Domes made of two dimensional crystals: magneto- and quantum-optical properties

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Acknowledgements I

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CNR IFN
Istituto di Fotonica e Nanotecnologie

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Acknowledgements II

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Acknowledgements II

<u>**Elena Blundo**</u>
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Salvatore Cianci, Federico Tuzi
Antonio Miriametro

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EQUAISE

QUANTERA
ERA-NET Cofund in Quantum Technologies

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Adam Babiński
Maciej Molas

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Institute of Experimental Physics, Faculty of Physics,
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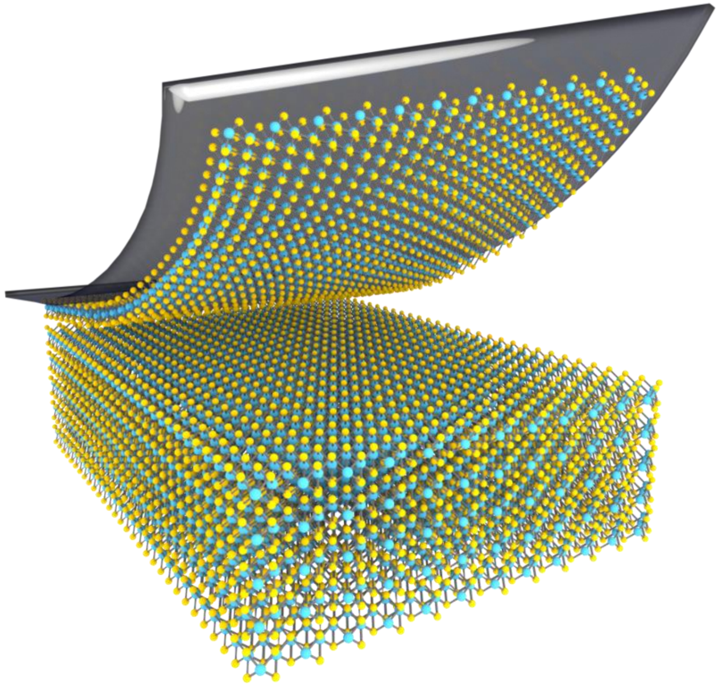
Outline

- Strain in 2D crystals
- Formation, characteristics and control of artificial domes in exfoliable materials
- Strain fields in curved membranes: optical, vibrational and magneto-optical properties
- Applications for site-controlled quantum light sources

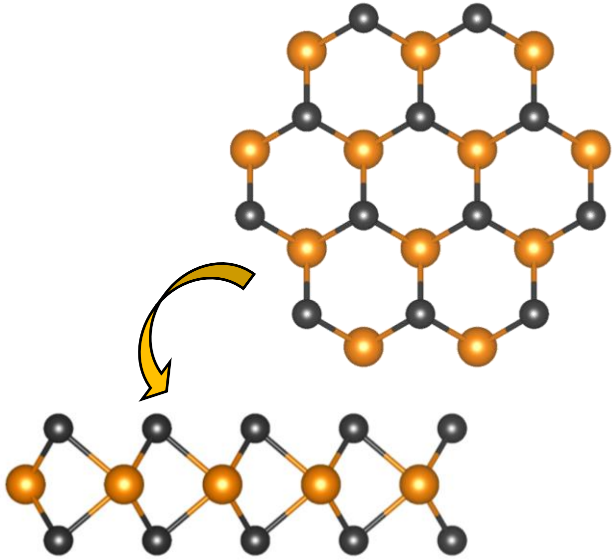
Two-dimensional crystals



MX_2

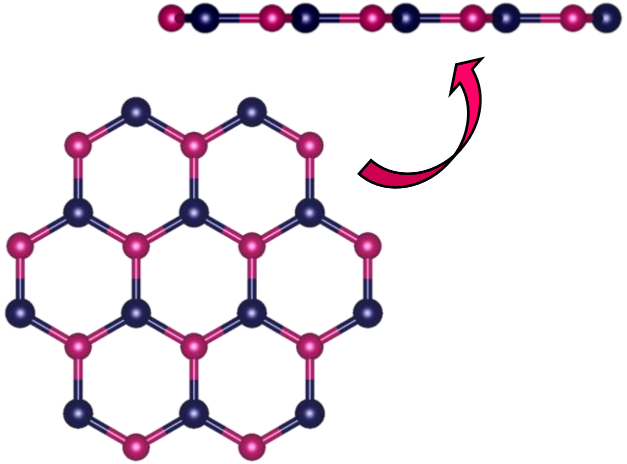
M: Mo, W

X: S, Se, Te



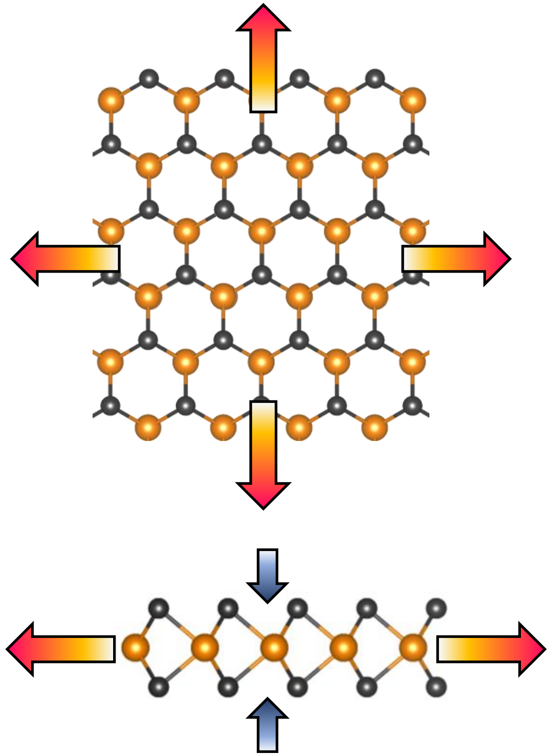
TMDs

hBN



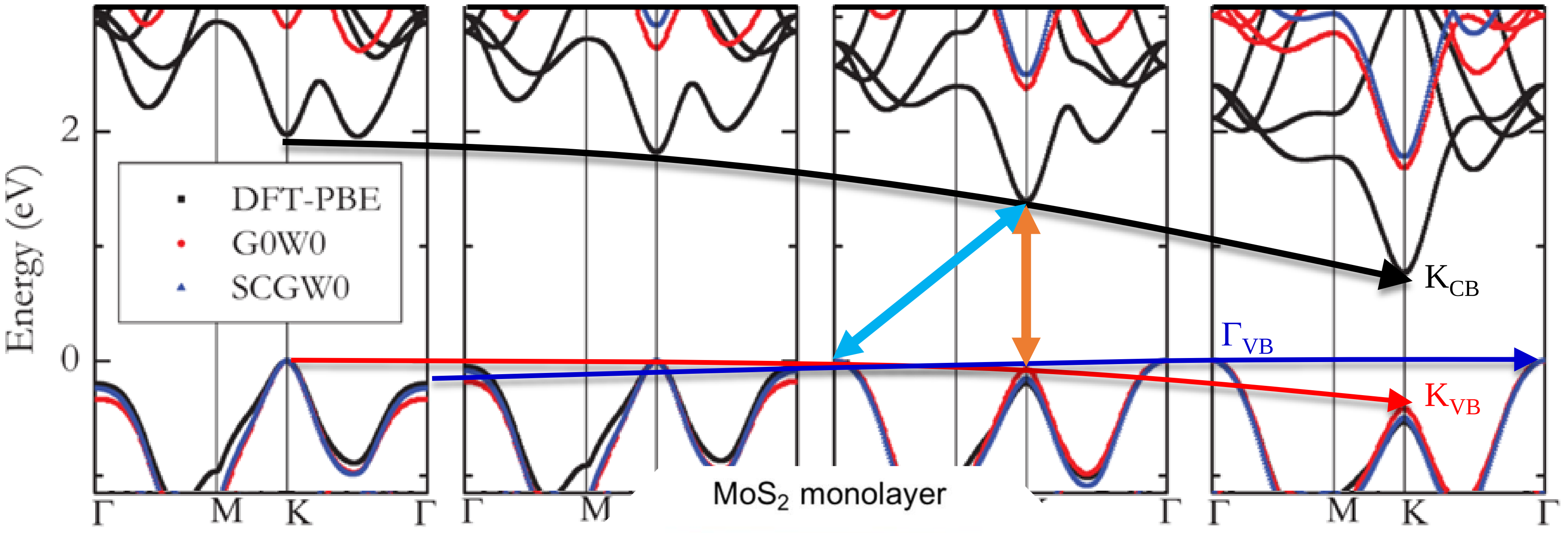
Why strain?

WS$_2$ monolayer



ε in-plane strain

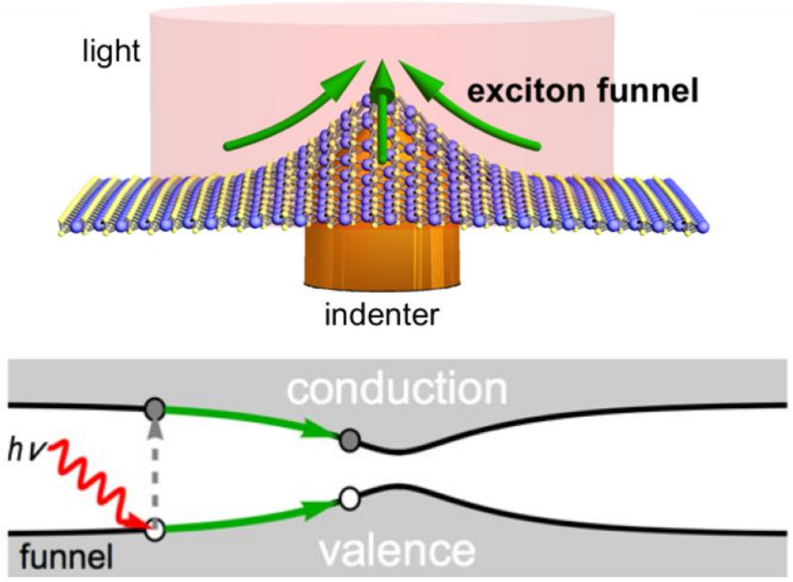
H. Shi *et al.*, Phys. Rev. B **87**, 155304 (2013)



ε = 0%

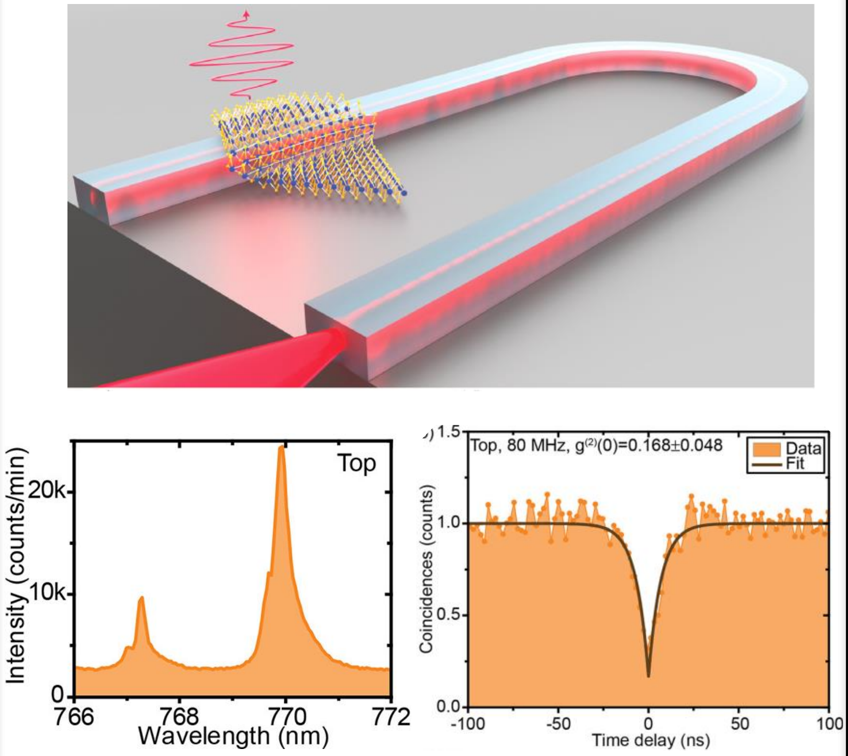
ε = 12%

MoS$_2$ monolayer

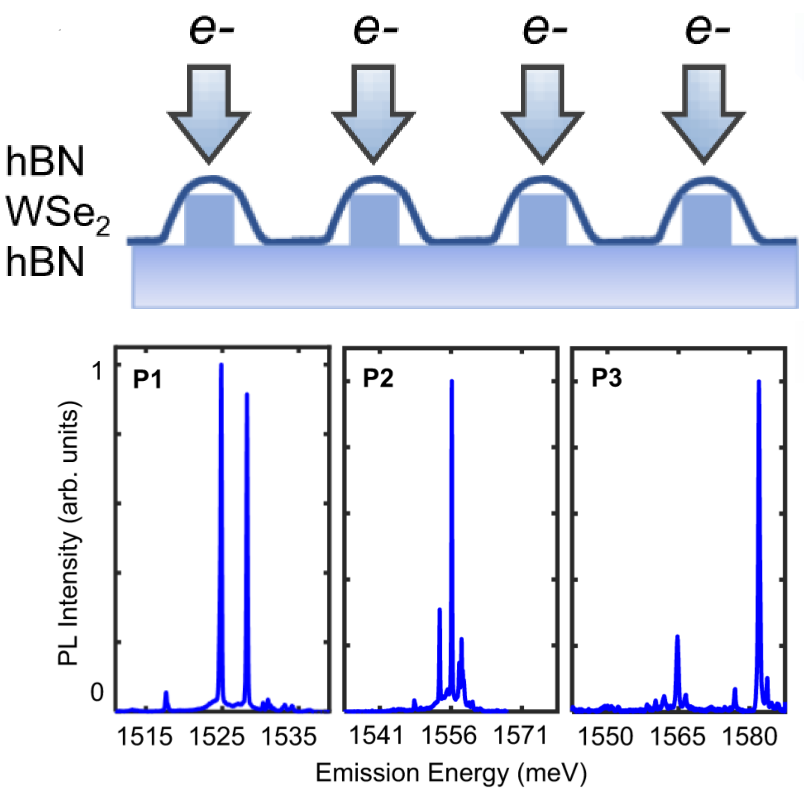


P. San-Jose, Phys. Rev. X **6**, 031046 (2016)

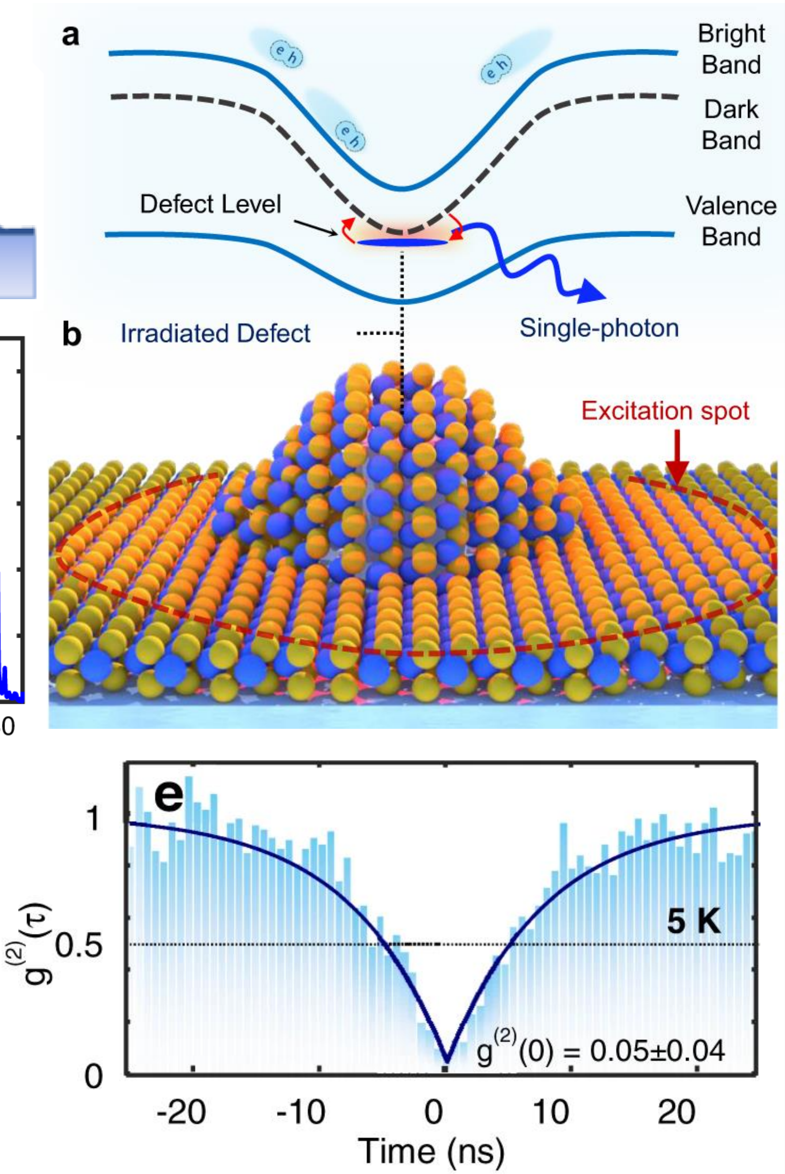
Why strain?



Carlos Errando-Herranz et al., ACS Photonics **8**, 1069 (2021)



K. Parto et al., Nat Commun **12,** 3585 (2021)

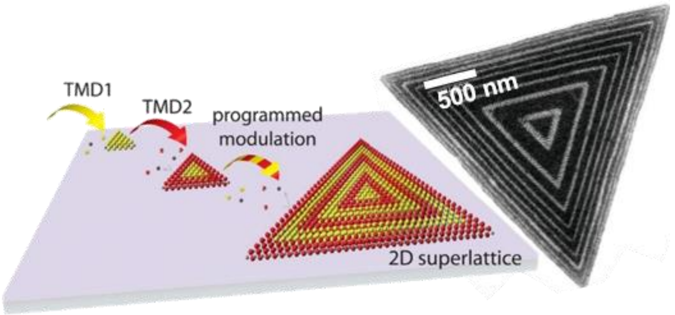


Quantum Technologies

Straining methods

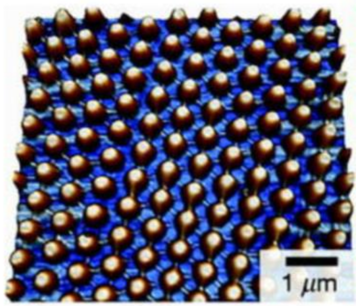
E. Blundo et al.
Appl. Phys. Rev. **8**, 021318 (2021)

Growth of superlattices



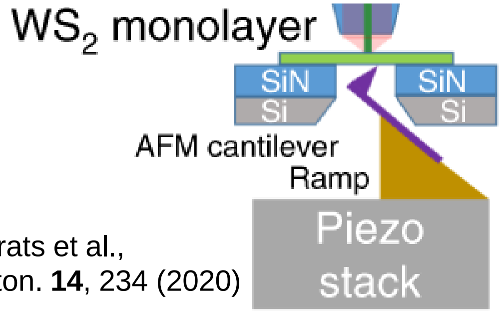
Xie et al., Science **359**, 1131 (2020)

Deposition on nanocones/pillars



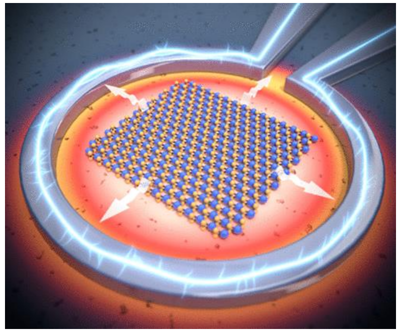
Li et al., J. Am. Chem. Soc. **138**, 5123 (2016)

Indenting



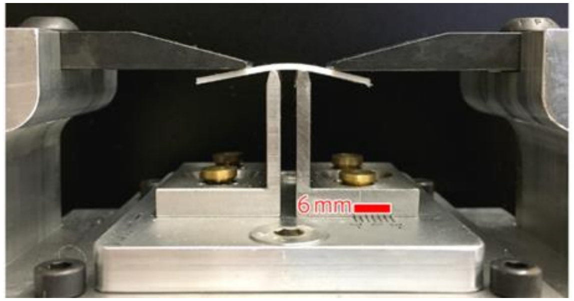
M. G. Harats et al.,
Nat. Photon. **14**, 234 (2020)

Stretching



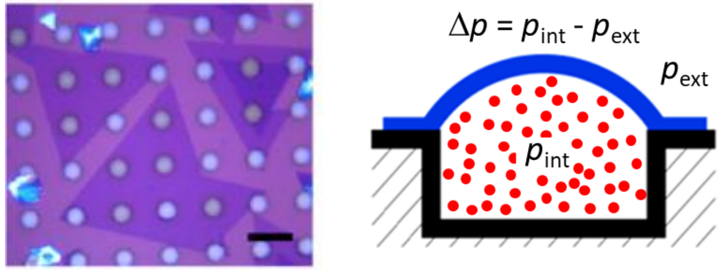
Ryu et al., Nano Lett. **20**, 5339 (2020)

Bending



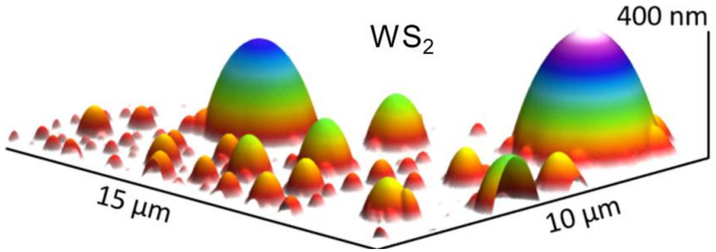
Wu et al., Nano Lett.**18**, 2351 (2018)

Bulging



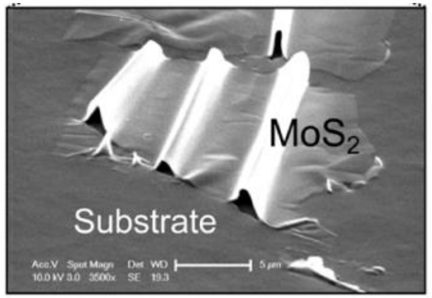
Lloyd et al., Nano Lett.**16**, 5836 (2016)

Bubbling



Blundo et al, Phys. Rev. Research **2**, 012024 (2020)

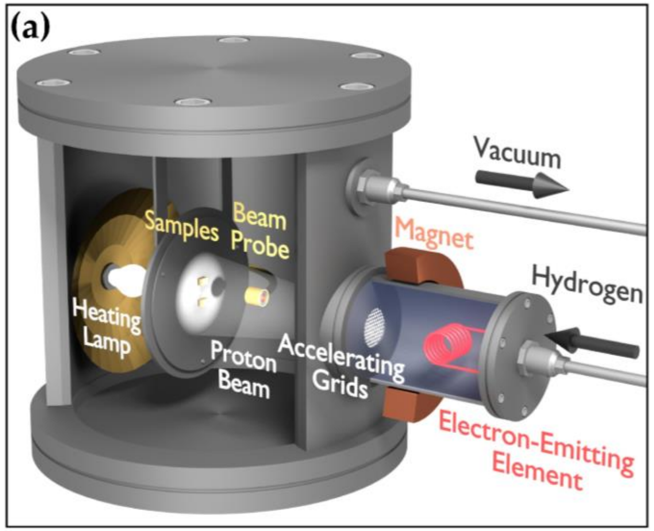
Wrinkling



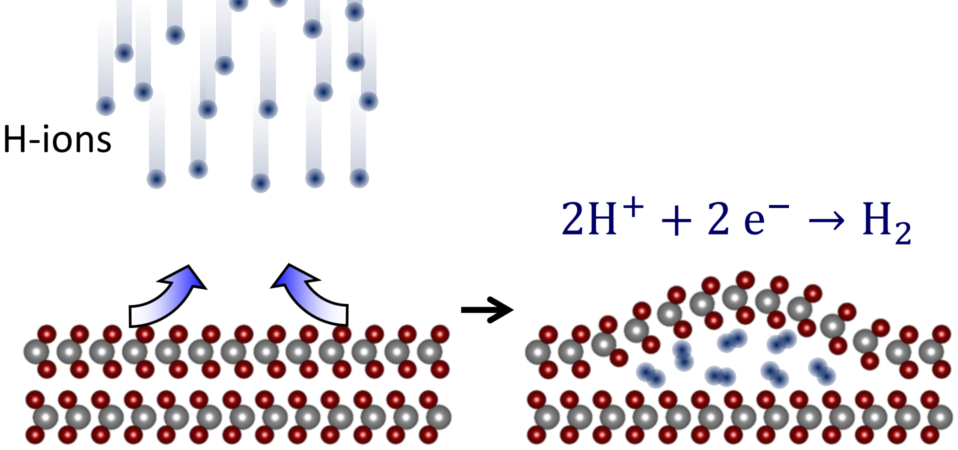
Castellanos-Gomez et al., Nano Lett.**13**, 5361 (2013)

Hydrogen irradiation of bulk TMDs

D. Tedeschi, E. Blundo et al., Adv. Mater. **31**, 1903795 (2019)

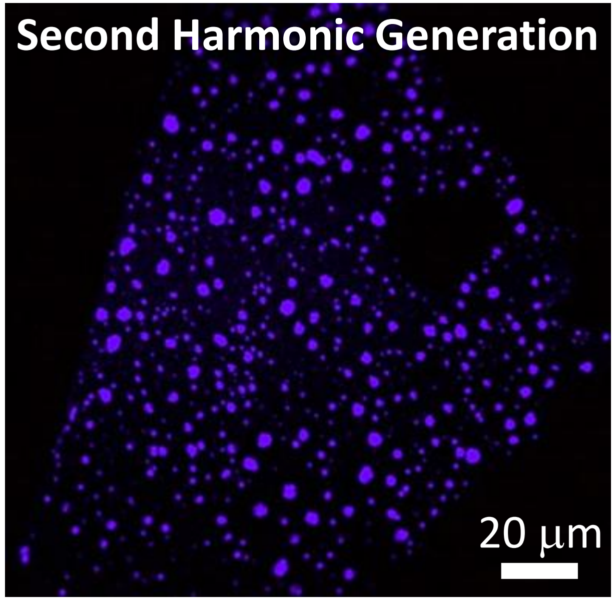


J. Felton, E. Blundo et al., Molecules **25**, 2526 (2020)



$2H^{+} + 2\,e^{-} \rightarrow H_2$

1 monolayer thick !



