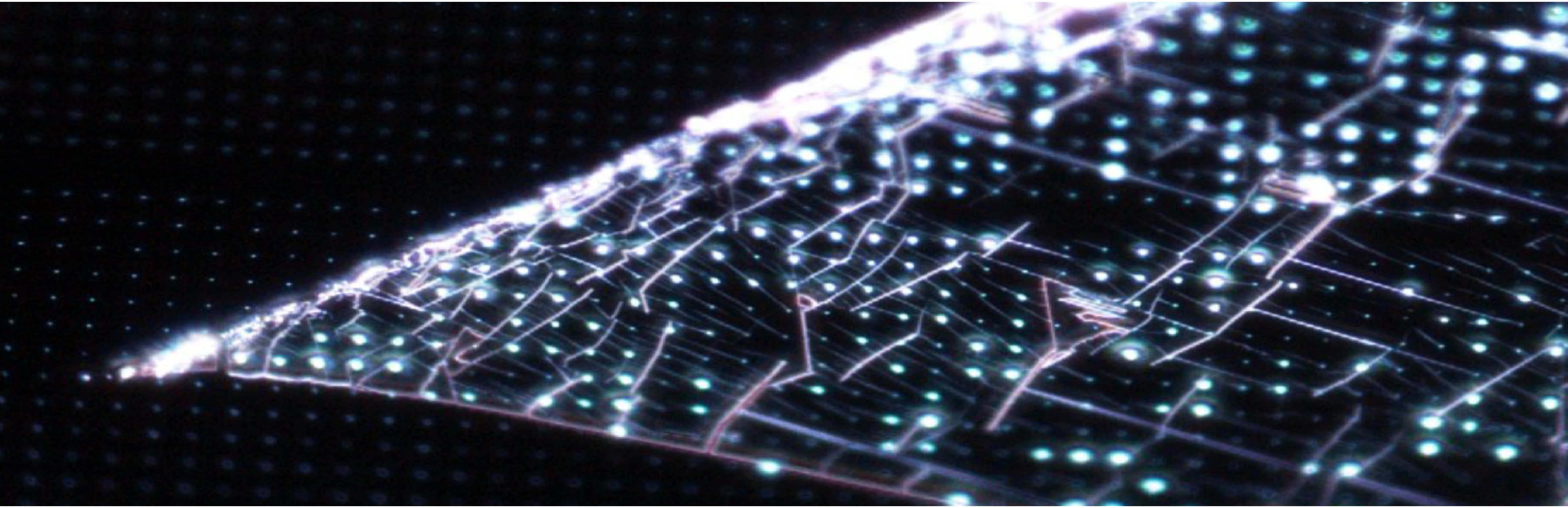
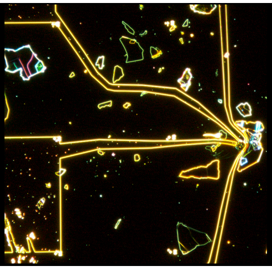
Quantum dots in 2d semiconductors - Large-scale, deterministic single-photon sources and quantum devices

Carmen Palacios-Berraquero, Dhiren M. Kara, Matteo Barbone, Alejandro R.-P. Montblanch, Pawel Latawiec, Marko Loncar, Andrea C. Ferrari and Mete Atatüre

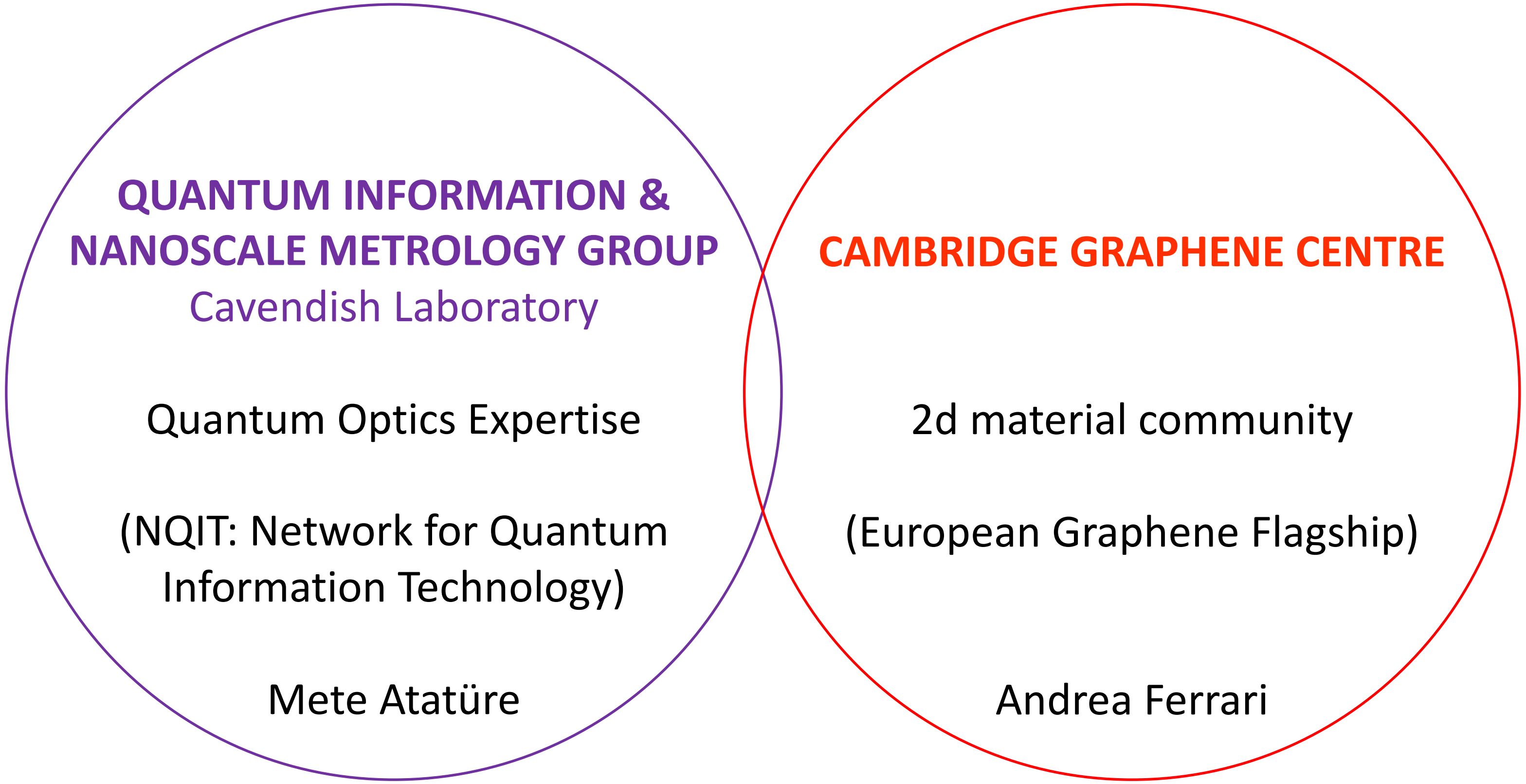


EPSRC
Engineering and Physical Sciences
Research Council

UNIVERSITY OF CAMBRIDGE



BACKGROUND



QUANTUM INFORMATION & NANOSCALE METROLOGY GROUP
Cavendish Laboratory

Quantum Optics Expertise

(NQIT: Network for Quantum Information Technology)

Mete Atatüre

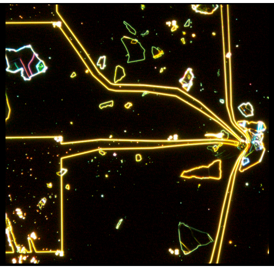
CAMBRIDGE GRAPHENE CENTRE

2d material community

(European Graphene Flagship)

Andrea Ferrari

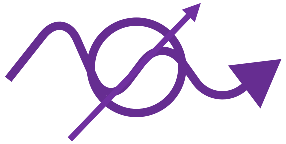
Funding - Nanotechnology Doctoral Training Centre (NanoDTC)



Photons for Quantum Info

Fast (speed of light)

Weak interaction with environment



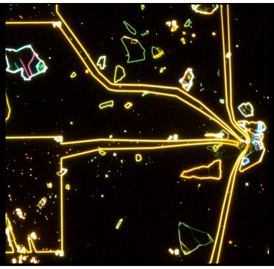
Polarisation

Path information…

Quantum Encryption

Single-photon source ● ● ● ● ● ● ● ● ● Quantum computing protocols

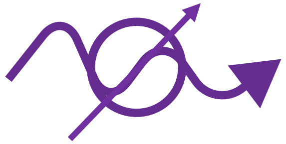
Random number generation



Photons for quantum info

Fast (speed of light)

Weak interaction with environment



Polarisation

Path information…

On-demand

Pure: no multi-photon events

High repetition rate

Indistinguishable

……….

Real-world tech

Scalable

Electrically triggered

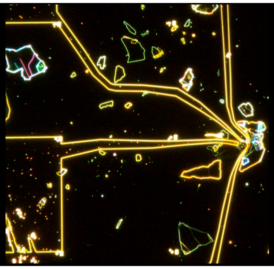
Operation temperature?

Good quantum efficiency

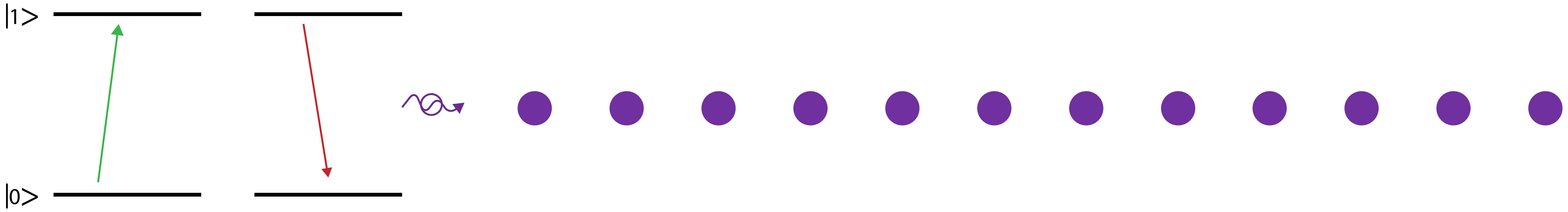
Good light extraction

Integrated in resonators

Compatible with current technology....



