# QUASAR

## Quantum States: Analysis and Realizations

efficient quantum computation and communication

→ significantly improved comprehension of the underlying principles of quantum physics

→ scalable analysis tools to study the dynamics, decoherence, as well as the applicability of (large) quantum states

→ reliable and robust quantum technology components

# main objectives

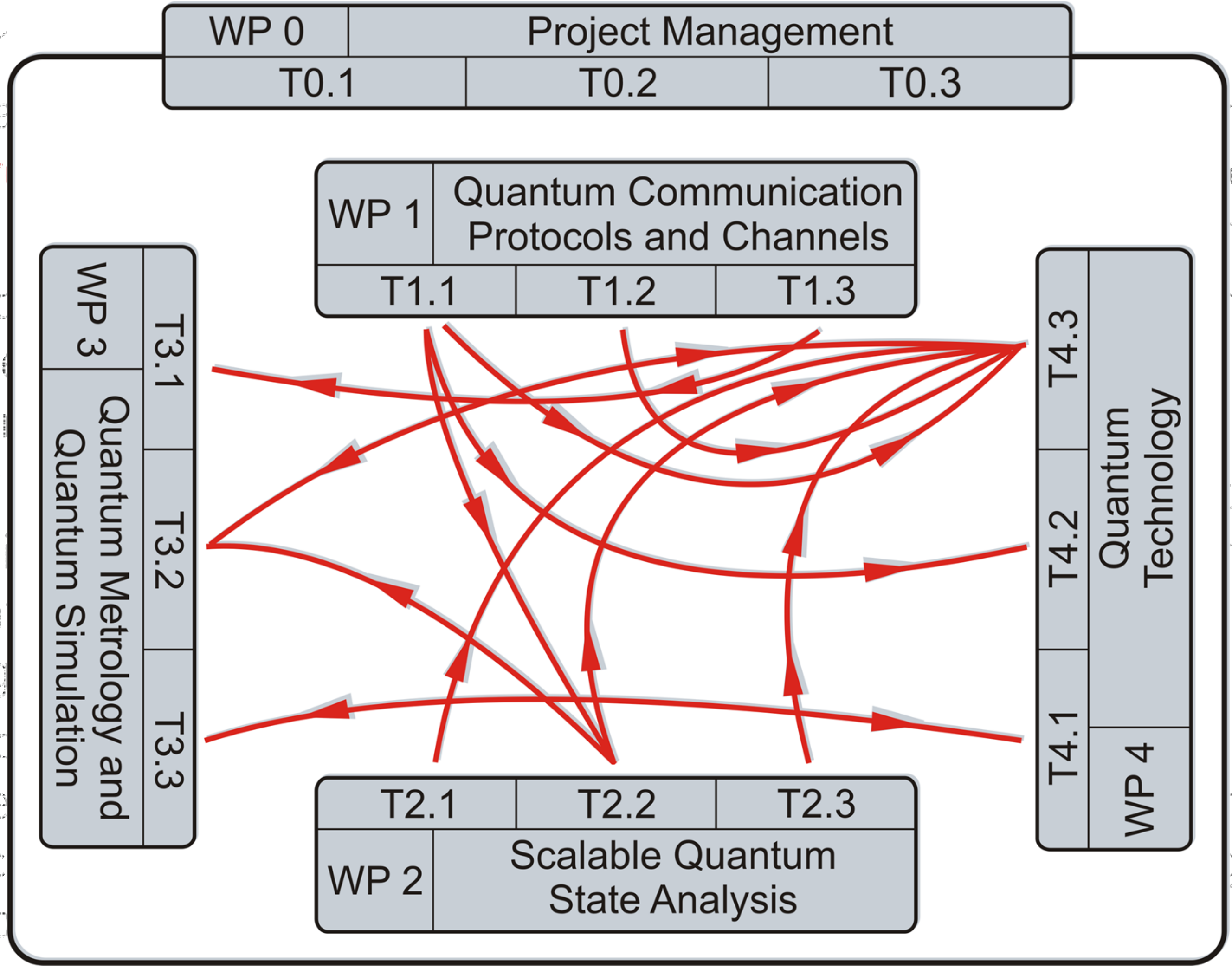
**QUASAR**

The main objectives of QUASAR are thus to

- apply foundational principles of quantum physics to identify **novel protocols** for quantum communication and to optimize the efficient usage of **quantum channels**, both in theory and experiment
- develop scalable methods for **quantum state analysis** and introduce application oriented witnesses with high statistical significance and robustness against experimental imperfections
- implement these methods to analyse the dynamics and their applicability for **quantum metrology** for different decoherence models and identify possible feedback protocols to adaptively optimize metrological tasks.
- develop a new approach for the production of highly integrated and reliable **waveguide quantum circuits** and implement photonic quantum logic operation for robust manipulation of high-dimensional multiqubit states and for quantum simulation tasks.

