Solid state sources for quantum communications

J. J. H. Eng, X. Lyu, M. Meunier, L. Kallioniemi, L. Ang, H. Zhang, N. Lecaron, Z. Jiang, A. Rasmita, Y. Yang, F. Zhou, H. Cai, S. Chenot, Z. Dong, W. Gao, and J. Zuniga-Perez

jesus.zuniga-perez@cnrs.fr

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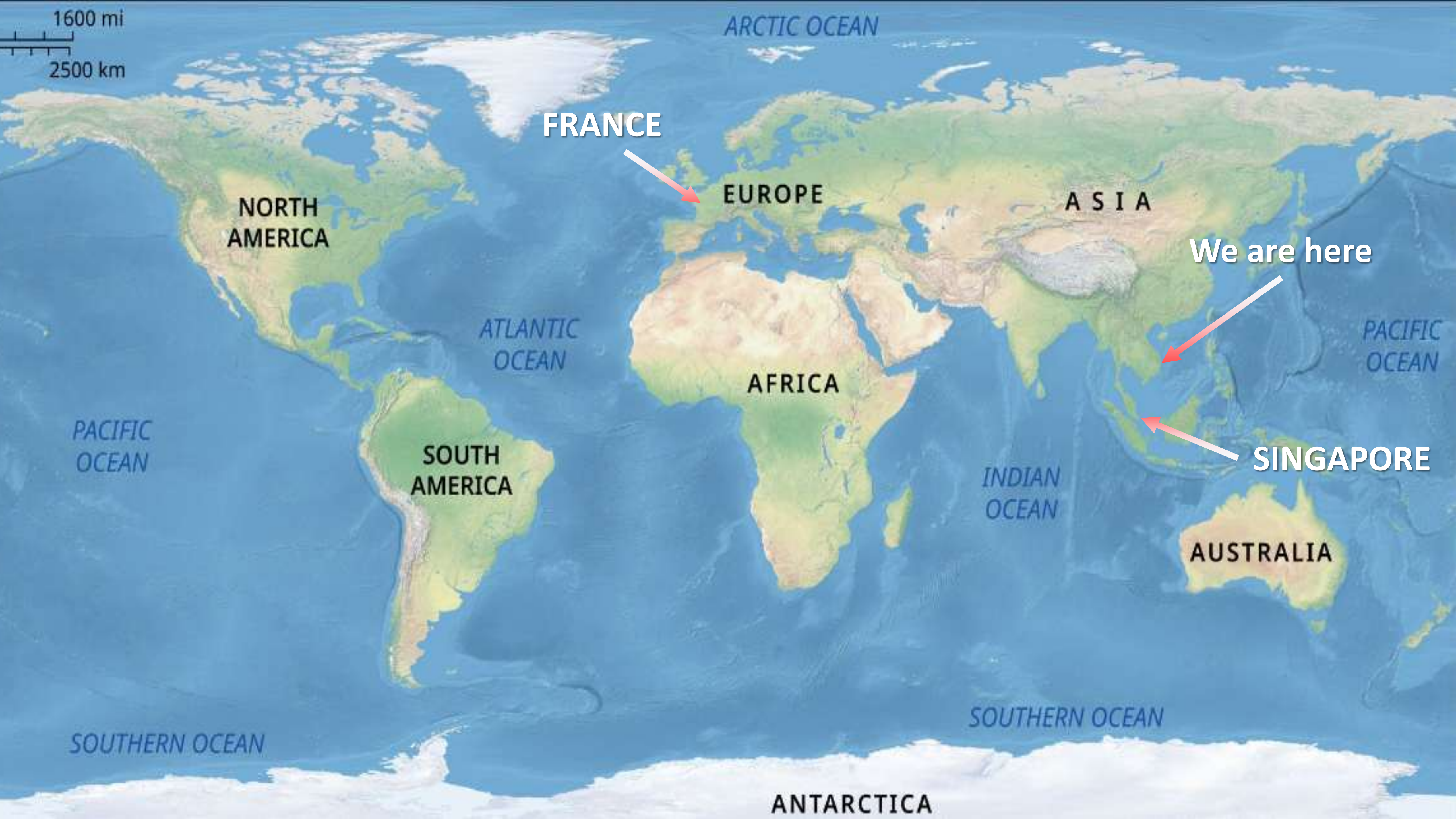
CRHEA MajuLab SPMS CQT Centre for Quantum Technologies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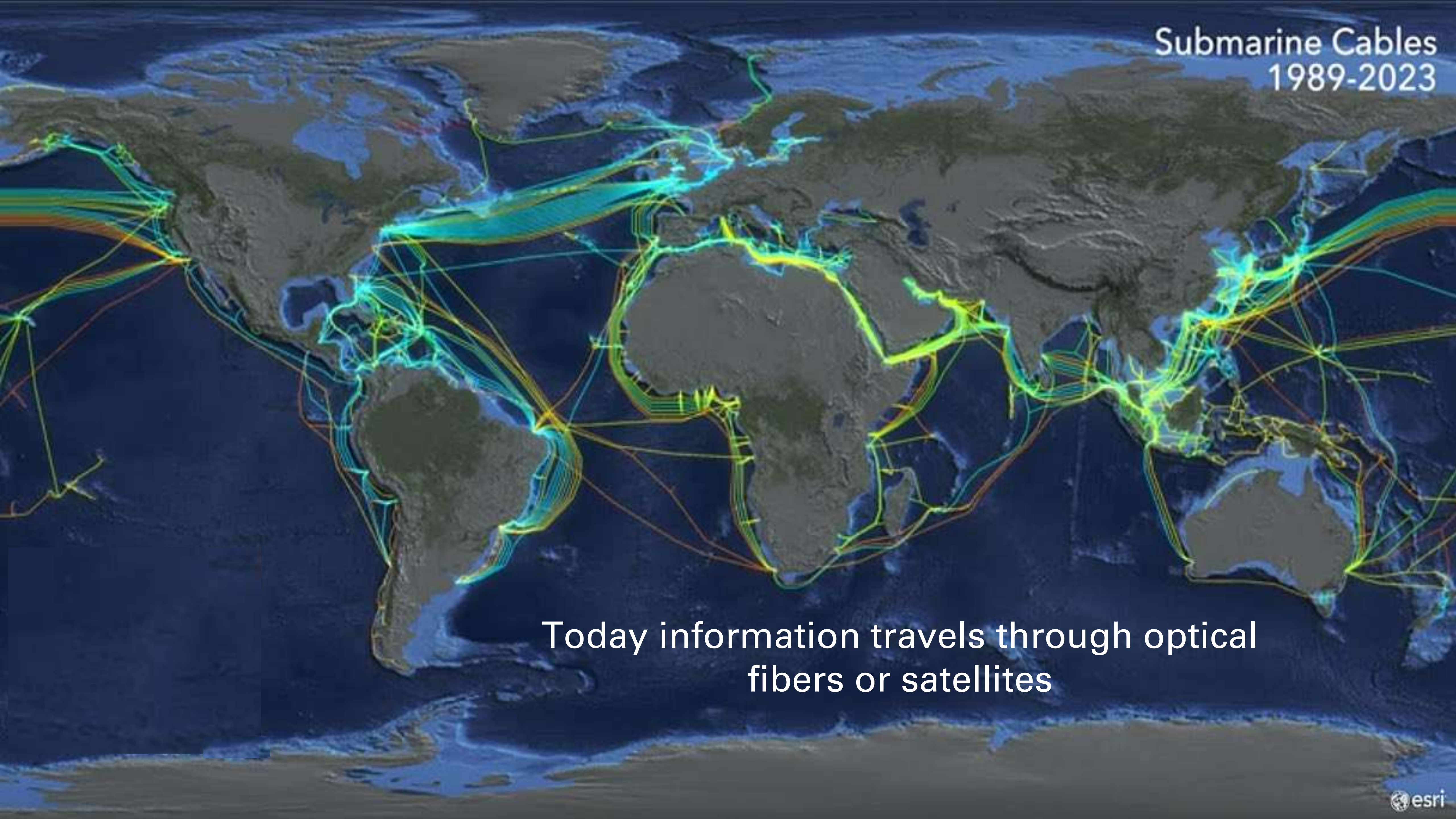
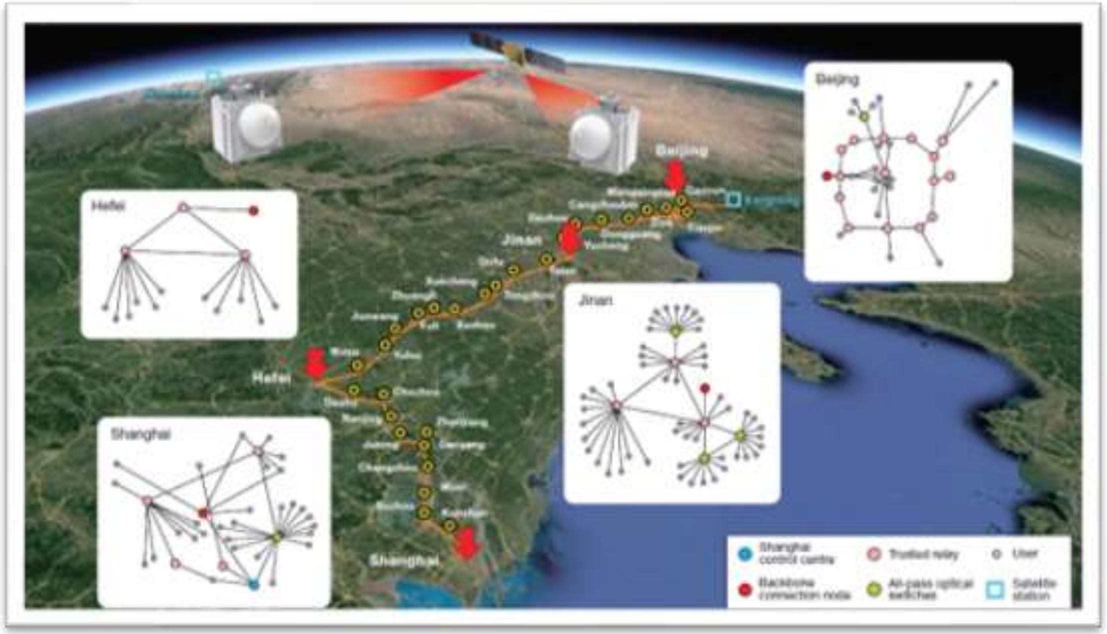