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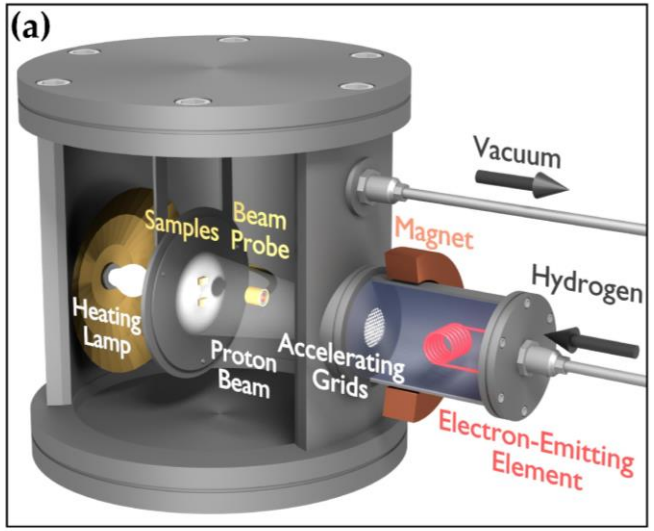
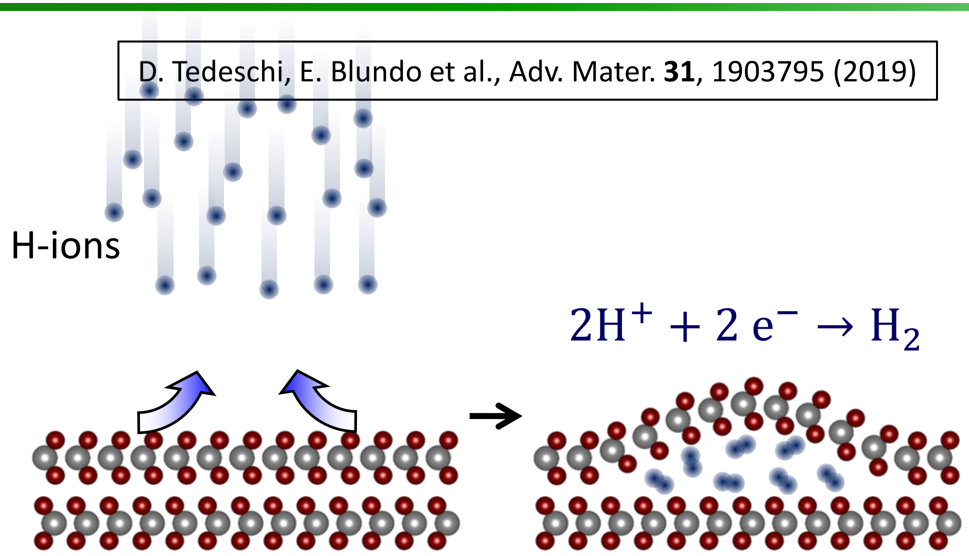


J. Felton, E. Blundo et al., Molecules **25**, 2526 (2020)



$$2H^{+} + 2\,e^{-} \rightarrow H_2$$

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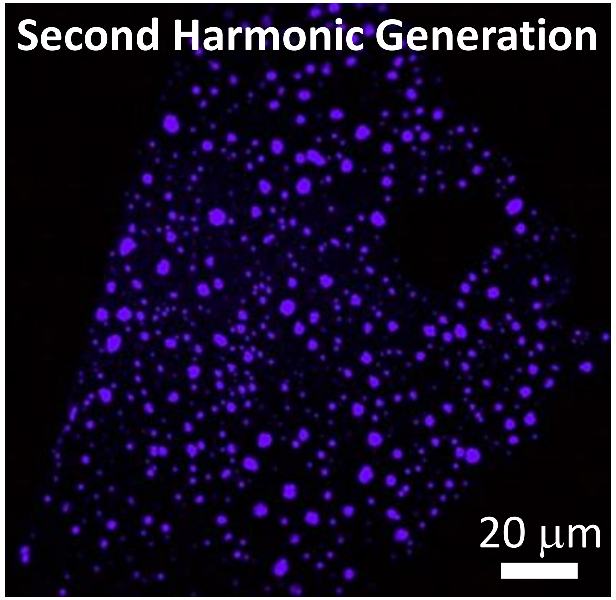
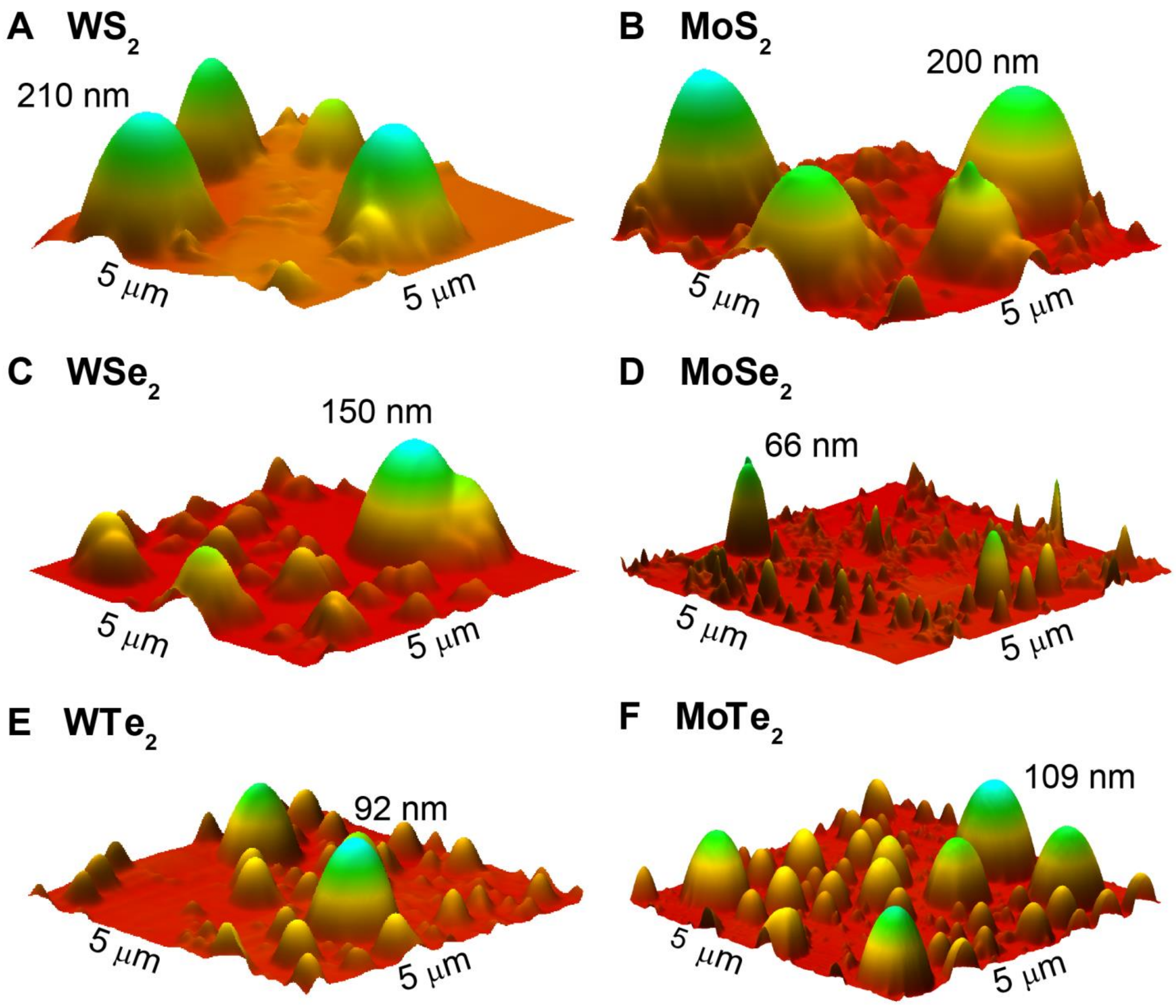
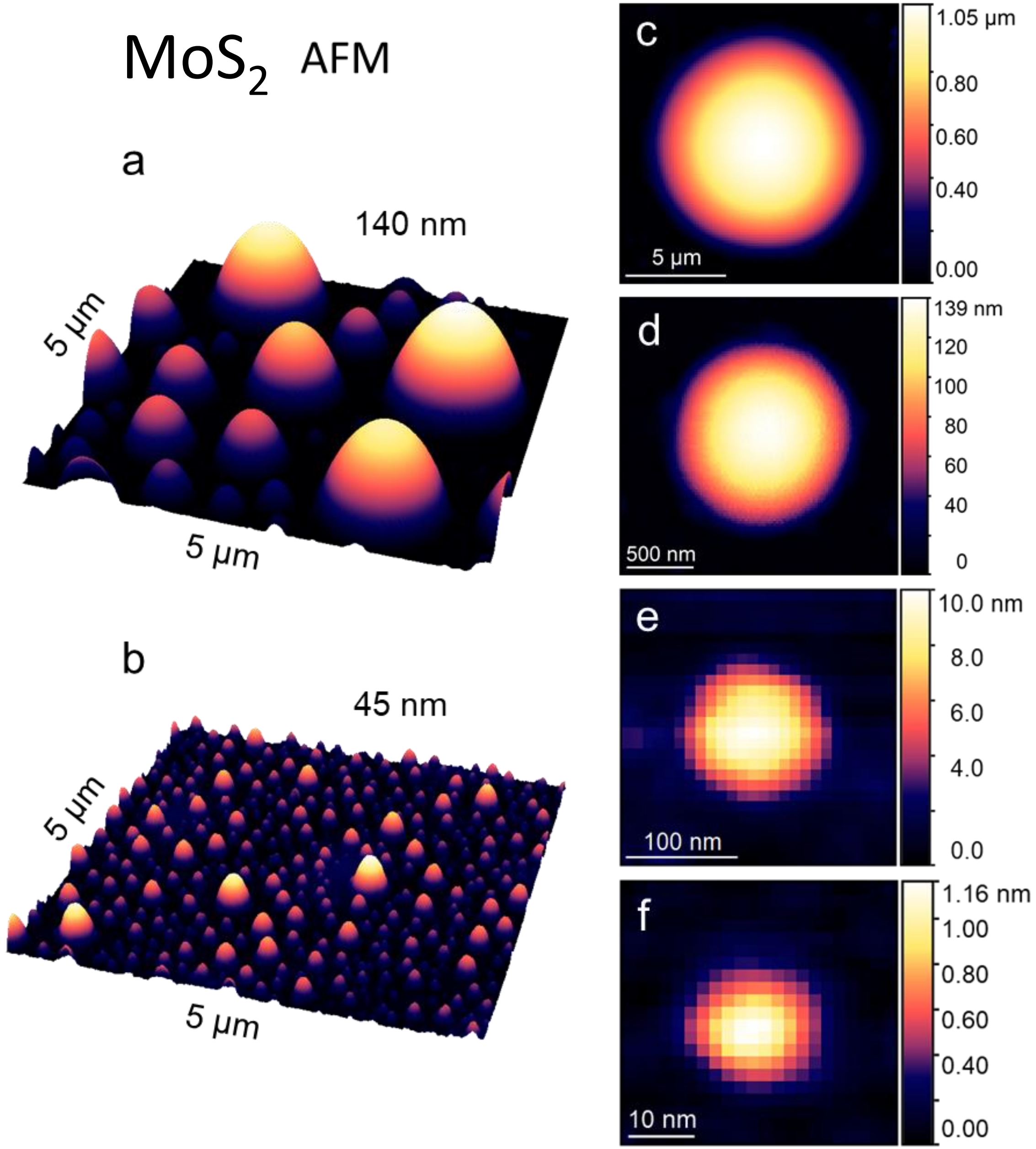