Traditional single-photon sources:



0-dimensions

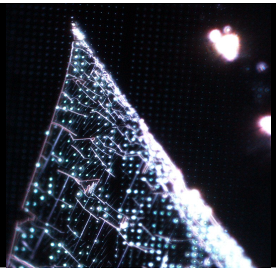
Atomic transitions

Cold atoms
ions

3-dimensions (solid state)

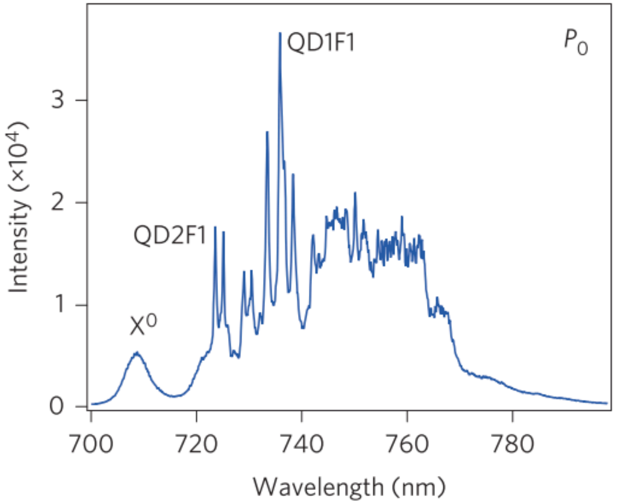
“atom-like” or “artificial atoms”

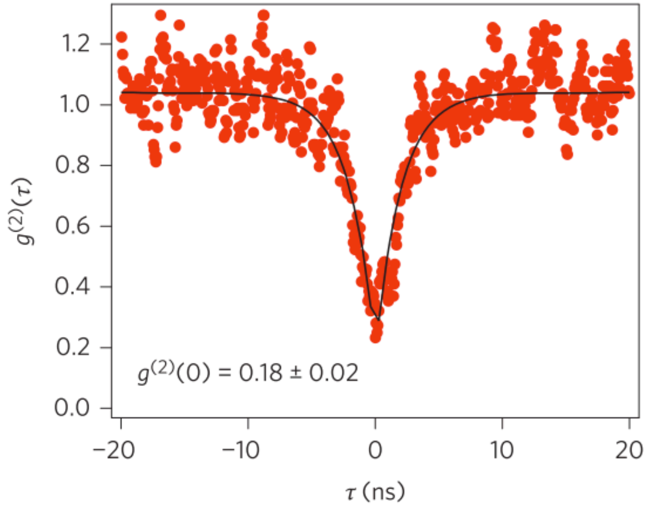
InGaAs quantum dots
Nitrogen vacancy centres in diamond



Non-traditional host: 2d semiconductors

Early 2015
Observation of single-photon emission at random locations in flakes





Research Article Vol. 2, No. 4 / April 2015 / *Optica* 347

optica

Single-photon emission from localized excitons in an atomically thin semiconductor

Philipp Tonndorf,[1,†] Robert Schmidt,[1,†] Robert Schneider,[1] Johannes Kern,[1] Michele Buscema,[2] Gary A. Steele,[2] Andres Castellanos-Gomez,[2] Herre S. J. van der Zant,[2] Steffen Michaelis de Vasconcellos,[1] and Rudolf Bratschitsch[1,*]

nature nanotechnology LETTERS
PUBLISHED ONLINE: 4 MAY 2015 | DOI: 10.1038/NNANO.2015.60

Optically active quantum dots in monolayer WSe_2

Ajit Srivastava[1*†], Meinrad Sidler[1†], Adrien V. Allain[2], Dominik S. Lembke[2], Andras Kis[2] and A. Imamoğlu[1*]

nature nanotechnology LETTERS
PUBLISHED ONLINE: 4 MAY 2015 | DOI: 10.1038/NNANO.2015.75

Single quantum emitters in monolayer semiconductors

Yu-Ming He[1,2], Genevieve Clark[3], John R. Schaibley[4], Yu He[1,2], Ming-Cheng Chen[1,2], Yu-Jia Wei[1,2], Xing Ding[1,2], Qiang Zhang[1,2], Wang Yao[5], Xiaodong Xu[3,4], Chao-Yang Lu[1,2*] and Jian-Wei Pan[1,2*]

nature nanotechnology LETTERS
PUBLISHED ONLINE: 4 MAY 2015 | DOI: 10.1038/NNANO.2015.67

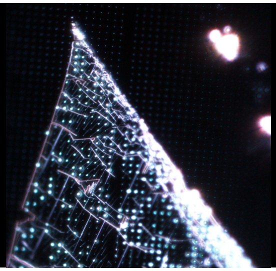
Single photon emitters in exfoliated WSe_2 structures

M. Koperski[1,2], K. Nogajewski[1], A. Arora[1], V. Cherkez[3], P. Mallet[3], J.-Y. Veuillen[3], J. Marcus[3], P. Kossacki[1,2] and M. Potemski[1*]

nature nanotechnology LETTERS
PUBLISHED ONLINE: 4 MAY 2015 | DOI: 10.1038/NNANO.2015.79

Voltage-controlled quantum light from an atomically thin semiconductor

Chitraleema Chakraborty[1], Laura Kinnischtzke[2,3], Kenneth M. Goodfellow[3,4], Ryan Beams[5] and A. Nick Vamivakas[1,3,4*]



Why bother with 2d materials

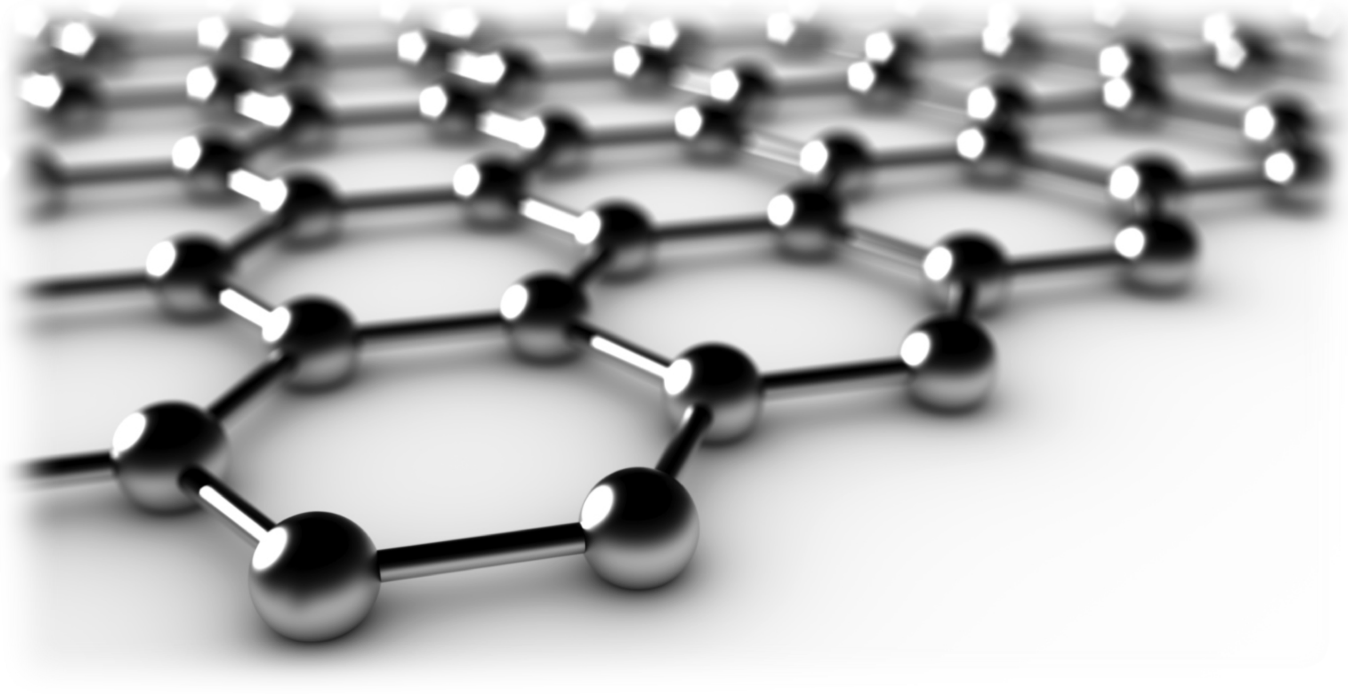
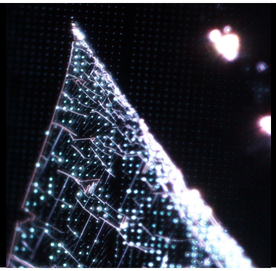


Image: Churchill lab

Technological convenience

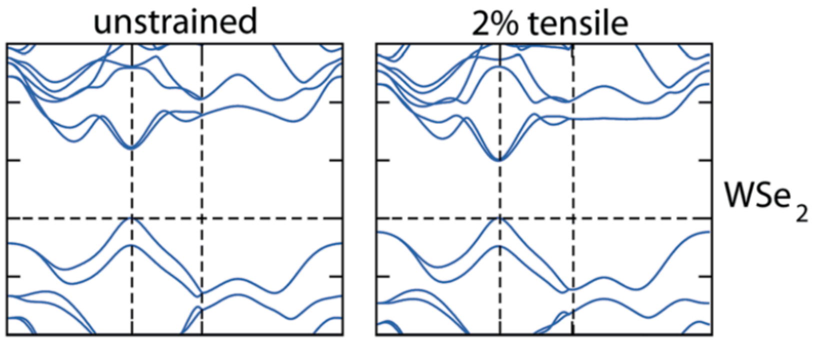
- No dangling bonds = ‘clean surfaces’
- Flexible
- Transparent
- Ease of interfacing
- Stackable into heterostructures
- Compatible with silicon industry
- *Survive near surfaces*
- *Good photon extraction possible*
- *Free of nuclear spins*



0d confinement - how?