Today information travels through optical fibers or satellites

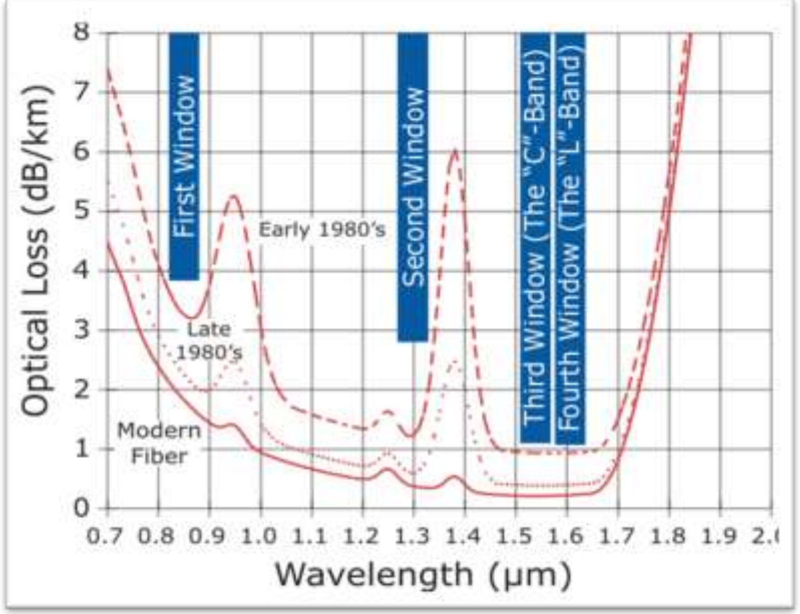
Quantum communications: single-photon emitters at telecomm λ

- Quantum internet will relie on existing infrastructures: satellite-based communications combined with local or regional optical-fiber networks

Y. A. Chen *et al.*, Nature **589** (2021) 214



- **Quantum sources emitting at 1.3μm or 1.55μm at room-tempereature** would be ideal, specially in terms of integration, although frequency conversion can be extremely efficient.

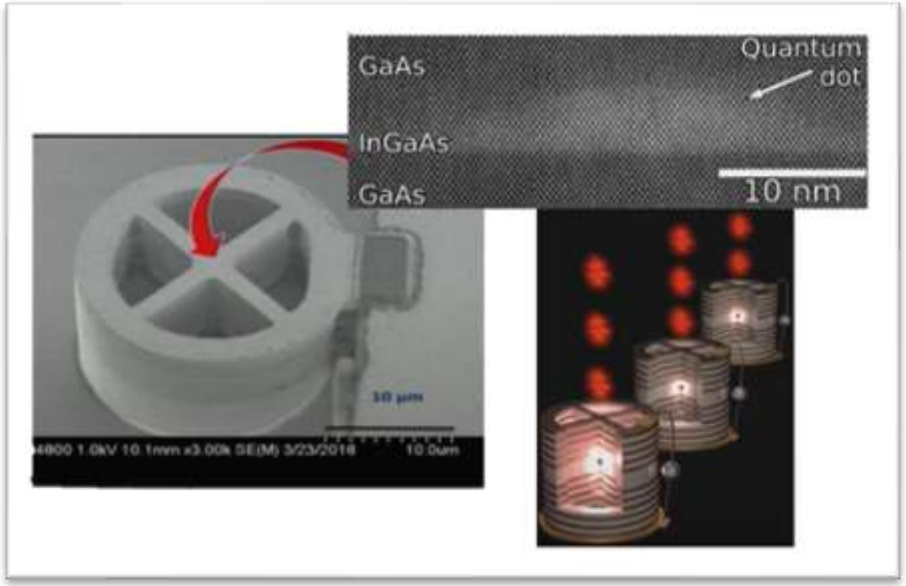


Quantum communications: single-photon emitters at telecomm. λ

- The most performant single-photon emitters are based on **epitaxial quantum dots**

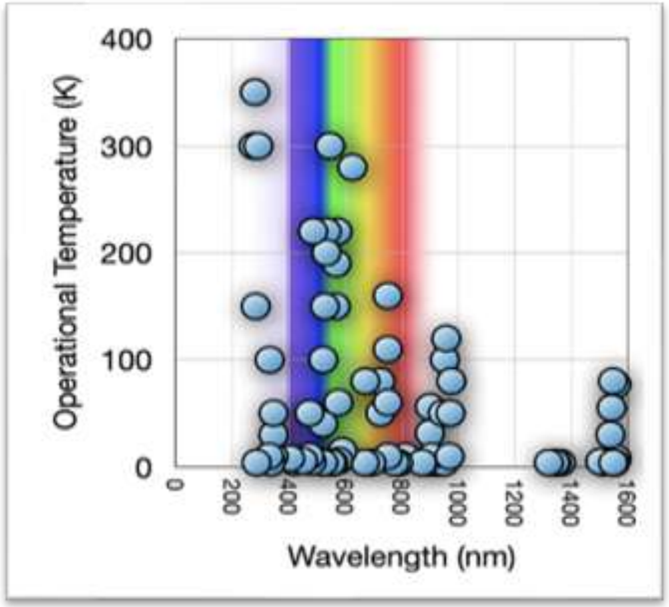
A. K. Nowak *et al.*, Nature Comm. **5** (2014) 3240

https://www.quandela.com/



- The operation temperature decreases with increasing wavelength: **telecom single-photon emitters need cryogenic cooling**.

- The purity of the emitter degrades with increasing temperature.



Y. Arakawa and M. J. Holmes, Appl. Phys. Rev. **7** (2020) 021309

Outline

- **Brief Motivation:**

  - Quantum communications at 300K

- **Colour-centers in GaN:** Telecommunication single-photon emitters

  - Coupling single-photon emitters to bulleyes antennas:
  - Nature of the emitters:
    - Why are we interested in determining their nature? Identification
    - Optically detected magnetic resonance.
    - Spin quantization axis




- **Entangled photon-pair sources in 2D materials:**

  - Bulk nonlinear crystals Vs « Thin » nonlinear crystals
  - Van der Waals $NbOCl_2$: transferable and broadband entangled photon-pair source
  - Rhombohedral BN: production of entangled-photon pairs in Van der Waals materials

- **Conclusions**

Colour centers in GaN: what are we talking about?

- **Colour centers** : Point defects in crystals that absorb certain colours

- **GaN:** 2nd semiconductor worldwide

LEDs & lasers

RFs and MWs

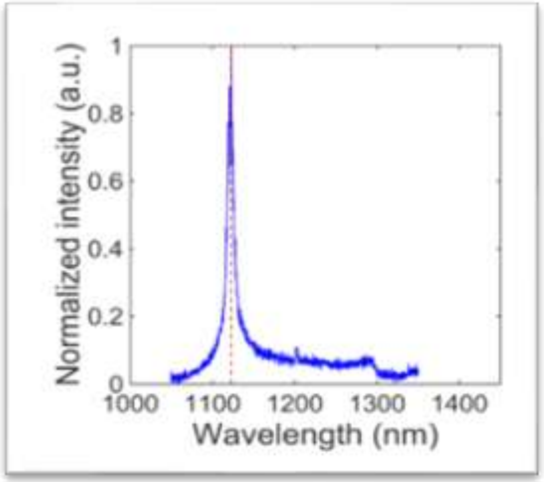
Power electronics

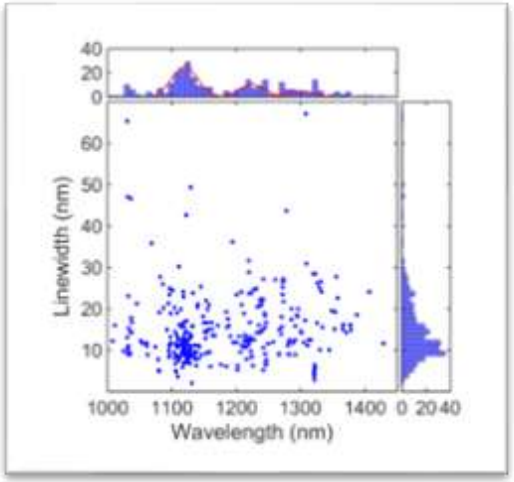
What we need to remember: - Colour centers are « naturally » present in crystals.
- GaN is widespread and has a mature technology

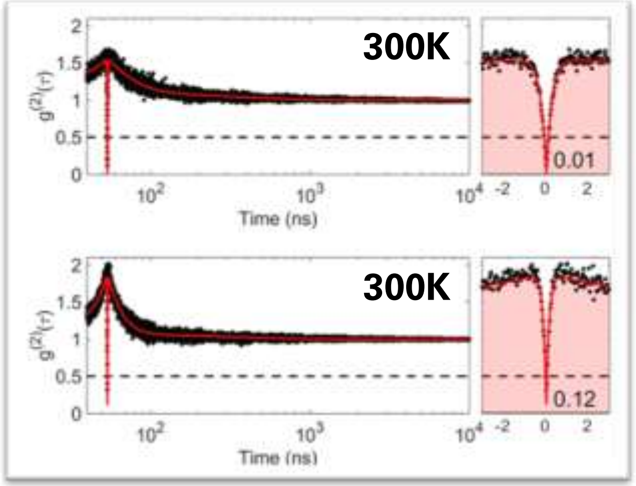
GaN: telecomunication single-photon emitters

