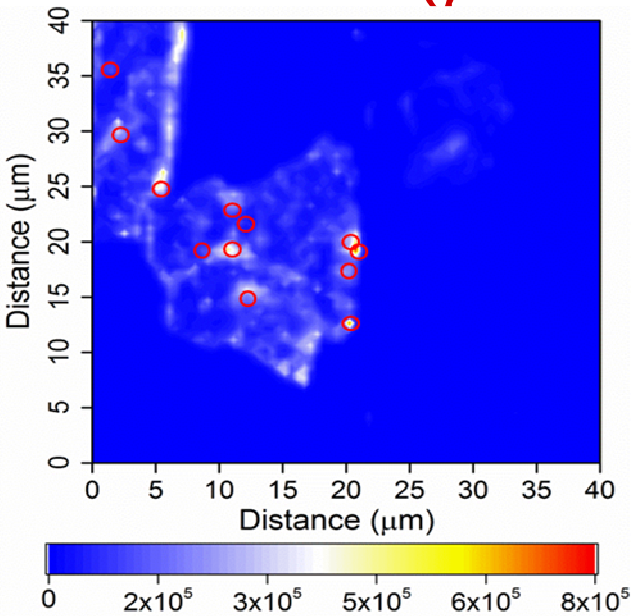


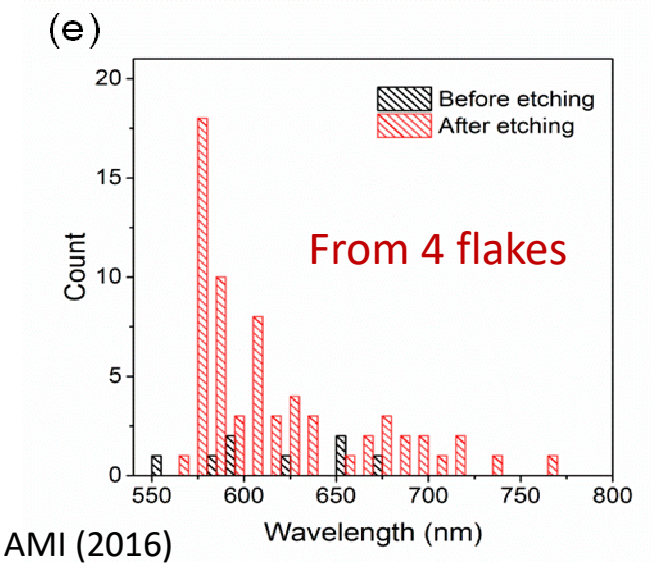

- Exfoliated and Annealed at 850°C

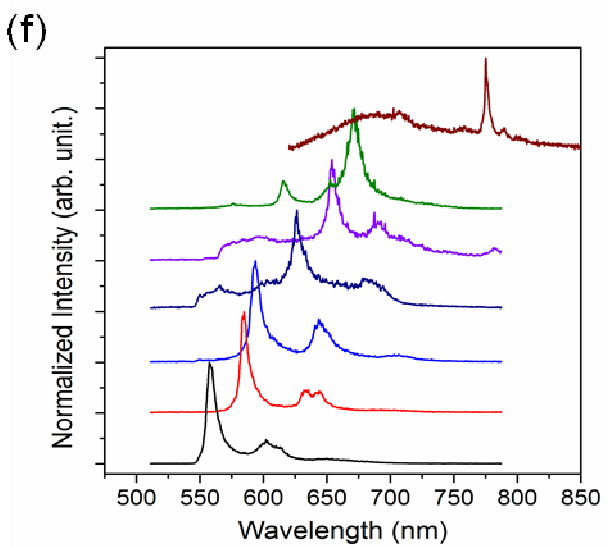
Choi et al., ACS AMI (2016)