Late 2015: we correlate single-photon emission sites with ‘bumps’ on the flakes, using AFM scans

Semiconductors :
Lattice deformation = change bandgap

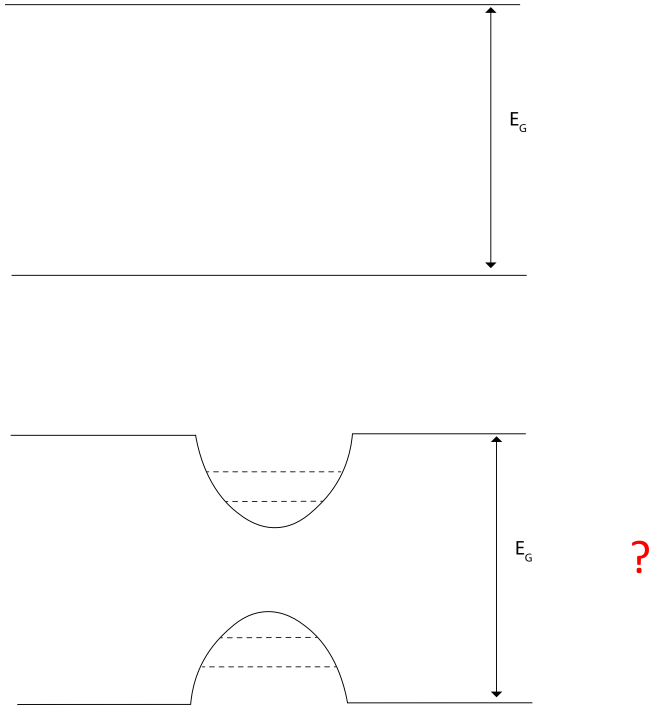


2. Amin, B. *et al. RSC Adv.* **4,** 34561 (2014).

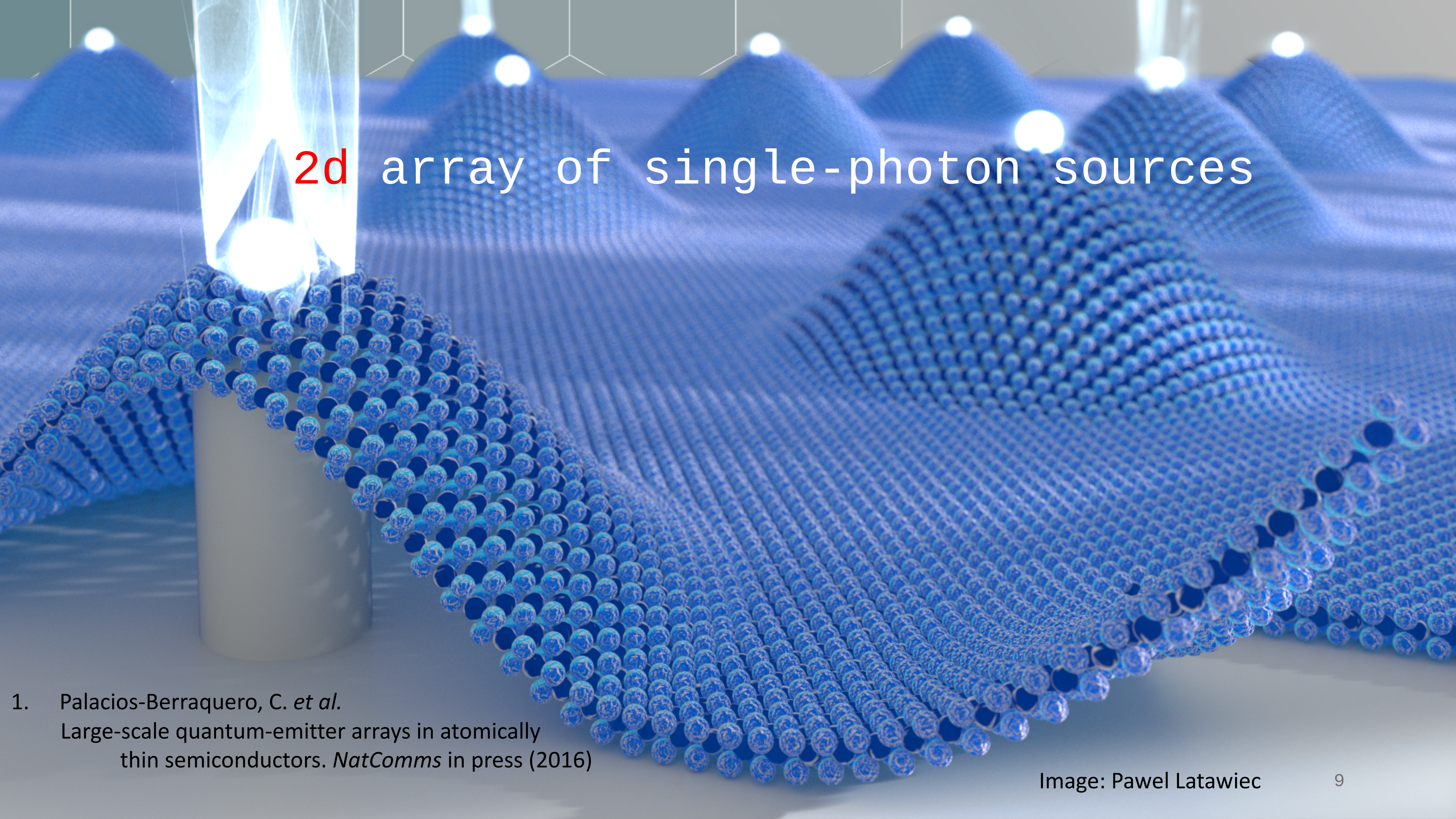
Key *

2-dimensionality:

Can apply deformation with nanoscale resolution

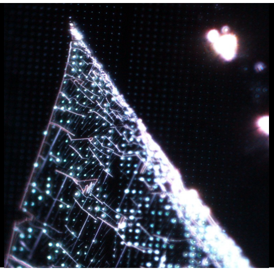


2d array of single-photon sources

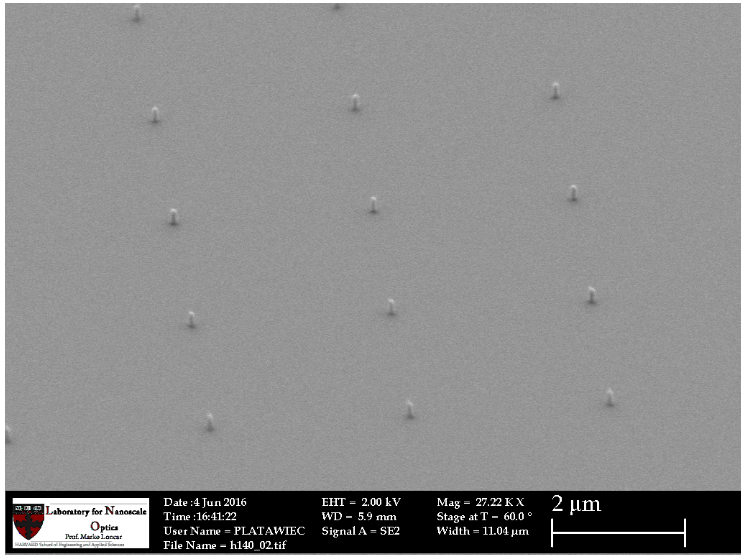


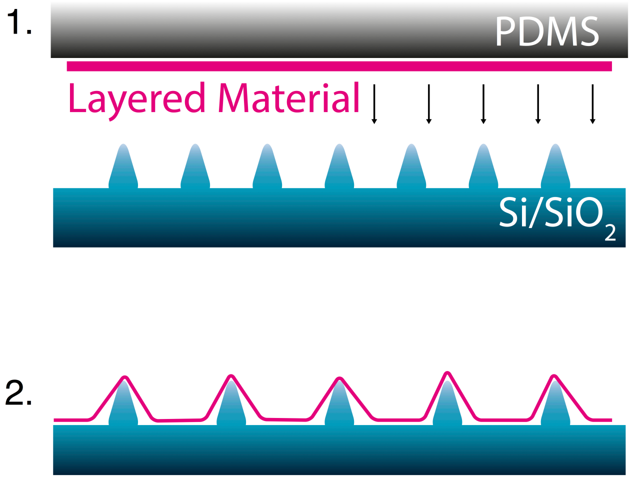
1. Palacios-Berraquero, C. *et al.* Large-scale quantum-emitter arrays in atomically thin semiconductors. *NatComms* in press (2016)