- GaN **can display** colour centers emitting single-photons from 1μm to 1.4μm at 300K

M. Meunier *et al.*, Nanophotonics **12** (2023) 1405-1419

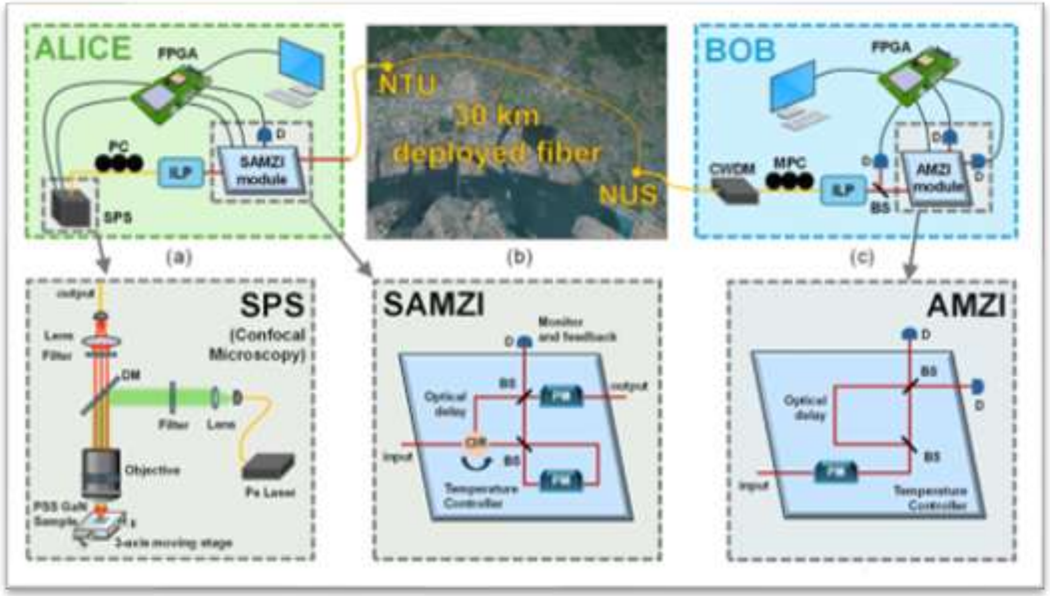


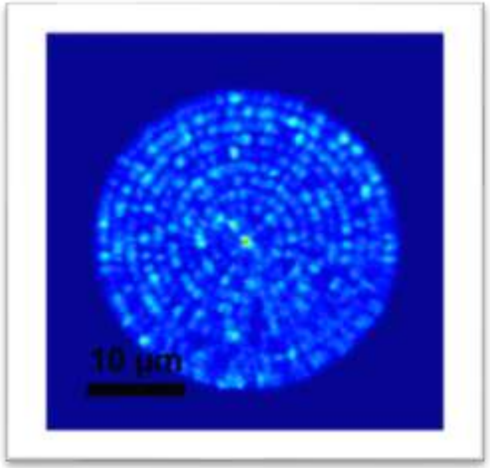




- Thanks to these emitters we have performed a real-field QKD demonstration in the Singaporean quantum network.

H. Zhang *et al.*, Phys. Rev. Appl. 23 (2025) 054022



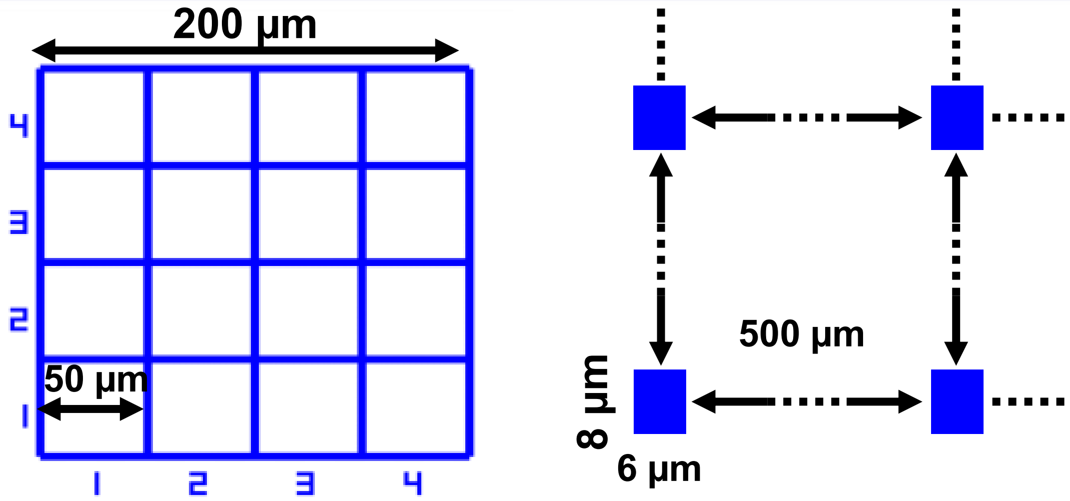


M. Meunier *et al.*, ACS Nano (submitted 2025)

Coupling to photonic structures: spatial alignment

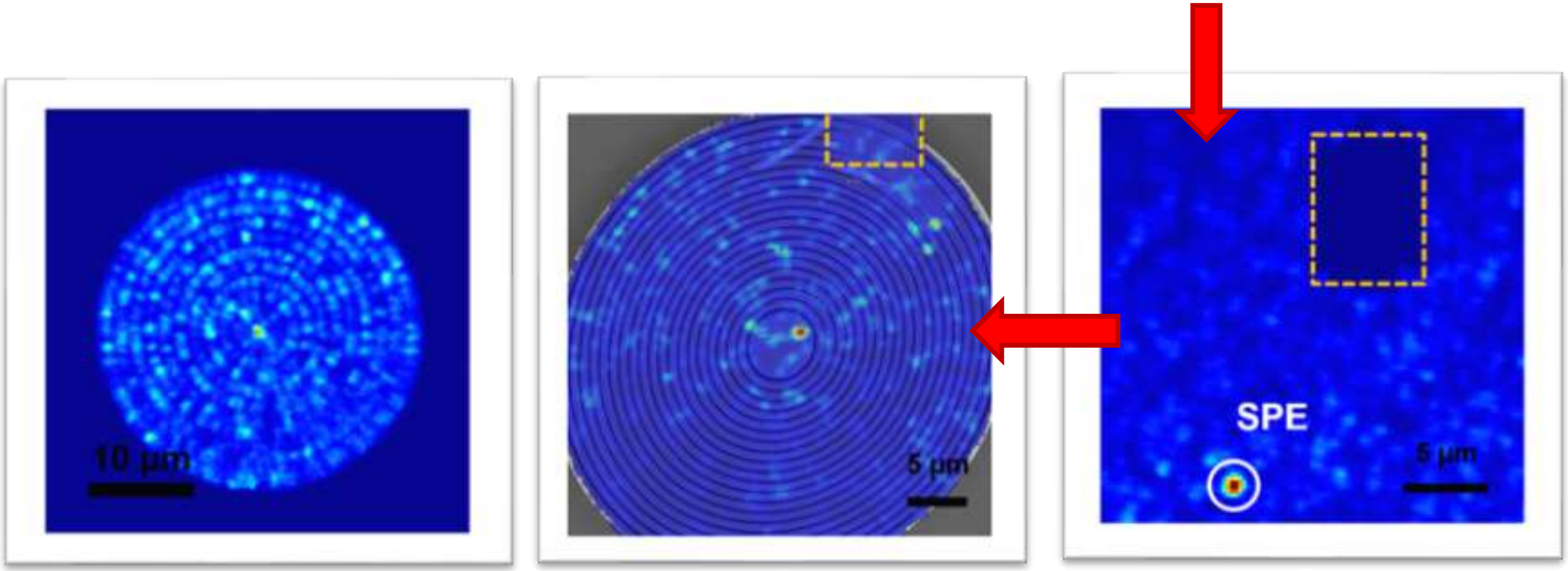
- Today we **can not create** telecom single-photon emitters in GaN **in predefined locations**

- To **couple them deterministically to photonic structures** we need to:
  1) Fabricate alignment marks
  2) Locate and characterize the emitters
  3) Fabricate the photonic structures around them



M. Meunier *et al.*, Nanophotonics **12** (2023) 1405-1419

MOTIVATION:
If we knew the nature of the defect, we might produce them deterministically