# *Controlled activation of emitters in exfoliated flakes*



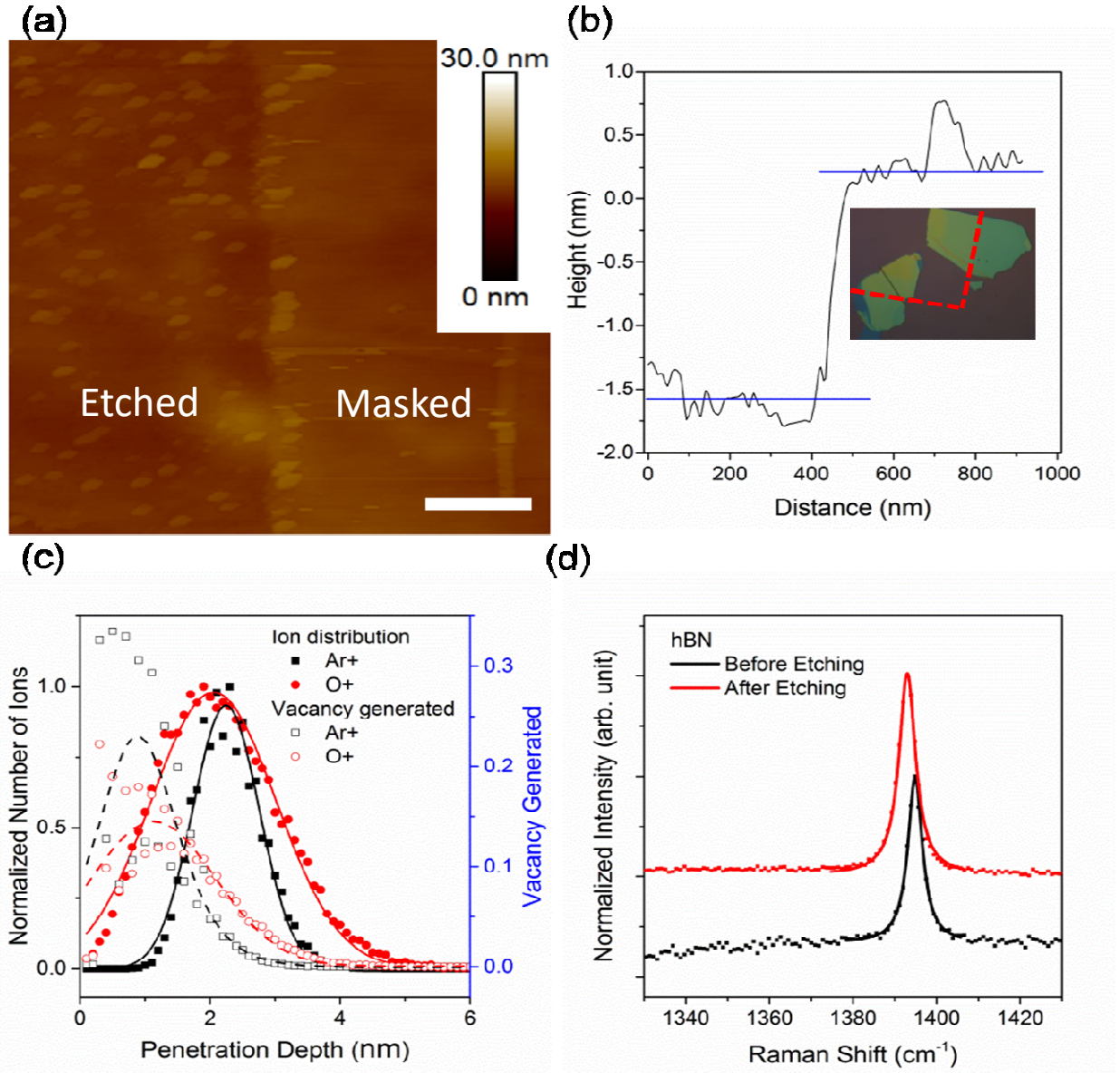




Choi et al., ACS AMI (2016)
Z. Xu et al., arXiv:1704.05154 (2017)
Also group of C Meriles arXiv:1712.01352

Plasma processing → Factor of ~ 7 more emitters

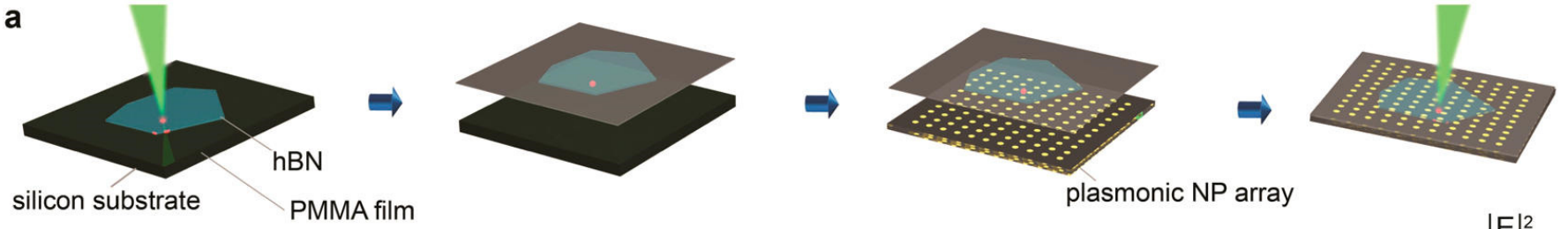
# *Controlled activation of emitters in exfoliated flakes*