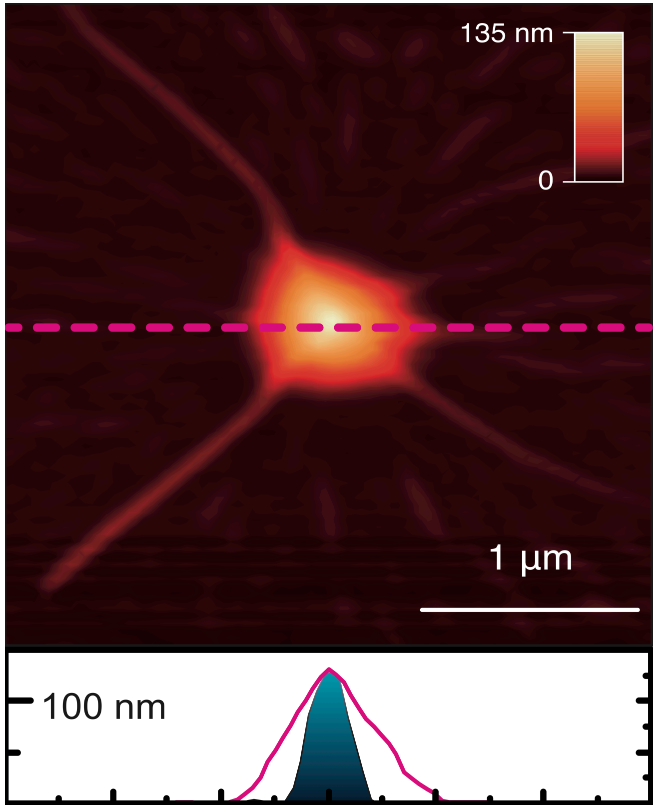
Image: Pawel Latawiec



Patterned nanopillars – tenting at the nanoscale

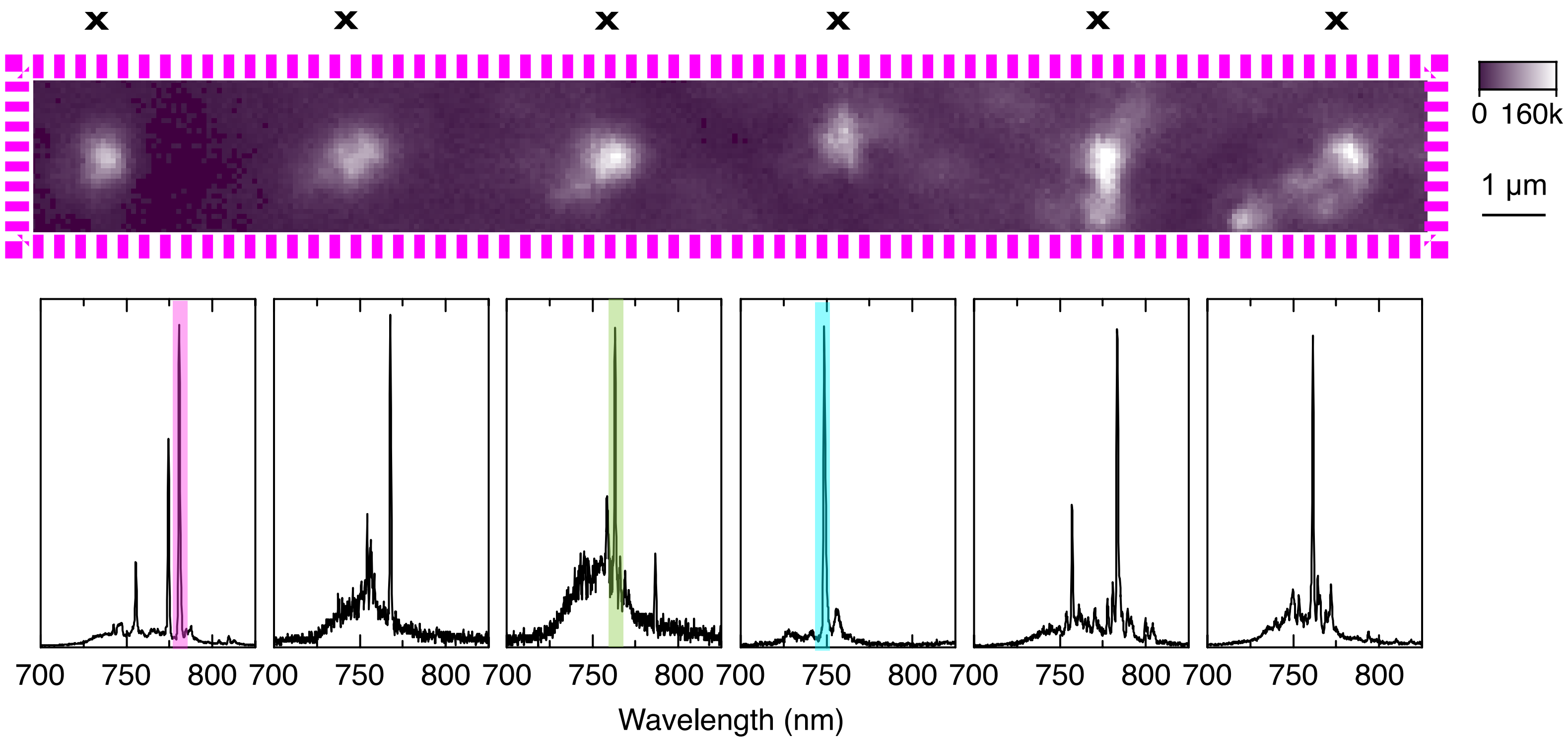


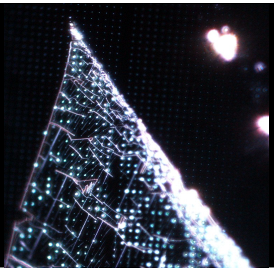




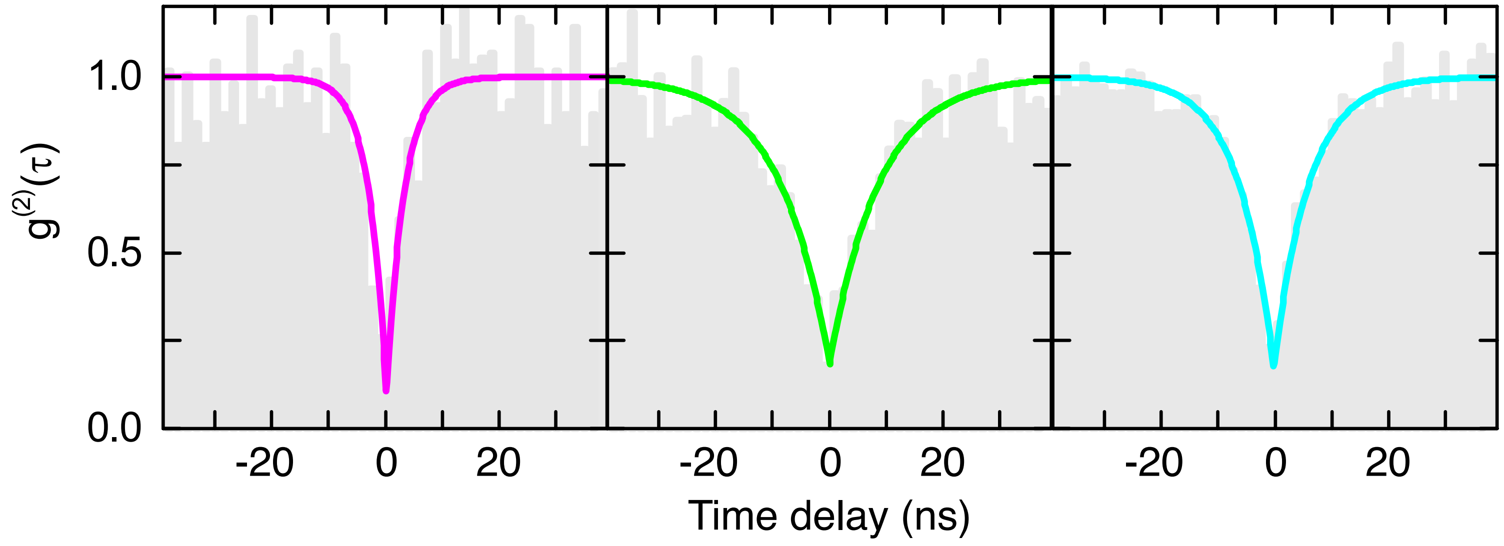
Nanofabrication by Pawel Latawiec, Loncar group, Harvard

(WSe_2)Photoluminescence





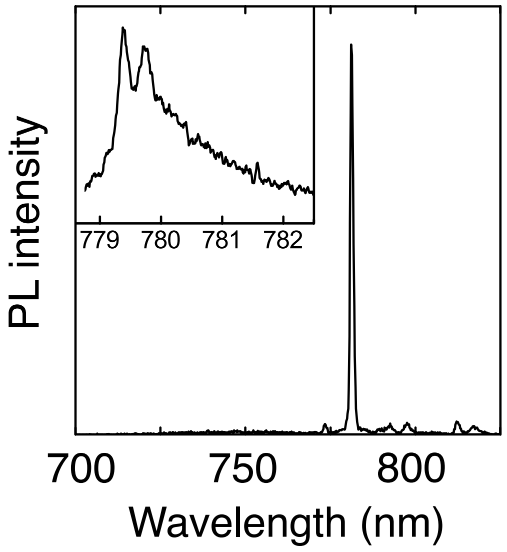
(WSe_2)Single-photon emission



0.0868 ± 0.0645

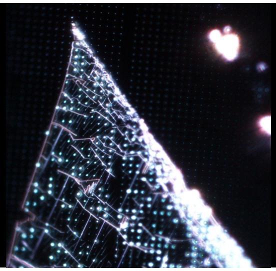
0.170 ± 0.021

0.182 ± 0.028

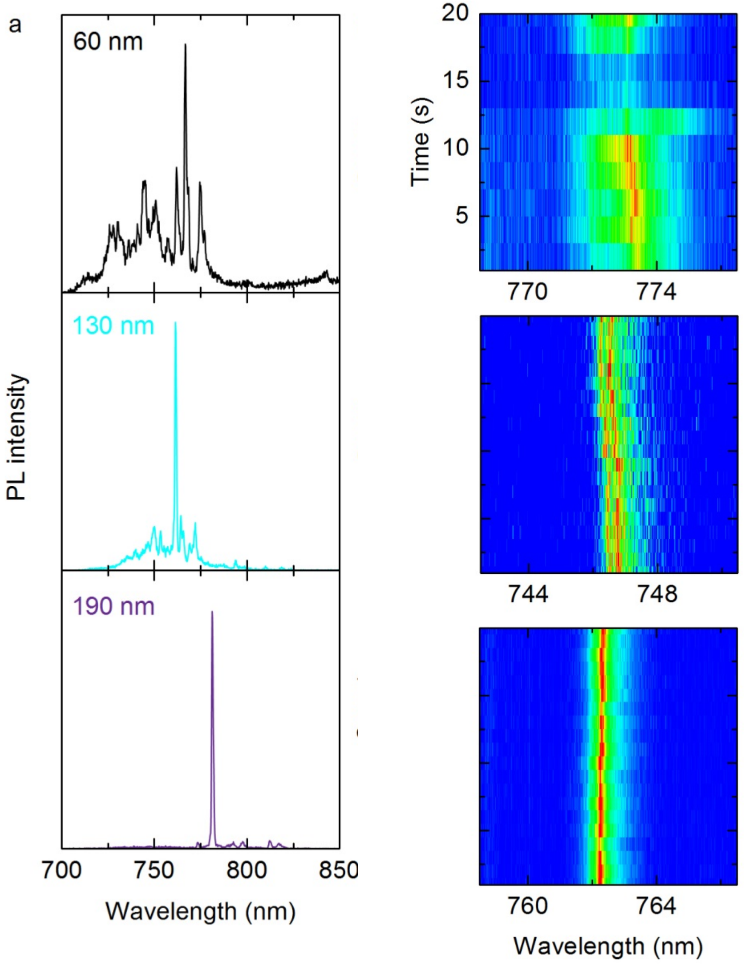


Similar to random 2d-quantum dots

- Emission wavelengths: 730- 820 nm
  (redshift of 70 -270 meV from $X^{0)}$
- Linewidths ~ 120 µeV
- Fine-structure splitting: ~ 200-730 µeV