QUASAR

The mair
• a ... ntify
novel pr ... e
efficient ... ment
• c ... nd
introduce
significar
• i ... their
applicabi ... models
and iden
metrolog
• c
integrate ... ment
photonic ... gh-
dimensio



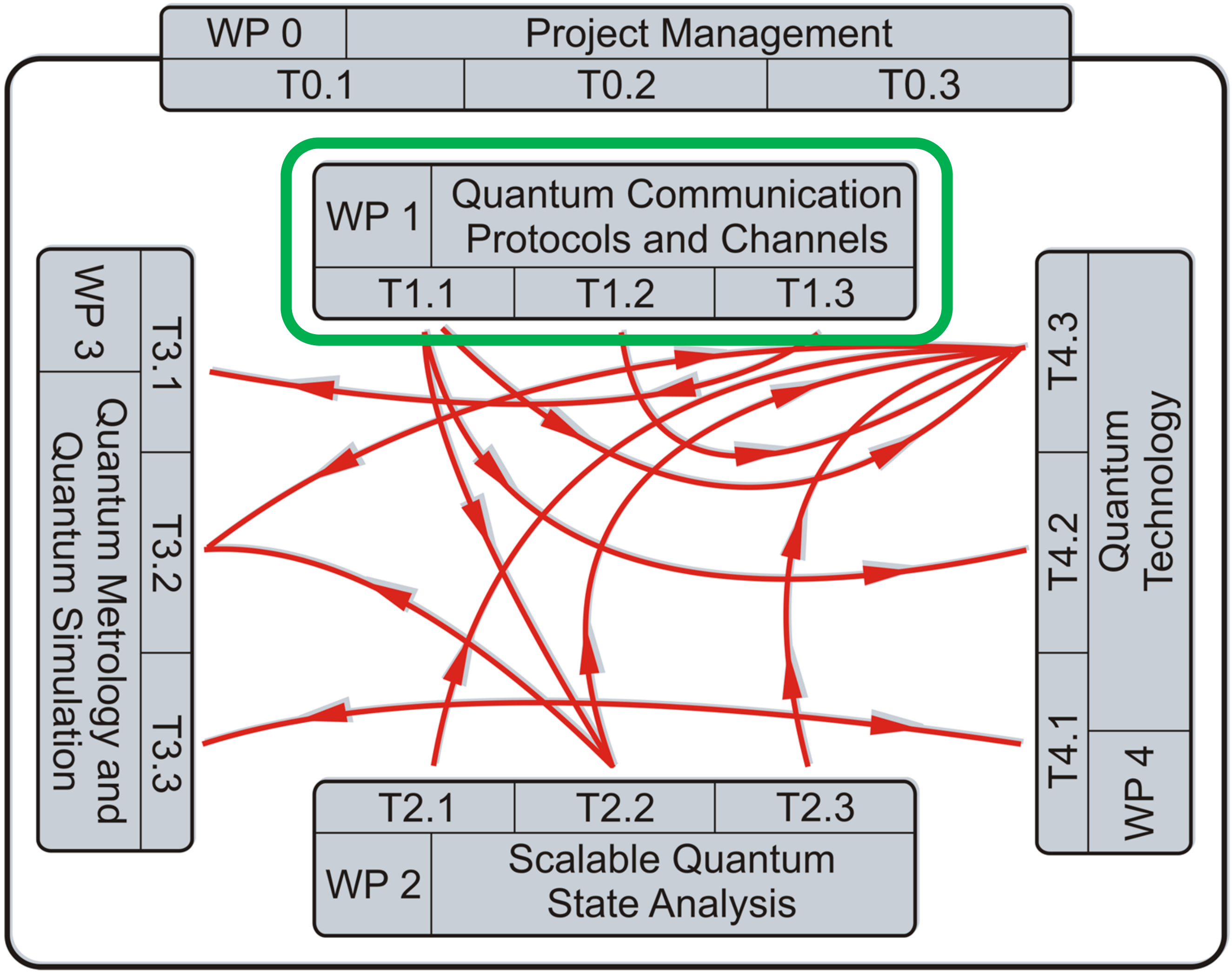
QUASAR

- University of Munich
- Austrian Academy of Sciences
- Sapienza Universita di Roma
- OPTOTEC SpA
- Warsaw University
- University of Gdansk
- University of the Basque Country
- University of Siegen