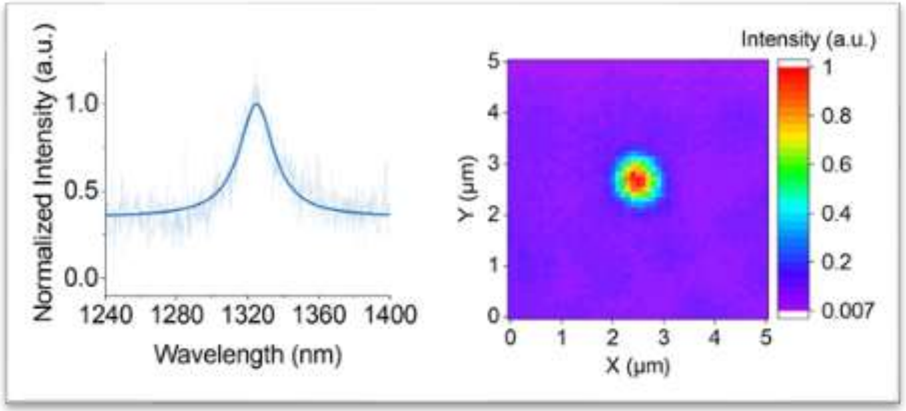


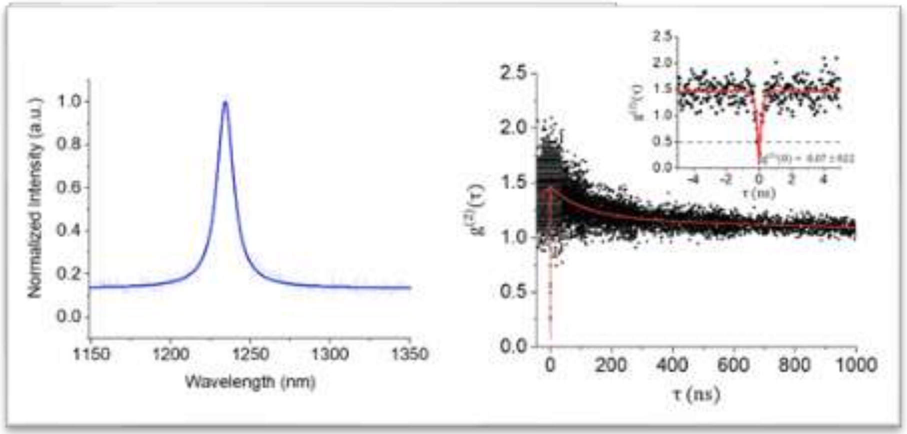
M. Meunier *et al.*, ACS Nano (submitted 2025)

Nature of the emitters: Optically detected magnetic resonance

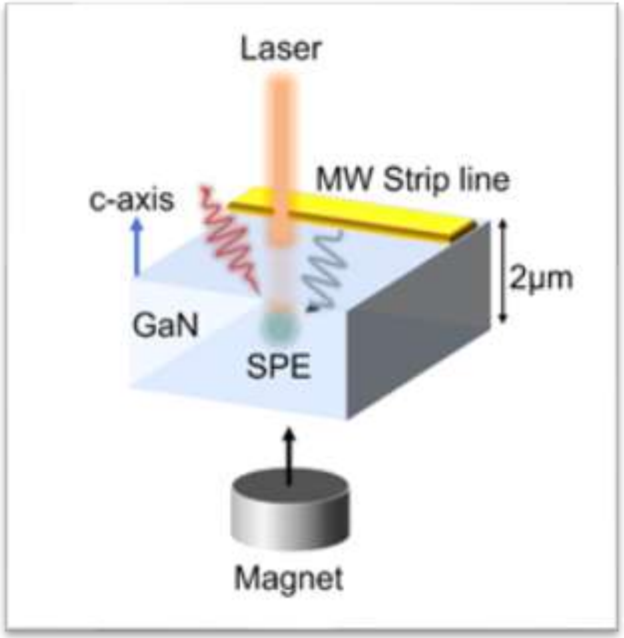
- **Magnetic resonance spectroscopy** explores the interaction of electronic (or nuclear) angular momenta with each other and with external magnetic fields

1. We choose a “standard” **O-band** single-photon emitter





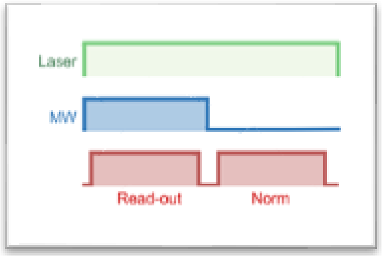
2. We fabricate a MW antenna nearby (+ we apply an external magnetic field)



3. We perform the optically-detected magnetic resonance (ODMR) measurement

$$ODMR\ Contrast = \frac{PL_{read-out} - PL_{norm}}{PL_{read-out} + PL_{norm}}$$

Nature of the emitters: Optically detected magnetic resonance



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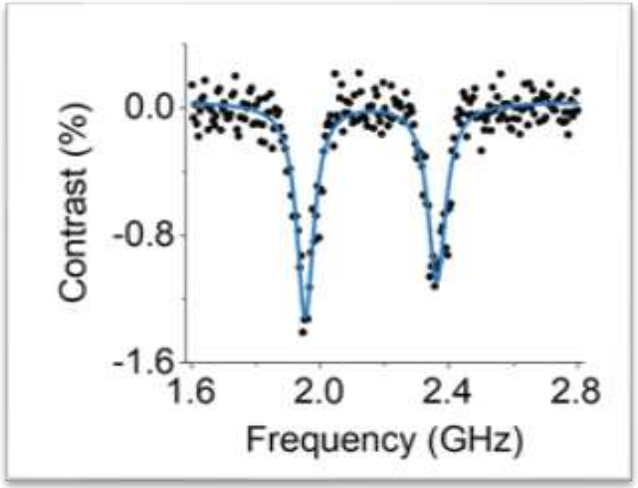


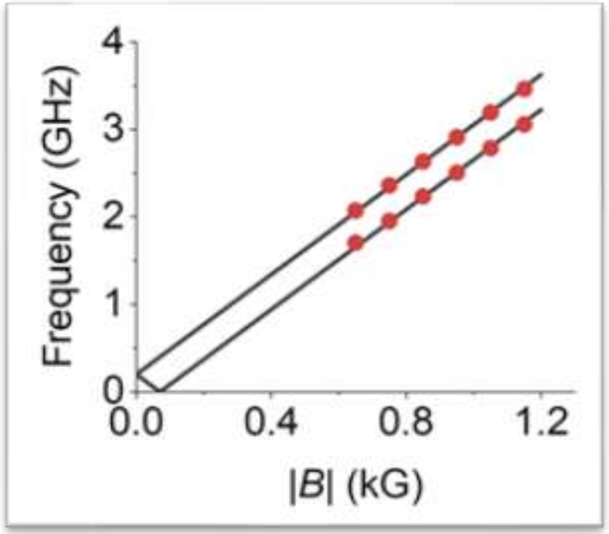
J. Eng *et al.*, Phys. Rev. Lett. **134** (2025) 083602

- Two distinct transitions

- Points to a system with Spin=1

$$H = DS_z^2 + E(S_x^2 - S_y^2) + g\mu_B \vec{B}.\vec{S}$$

$$\left| D \pm \sqrt{E^2 + (\gamma B_z)^2} \right|$$



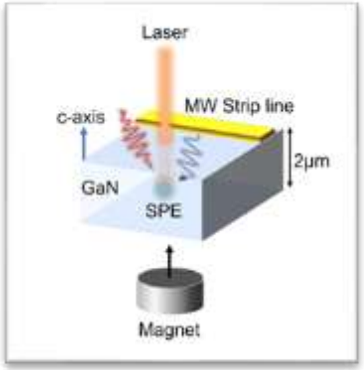
- Linear dependence on the applied magnetic field

- A giromagnetic ratio γ = 28.55 ± 0.14GHz/T

Nature of the emitters: Spin quantization axis

- **Magnetic resonance spectroscopy** explores the interaction of electronic (or nuclear) angular momenta with each other and with external magnetic fields

- To determine the direction of the **defect spin quantization axis** we need to measure ODMR as a function of the B-field orientation (for constant field strength)



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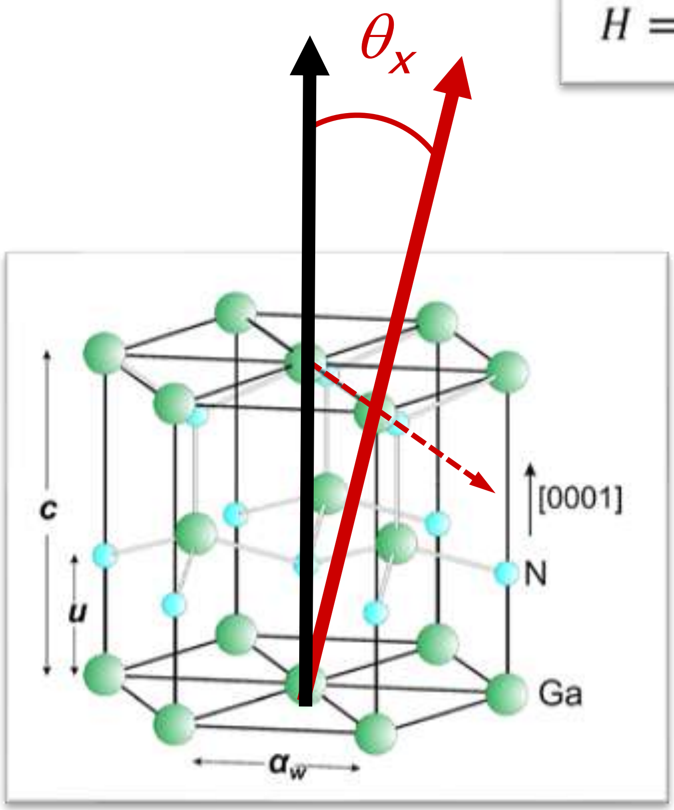