Domes in TMDs



D. Tedeschi. E. Blundo *et al.*, Adv. Mat. **31**, 1903795 (2019)

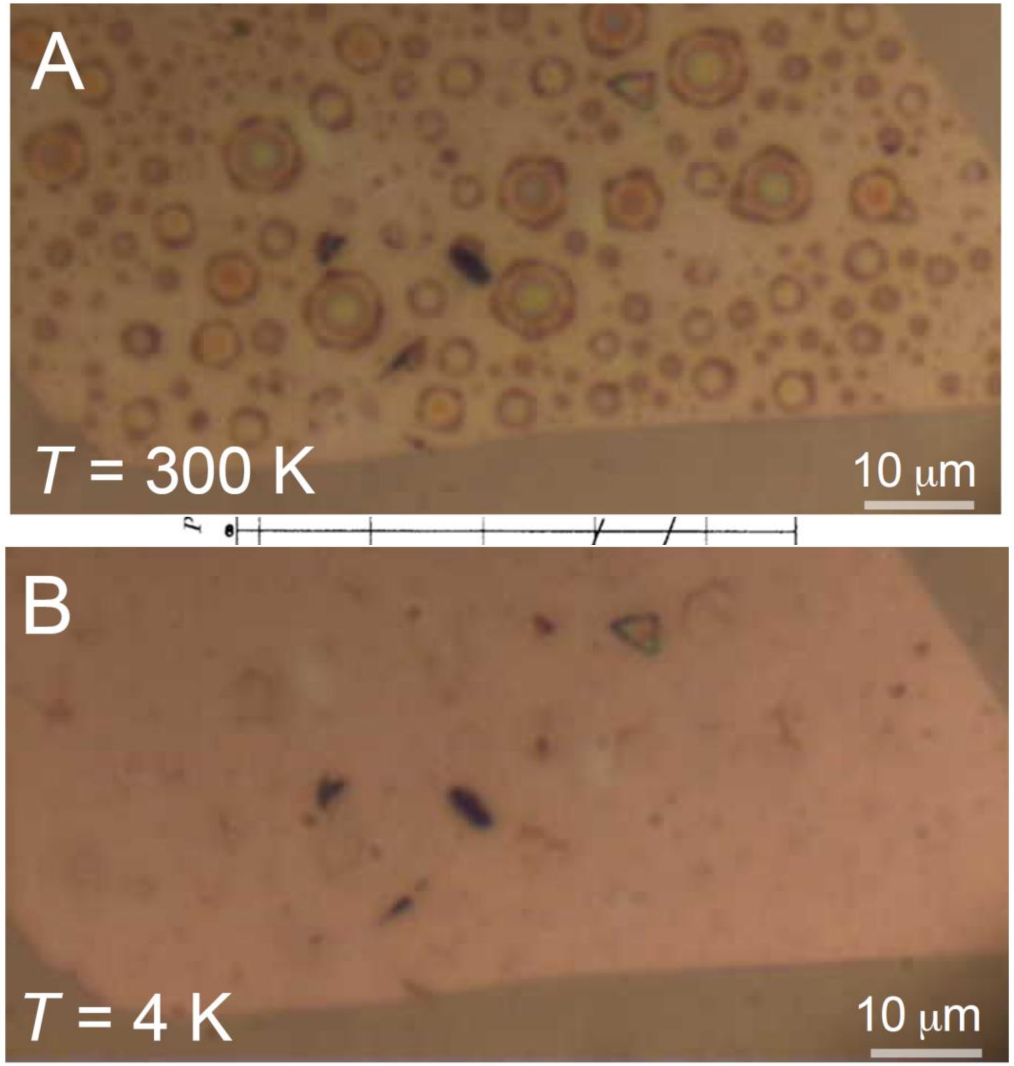
Domes in TMDs: Size

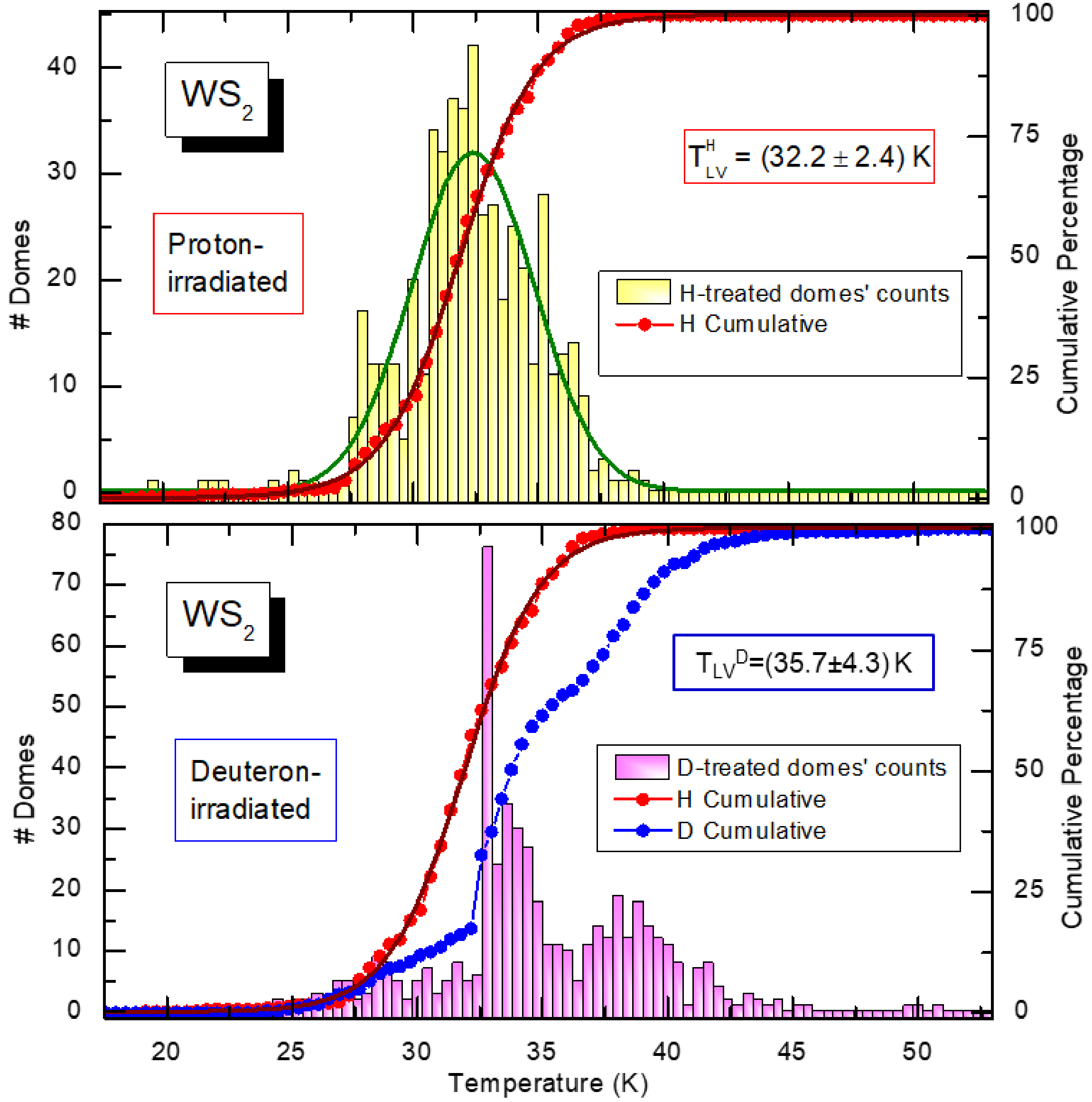


Three orders of magnitude variation in size is possible

Evidence of H_2 molecules within the domes

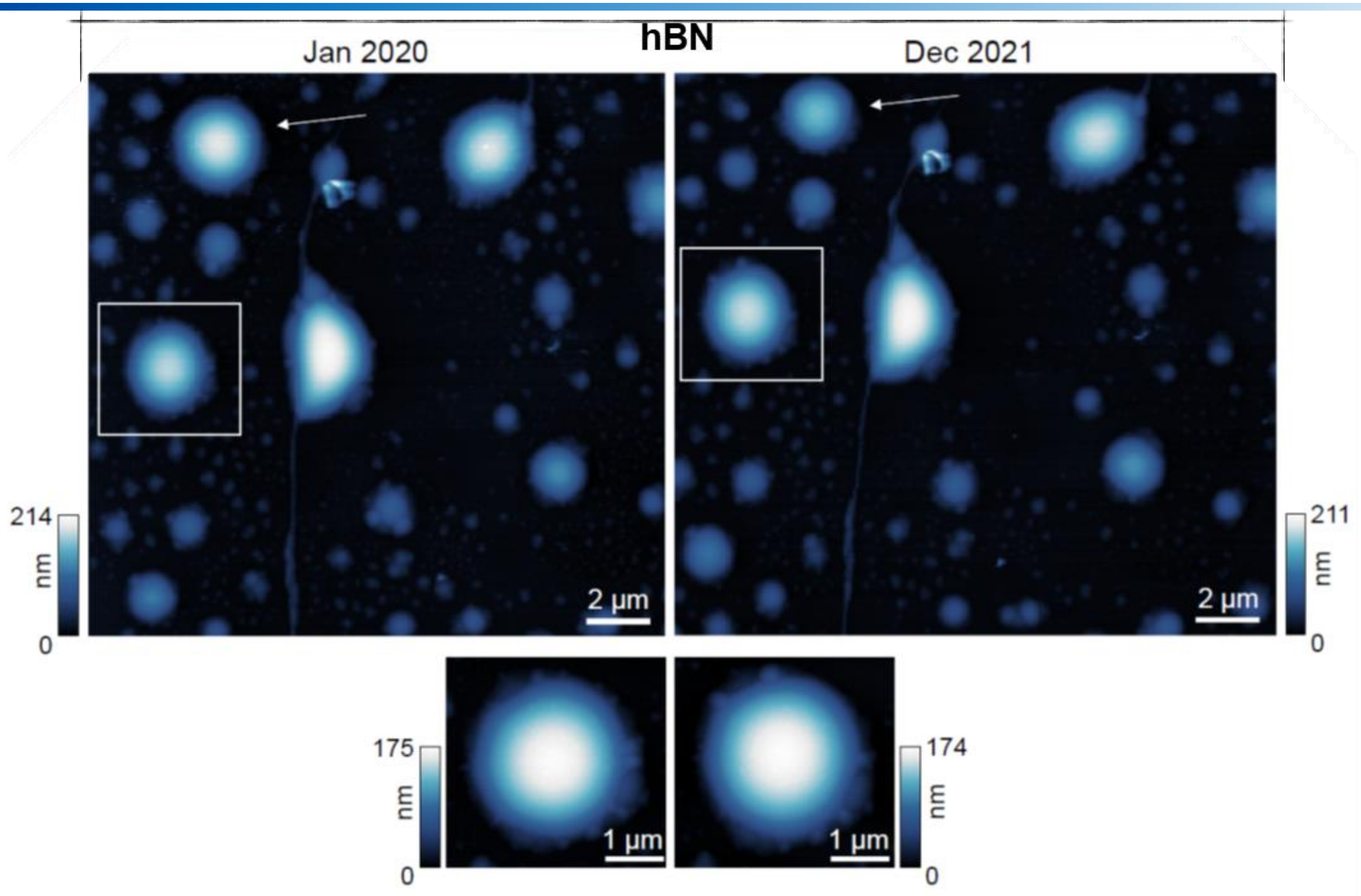
d_H=8×10^{16} protons/cm^2





Domes in TMDs: Main features

Durability > 3 yrs

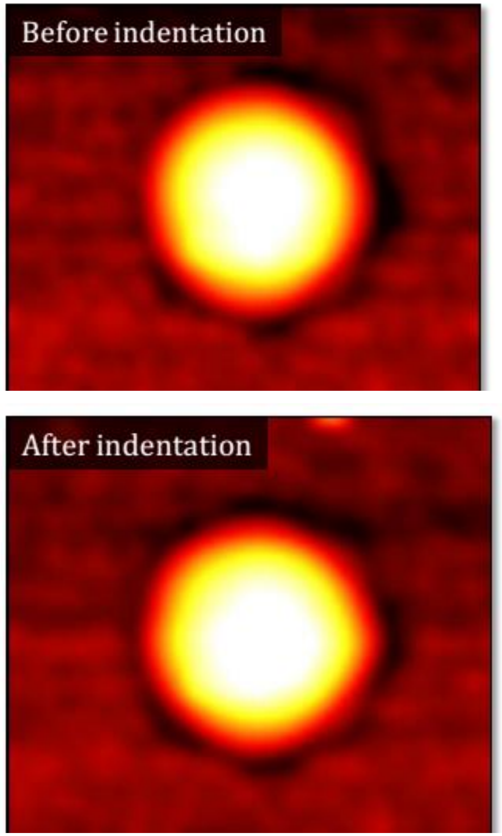


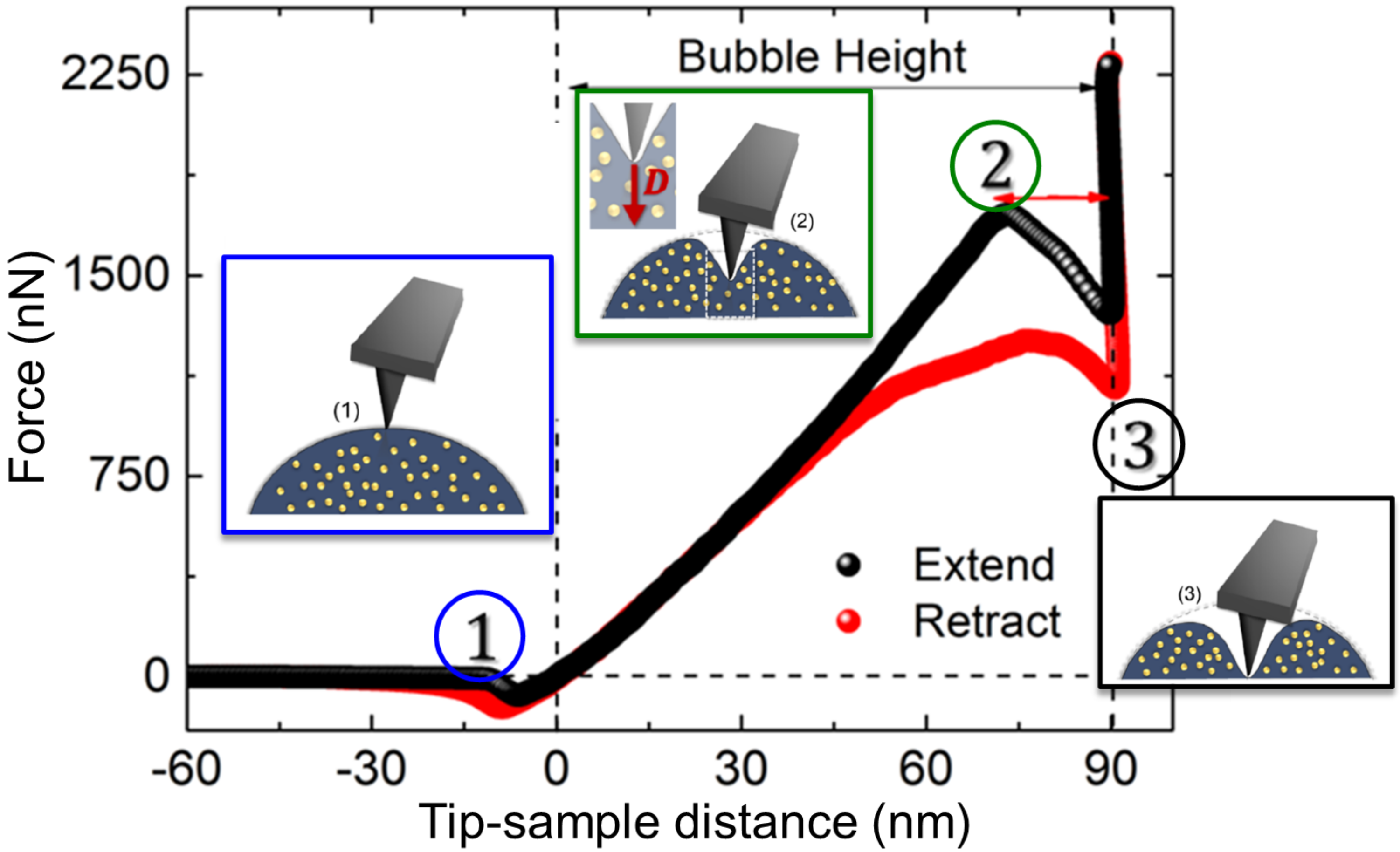
E. Blundo et al., Nano Lett. **22**, 1525 (2022)

Domes in TMDs: Main features

Durability > 3 yrs

Robustness





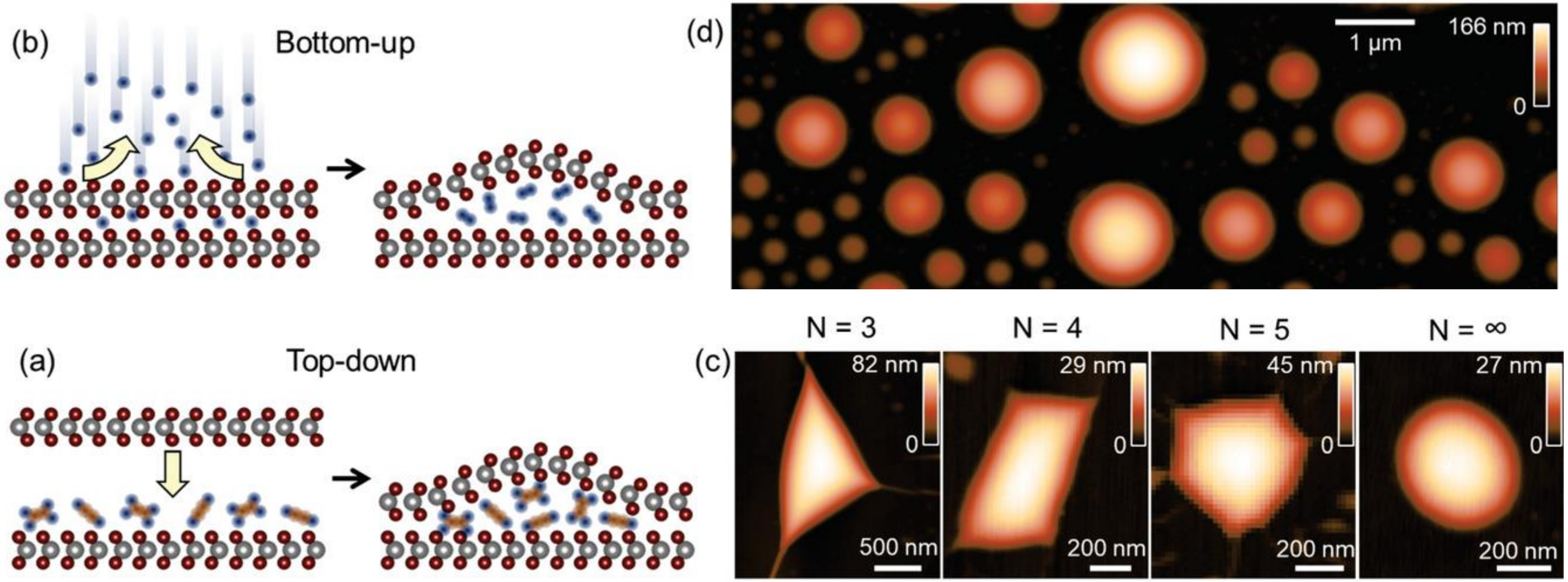
C. Di Giorgio et al., ACS Appl. Mater. Interfaces **13**, 48228 (2021)

Domes in TMDs: Main features

Durability > 3 yrs

Robustness

Regular/
reproducible shape

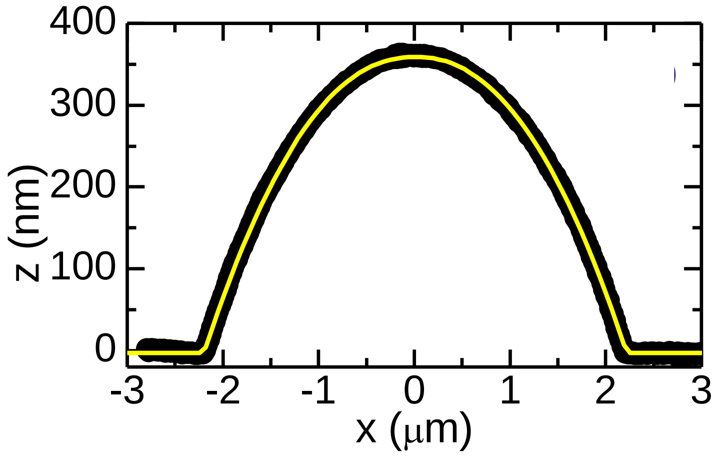


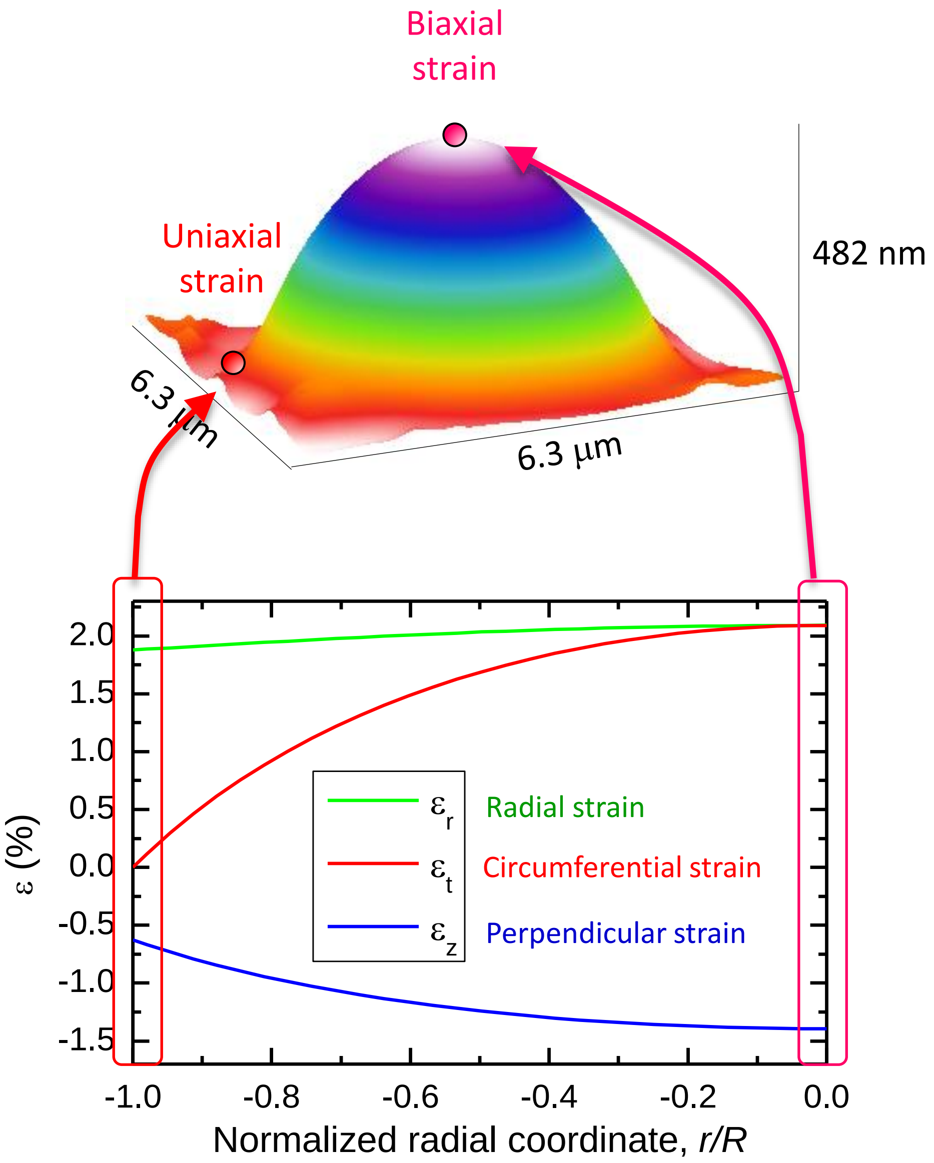
D. Tedeschi. E. Blundo *et al.*, Adv. Mat. **31**, 1903795 (2019)

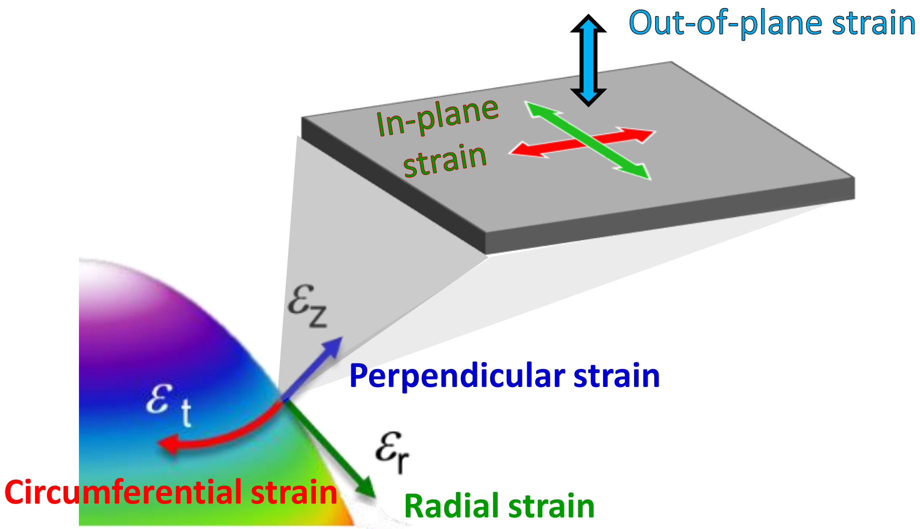
Strain field

FEM (Finite-Element Method) calculations, within the framework of nonlinear membrane theory