project start: 1.1.2012, kick-off meeting 9.1.2012, duration 2 years

# WP1 QC Protocols and Channels

QUASAR



# WP1 QC Protocols and Channels

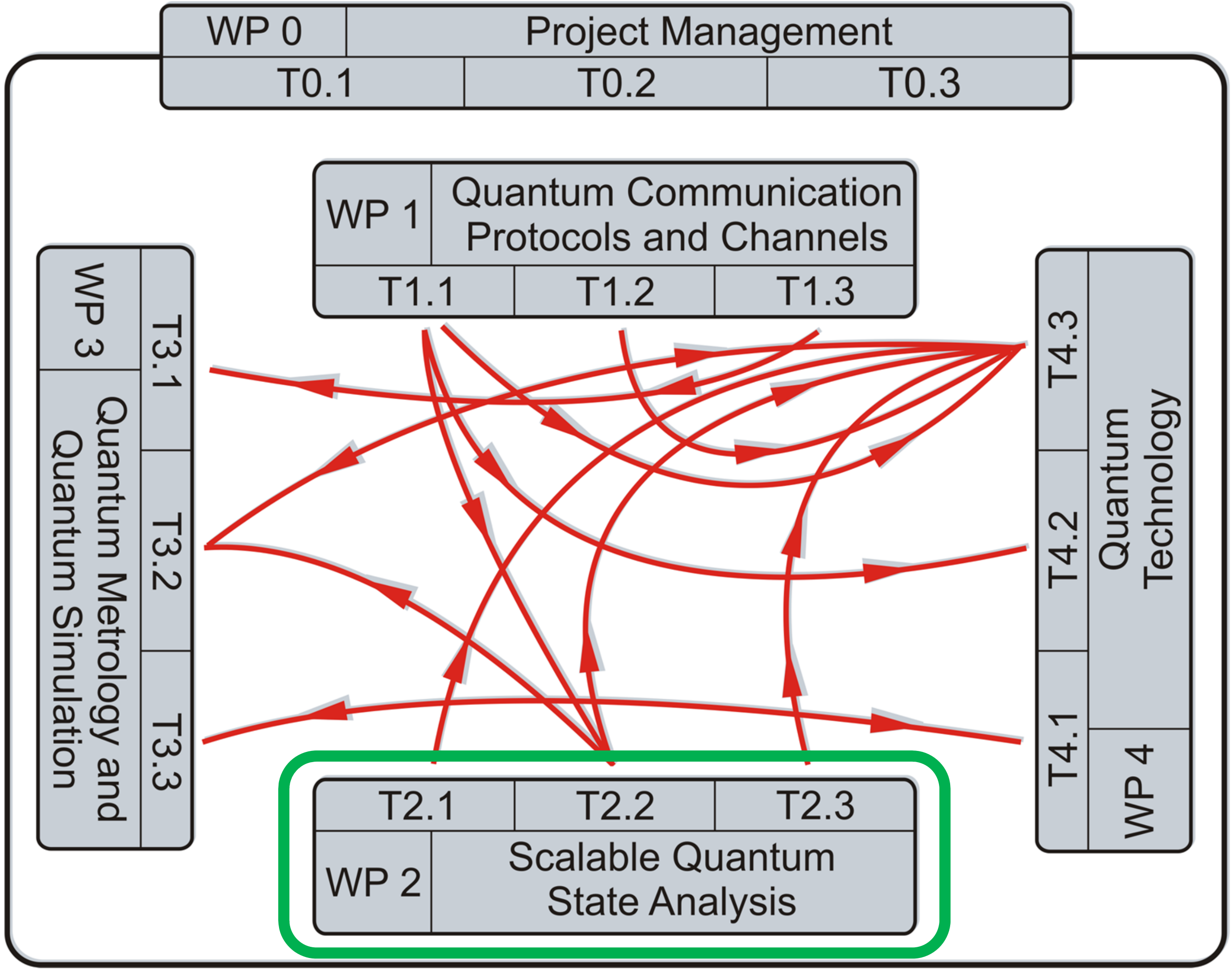
QUASAR

study fundamental features
→ design new quantum communication protocols and channels (LMU, UG, USI)

- Bell- and Kochen Spekker inequalities
  ⇔ information processing (protocols/speed up)
- quantum channels (states/decoherence)

# WP2 Scalable Quantum State Analysis

QUASAR



efficient, scalable tools for state tomography
for determination of the applicability of quantum states in specific tasks
(USI, UWAW, BILB, GD, LMU, UNIROMA1)

- scalable quantum state tomography
- application-based witness
- optimize witness for large statistical significance

- efficient state analysis n-qubits

  - state is element of subspace
    - subspace dimension O(poly(n))

      MPS, permutationally invariant states

    → tomography in subspace with effort O(poly(n))

M. Cramer et al., Nat. Commun., **1** 149, (2010)
G. Toth, et al, PRL **105**, 250403 (2010)

  - low rank states
    - compressed sensing

      low rank states r

    → tomography with effort $r*2^n$

- properties of PI-operators
  - can be decomposed into $\mathcal{L}_N$ local measurements

$$\mathcal{O} = \sum_j c_j A_j^{\otimes N} \qquad \mathcal{L}_N = \tfrac{2}{3}N^3 + N^2 + \tfrac{4}{3}N$$

  - density matrix is sum of correlation tensor elements

$$(X^{\otimes k} \otimes Y^{\otimes l} \otimes Z^{\otimes m} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}}$$

  - can be evaluated using

$$\langle (X^{\otimes k} \otimes Y^{\otimes l} \otimes Z^{\otimes m} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}} \rangle = \sum_{j=1}^{\mathcal{D}_N} c_j^{(k,l,m)} \langle (A_j^{\otimes(N-n)} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}} \rangle$$

with only $\mathcal{D}_N = \binom{N+2}{N} = \frac{1}{2}(N^2 + 3N + 2)$ settings!