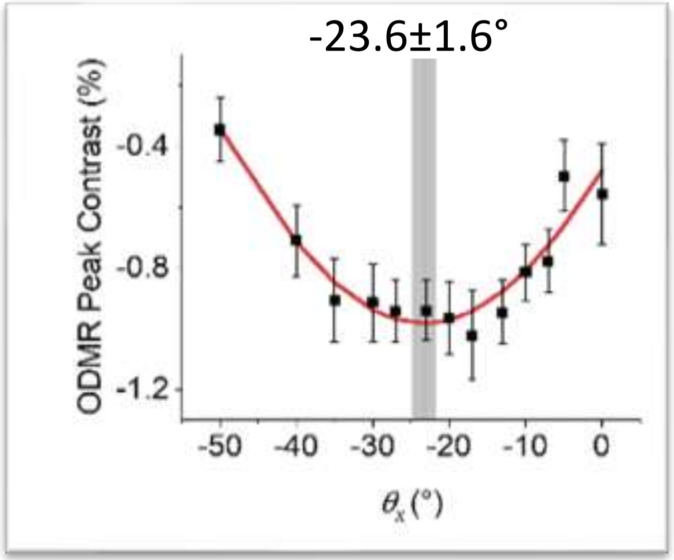

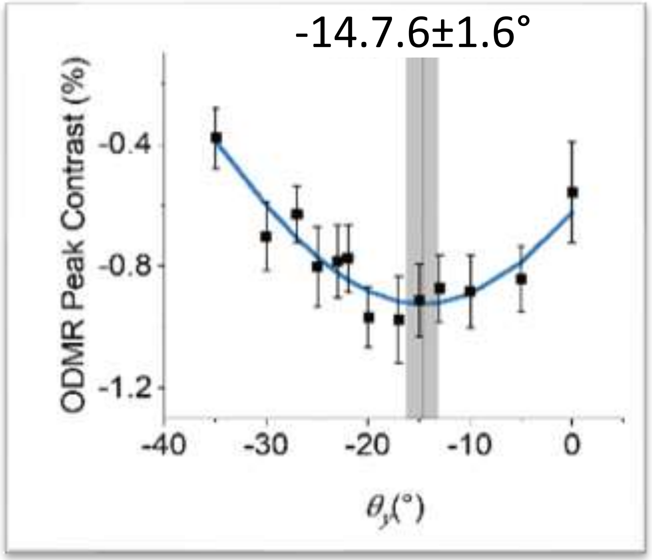

J. Eng *et al.*, Phys. Rev. Lett. **134** (2025) 083602

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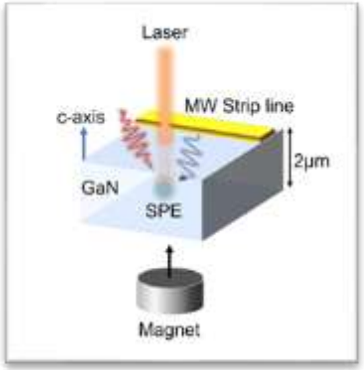
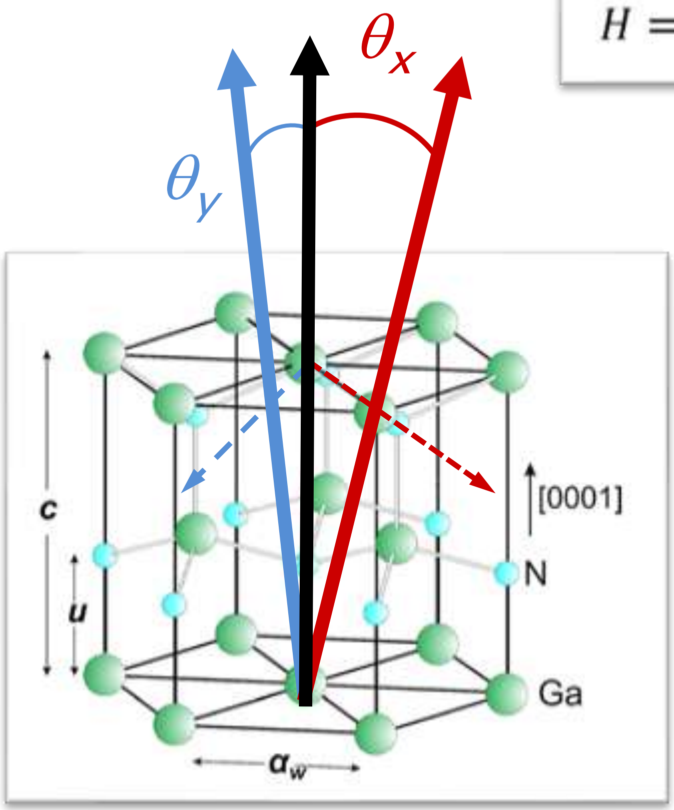
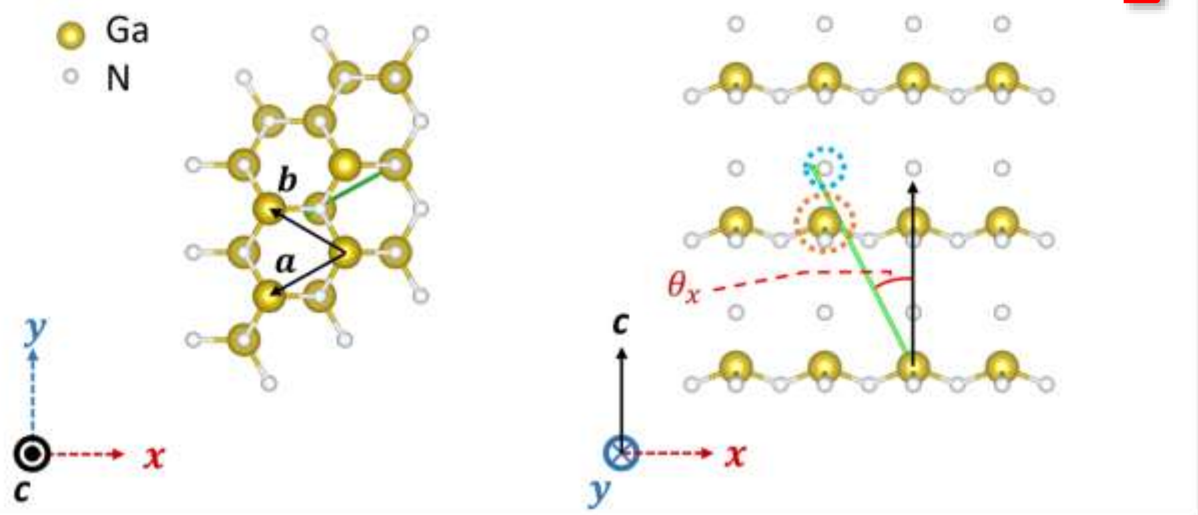


$$H = DS_z^2 + E(S_x^2 - S_y^2) + g\mu_B \vec{B}.\vec{S}$$



Angle $\theta = 27 \pm 2°$ with respect to the *c*-axis
Azimuthal angle $\varphi = 1.3 \pm 1.1°$ with respect to the *a*-axis.



Does not correspond to any lattice vector

J. Eng *et al.*, Phys. Rev. Lett. **134** (2025) 083602

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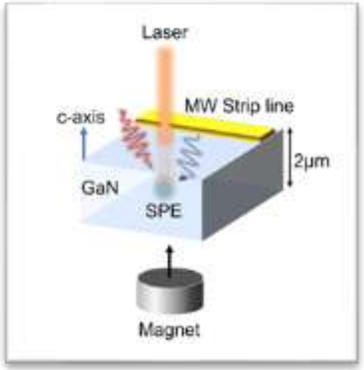
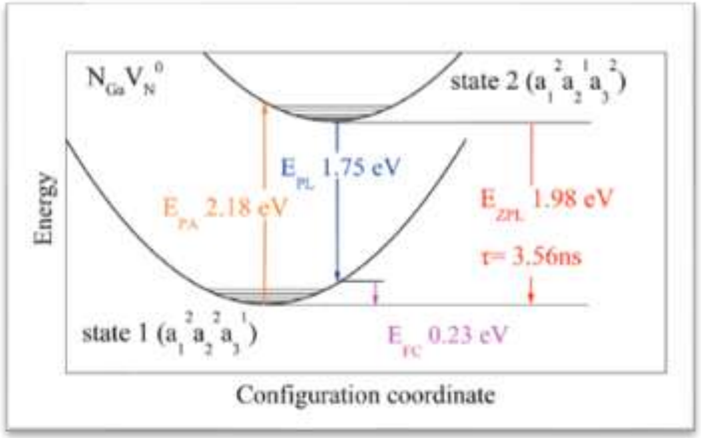
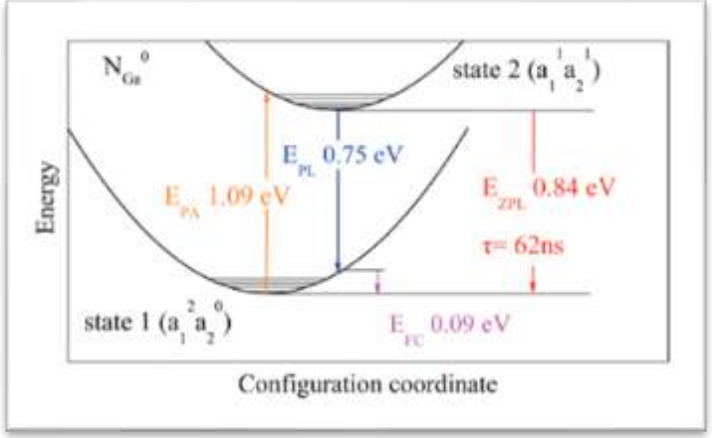


$$H = DS_z^2 + E\left(S_x^2 - S_y^2\right) + g\mu_B \vec{B}.\vec{S}$$

- We "hope" that by **correlating ab-initio calculations on point defects in GaN and our experimental data** (lifetime, spin quantization axis orientation, "energy level diagram", ...) it will be possible to assess the exact nature of the defect/s.