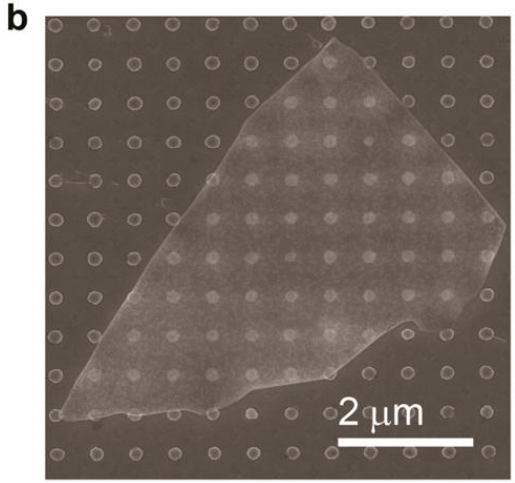


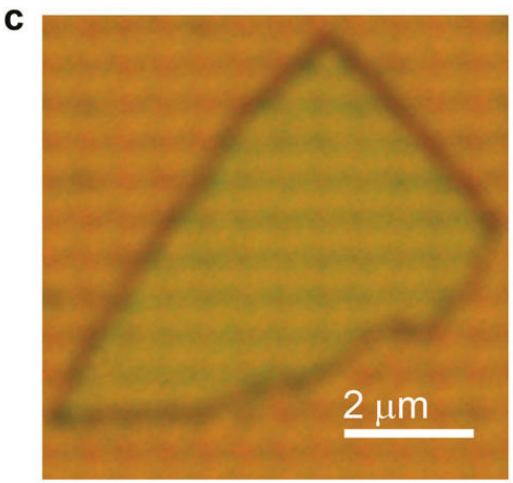

Z. Xu et al., arXiv:1704.05154 (2017)

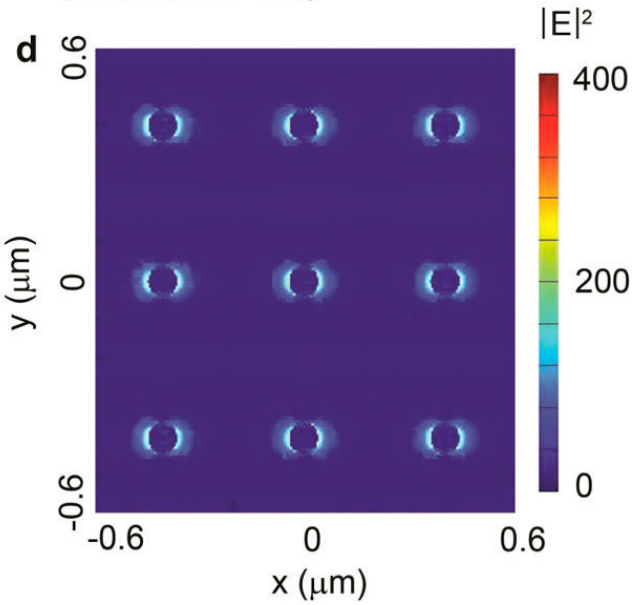
Emitters are formed in the top ~ 2 nm!