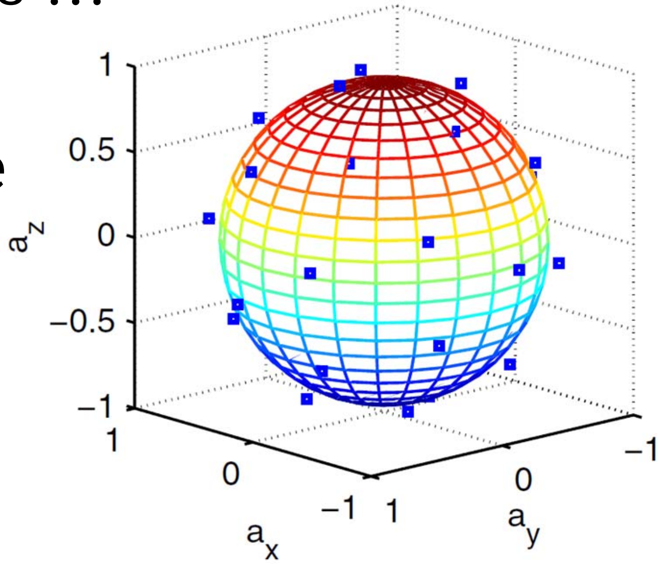
G. Toth, et al, PRL **105**, 250403 (2010)

# PI-tomography

QUASAR

possible states: GHZ, W, Dicke, Singlets,
decoherence free states …

- test, whether state is close to PI-state
  → measure $X^{\otimes 4}$, $Y^{\otimes 4}$, and $Z^{\otimes 4}$



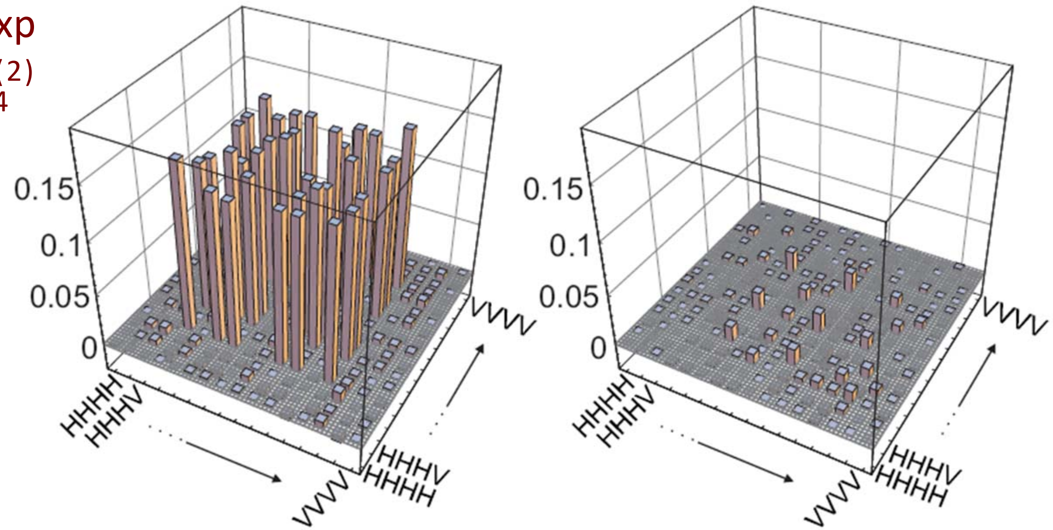

- choose set of $A_j$ and $c_j$,
  optimize, e.g., for minimum variance

- need only $\mathcal{D}_N = \binom{N+2}{N} = \frac{1}{2}(N^2 + 3N + 2)$ settings!