pillar height dependence



3 sets of nanopillar heights: **60** **130** **190** nm

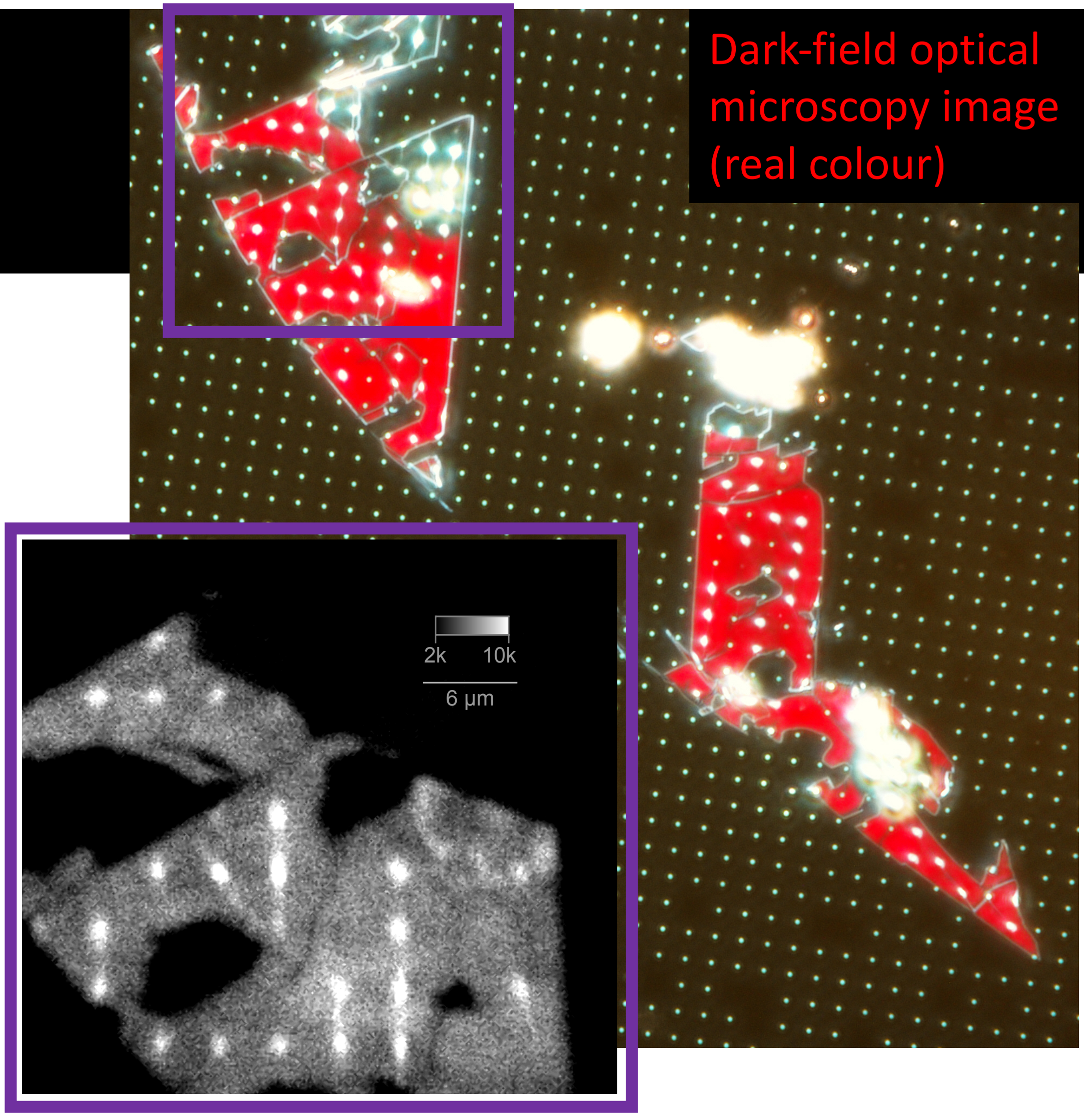
With increasing pillar height…

- number of narrow lines: reduction
- Reduction in spectral wandering

- No appreciable change in emission wavelength

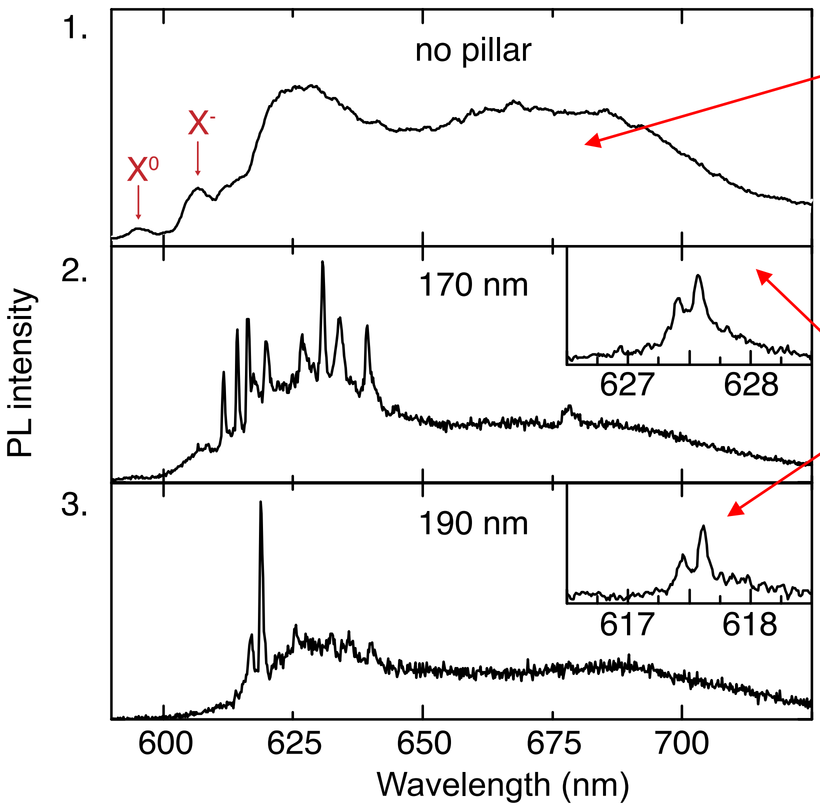
*Key improvement vs. naturally-occurring
potential for tunability

Generalisation of the method (WS_2)



Dark-field optical microscopy image (real colour)

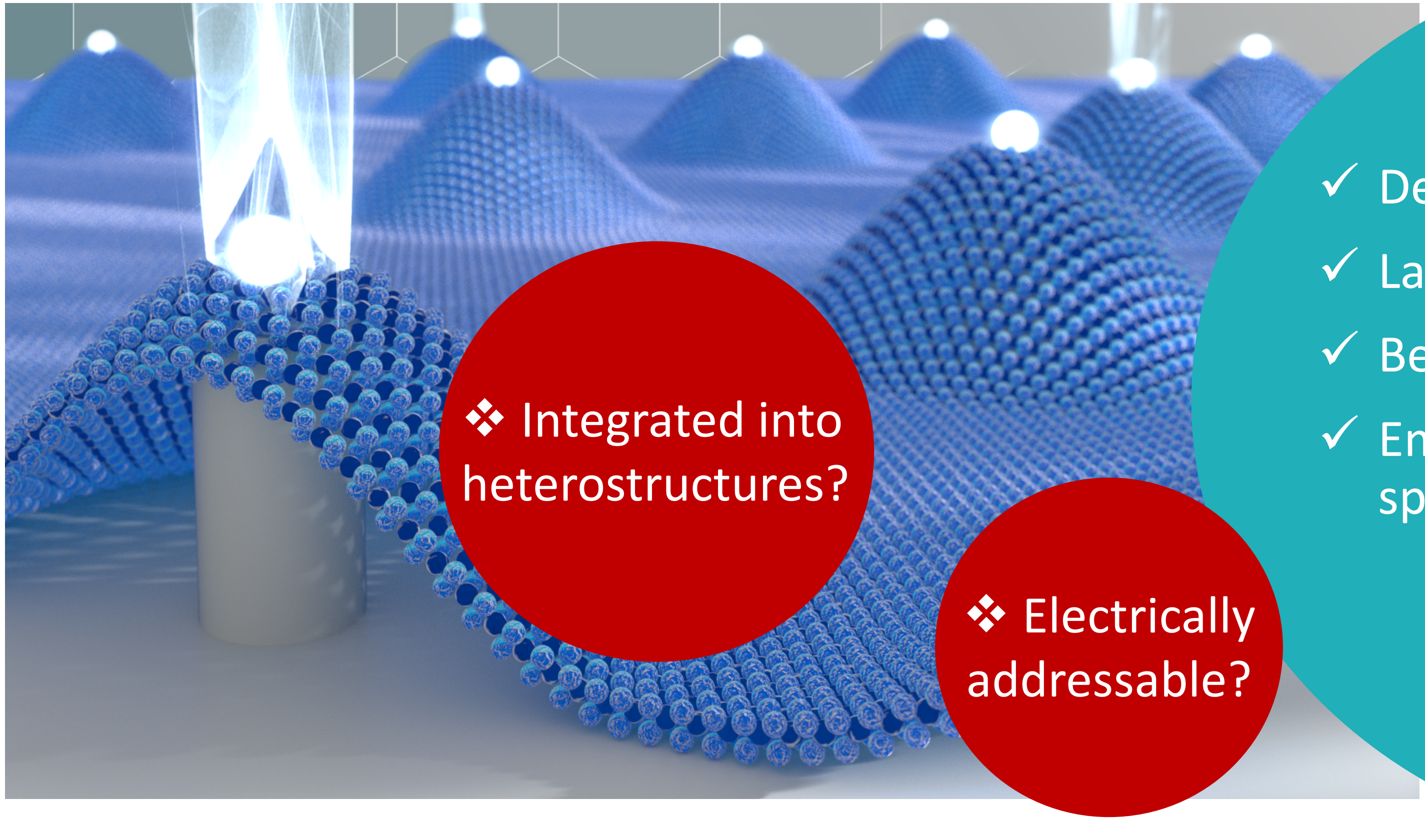
Photoluminescence raster scan at 4K



Broad spectral background at low temperatures

Fine-structure splitting appearing for the first time

Recap I

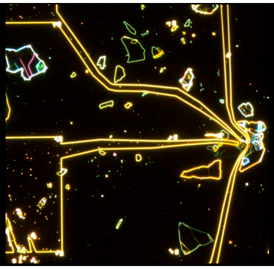


❖ Integrated into heterostructures?