Charge	−1	0	+1
Spin	Down	Down	Down
ZPL	0.86 eV (1426 nm)	1.98 eV (625 nm)	0.94 eV (1323 nm)
Transition rates r [s^{-1}]	1.62×10^8	2.81×10^8	5.72×10^6
Lifetime τ [ns]	6.19	3.56	175
Transition channel	a_3 to a_4	a_2 to a_3	a_2 to a_3
Suitable for room temperature SPE	No	Yes	Yes

J. Yuan *et al.*, Advanced Optical Materials **11** (2023) 2202158

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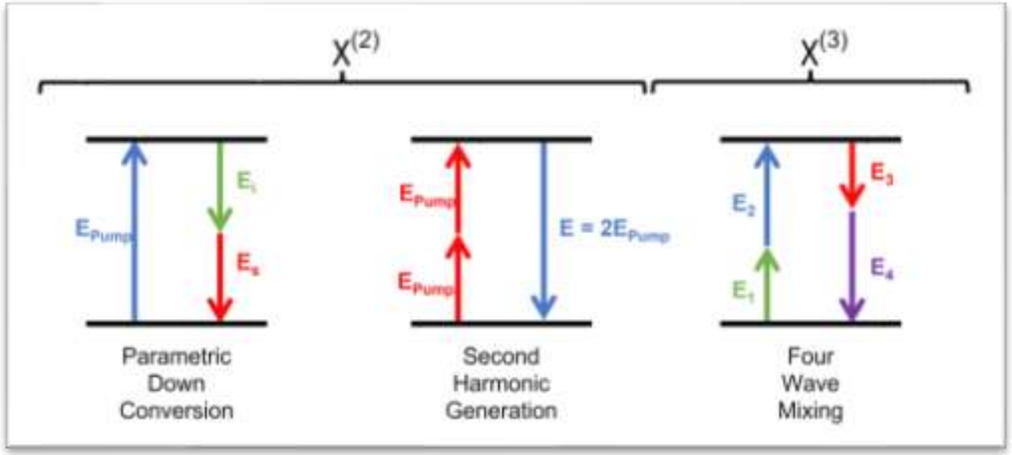
  - Van der Waals $NbOCl_2$: transferable and broadband entangled photon-pair source
  - Rhombohedral BN: production of entangled-photon pairs in Van der Waals materials
- **Conclusions**



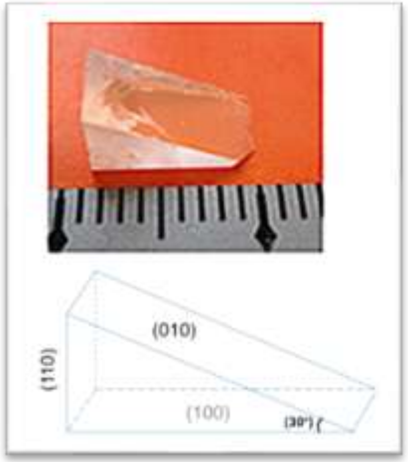

Motivation: issue with entanglement production

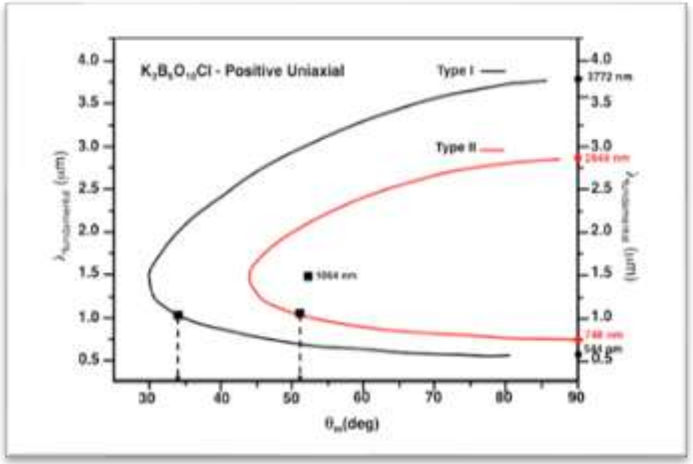
- **Entangled photon pair generation**: the most widely used process is spontaneous parametric dowconversion (SPDC).

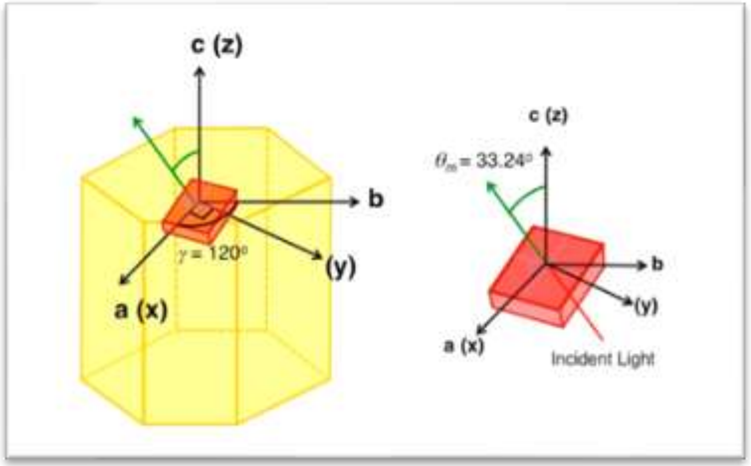


- **SPDC** requires fullfilment of energy-conservation and of momentum-conservation (**phase matching conditions**)

W. Zhang et al., Chem. Mater. ***29*** *(2017) 2655*







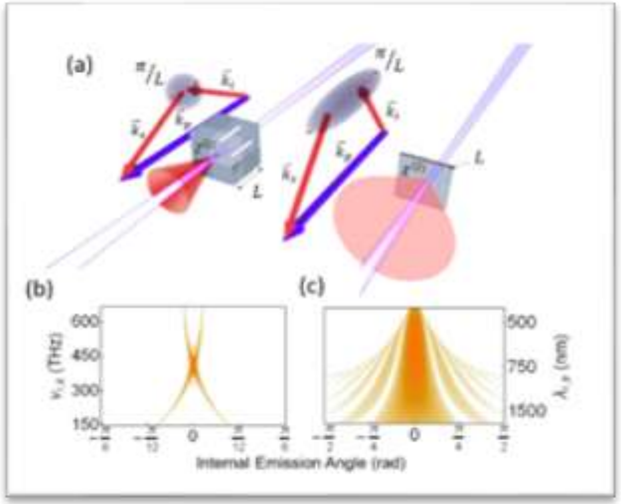
MAJOR PROBLEMS: Narrow-band, very rigid design (one crystal=one wavelength), extremely sensitive to optical alignment (i.e. very sensitive to vibrations)

Motivation: issue with entanglement production

- To circumvent phase-matching: **nonlinear medium shorter than the coherence length**

ADVANTAGES: Broadband and large « angular acceptance »

Potential interest of 2D materials



C. Okoth et al. Phys. Rev. Lett. ***123****, 263602 (2019)*

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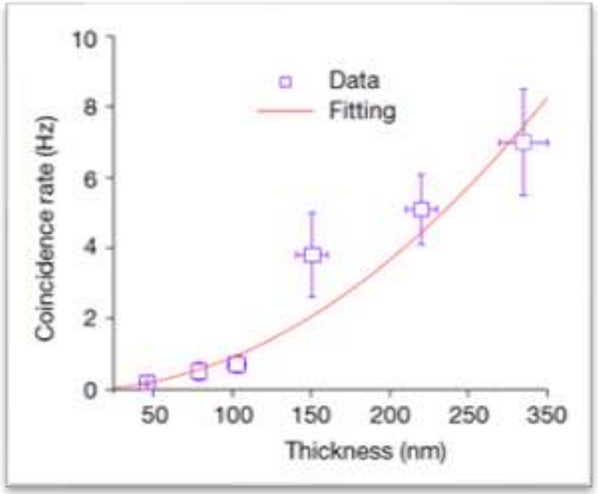
- **Issues for nonlinear optics:**

1) As size shrinks strong reduction of emission rate

The generation rate squares as

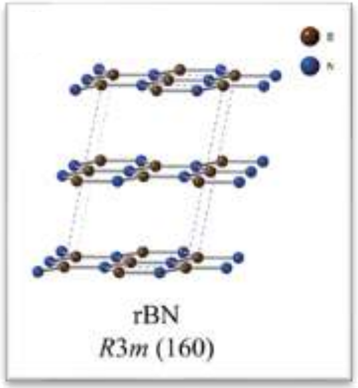
$$\propto \frac{1}{d^2}$$

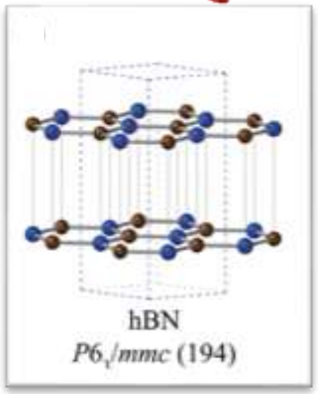


Q. Guo et al., Nature ***613****, 53 (2023)*

2) Many 2D are centrosymetric

~~$\chi^{(2)}_{ijk}$~~





Y. Nikaido et al., J. Phys. Chem. C ***126*** *(2022) 6000*

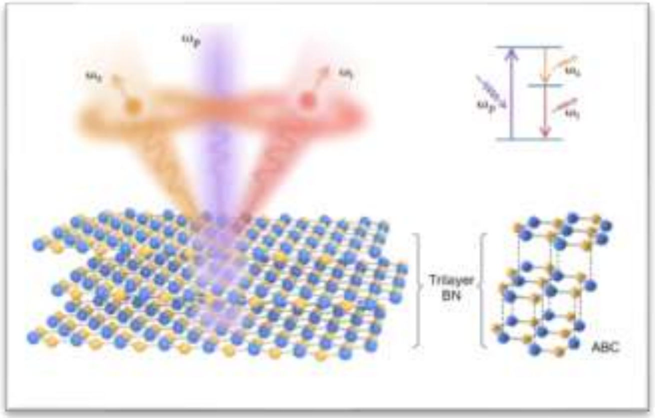
Nonlinear optics with r-BN: source of entangled-photons