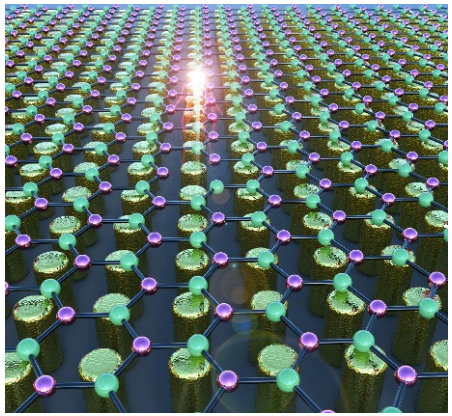
# *Plasmonic coupling*



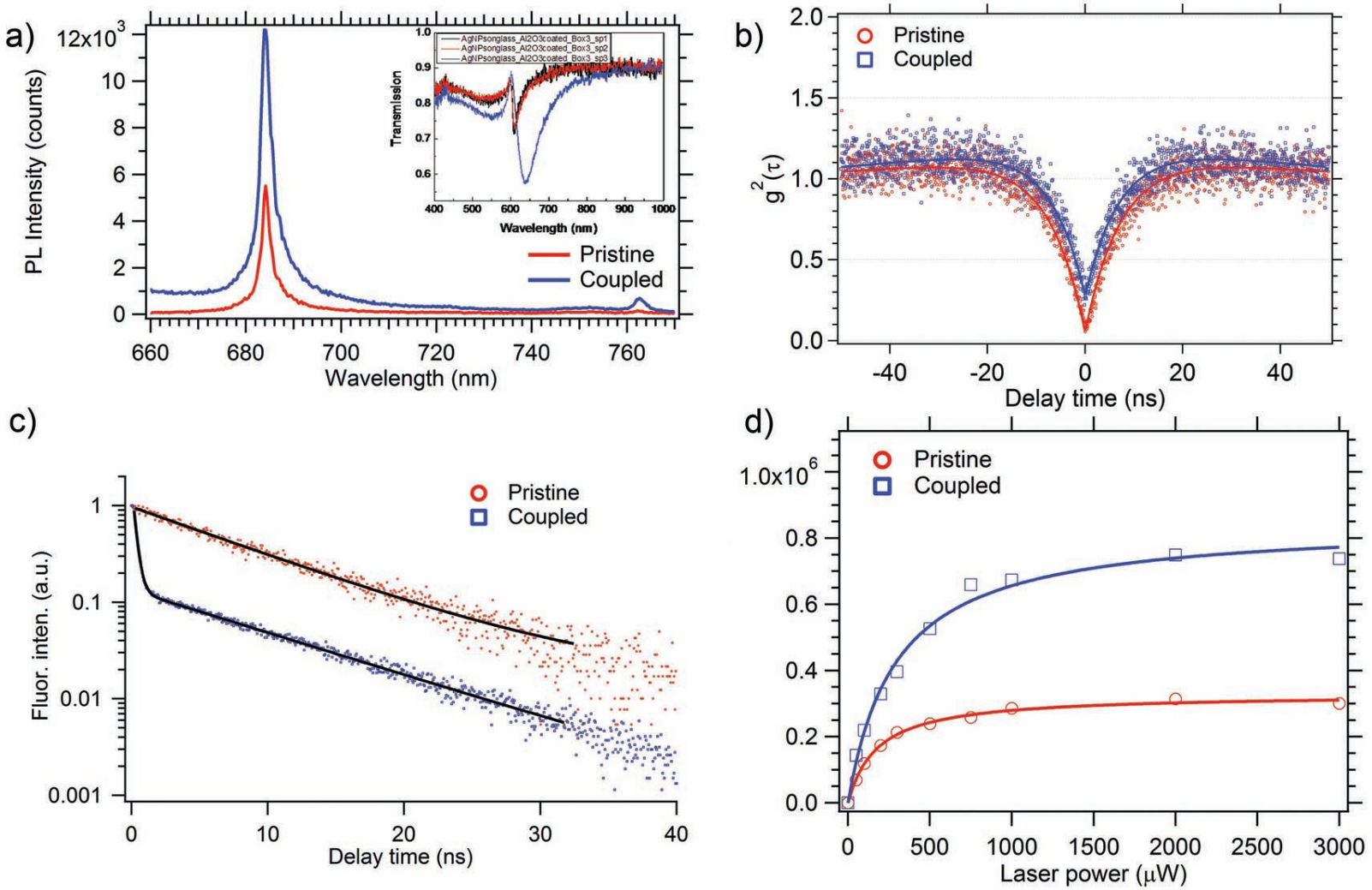



D Wang, T Tran, Z Xu et al., Nanolett (2017)