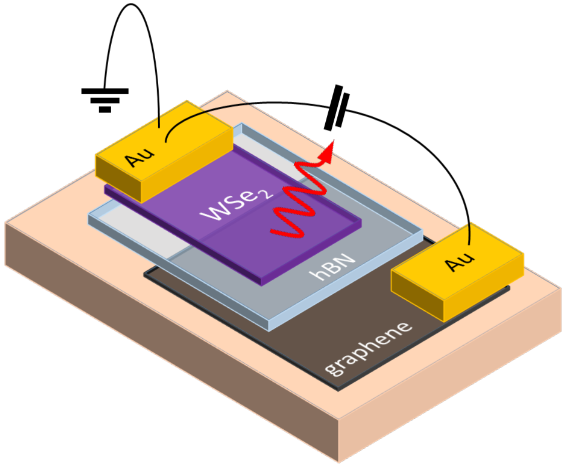
❖ Electrically addressable?

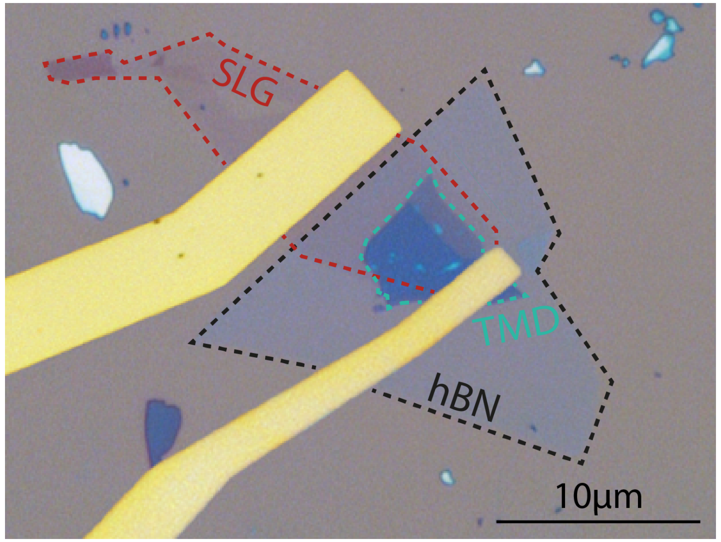
Single-photon sources…

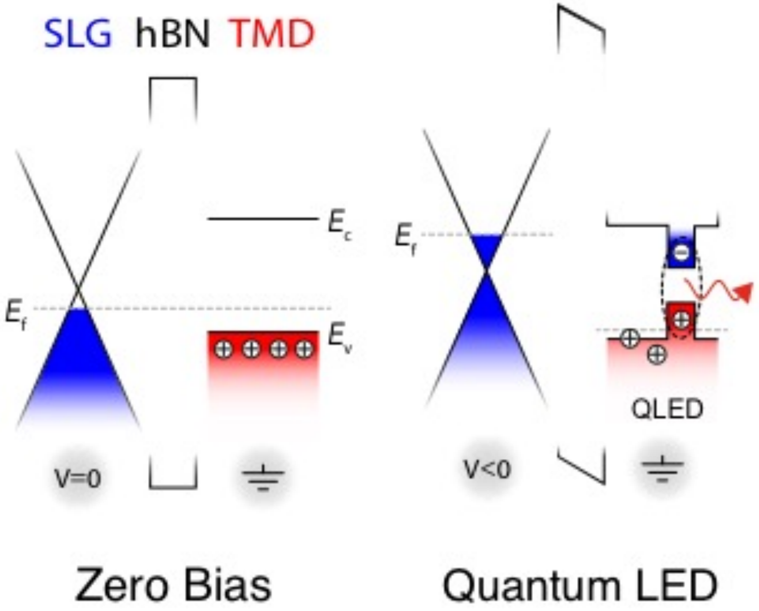
- ✓ Deterministic locations
- ✓ Large-scale
- ✓ Better optical quality than random
- ✓ Emission across the visible spectrum



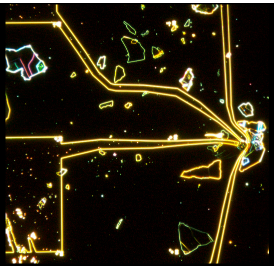
2d quantum LED (random QDs)