- **Intrinsic properties of r-BN:**

1. **Crystal symmetries**:

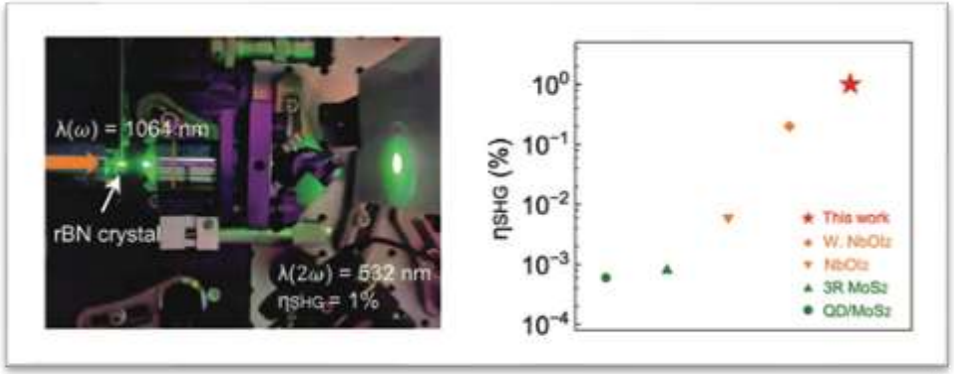
   → Broken out-of-plane inversion symmetry.

   → Preserved in-plane inversion symmetry.



2. **Strong nonlinear coefficients**:

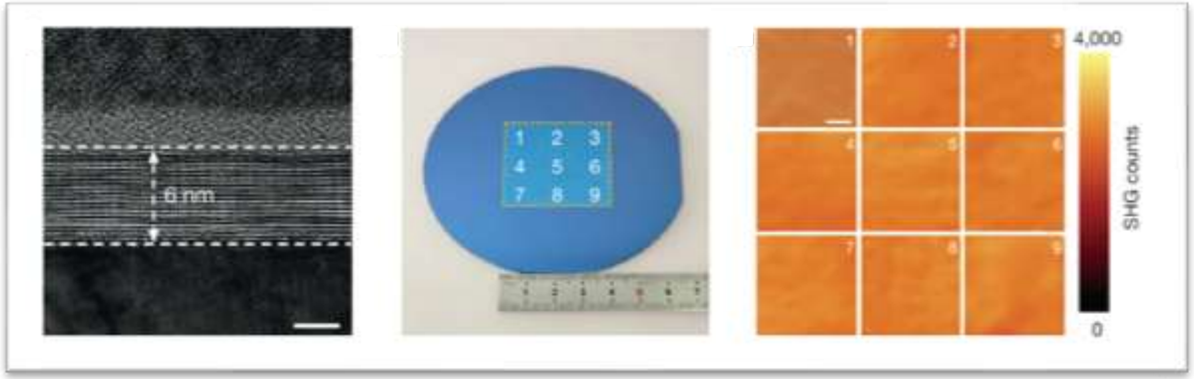
   → Larger than other nonlinear 2D crystals.



J. Qi *et al.*, Adv. Mater. **36** (2024) 2303122

3. **r-BN layers can be grown**:

   → Large crystals accessible.



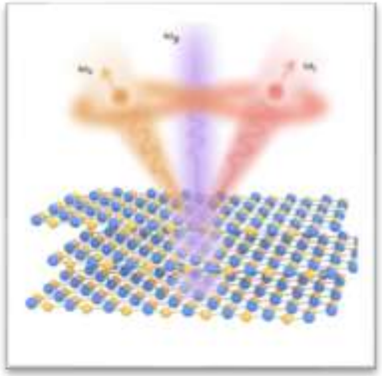
L. Wang *et al.*, Nature **629** (2024) 74

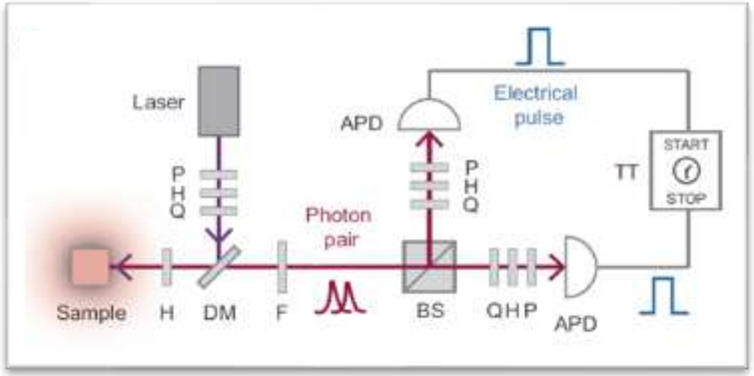
Nonlinear optics with r-BN: measuring/producing entangled-photons

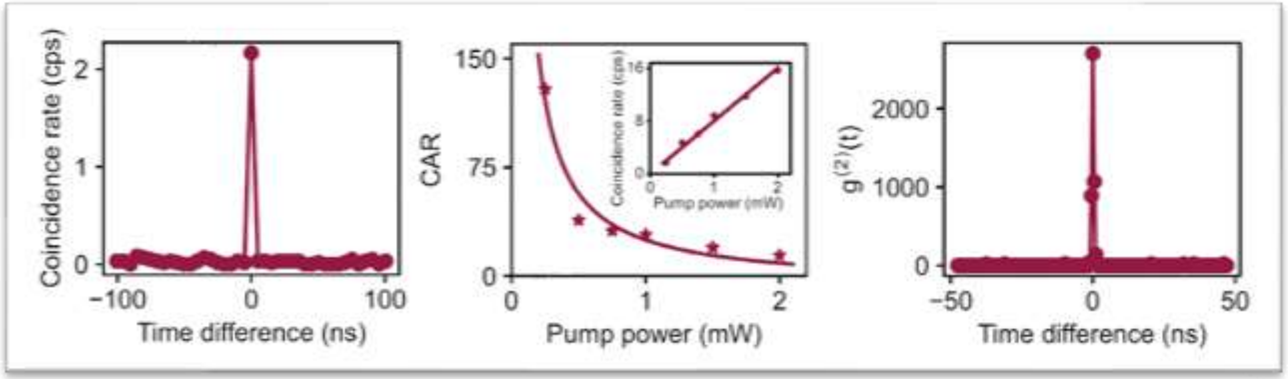
1. Characterization:

X. Lyu *et al.*, Nat. Comm. **16** (2025) 1899

→ Standard **Hanbury Brown-Twiss** setup: biphoton states

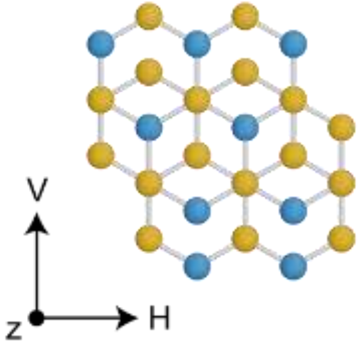






2. Symmetry-based considerations:

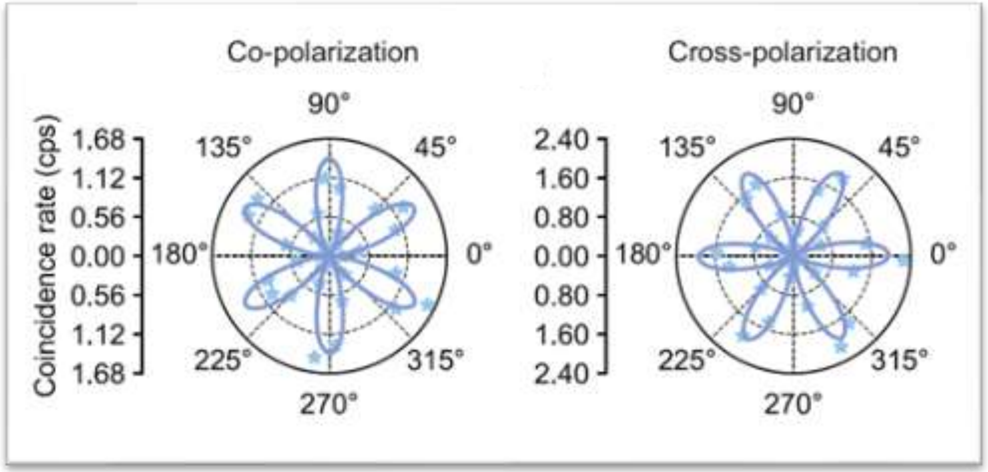
→ By changing the **pump polarization** we can produce **different entangled states.**



$$\chi^{(2)}_{yyy} = -\chi^{(2)}_{yxx} = -\chi^{(2)}_{xxy} = -\chi^{(2)}_{xyx} = |\chi^{(2)}|$$

y excitation: $\xrightarrow{\chi^{(2)}_{yyy} \quad \chi^{(2)}_{xxy}}$ $|xx|$ and $|yy|$

x excitation: $\xrightarrow{\chi^{(2)}_{xyx} \quad \chi^{(2)}_{yxx}}$ $|xy|$ and $|yx|$