With Prof T. Odom @ Northwestern

# *Plasmonic coupling*



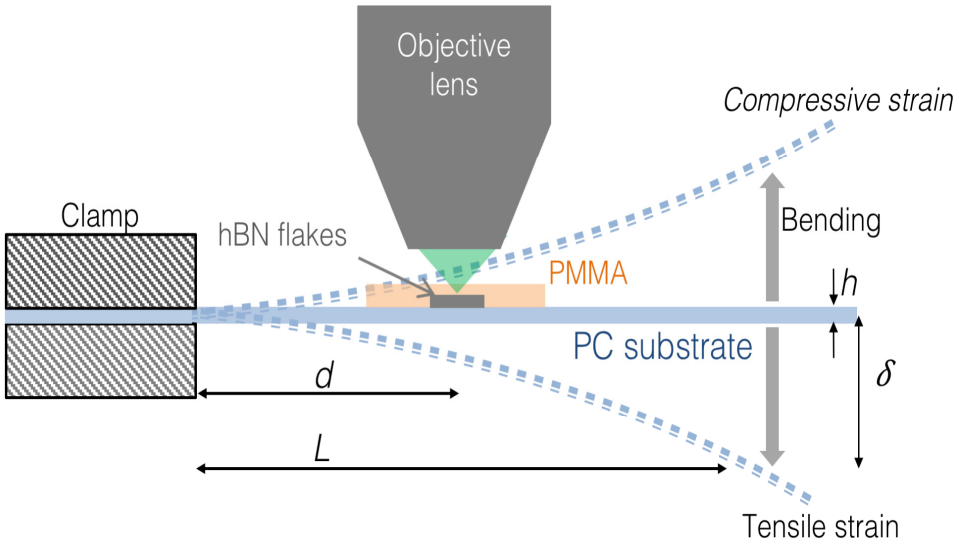

**Same emitter!**

**Deterministic transfer**

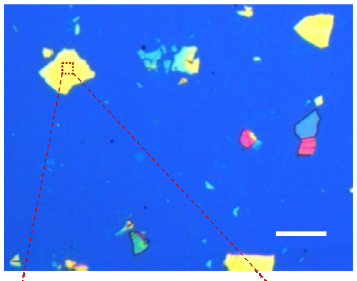
D Wang, T Tran, Z Xu et al., Nanolett (2017)