# PI-tomography

QUASAR

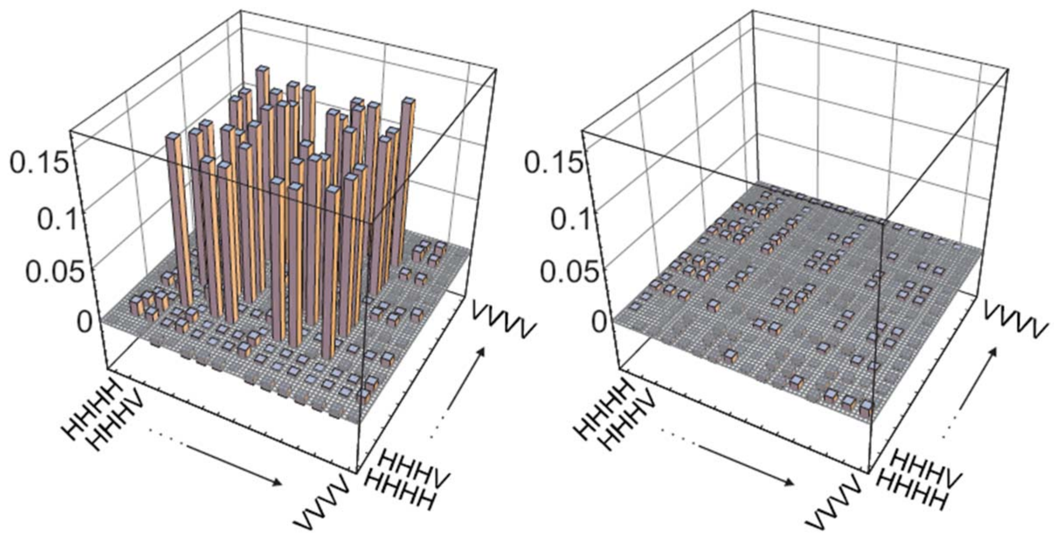
$\rho^{exp}_{D_4^{(2)}}$




81 settings

$F_{D_4^{(2)}} = 0.873 \pm 0.005$

$\rho^{exp}_{PI}$




15 settings

$F_{D_4^{(2)}} = 0.852 \pm 0.009$

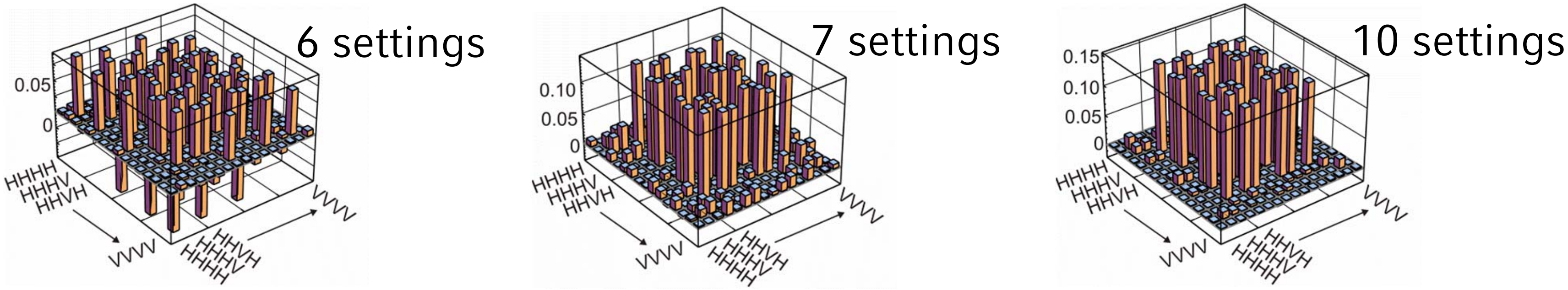
$F\left(\rho^{exp}_{full}, \rho^{exp}_{PI}\right) = 0.947 \ \ (\text{max.}\,0.964)$

G. Toth, et al, PRL **105**, 250403 (2010)

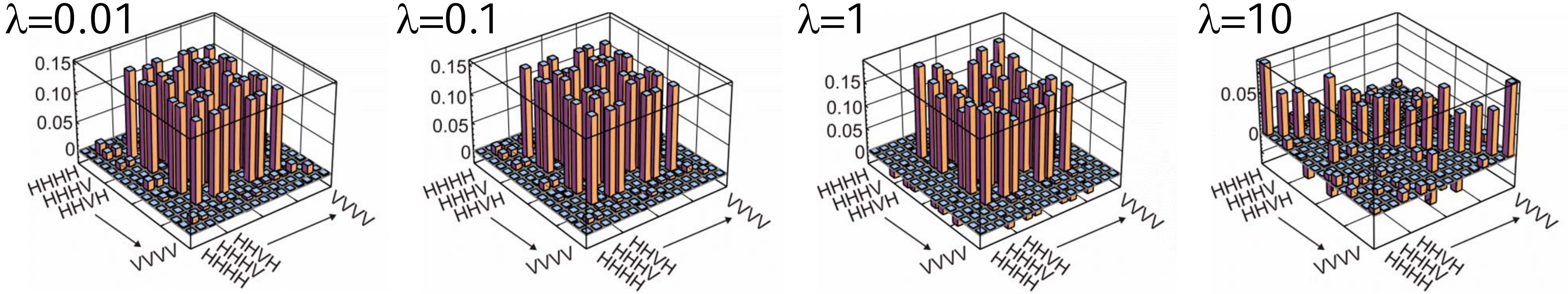
## PI + CS

QUASAR

- approximation in respective subspace (noise?)
- CS: sensitivity to no. of settings and fitting parameters




L1 regularisation: $min\left(\sum_k \left(Tr\left(\rho_{guess}P_k\right) - f_k\right)^2 - \lambda Tr\left(\rho_{guess}\right)\right)$