$\chi^{(2)}_{yyy}$ $\chi^{(2)}_{xyx}$

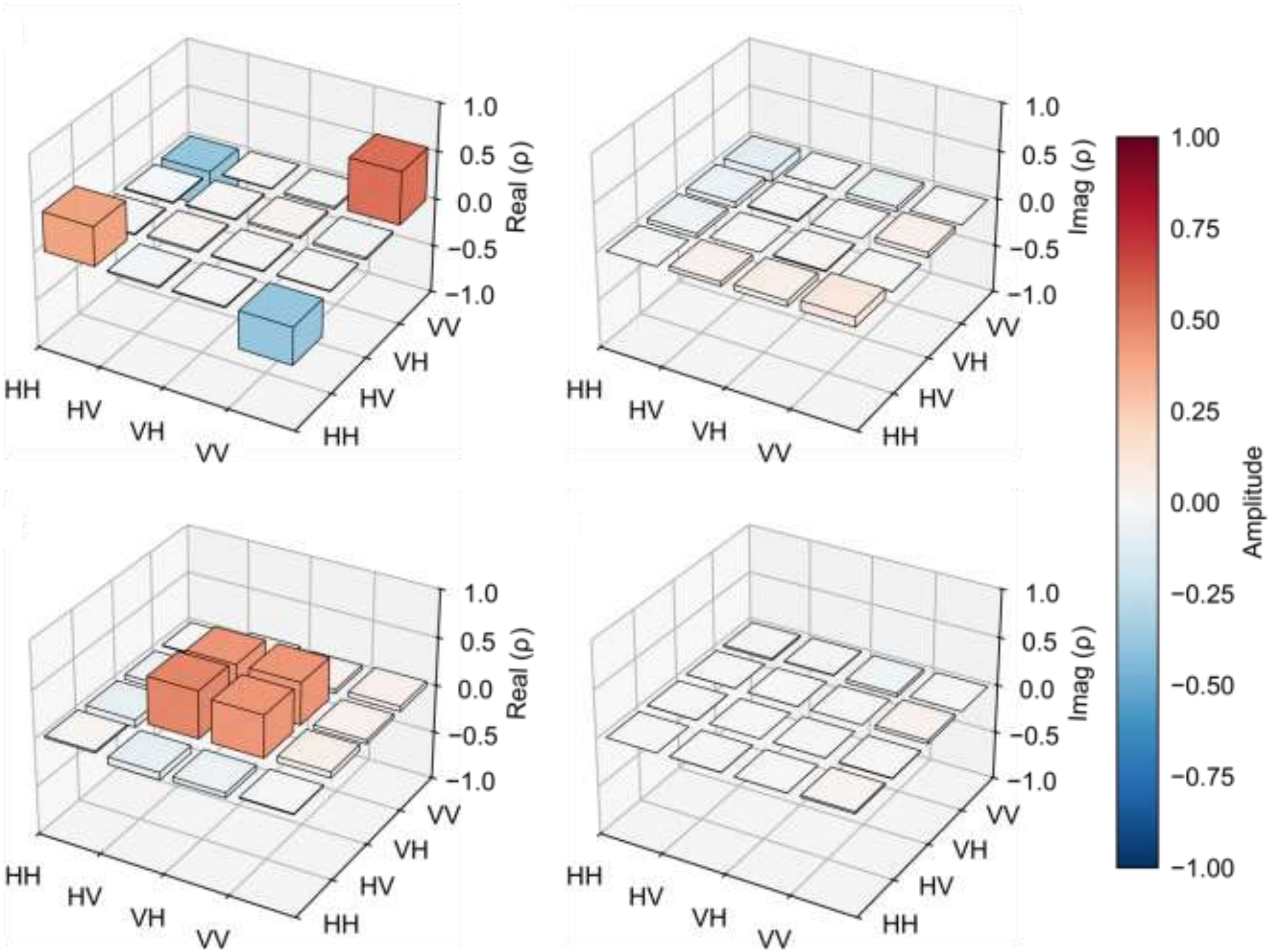
Nonlinear optics with r-BN: producing Bell states

3. Quantum tomography of the states produced:

X. Lyu *et al.*, Nat. Comm. **16** (2025) 1899

Pump || Armchair

Pump || Zigzag



$\frac{1}{\sqrt{2}}(|\mathbf{HH}\rangle - |\mathbf{VV}\rangle)$

Fidelity: 94%

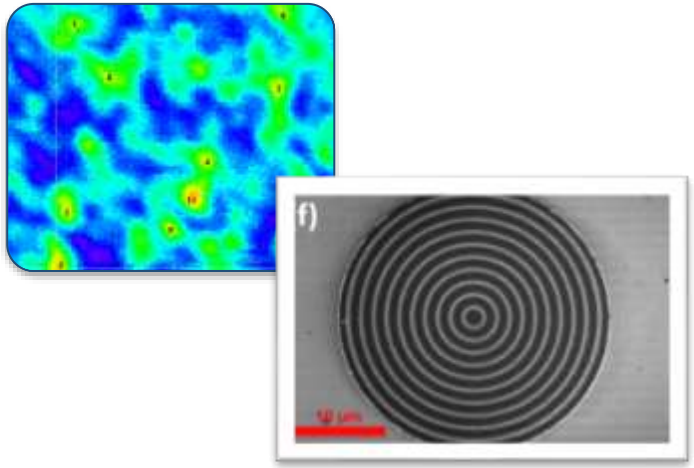
Switch between Bell states by tuning pump polarization

$\frac{1}{\sqrt{2}}(|\mathbf{HV}\rangle + |\mathbf{VH}\rangle)$

Fidelity: 92%

Conclusions

- **Colour centers (point-defects) in GaN can operate as bright telecom single-photon emitters**



- They **appear systematically** in certain GaN thin films samples.
- **Photonic structures** can be processed and **enhance their brightness**

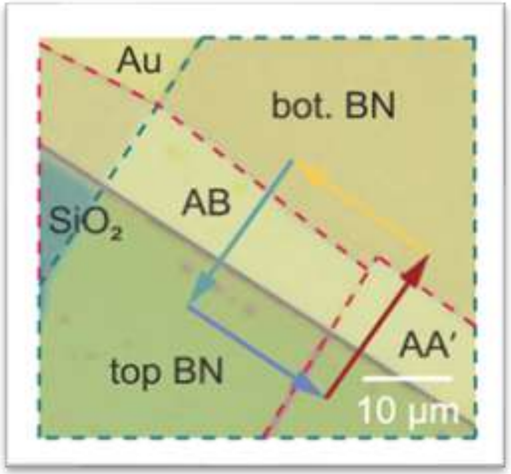
- We can not produce them yet in pre-designed locations
- Upon processing, some emitters are destroyed

M. Meunier *et al.*, Nanophotonics **12** (2023) 1405-1419

H. Zhang *et al.*, Phys. Rev. Appl. **23** (2025) 054022

J. Eng *et al.*, Phys. Rev. Lett. **134** (2025) 083602

- **Nonlinear photonics with 2D materials**



- Some have **intrisinsic large nonlinear coefficients.**
- **Low-symmetry** materials can **produce easily different entangled states**
- By controlling their thickness **they can be made broadband**

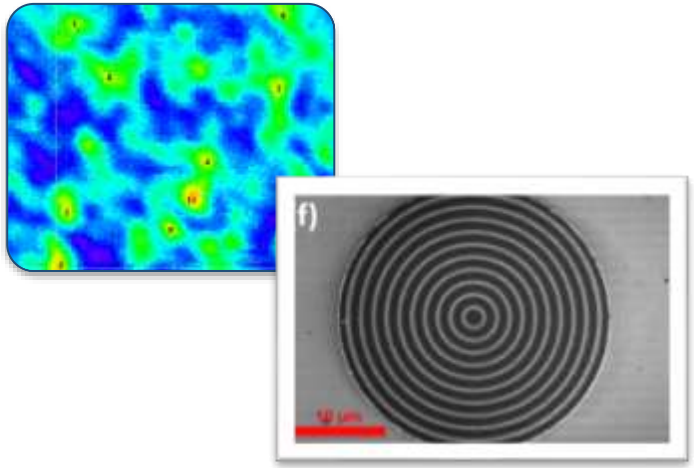
- The **production rate** of entangled-photon pairs **needs to be enhanced**
- Efficient coupling to **integrated photonics needs to be demonstrated**

X. Lyu *et al.*, Nat. Comm. **16** (2025) 1899

X. Lyu *et al.*, Nat. Comm. **16** (2025) 4987

Conclusions

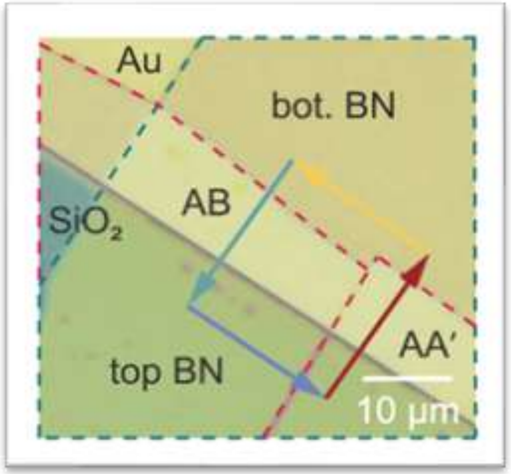
- **Colour centers (point-defects) in GaN can operate as bright telecom single-photon emitters**
  - They **appear systematically** in certain GaN thin films samples.
  - **Photonic structures** can be processed and **enhance their brightness**



What's next for GaN?

- **Electrical injection**
- **On-chip integration**

- **Nonlinear photonics with 2D materials**
  - Some have **intrisinsic large nonlinear coefficients.**
  - **Low-symmetry** materials can **produce easily different entangled states**
  - By controlling their thickness **they can be made broadband**



What's next for 2D?

- **Tuning of entangled states**
- **Proof-of-concept usercase**

THANK YOU!

Funding agencies

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