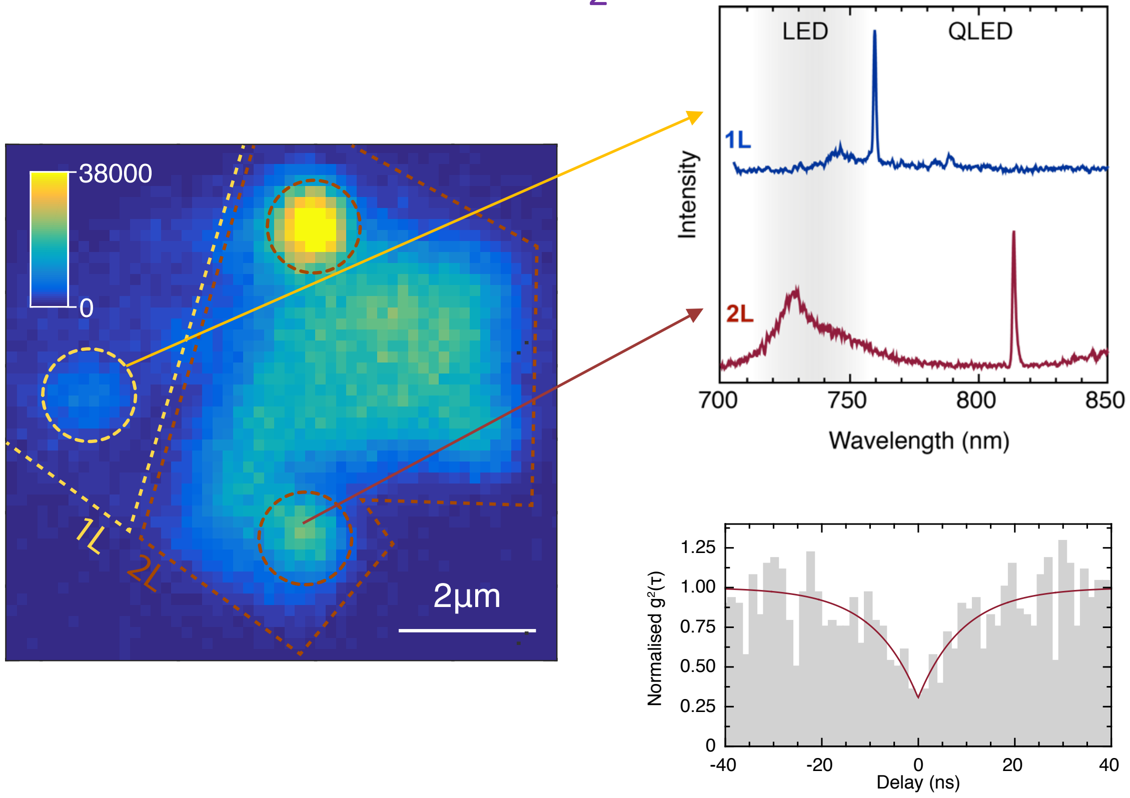


2. Palacios-Berraquero, C. *et al.* Atomically thin quantum light-emitting diodes. *Nat. Commun.* **7,** 12978 (2016).

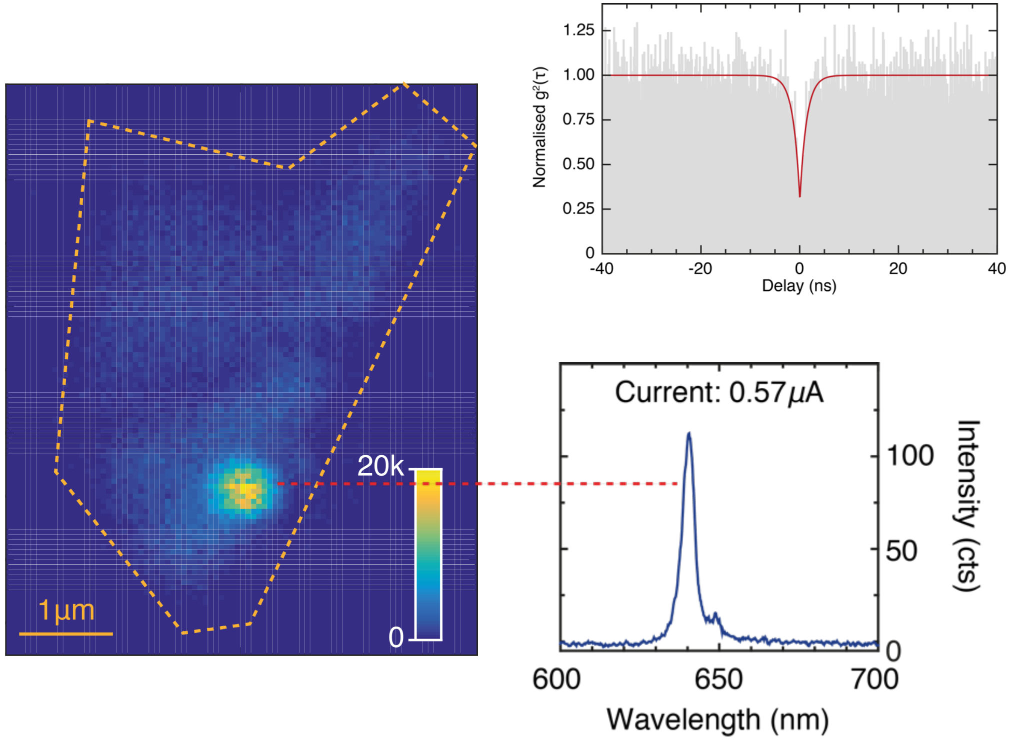


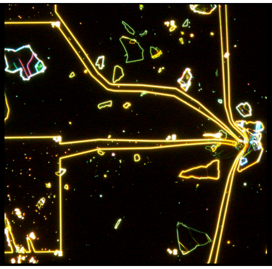
Quantum electroluminescence

WSe_2

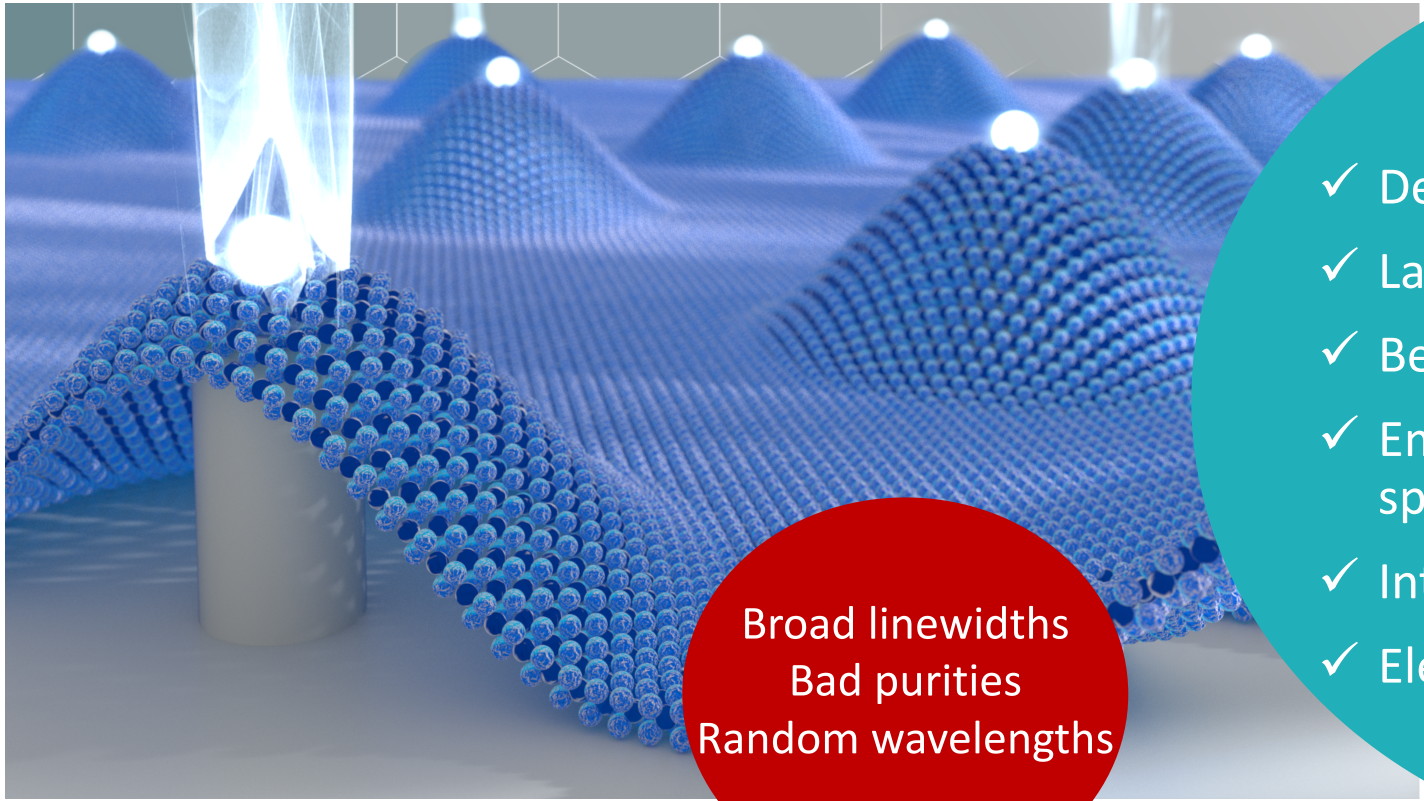


WS_2





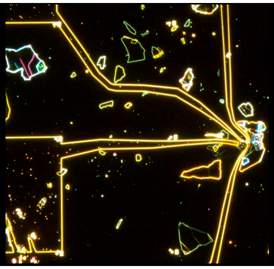
2d-single photon sources…



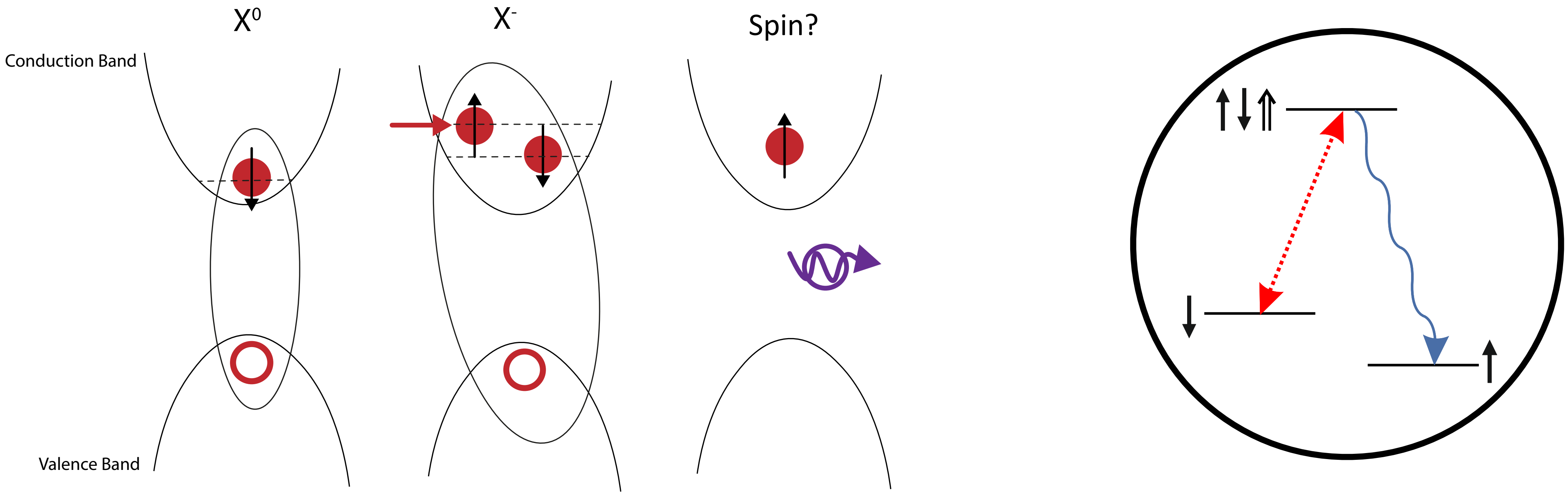
Broad linewidths
Bad purities
Random wavelengths
….

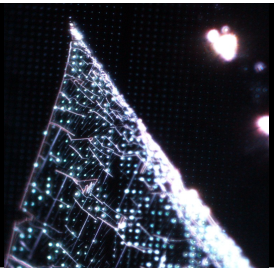
Single-photon sources…

- ✓ Deterministic locations
- ✓ Large-scale
- ✓ Better optical quality than random
- ✓ Emission across the visible spectrum
- ✓ Integrated into heterostructures
- ✓ Electrically addressable



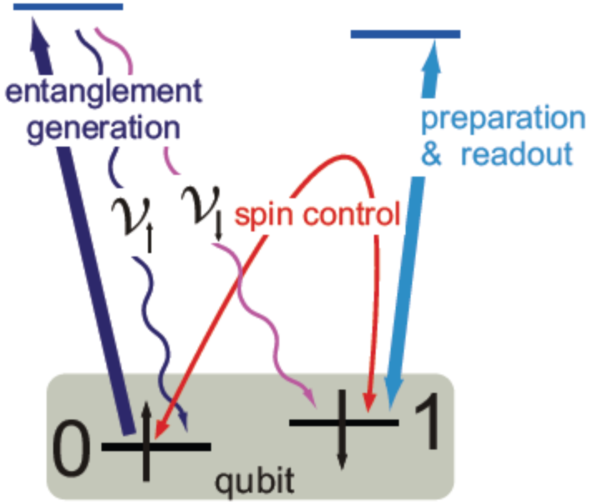
Controllable QD charging



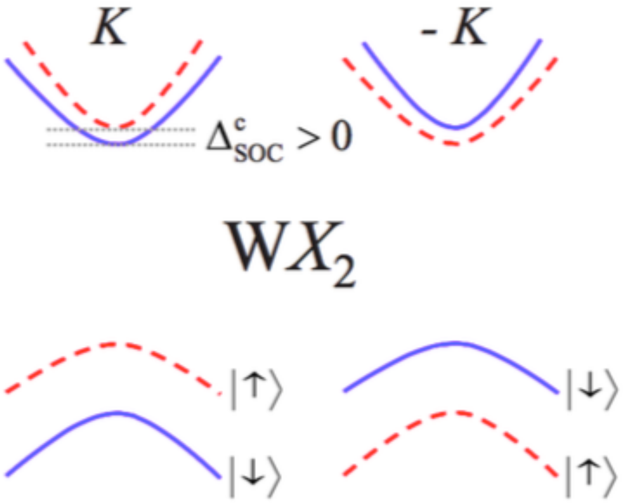


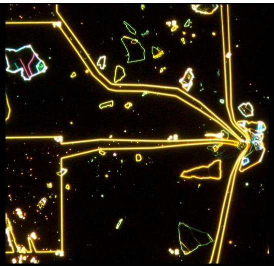
History from III-V QDs…

Advances using III-V QD trion structure..

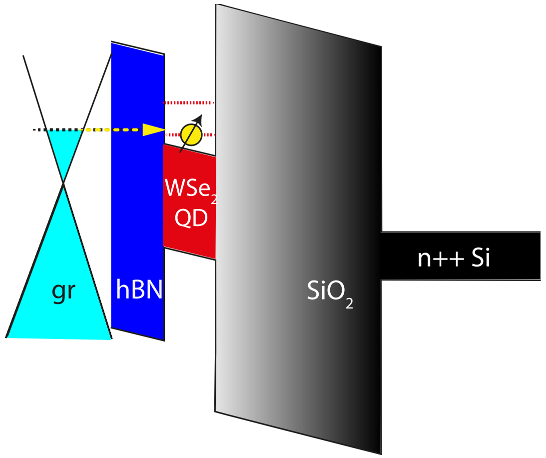


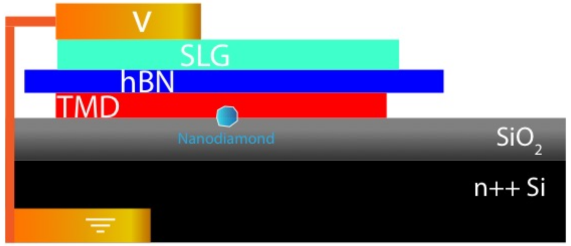
Initialisation:
Science 312, 551 (2006)
Single qubit gates:
Nature 456, 218 (2008)
Readout:
Nature 467, 297 (2010)
Coherence:
Nat. Photon. 4, 367 (2009),
Nat. Comms. 7, 12745 (2016).
Spin-photon entanglement:
Nature 491, 421 & 426 (2012)