E. Blundo et al, Phys. Rev. Lett. **127**, 46101 (2021)

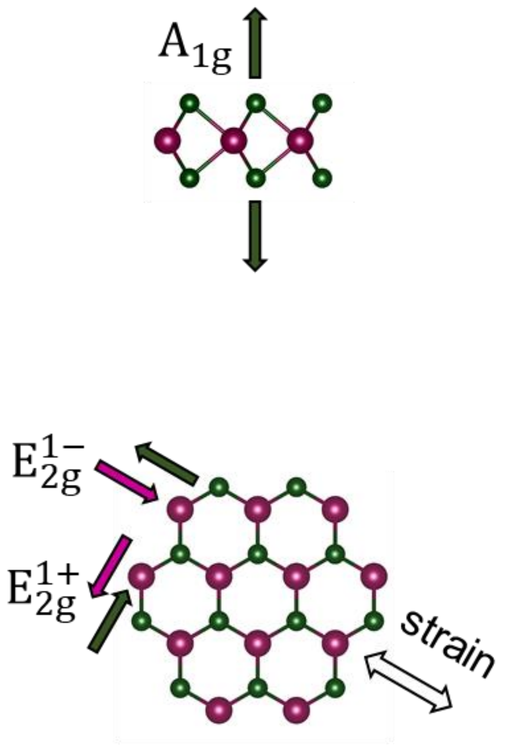


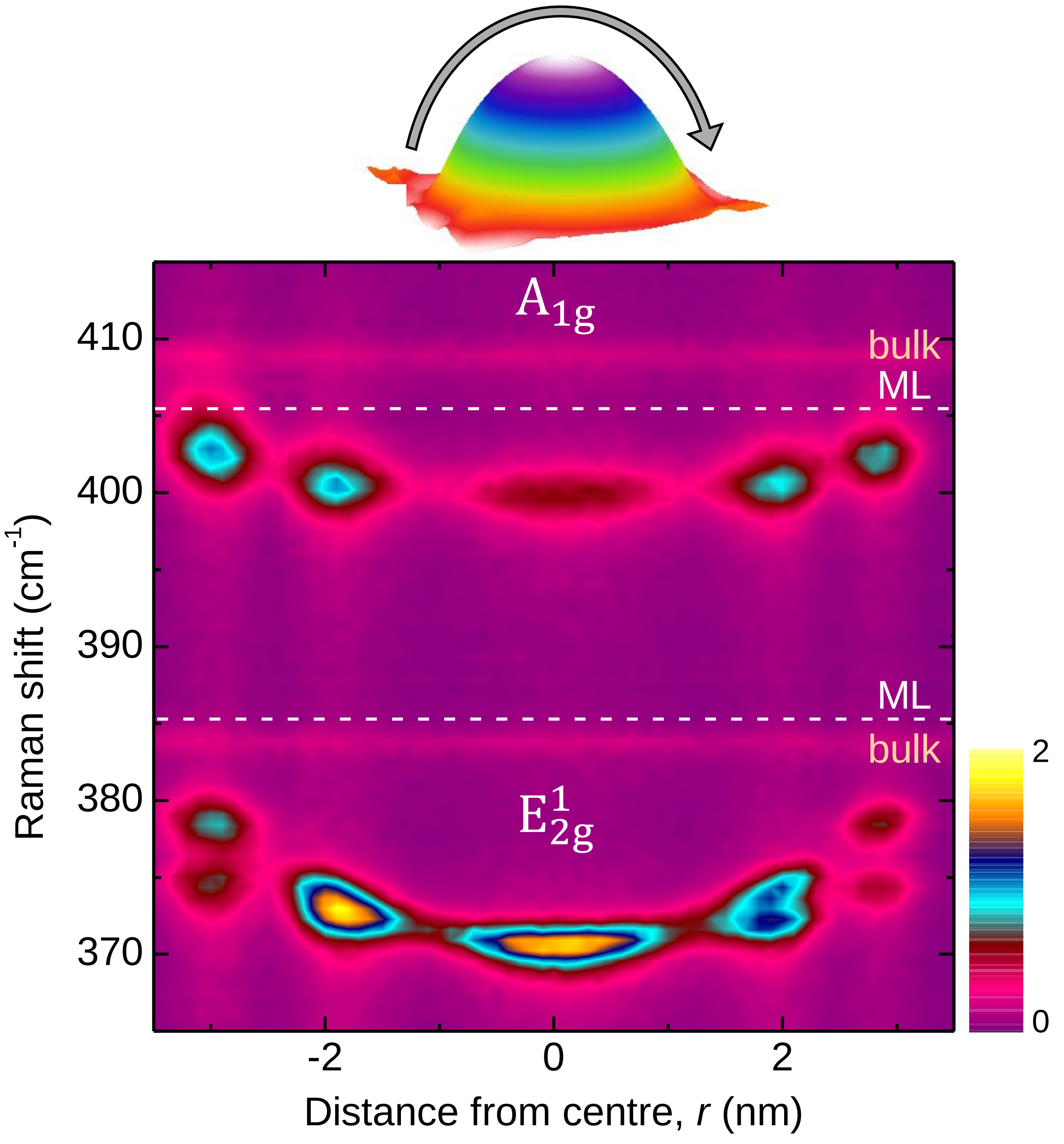


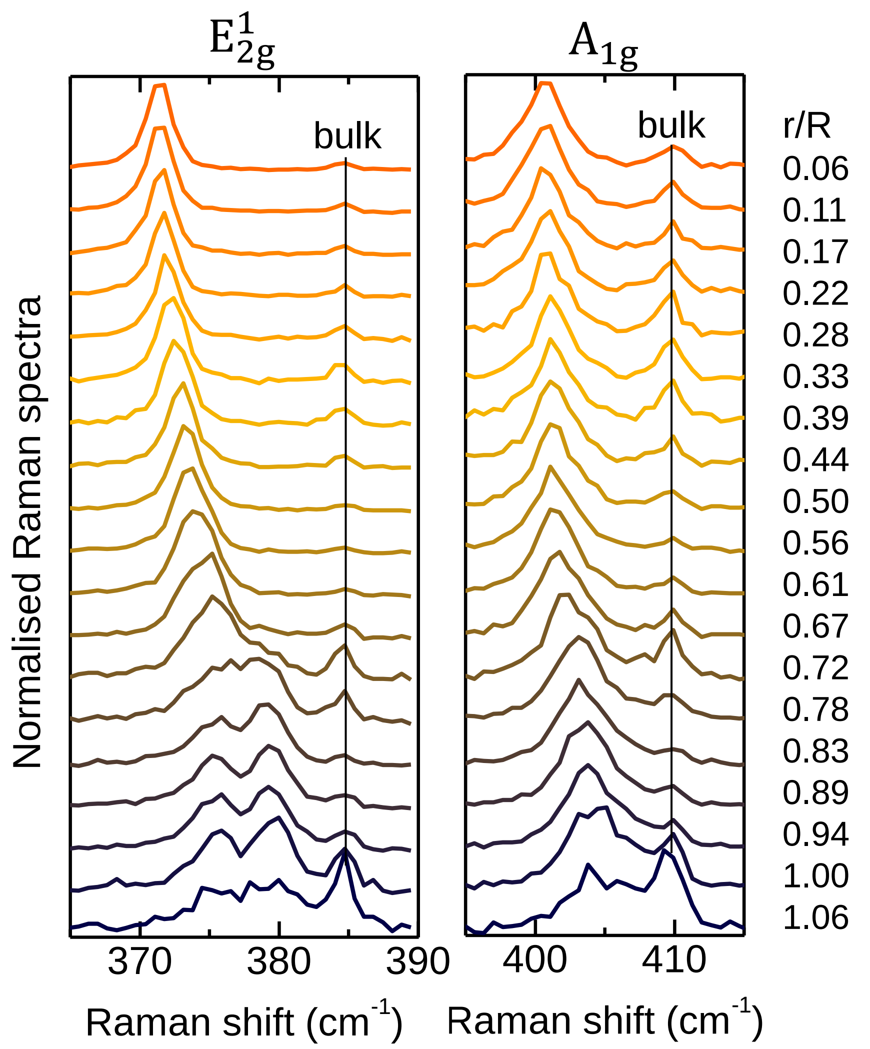


Micro-Raman measurements – MoS_2

E. Blundo et al, Phys. Rev. Lett. **127**, 46101 (2021)







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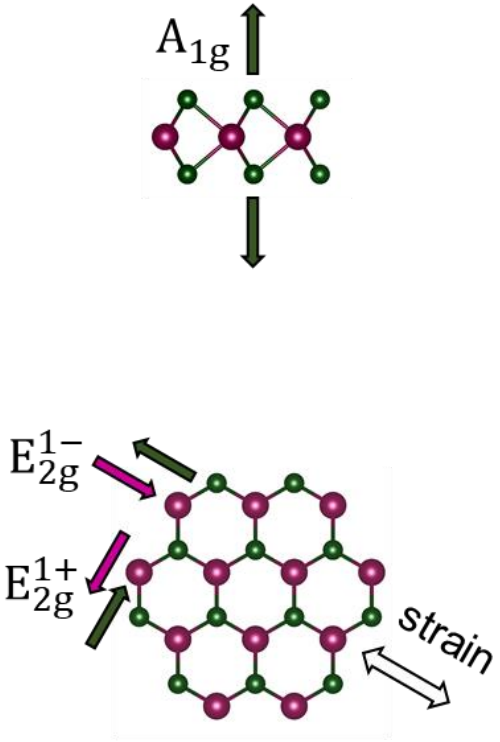
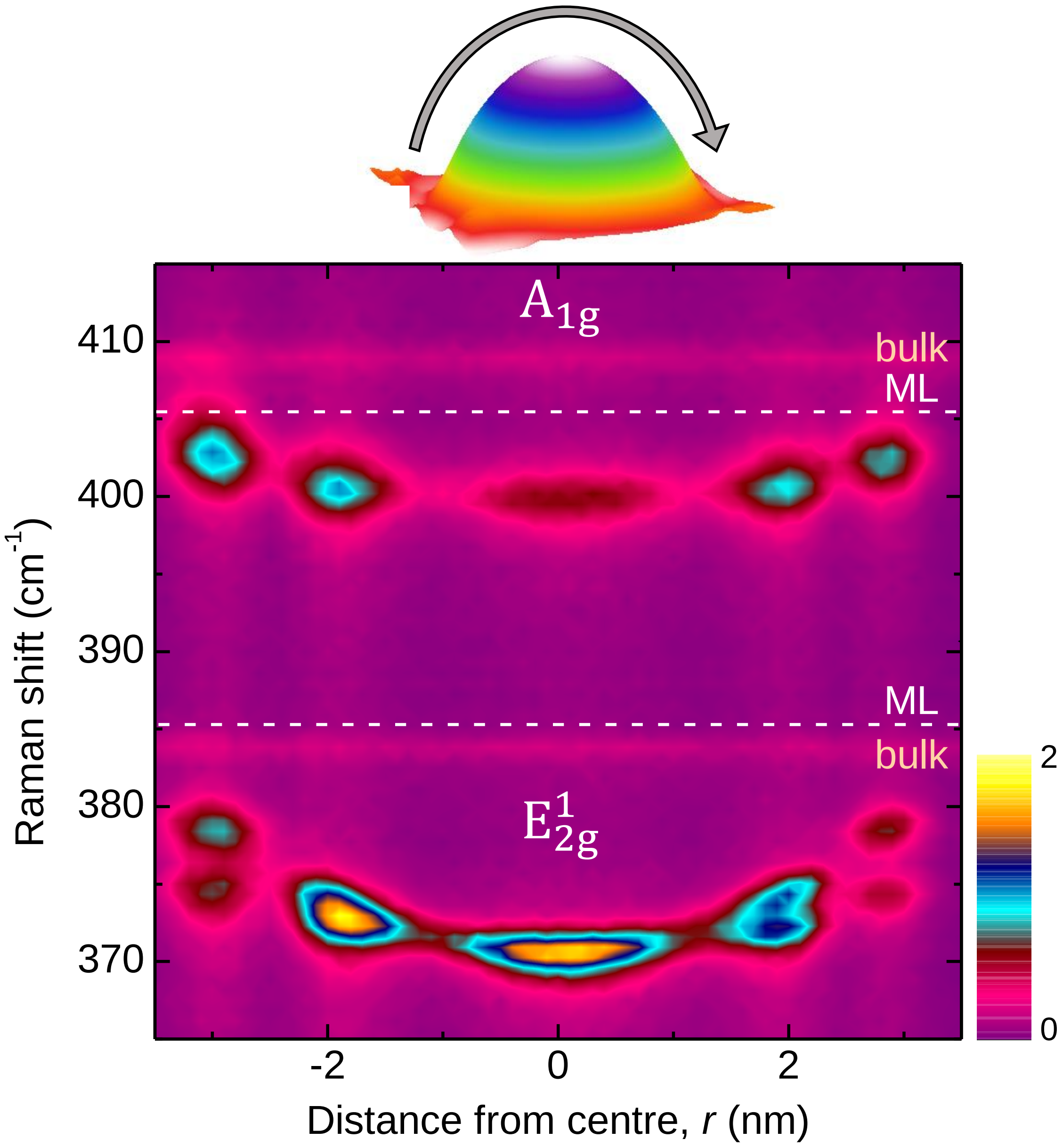
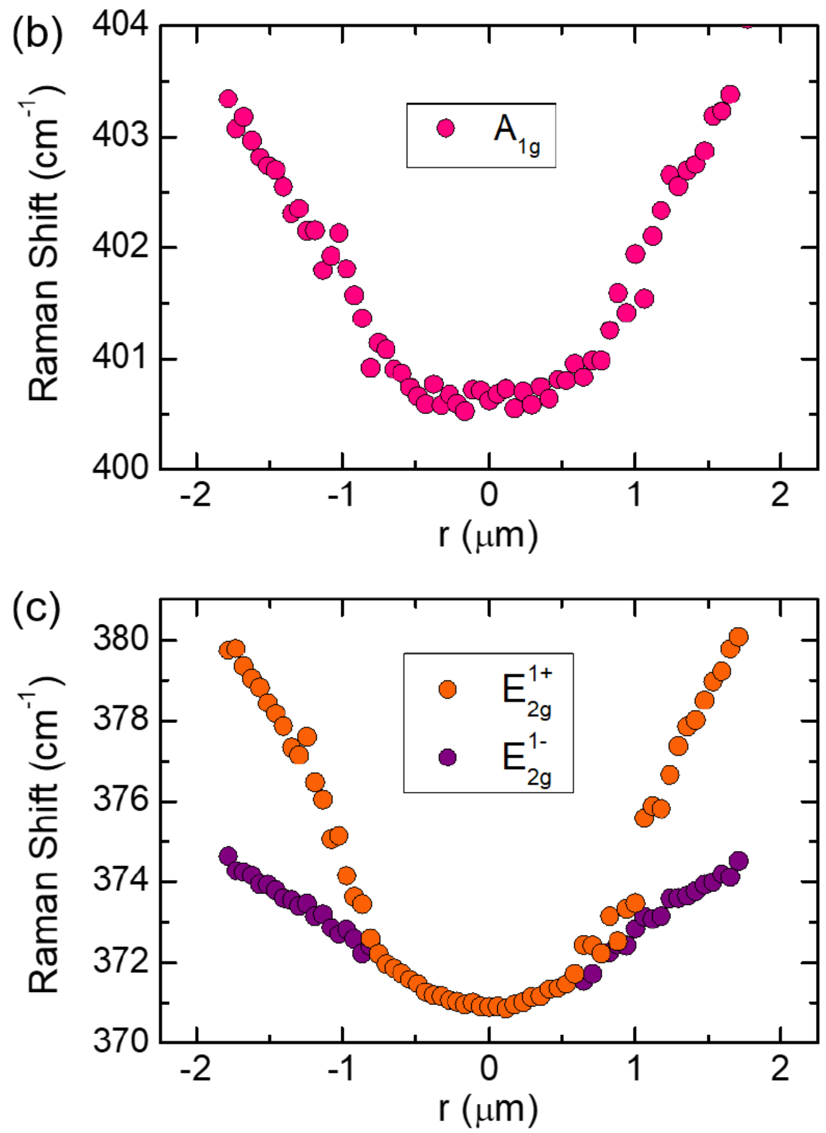
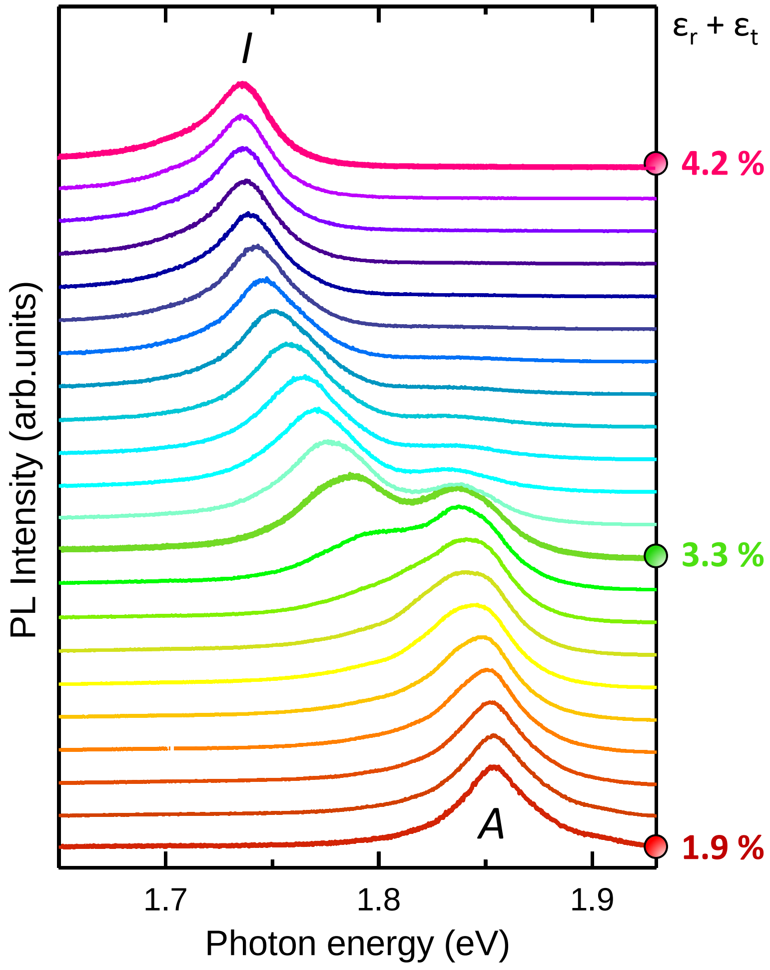


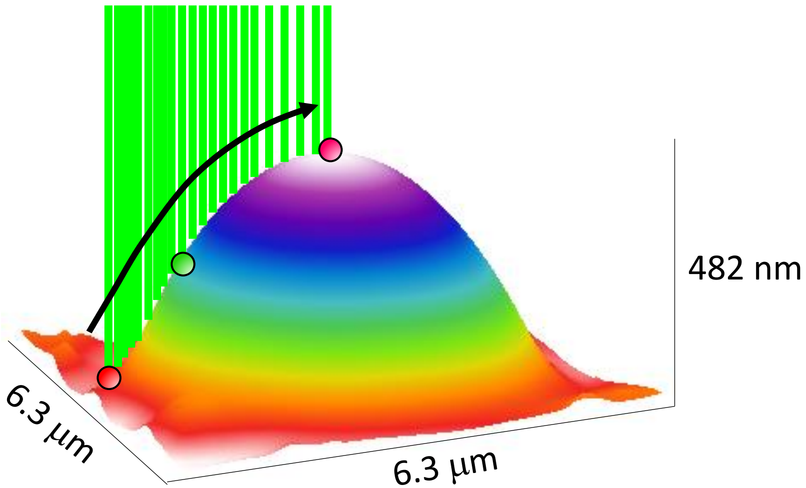


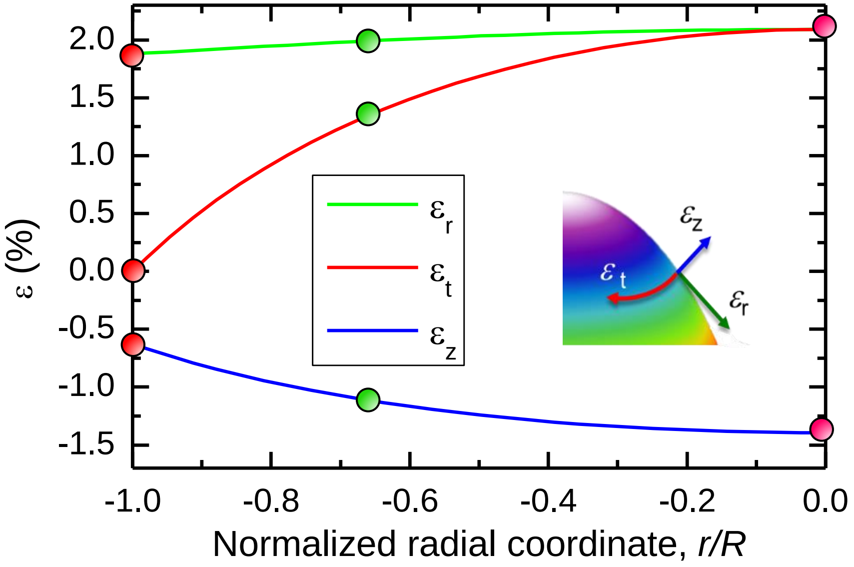


Micro-PL mapping of WS_2 domes



E. Blundo et al., Phys. Rev. Res. **2**, 012024 (2020)





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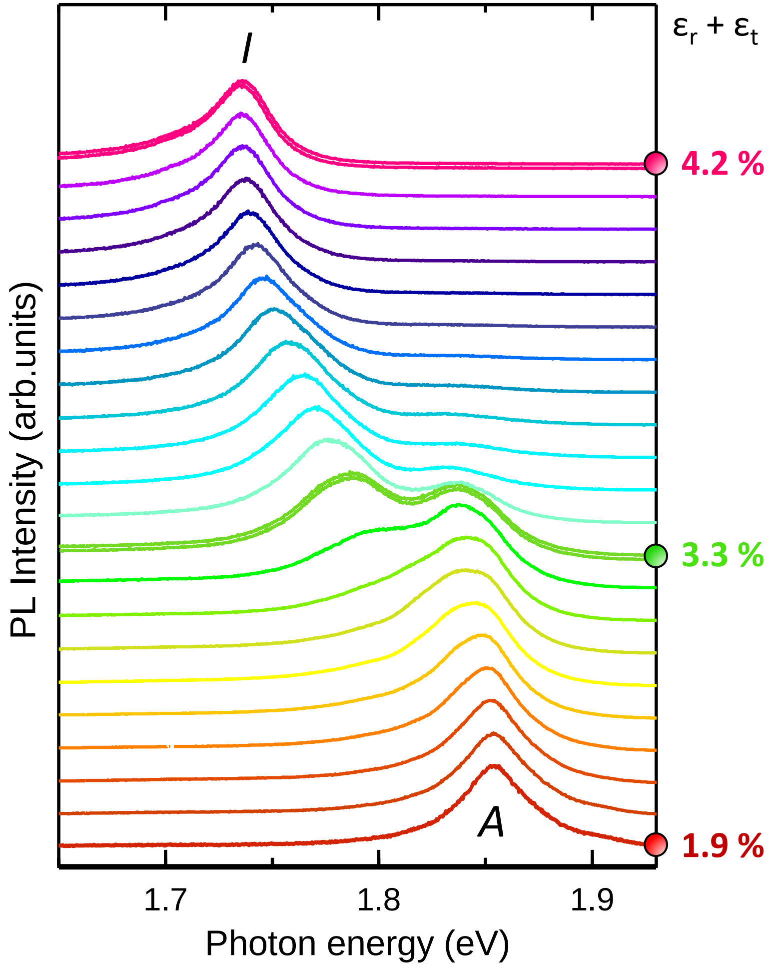
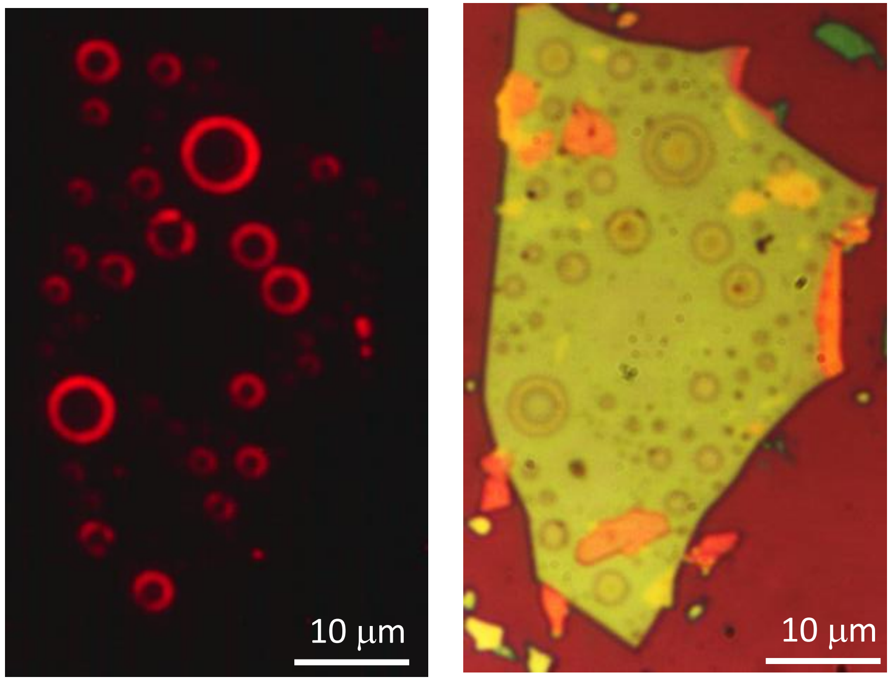
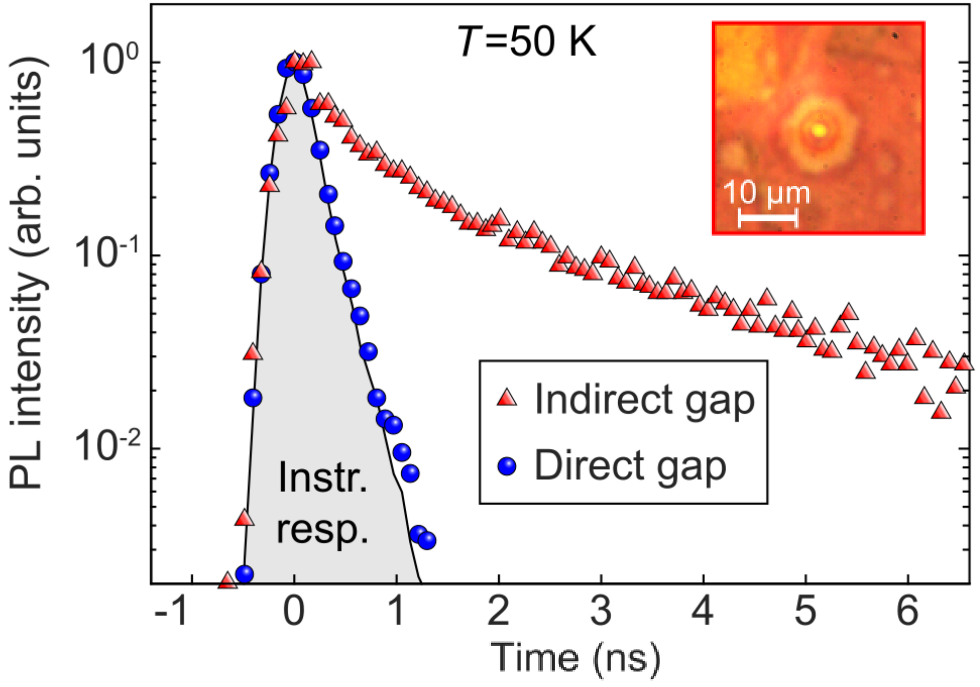


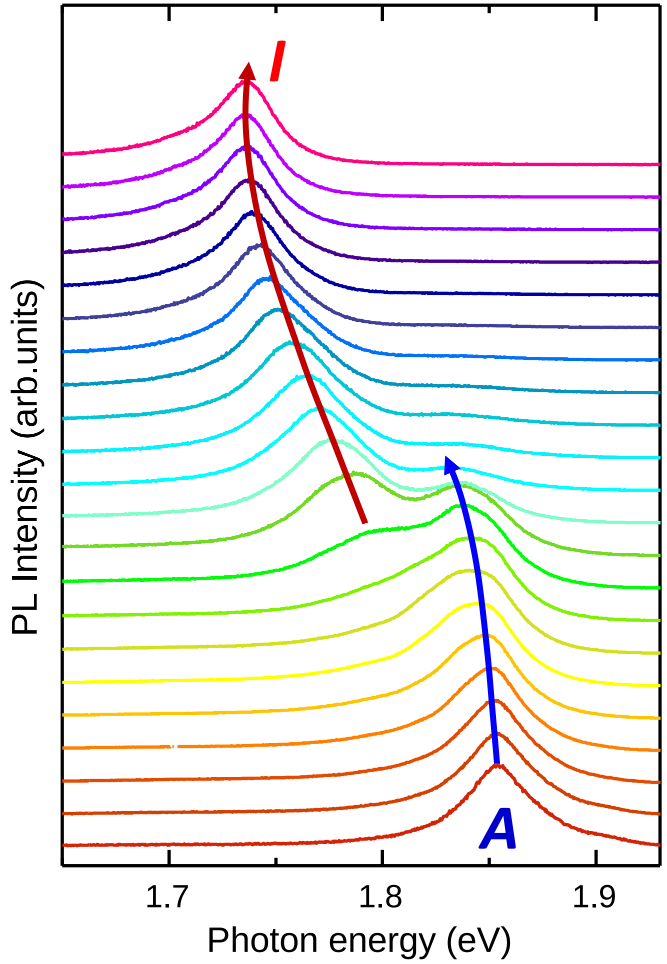


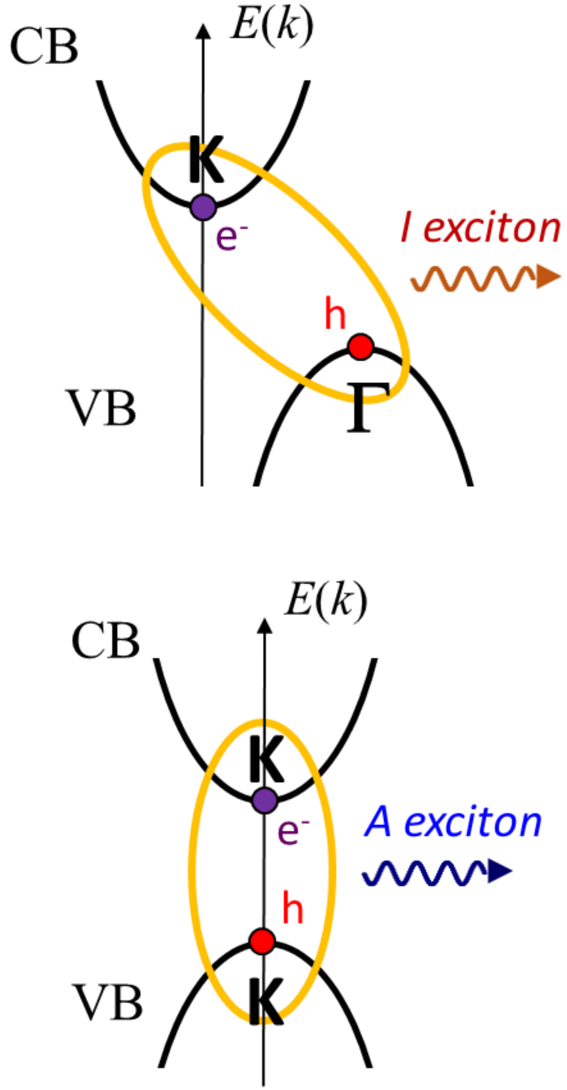
Creation of highly efficient anular regions

E. Blundo et al., Phys. Rev. Res. **2**, 012024 (2020)

Micro-PL mapping of WS_2 domes







E. Blundo *et al.*, Phys. Rev. Res. **2**, 012024 (2020)

Magneto-PL measurements of WS_2 domes

Proposal for magnet time at the **High Field Magnet Laboratory (up to 30 T).** PI: A. Polimeni