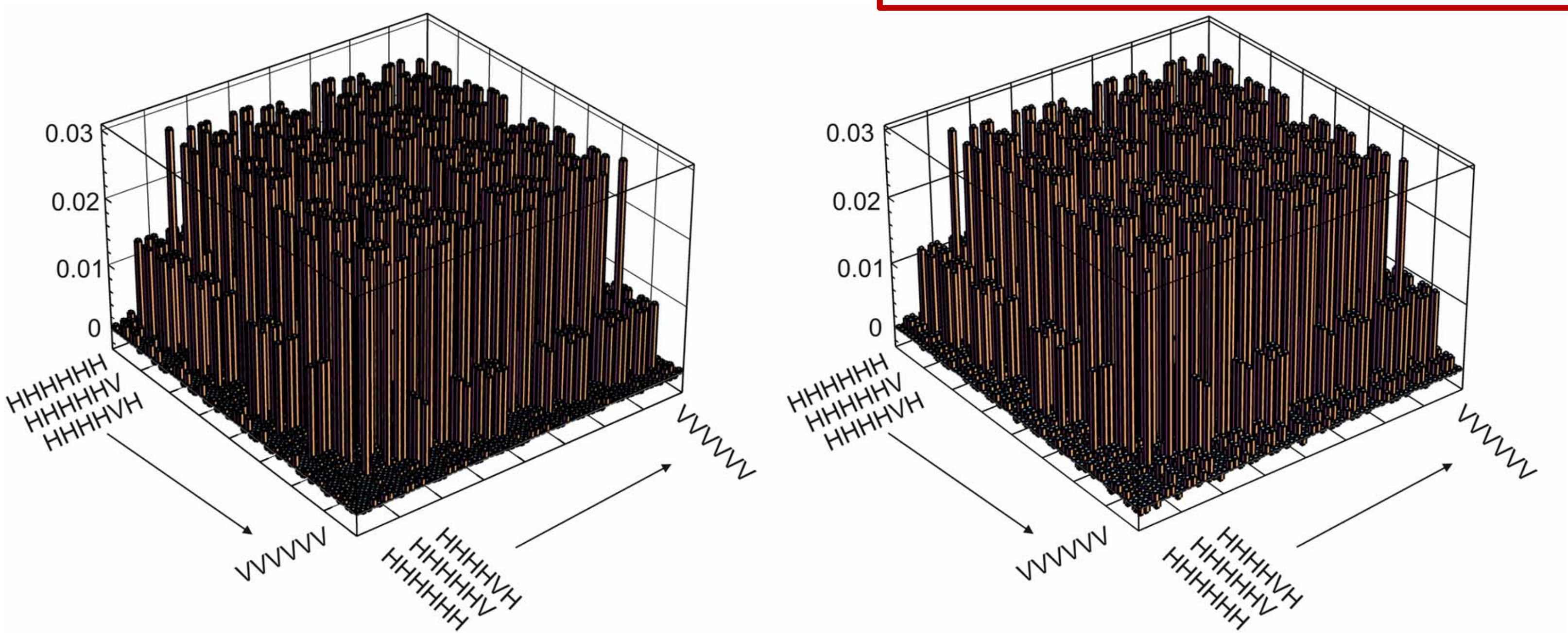



- combine PI + CS
  2 settings for 4 qubit state !?!

- six-qubit tomography $D_6^{(3)}$

  with 28 (instead of 729) settings

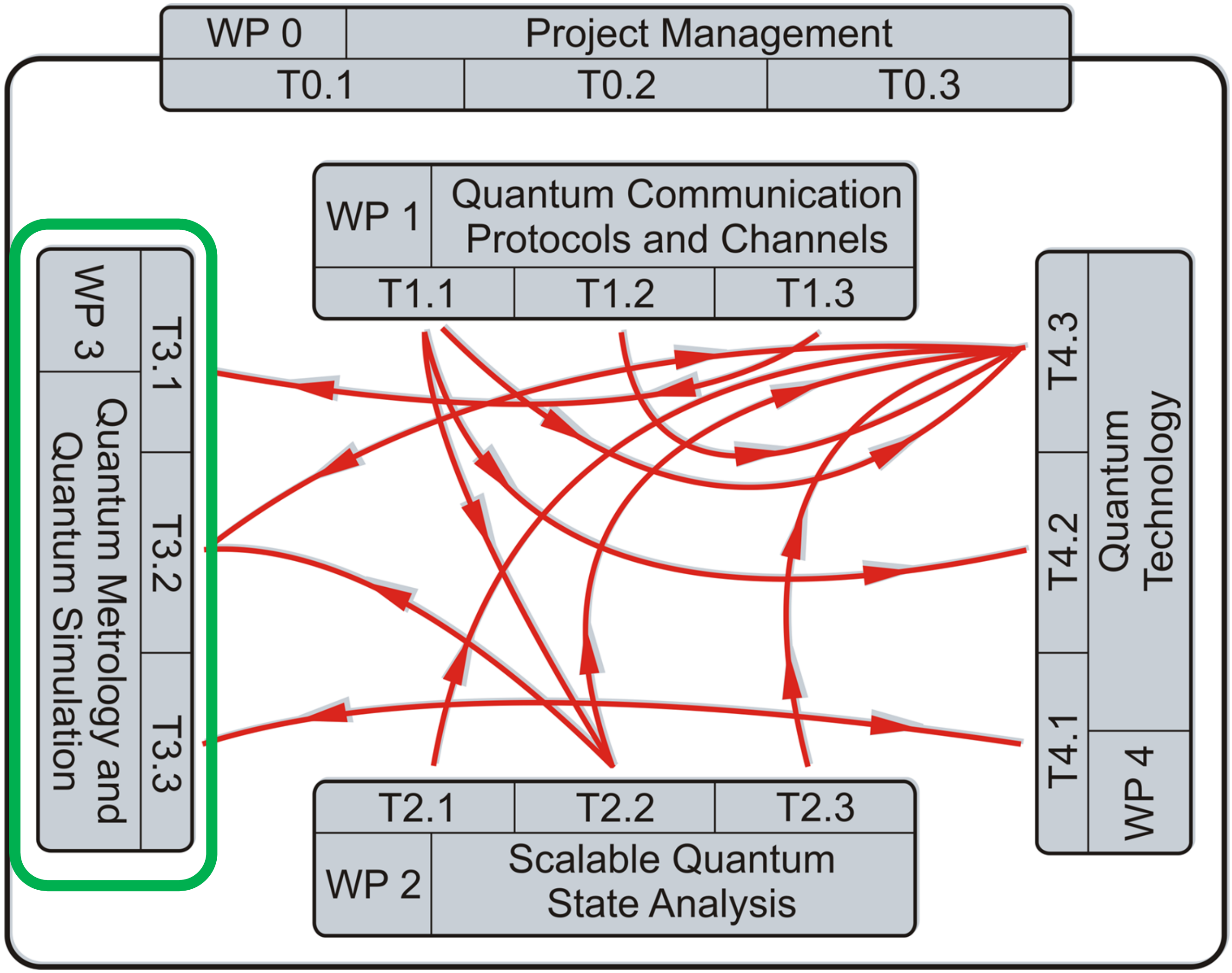
PI+CS: only $X^{\otimes 6}$, $Y^{\otimes 6}$, and $Z^{\otimes 6}$,