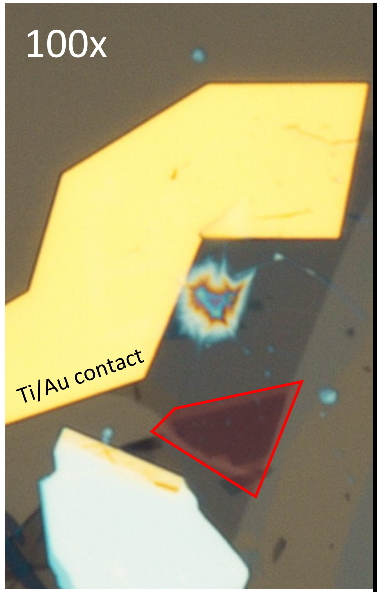




Preliminary: QDot charging



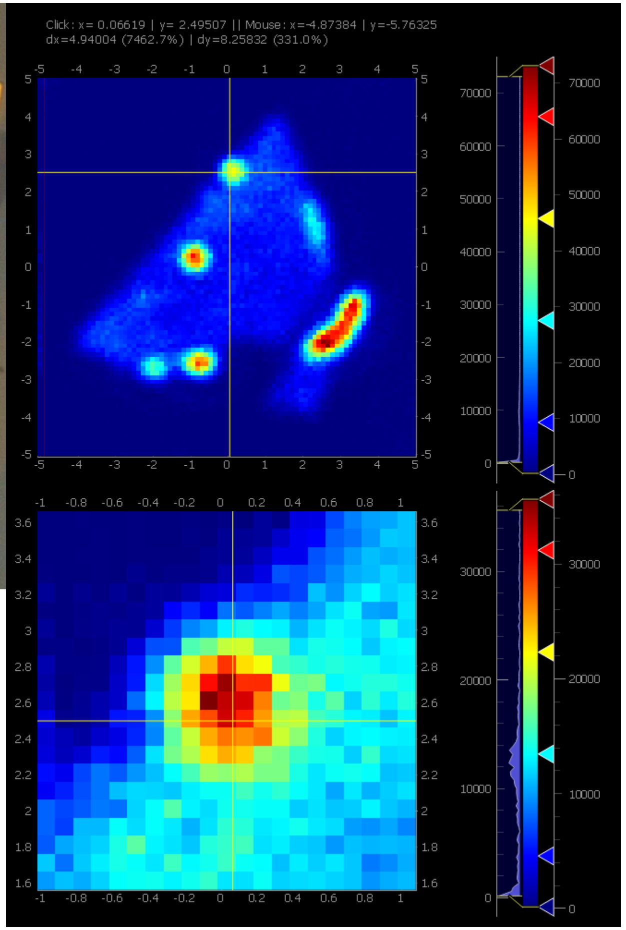




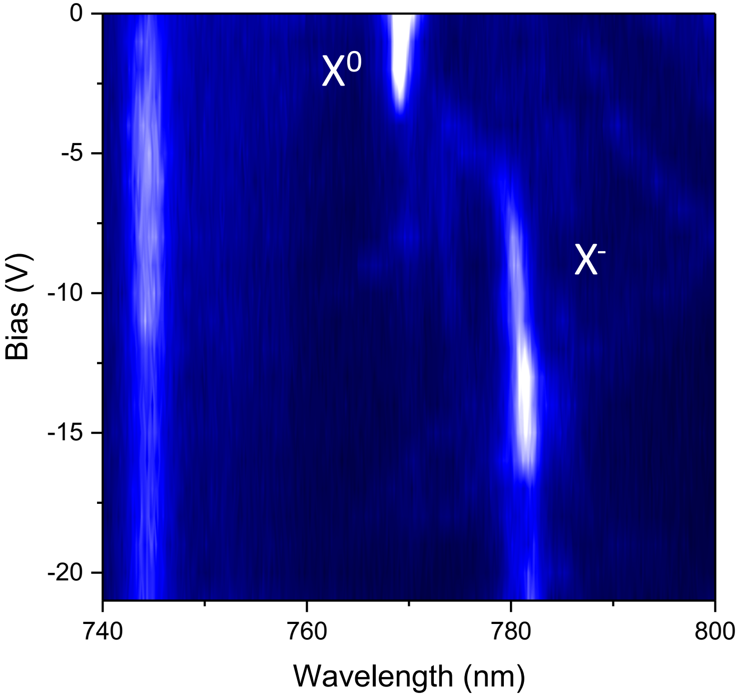
Gr: 1L

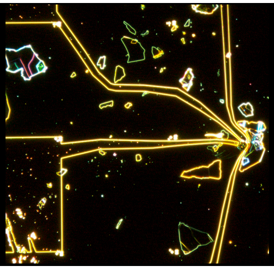
hBN: ~ 5L

WSe2: 1L



Click: x= 0.06619 | y= 2.49507 || Mouse: x=-4.87384 | y=-5.76325
dx=4.94004 (7462.7%) | dy=8.25832 (331.0%)





Current & future projects

Inter-valley coupling

$$\mathcal{H}_{exchange}=\frac{1}{2}\begin{pmatrix} +\delta_0 & +\delta_1 & 0 & 0 \\ +\delta_1 & +\delta_0 & 0 & 0 \\ 0 & 0 & -\delta_0 & +\delta_2 \\ 0 & 0 & +\delta_2 & -\delta_0 \end{pmatrix}$$

emission wavelength

Shape tuning

Wafer-scale devices

Jing Kong @ MIT: CVD-grown samples

Deterministic QDs in 2d-material

Strain mapping

scanning electron diffraction

Cavities

Interfacing with photonic structures

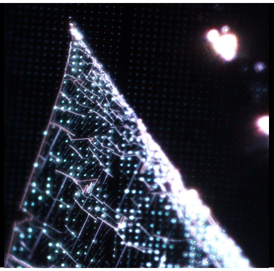
Waveguides

Coupling to other quantum systems

Functional pillars

Sensing

Implanted colour centres



THE TEAM : CAM^2

Quantum Information & Nanoscale Metrology Group

Mete Atatüre

Dhiren Kara

Matteo Barbone

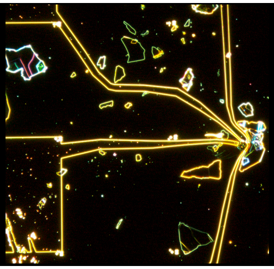
Alejandro R.-P. Montblanch

Nanopatterned substrates (Harvard)

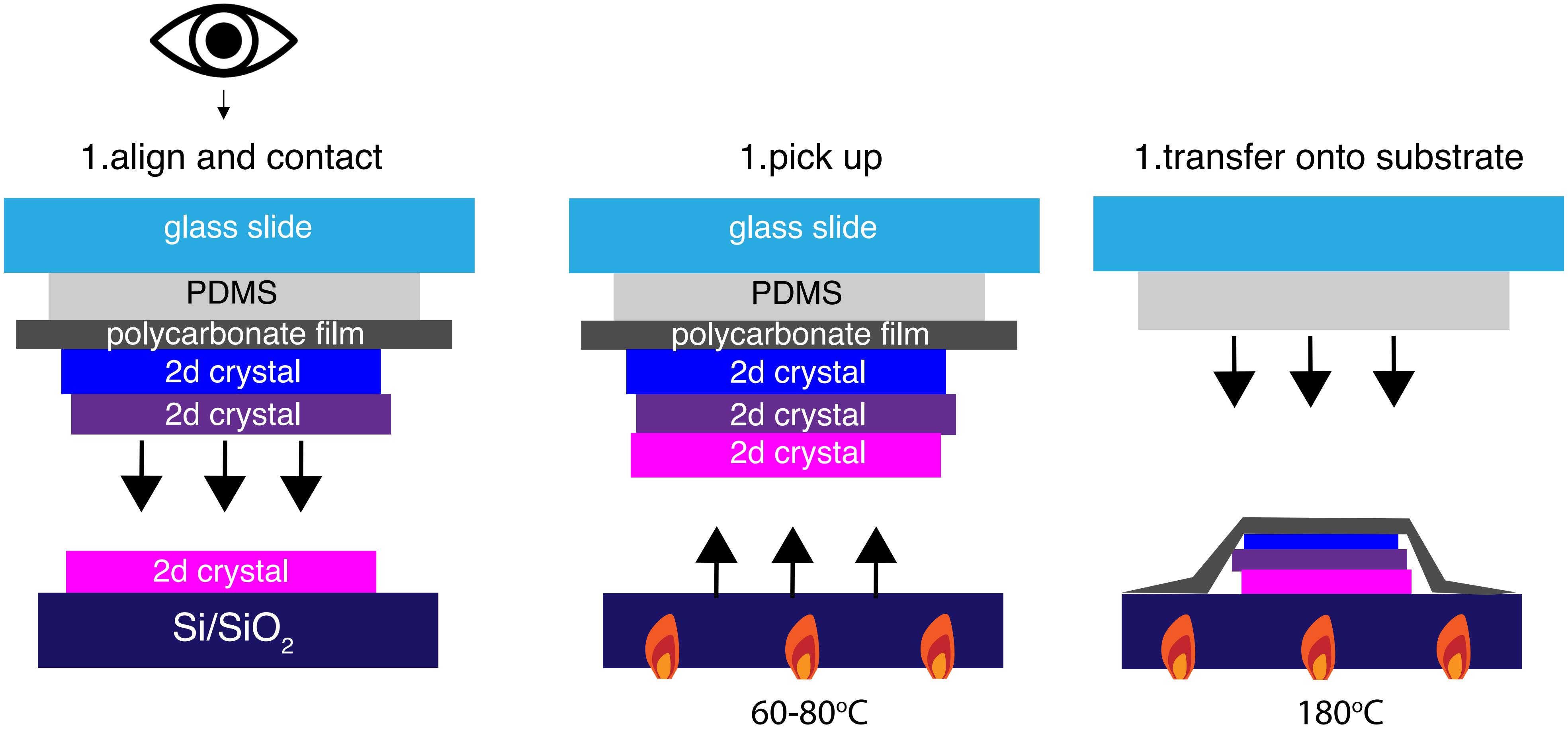
Pawel Latawiec
Marko Loncar

Cambridge Graphene Centre

Andrea Ferrari
Xiaolong Chen
Ilya Goyhkman
Duhee Yoon
Anna K. Ott



PC dry transfer



1.align and contact

glass slide

PDMS

polycarbonate film

2d crystal

2d crystal

2d crystal

Si/SiO$_2$

1.pick up

glass slide

PDMS

polycarbonate film

2d crystal

2d crystal

2d crystal

60-80°C

1.transfer onto substrate

180°C