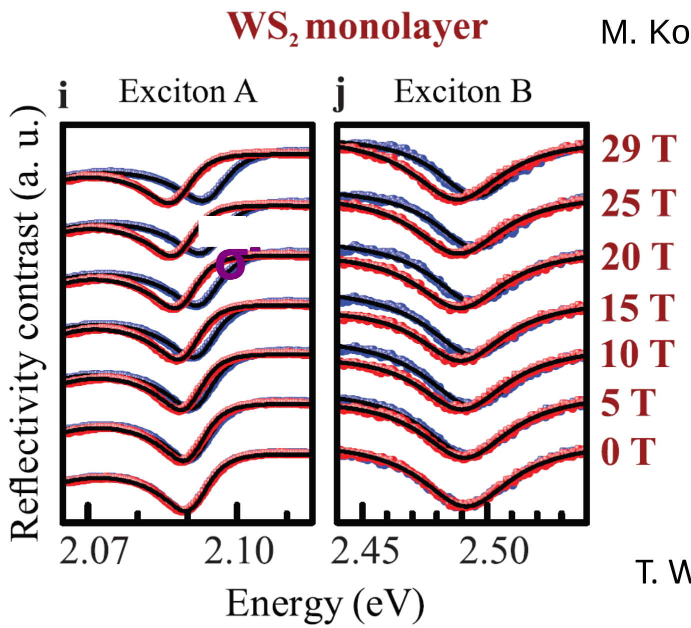
Proposal for magnet time (**ISABEL**) at the **Regional Partner 'University of Warsaw' (up to 12 T).** PI: E. Blundo

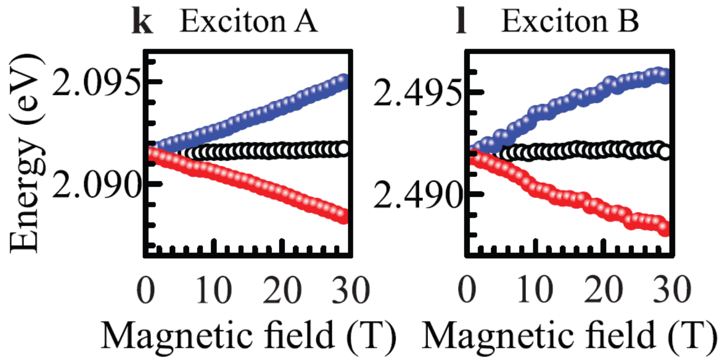
HFML Science in High Magnetic Fields

UNIWERSYTET WARSZAWSKI

Magneto-PL measurements of WS_2 monolayers

M. Koperski et al., 2D Mater. **6**, 015001 (2019)



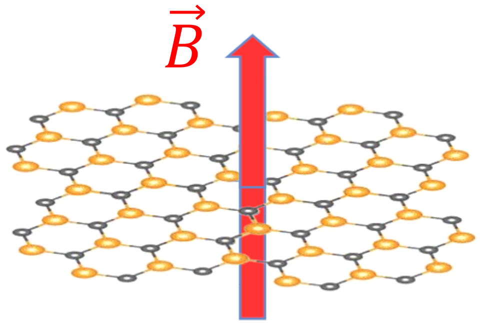


Line	g-factor
Exciton A	−3.7 ± 0.2
Exciton B	−4.9 ± 1.2

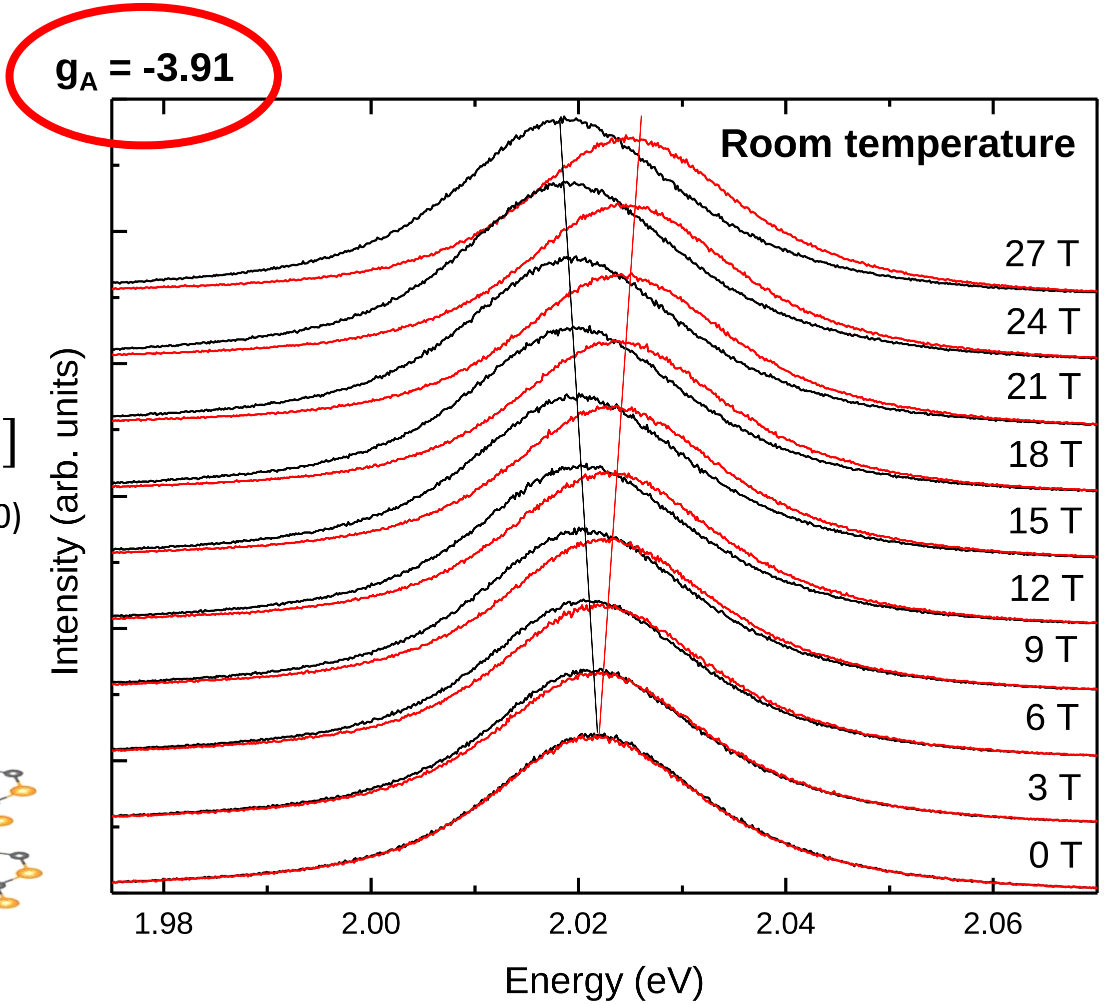
$$\Delta E_Z^A = g_A \mu_B B$$

$$g_A = 2[L_z(CB_+) - L_z(VB_+)]$$

T. Woźniak et al., Phys. Rev. B **101**, 235408 (2020)

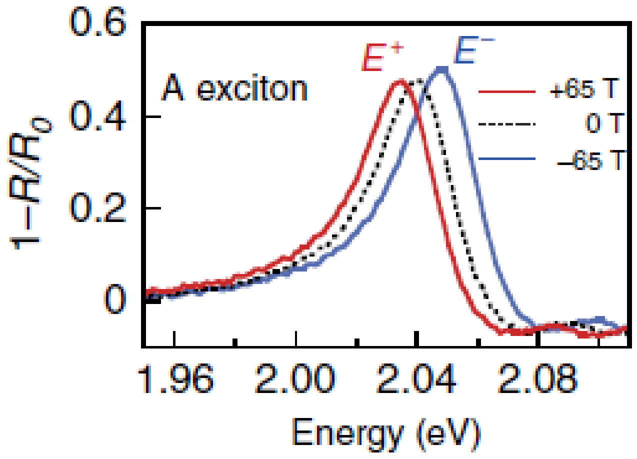


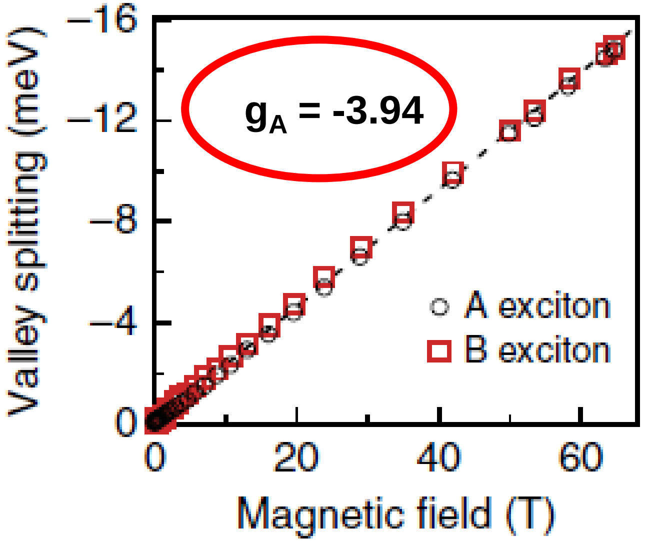
E. Blundo et al., Phys. Rev. Lett. **129**, 067402 (2022)

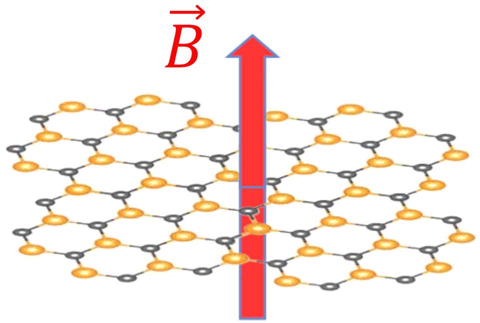


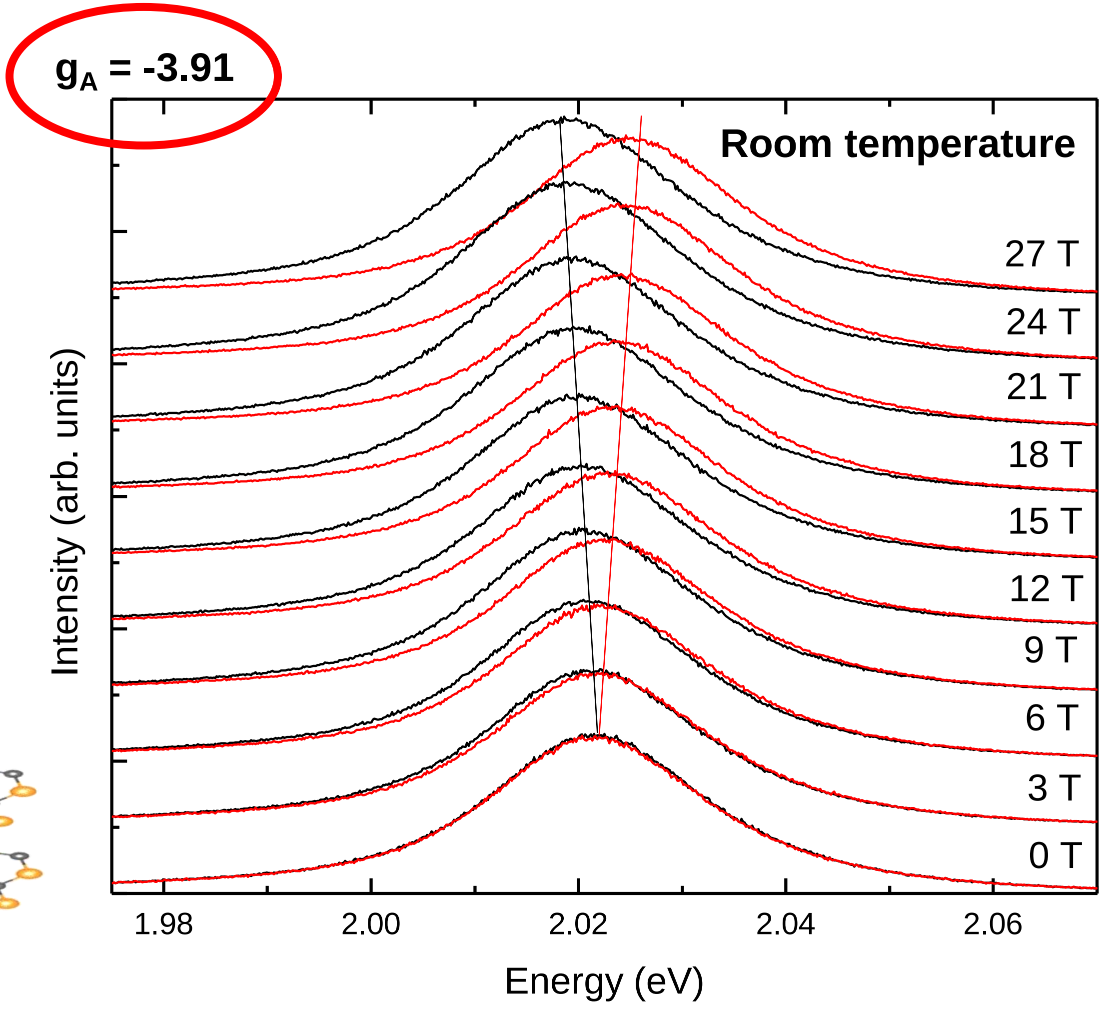
Magneto-PL measurements of WS_2 monolayers

E. Blundo et al., Phys. Rev. Lett. **129**, 067402 (2022)



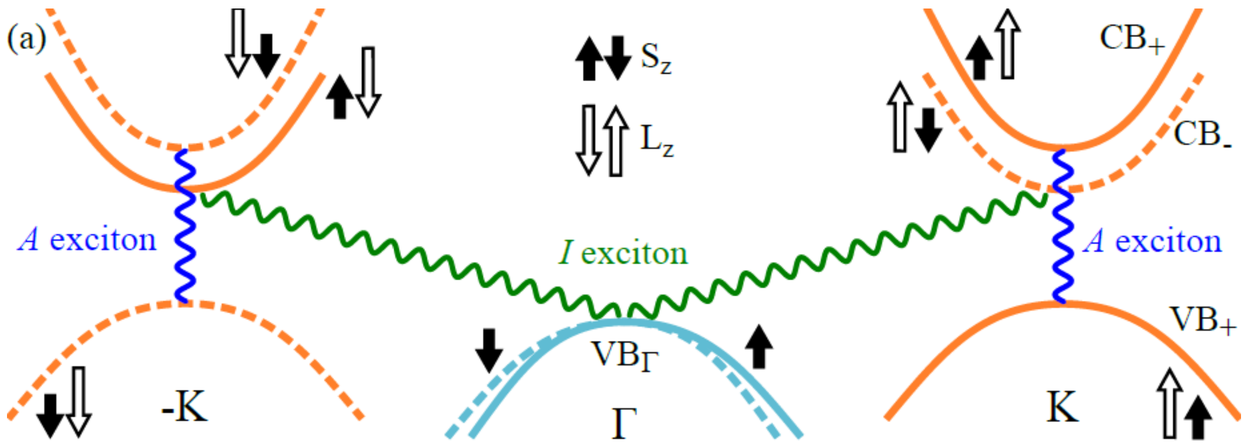


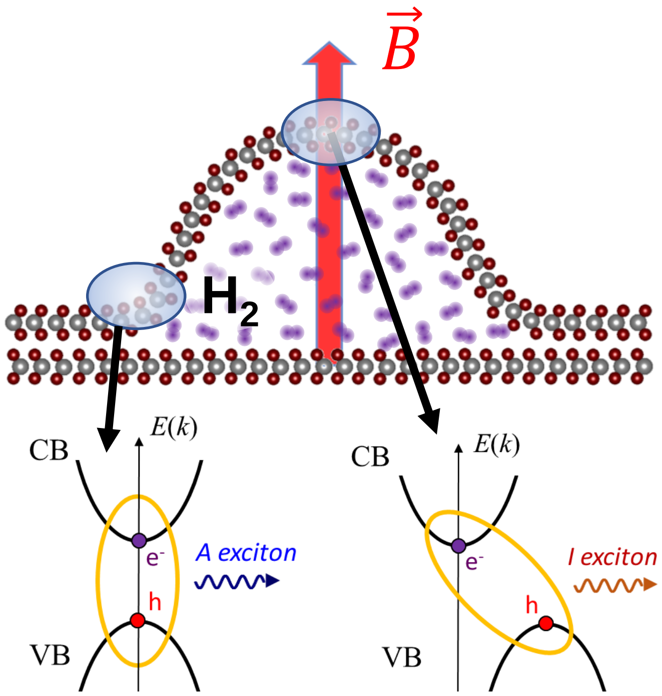




Stier et al., Nat. Commun. **7**, 10643 (2016)

Magneto-PL measurements of WS_2 domes



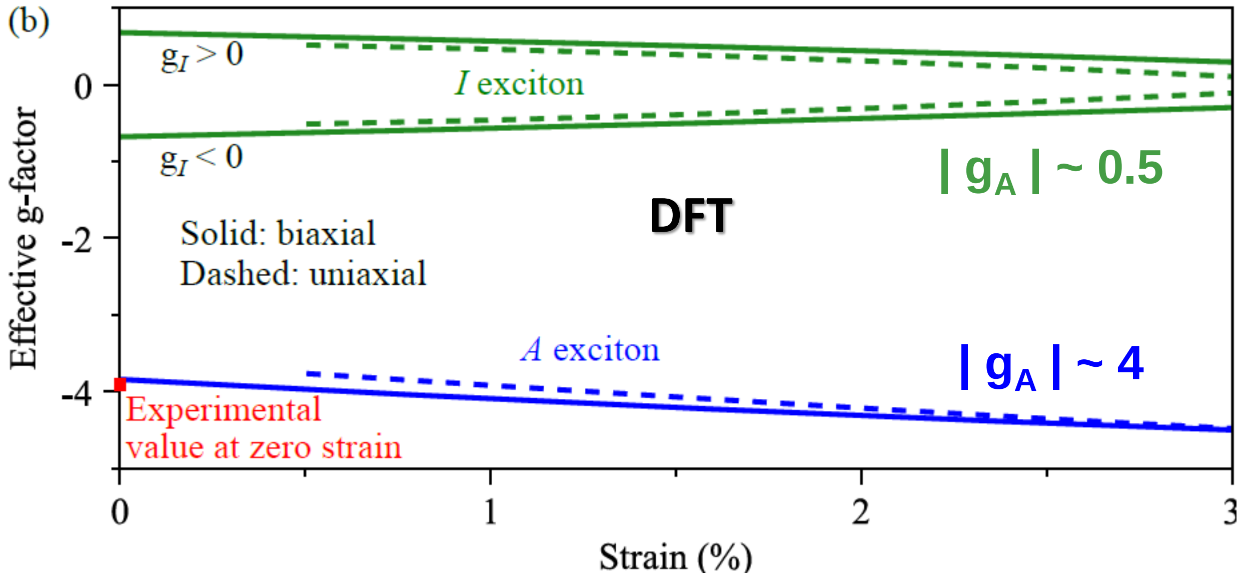


$$\Delta E_Z^{A(I)} = g_{A(I)} \mu_B B$$

$$g_A = 2[L_z(CB_+) - L_z(VB_+)]$$

$$g_I = 2[L_z(CB_-) - 2]$$

How does $g_{A(I)}$ change with strain?

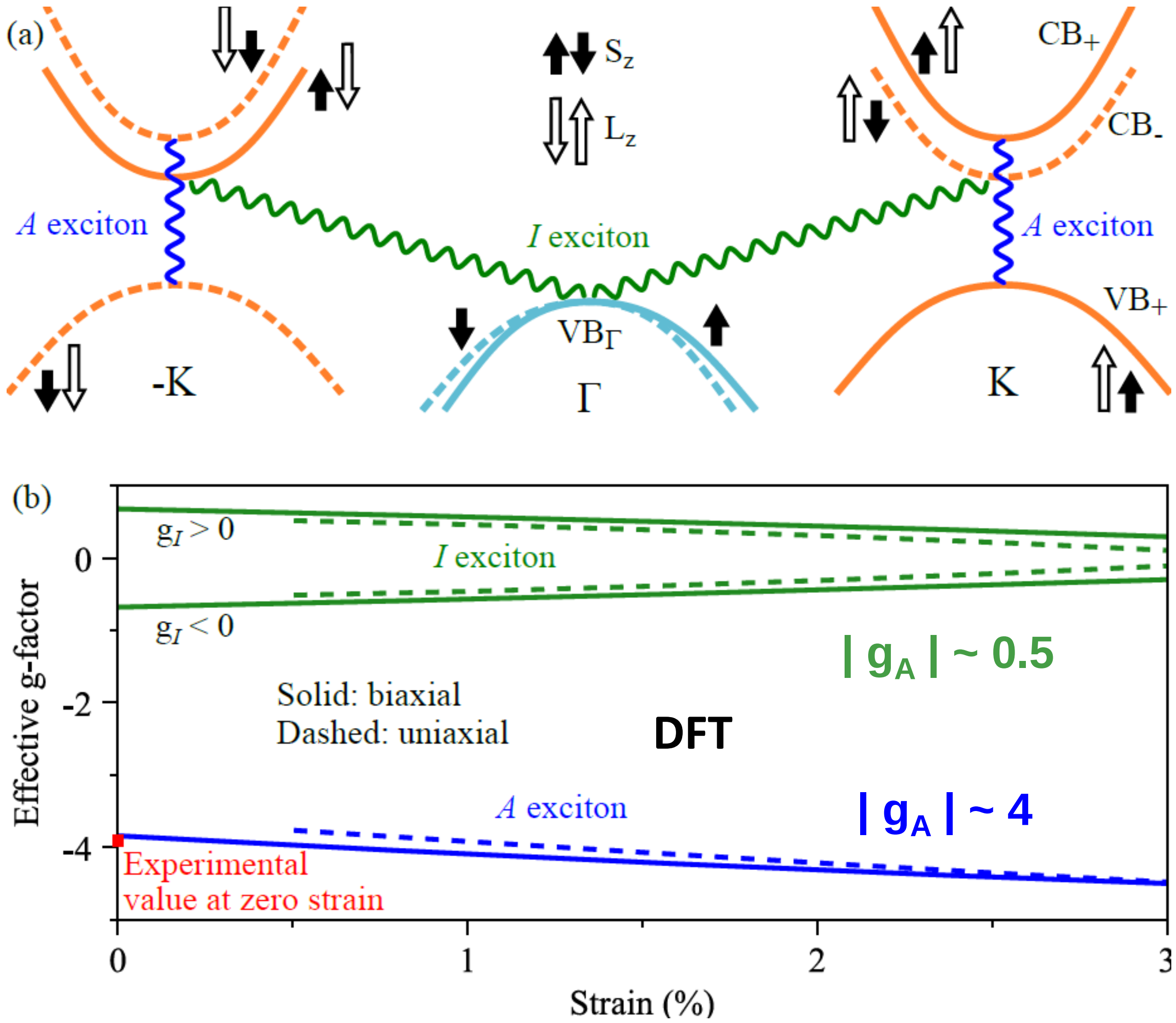


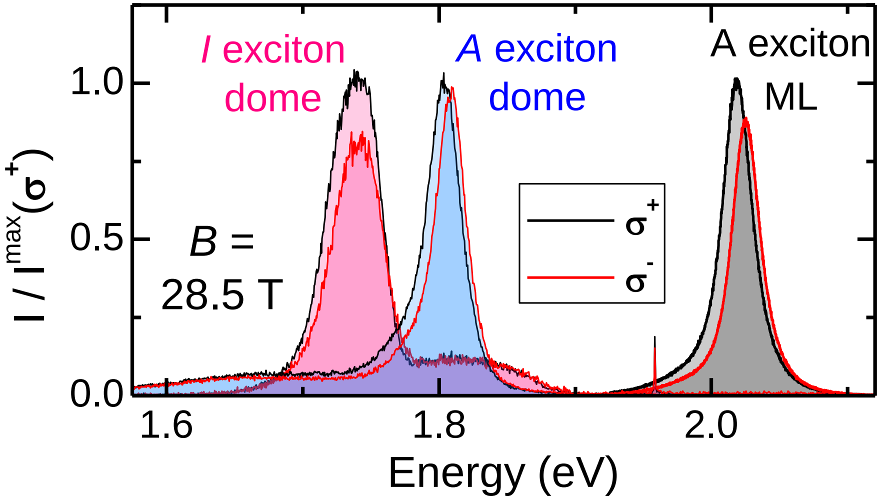
$g_{A(I)}$ should not change with strain