$$\rho_{meas} = p\,\rho_{D_6^{(3)}} + (1-p)\left[\tfrac{4}{7}\rho_{D_6^{(3)}} + \tfrac{3}{14}\left(\rho_{D_6^{(2)}} + \rho_{D_6^{(4)}}\right)\right]$$

# WP3 QU Metrology and Simulation

QUASAR

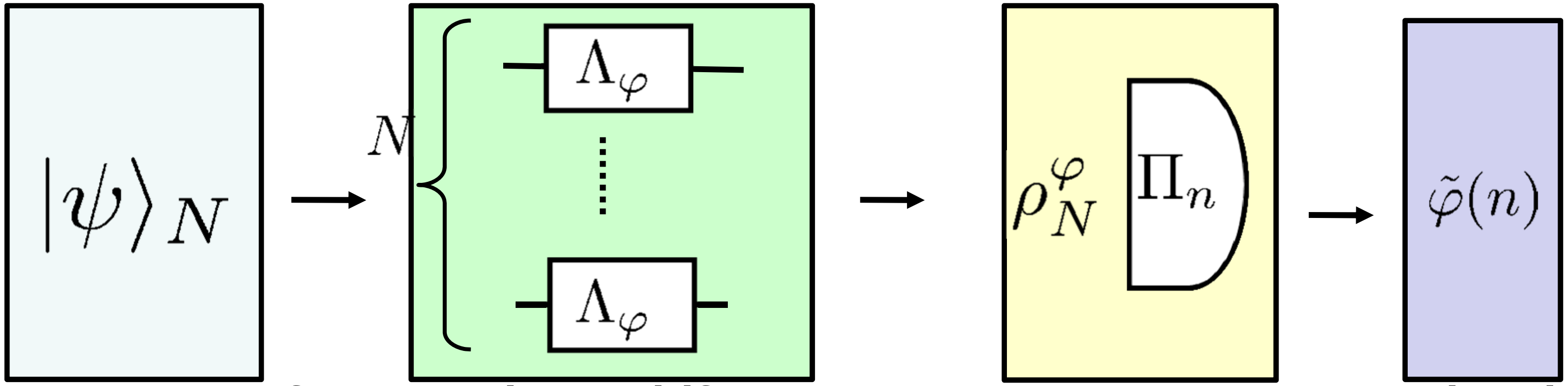


develop new methods for quantum metrology and quantum simulation

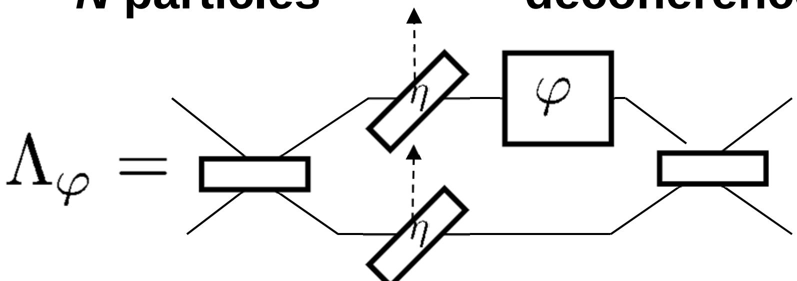
(UWAW, BILB, USI, OEAW, UNIROMA1)

- Fundamental bounds on quantum precision enhancement due to decoherence
- Reconfigurable detection schemes and the role of feedback in quantum parameter estimation
- quantum logic networks for efficient simulation

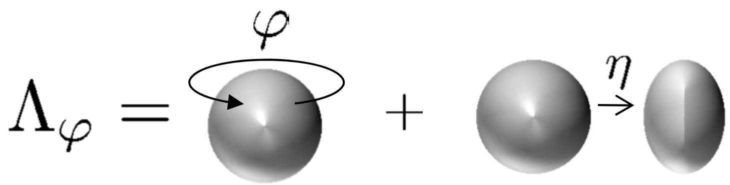
- Fundamental bounds on quantum enhancement