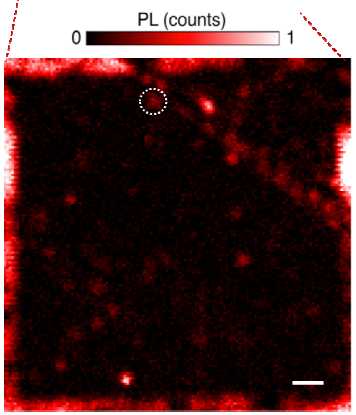
With Prof T. Odom @ Northwestern

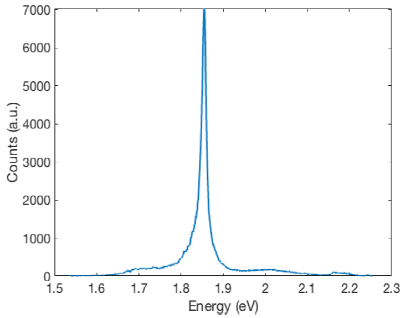
# *Emission control via strain*



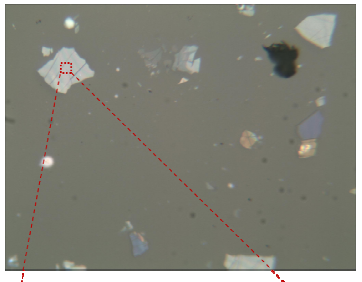

Before transfer

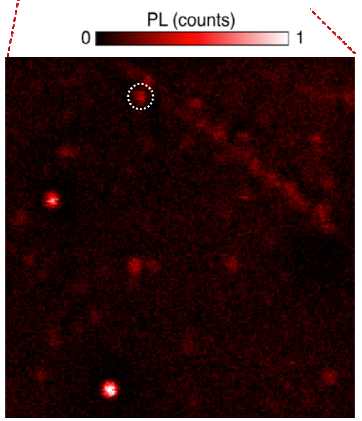


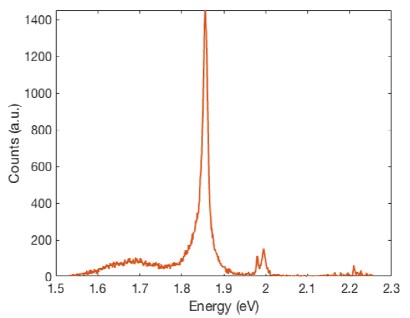



After transfer

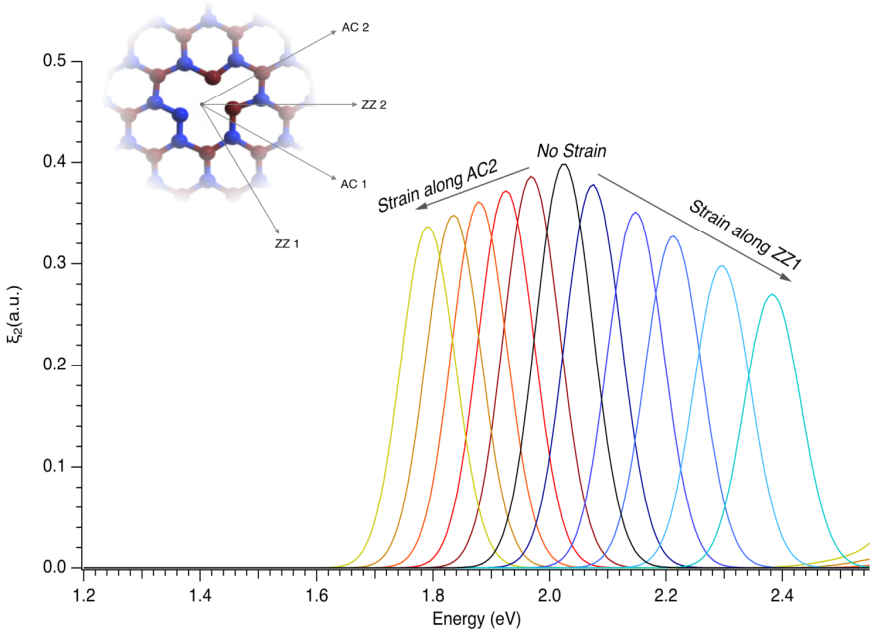


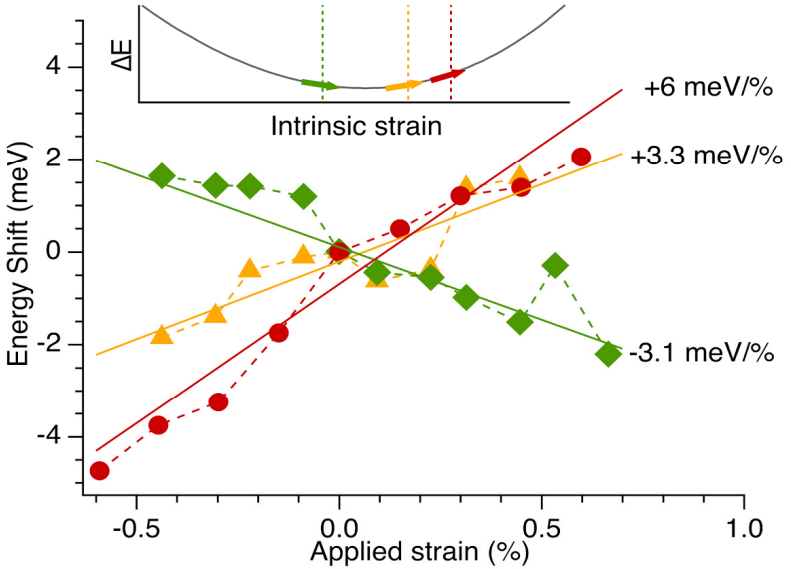


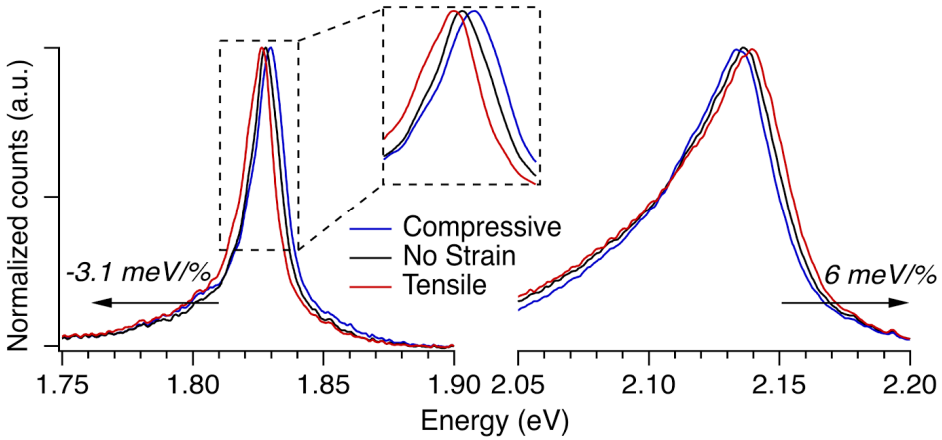



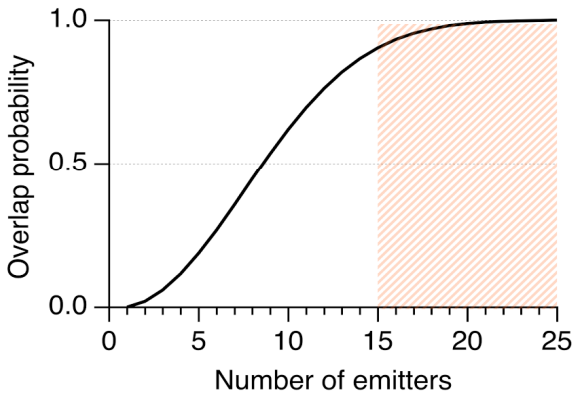

Grosso et al., nature comms (2017)

# *Emission control via strain*



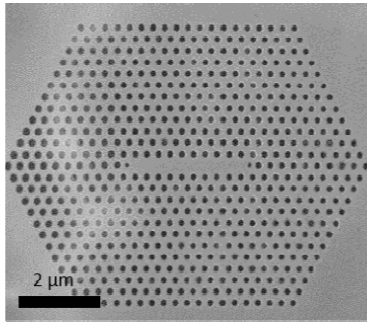

Much more than color centers in diamond

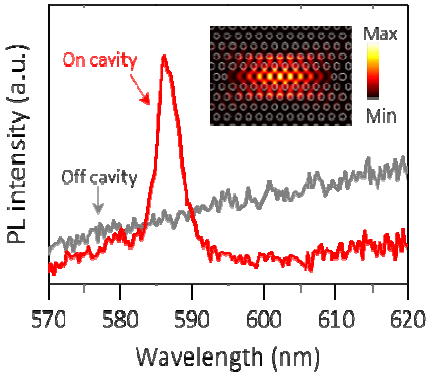
Grosso et al., nature comms (2017)