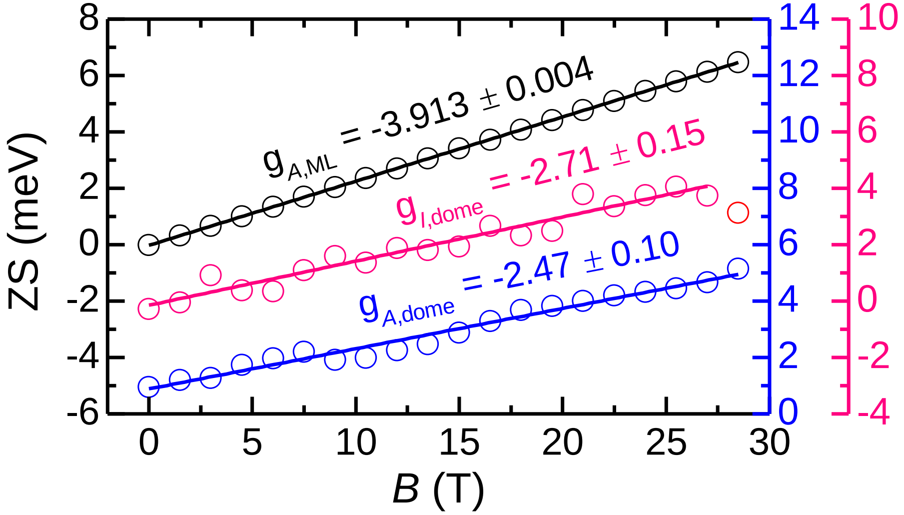
A and *I* excitons should show very different splittings

E. Blundo et al., Phys. Rev. Lett. **129**, 067402 (2022)

Magneto-PL measurements of WS_2 domes







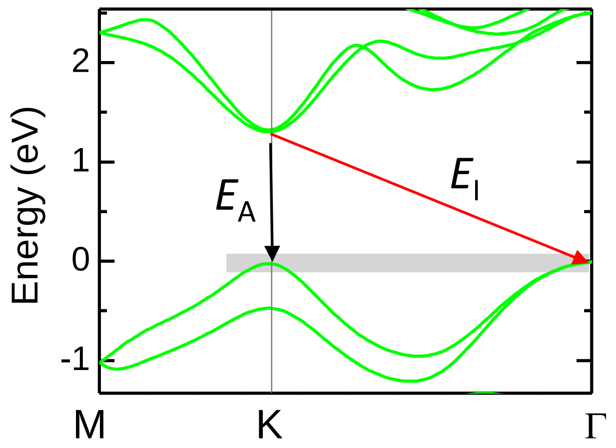
A and I excitons show <u>very similar splittings</u>

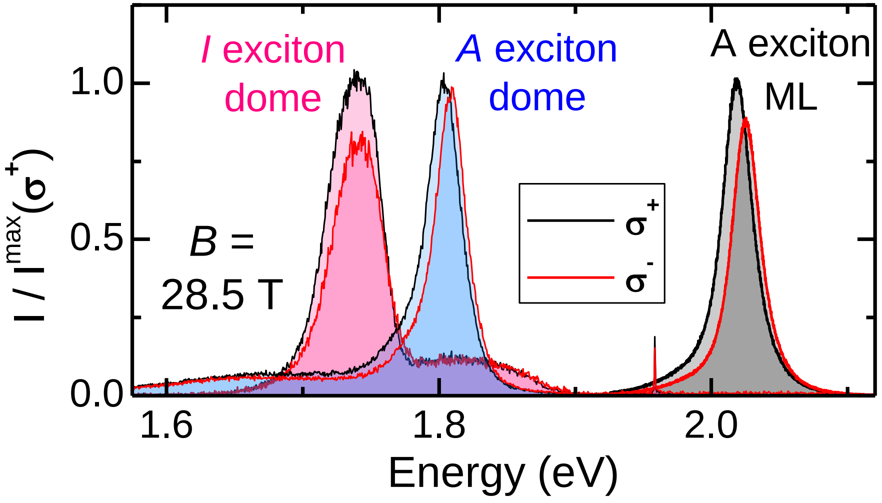
$g_{A(I)}$ should not change with strain

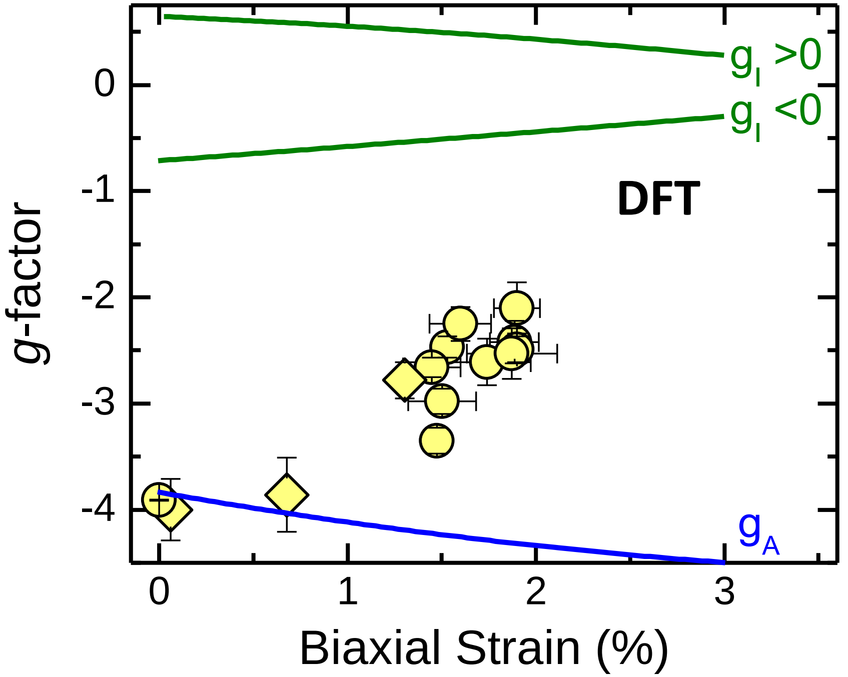
Theory-wise *A* and *I* excitons should show <u>very different splittings</u>

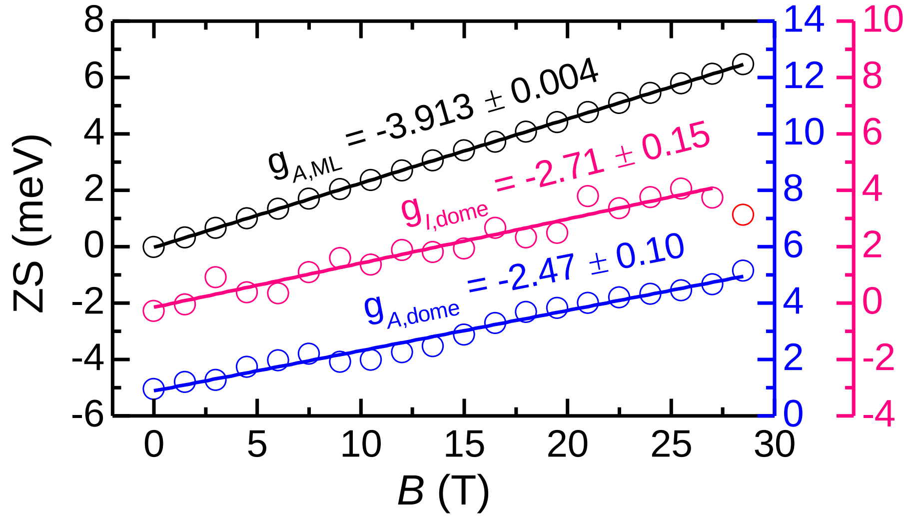
E. Blundo et al., Phys. Rev. Lett. **129**, 067402 (2022)

Magneto-PL measurements of WS_2 domes







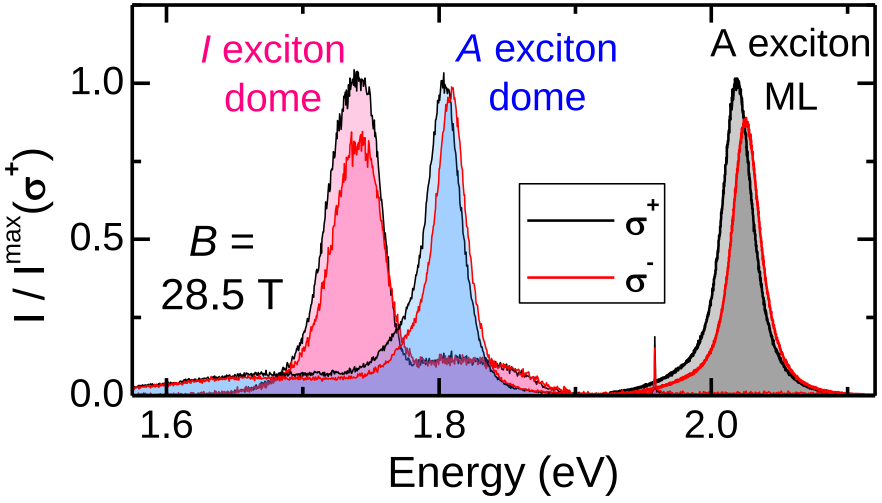


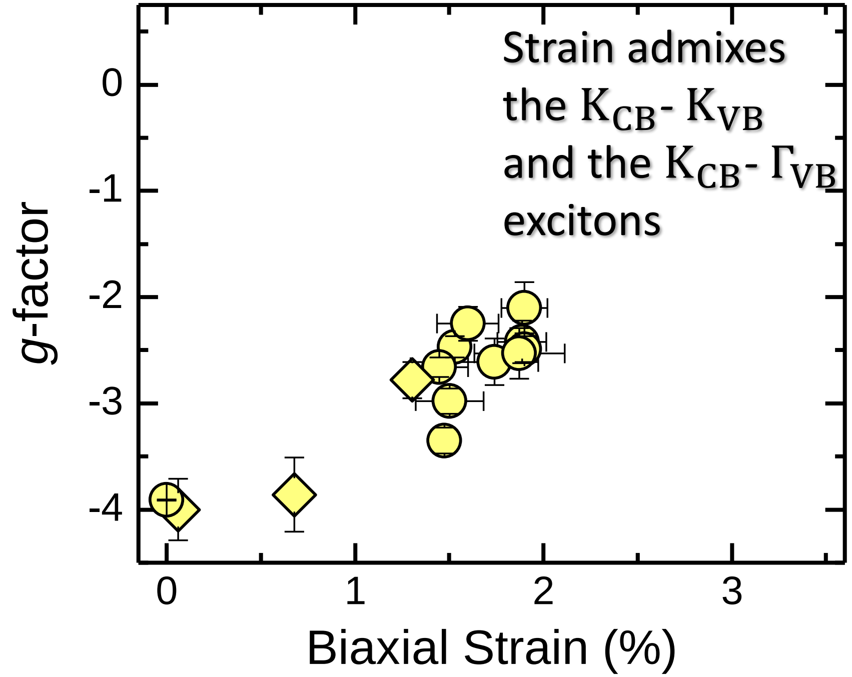
E. Blundo et al., Phys. Rev. Lett. **129**, 067402 (2022)

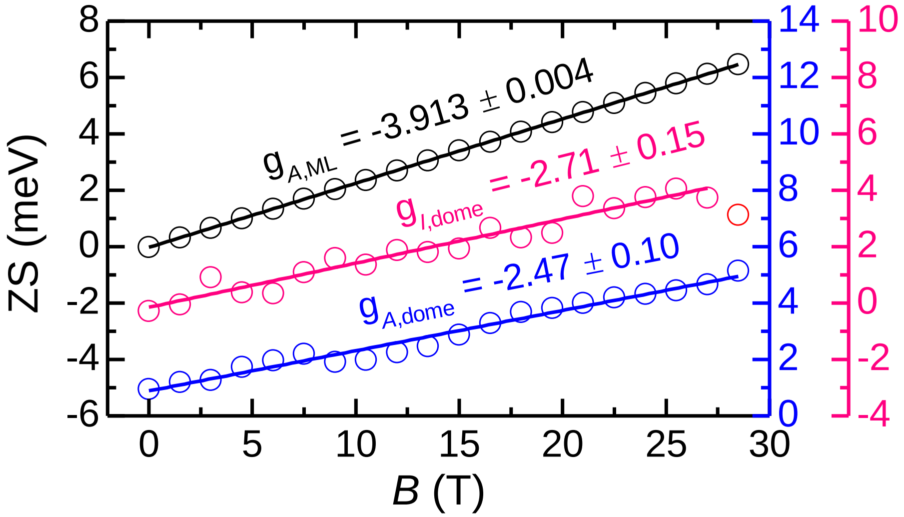
Magneto-PL measurements of WS_2 domes

Strain-induced A and I exciton hybridisation

$$\begin{bmatrix} E_A + \frac{1}{2} g_A \mu_B B & 0 & \Delta_1 & \Delta_2 \\ 0 & E_A - \frac{1}{2} g_A \mu_B B & -\kappa \Delta_2^* & \kappa \Delta_1^* \\ \Delta_1^* & -\kappa \Delta_2 & E_I + \frac{1}{2} g_I \mu_B B & 0 \\ \Delta_2^* & \kappa \Delta_1 & 0 & E_I - \frac{1}{2} g_I \mu_B B \end{bmatrix}$$



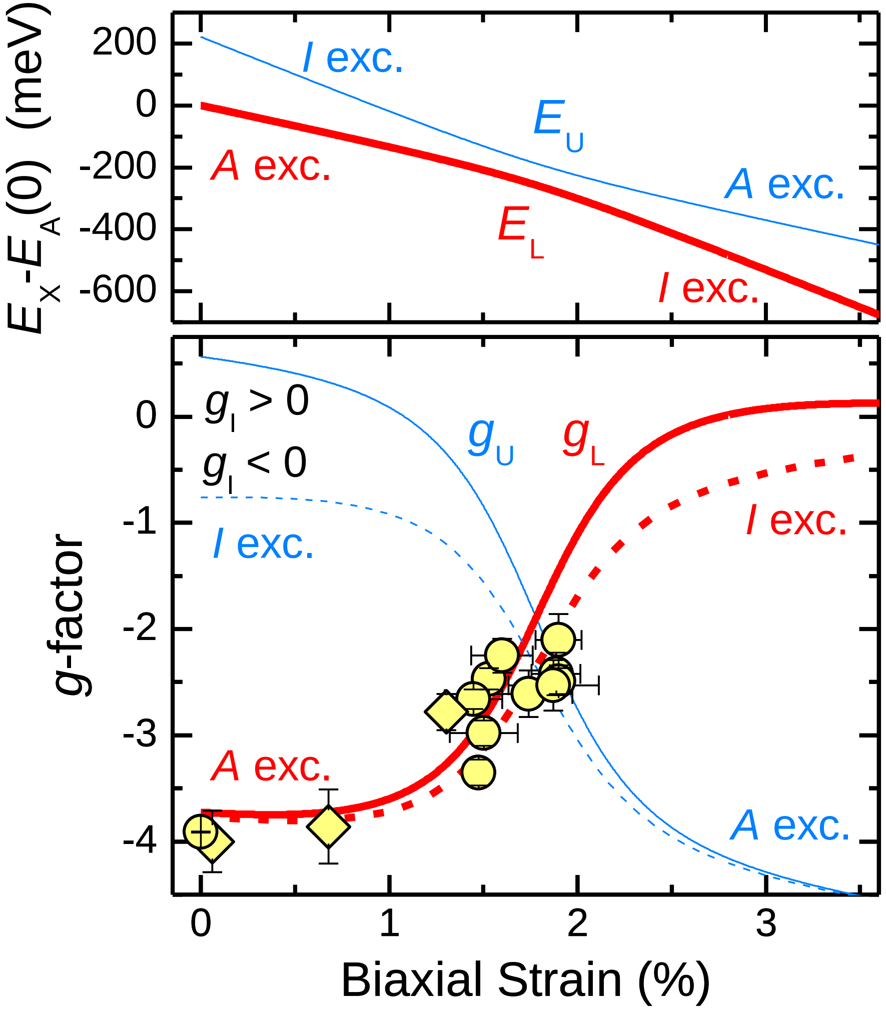




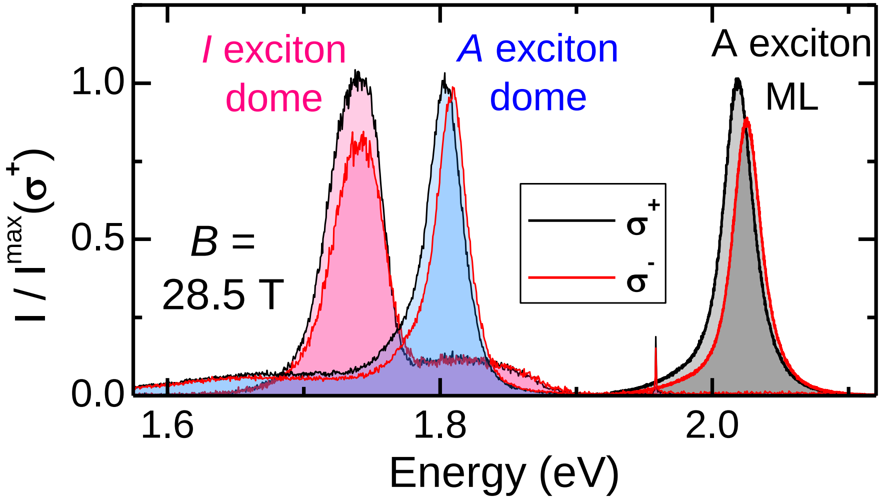
E. Blundo et al., Phys. Rev. Lett. **129**, 067402 (2022)

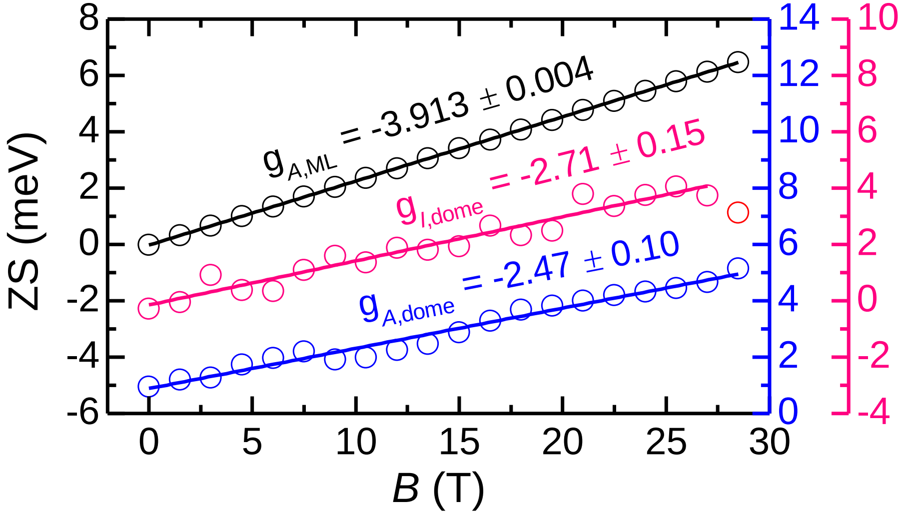
Magneto-PL measurements of WS_2 domes

$$\begin{bmatrix} E_A + \frac{1}{2}g_A\mu_B B & 0 & \Delta_1 & \Delta_2 \\ 0 & E_A - \frac{1}{2}g_A\mu_B B & -\kappa\Delta_2^* & \kappa\Delta_1^* \\ \Delta_1^* & -\kappa\Delta_2 & E_I + \frac{1}{2}g_I\mu_B B & 0 \\ \Delta_2^* & \kappa\Delta_1 & 0 & E_I - \frac{1}{2}g_I\mu_B B \end{bmatrix}$$



$\Delta_1 = 35$ meV
$\Delta_2 = 0$



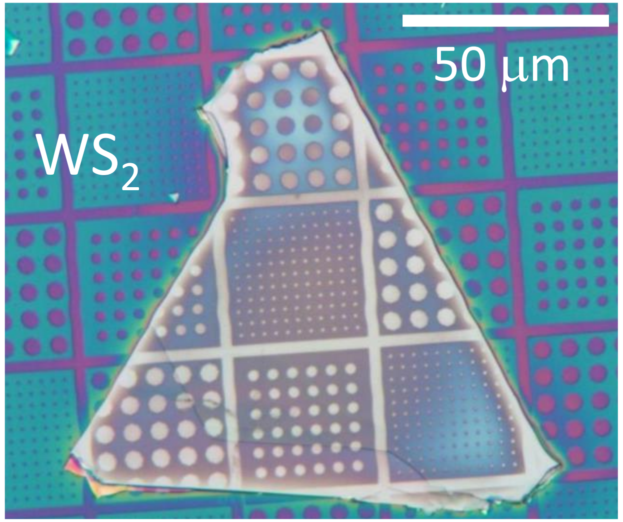


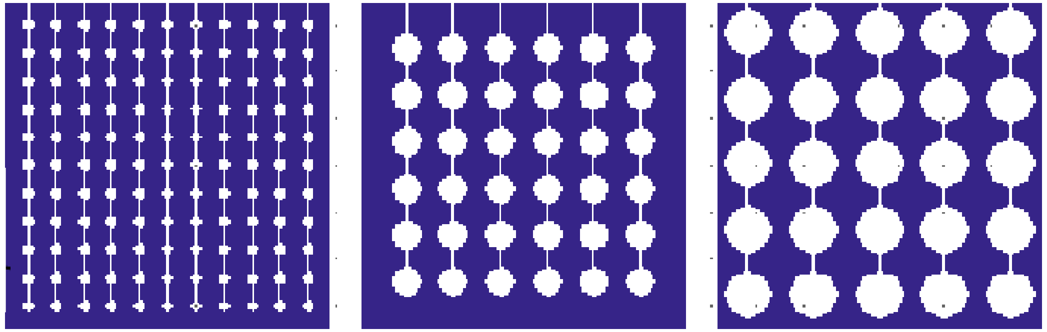
Zeeman-splitting measurements unveil exciton hybridization

Phonons? Disorder?

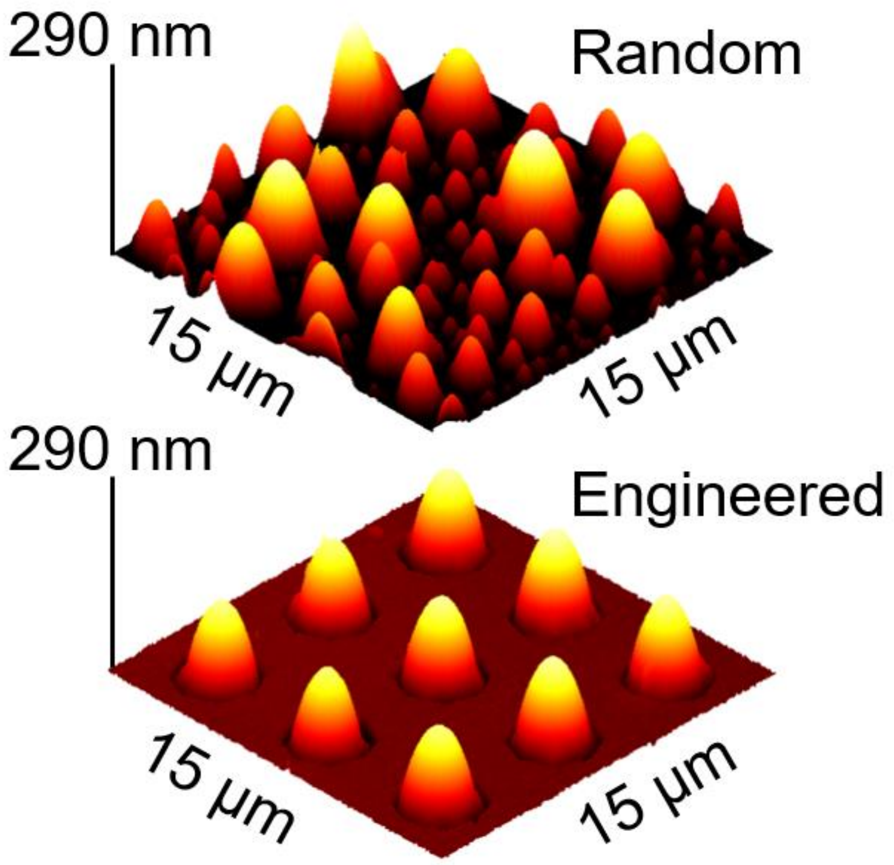
E. Blundo et al., Phys. Rev. Lett. **129**, 067402 (2022)

Controlled dome formation



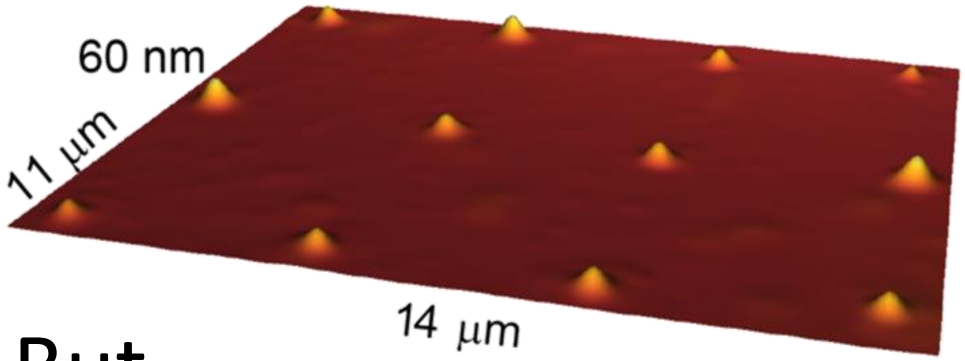


S = 1 μm 3 μm 5 μm



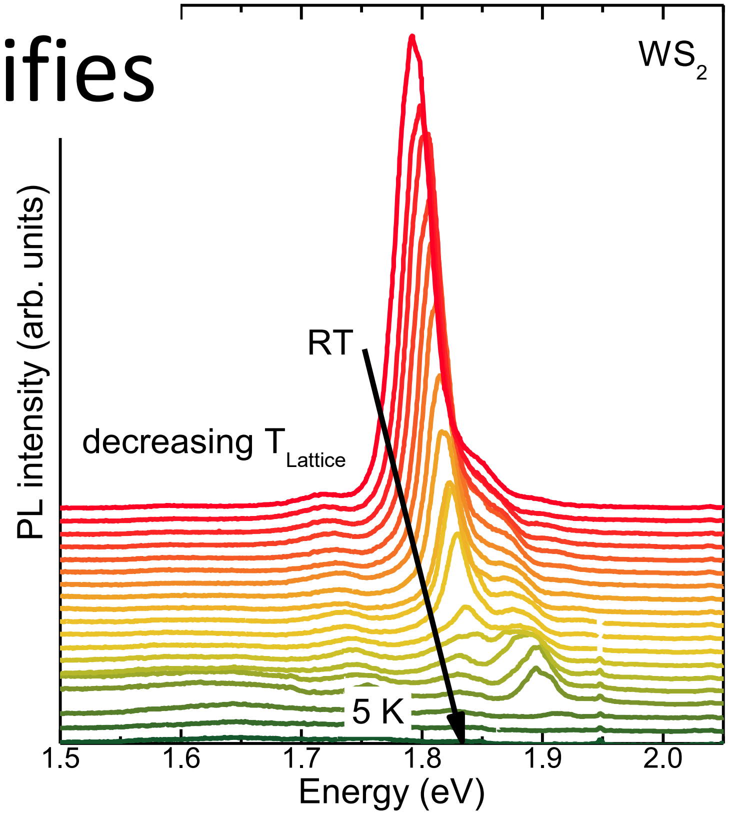
E. Blundo et al., Adv. Mat. Interfaces **7**, 2000621 (2020)

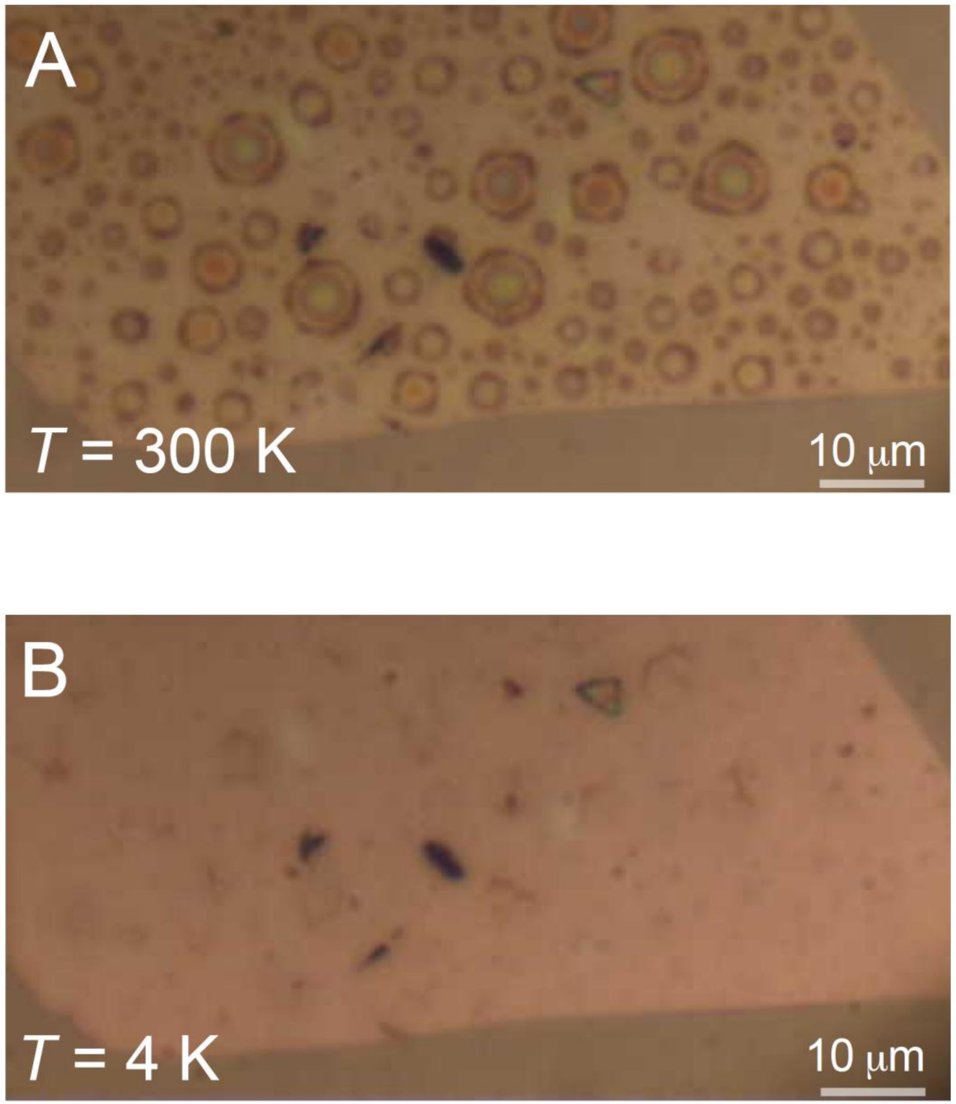
Space-controlled emitters?

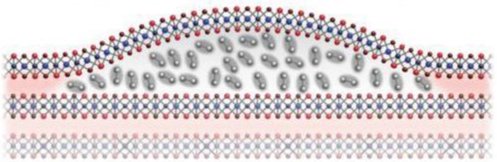


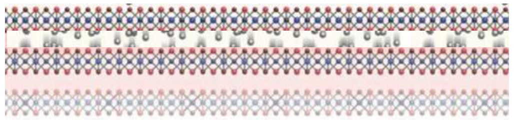
But…

H_2 liquifies



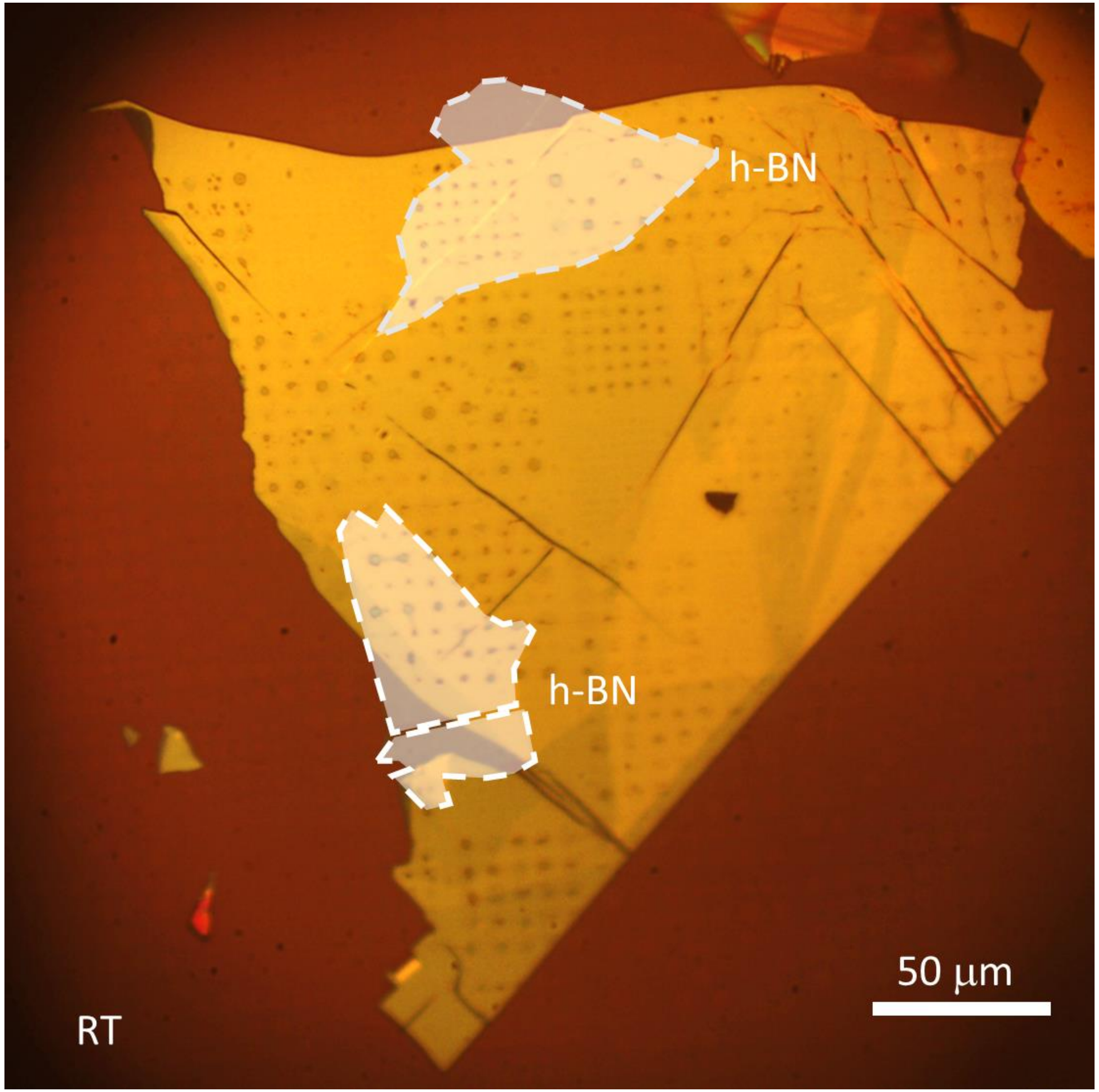






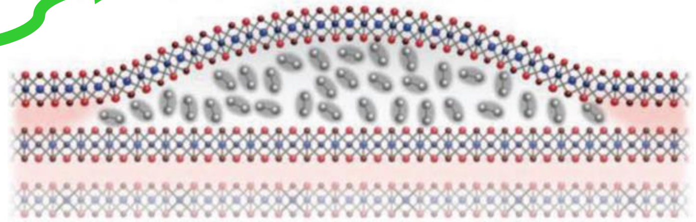
hBN heterostructuring

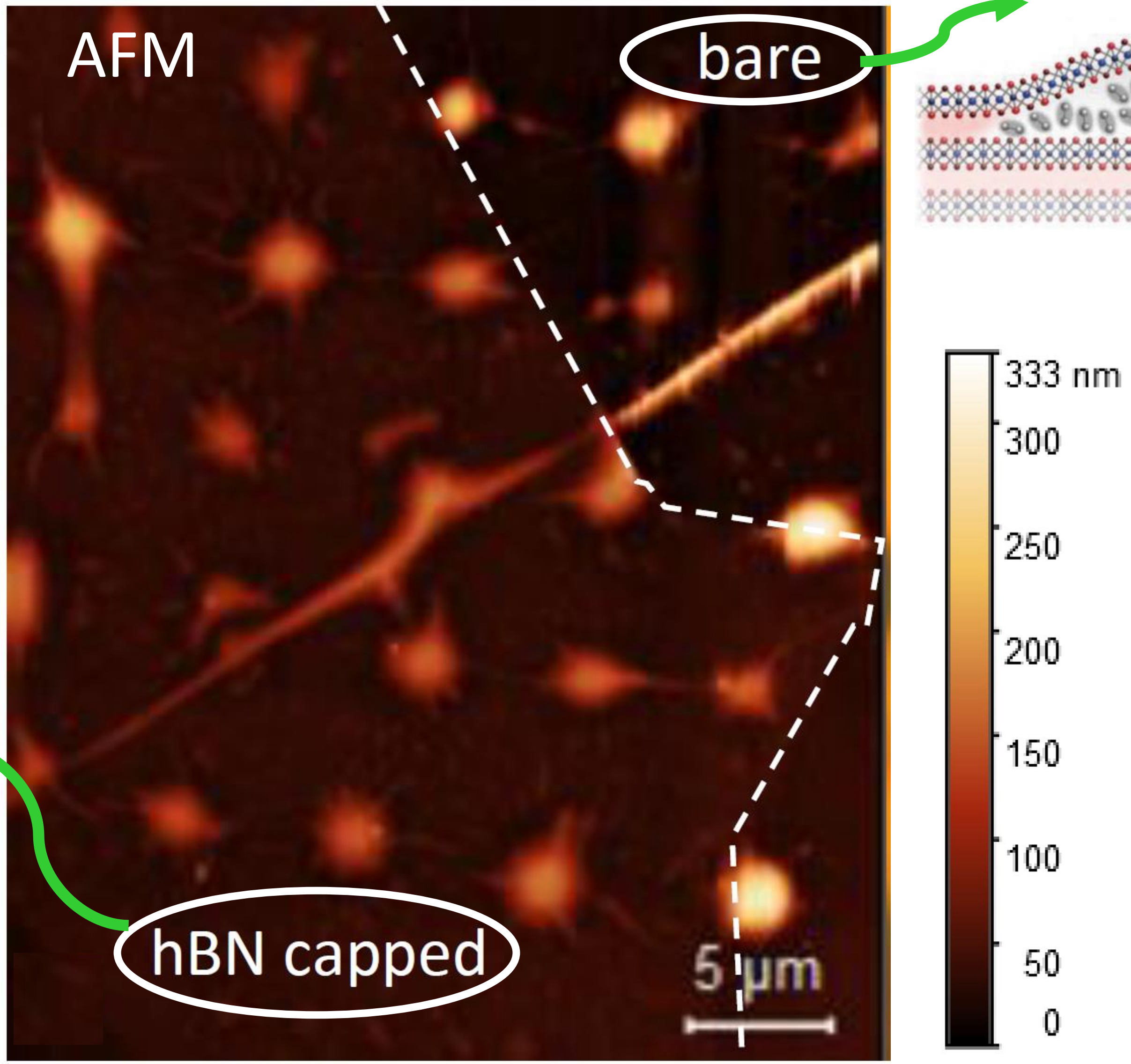
How to circumvent H_2 liquefaction?