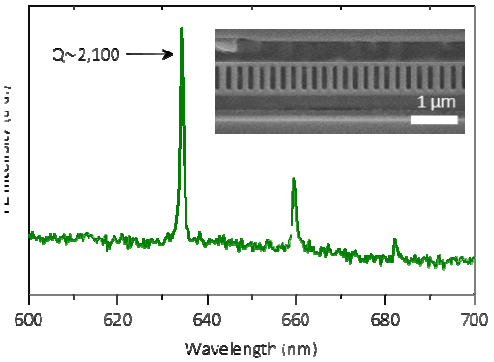
# *Summary*

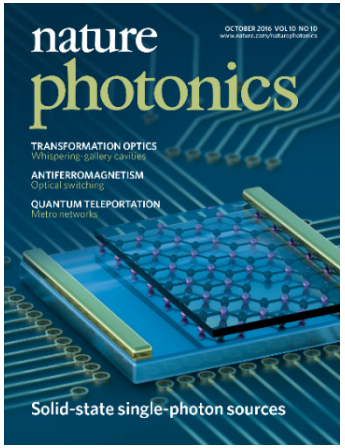
- Discovery of a new platform of quantum emitters in 2D materials
  *Tran et al.,Nature Nano (2016)*
- Robust high temperature luminescence *(Kianinia et al., 2016)*
- Plasmonics coupling *(Tran, Wang, Xu et al., Nanolett (2017);Nguyen, Kim et al., nanoscale (2018)*
- Strain engineering *(Grosso et al., nature comms (2017);*
- Super Resolution imaging *(Kianinia, Bradac et al., nature comms 2018)*

*Vision: a fully integrated 2D quantum system on a single chip*




Kim, Froch et al., arXiv:1801.04399

# *Acknowledgments*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**30 min ride…**

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