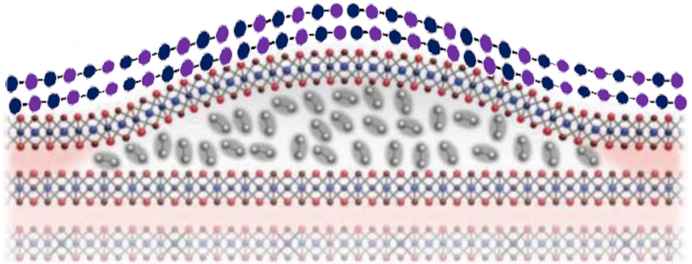
hBN heterostructuring

bare MoS_2



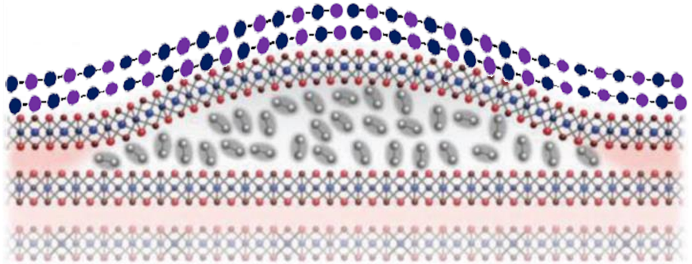


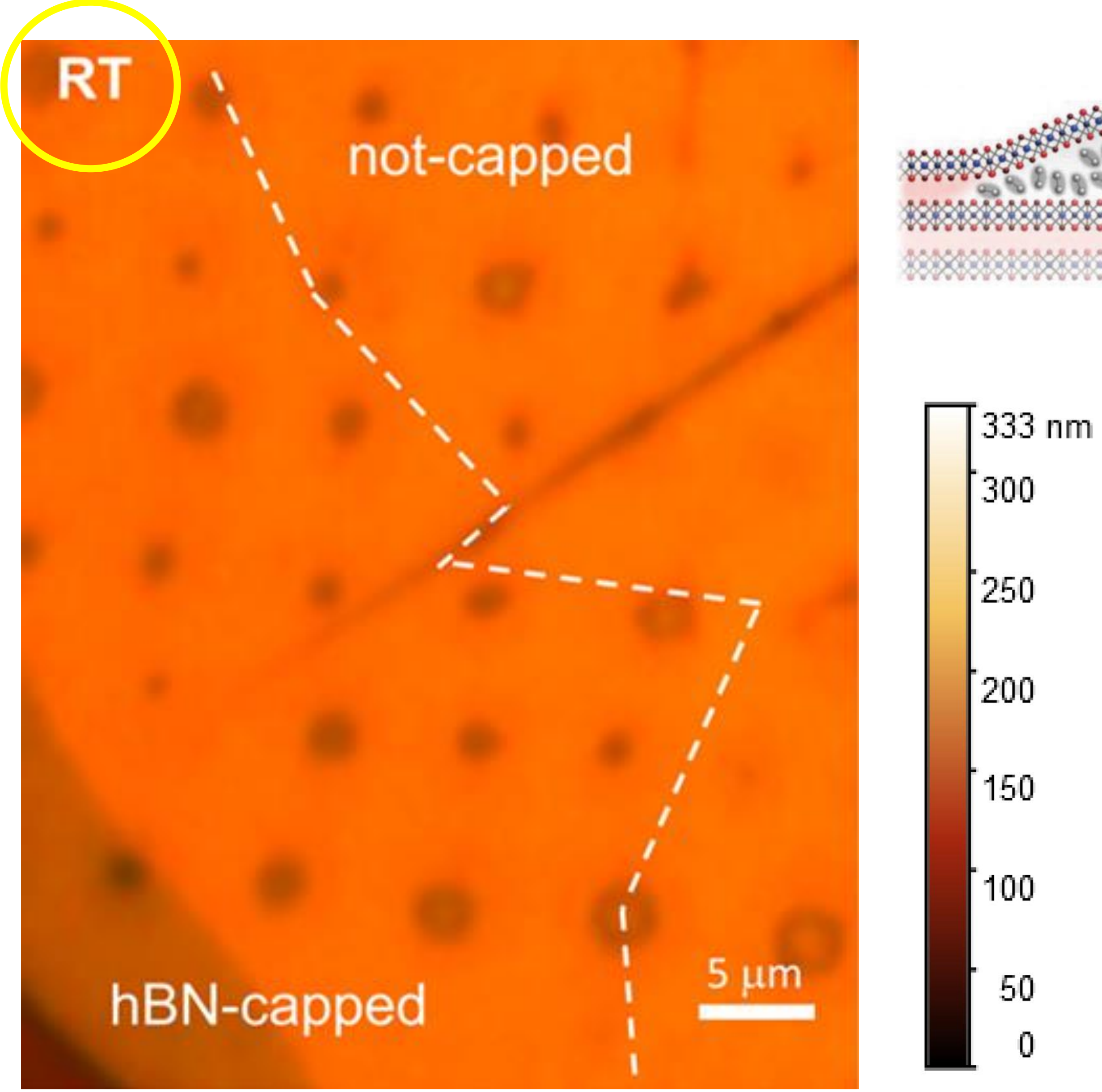
hBN-capped MoS_2



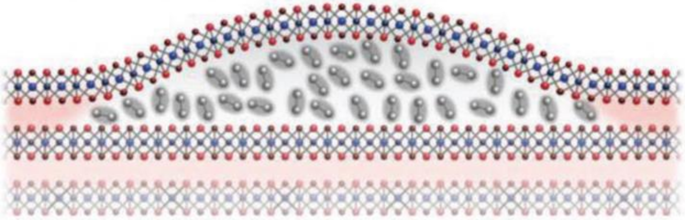
hBN heterostructuring

hBN-capped MoS_2



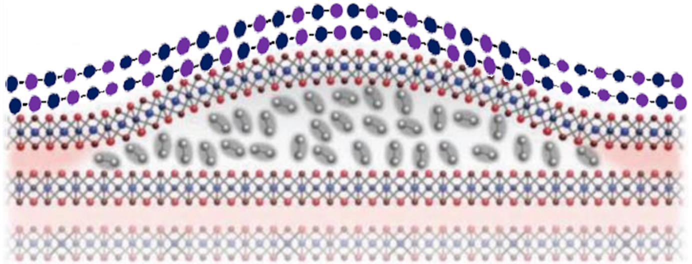


bare MoS_2

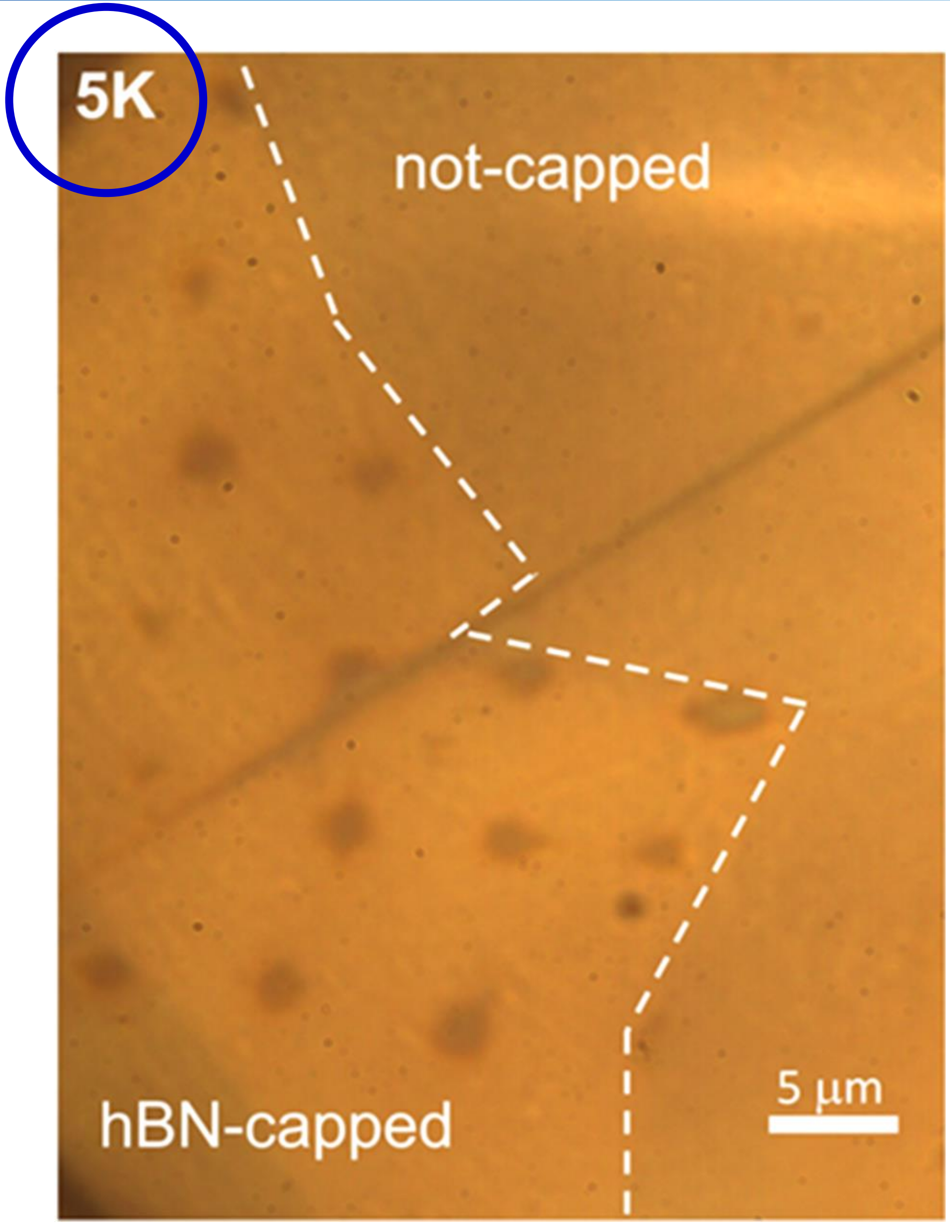


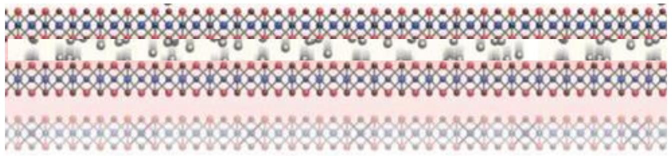
hBN heterostructuring

hBN-capped MoS_2



capped domes do not deflate

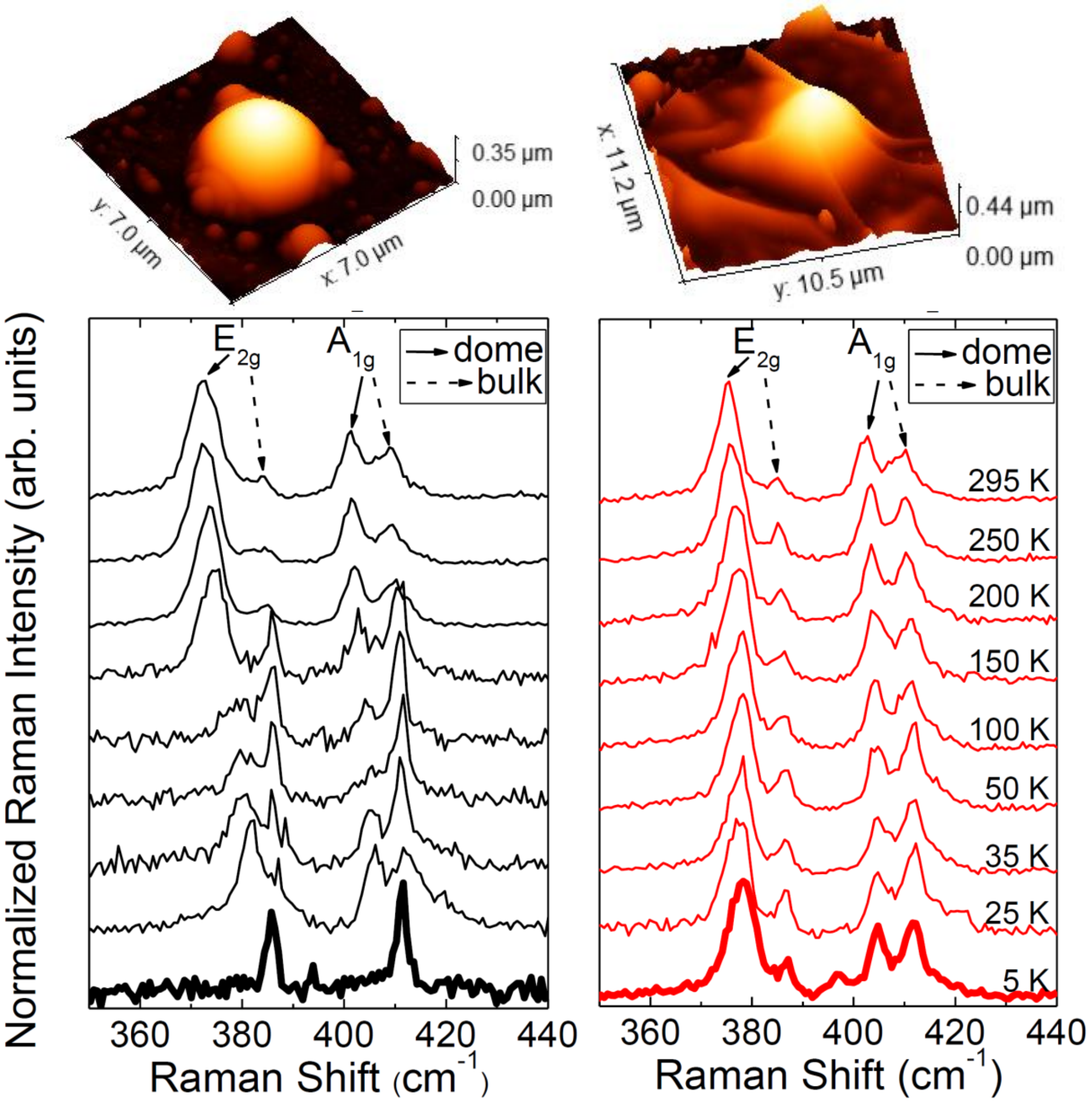


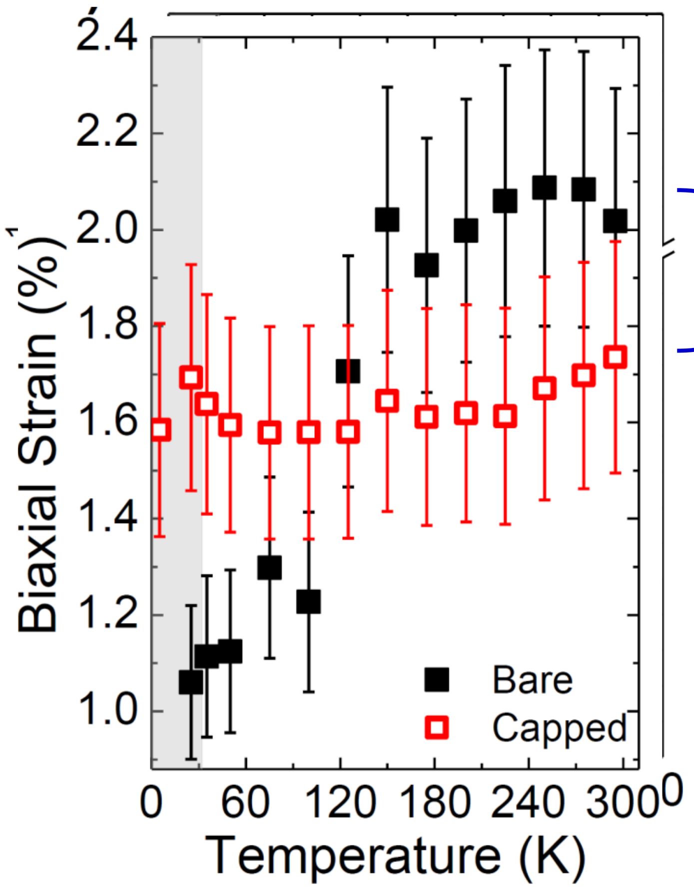


hBN heterostructuring

bare MoS_2 dome

hBN-capped MoS_2 dome

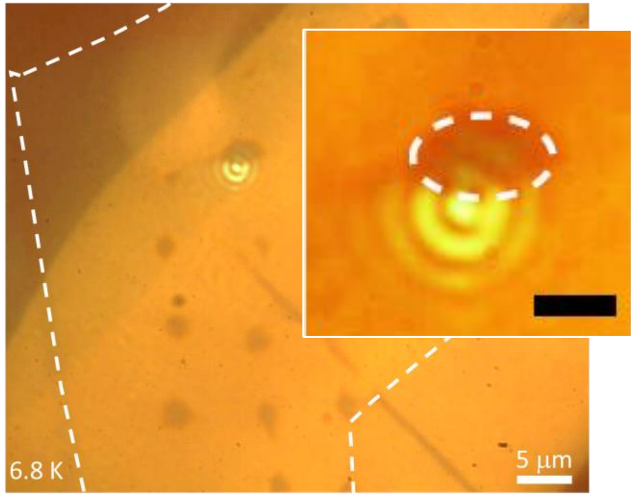


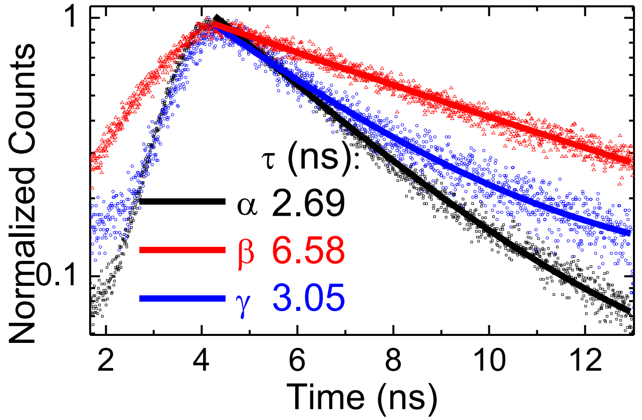


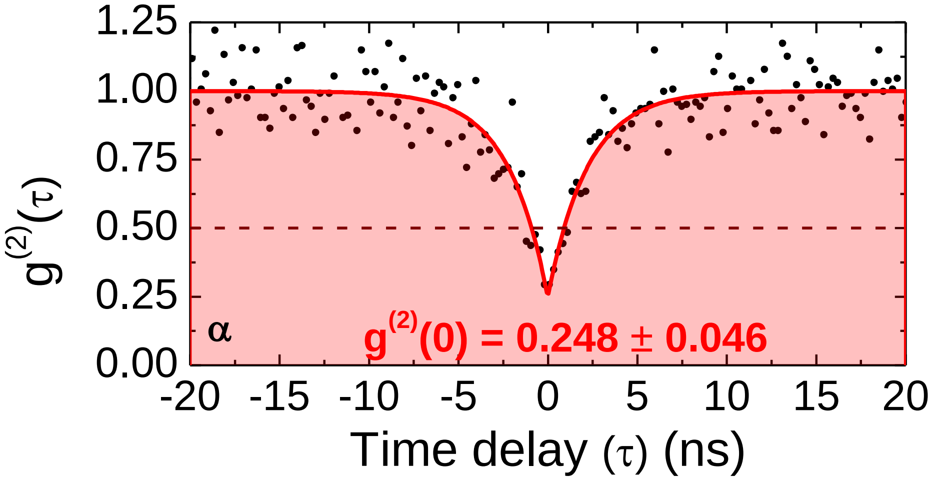
hBN capping causes strain decrease: Elastic energy transfer

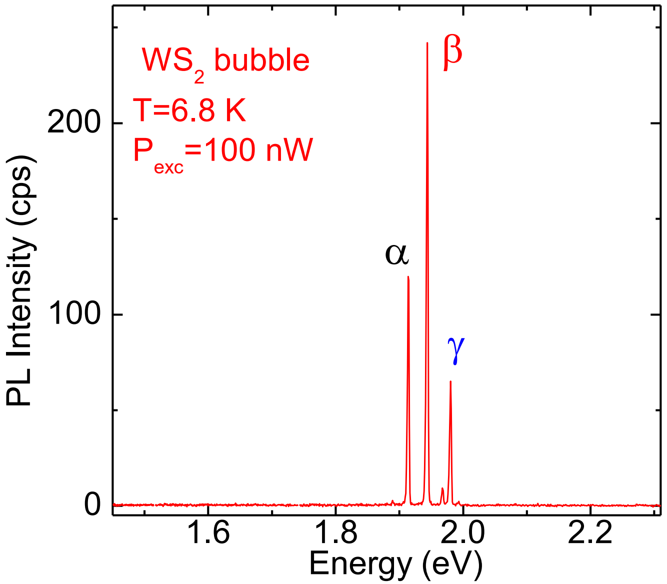
$$\varepsilon(T) = \frac{1}{2} \cdot \left(\frac{\omega_{E_{2g}}^{ML}(T) - \omega_{E_{2g}}^{dome}(T)}{\omega_{E_{2g}}^{ML}(T)} \right) \frac{1}{\gamma_{E_{2g}}}$$

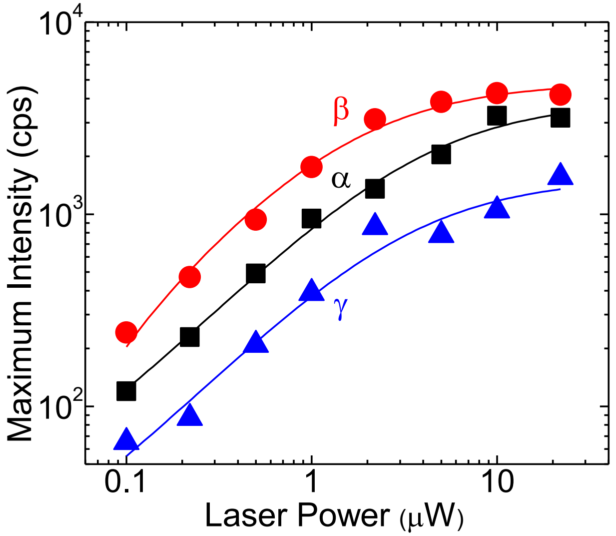
Space-controlled quantum emitters

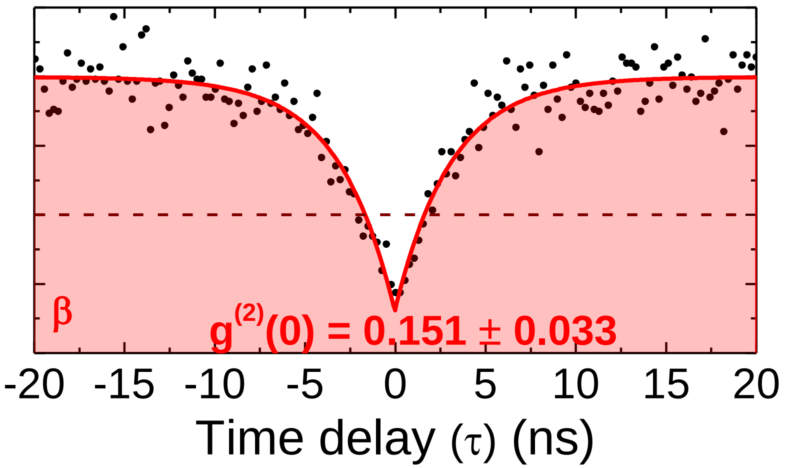




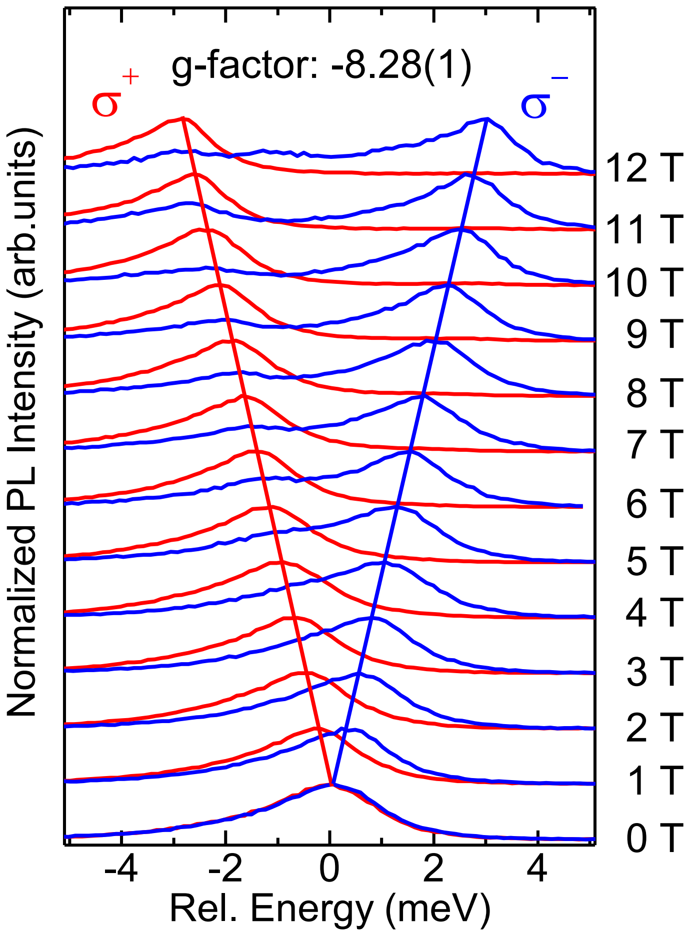


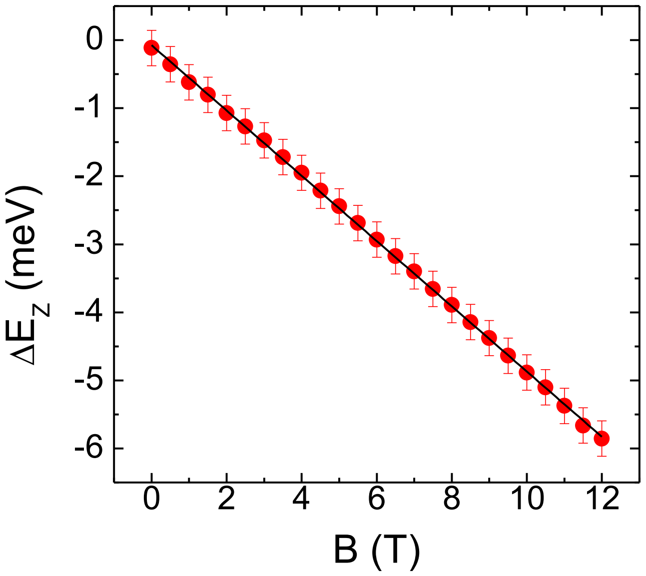


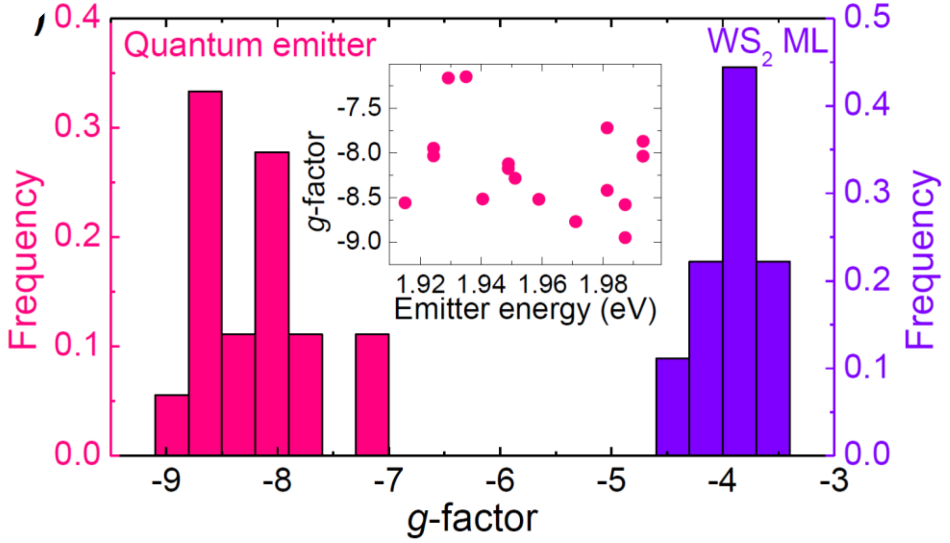




Space-controlled quantum emitters





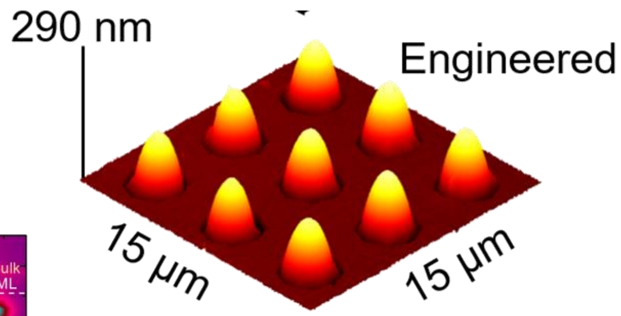


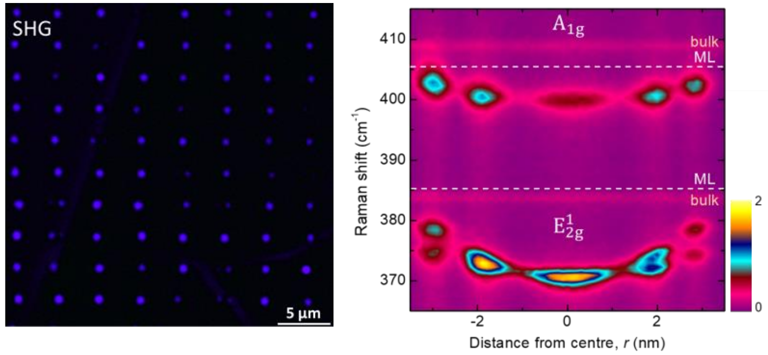
$$\Delta E_{\mathrm{Z}} = g_{\mathrm{exc}}\,\mu_{\mathrm{B}}\,B$$

Like for WSe_2 quantum emitters, the large *g* value indicates the involvements of an electron in a defect state and a hole in the valence band

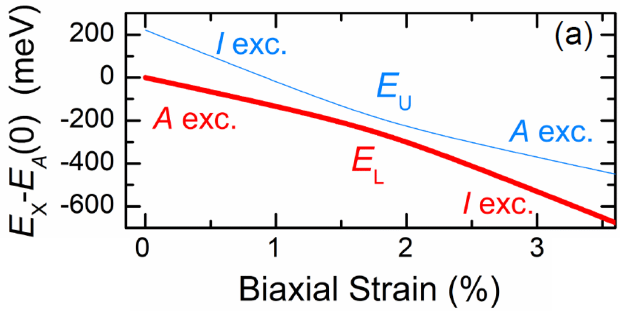
Conclusions

- Durable, spatially controlled domes can be created in TMDs and hBN

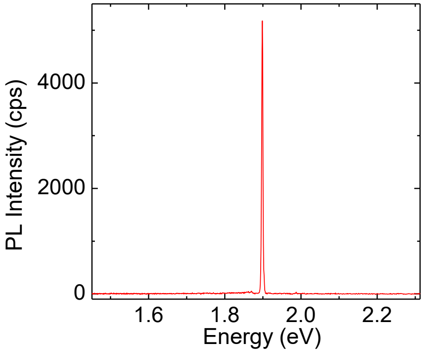


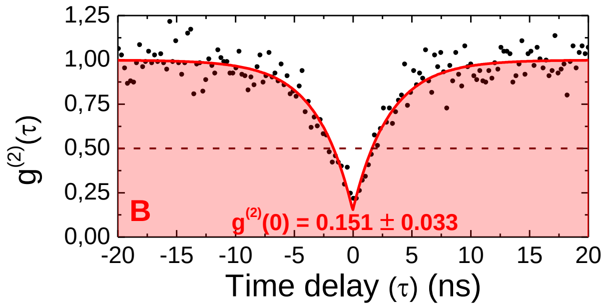


- The domes host complex strain field and act as efficient light emitters



- Complex strain fields give access to exciton hybridization phenomena





- Applications for site-controlled quantum light sources