**Input state of *N* particles** | **phase shift + decoherence** | **measurement** | **estimation**



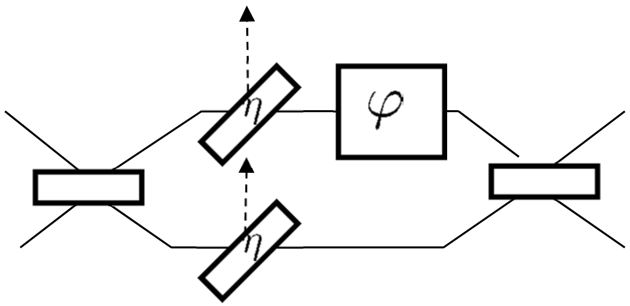

**Interferometer with losses (gravitational wave detectors)**



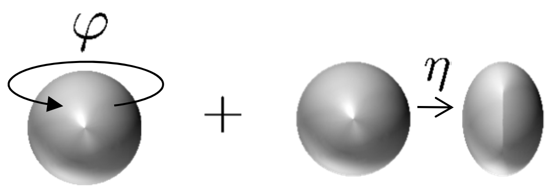

**Qubit rotation + dephasing (atomic clock frequency callibrations)**

- Decoherence destroys Heisenberg scaling $\Delta\tilde{\varphi} \approx \frac{1}{N}$

→ In presence of decoherence:

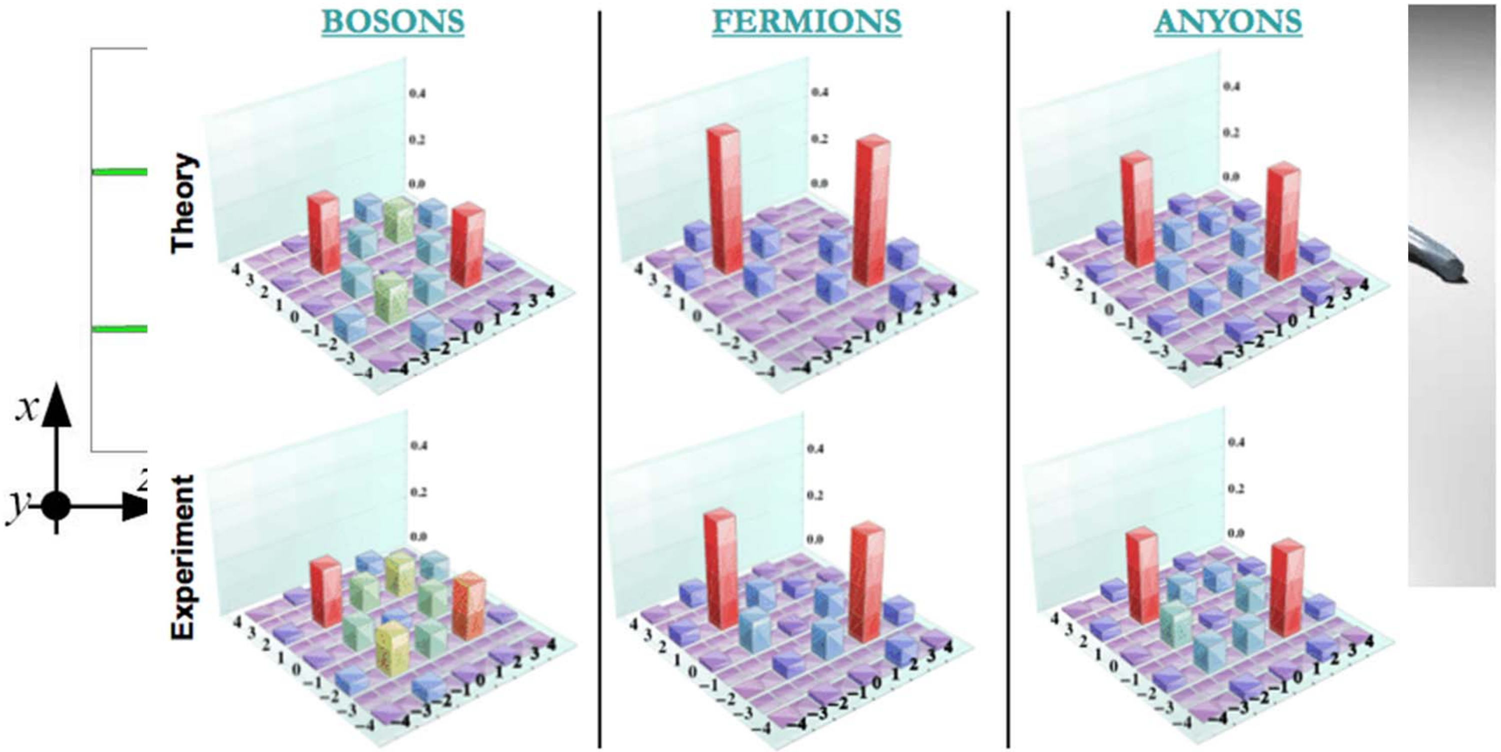



$$\Delta\tilde{\varphi} \geq \sqrt{\frac{1-\eta}{\eta}}\frac{1}{\sqrt{N}}$$



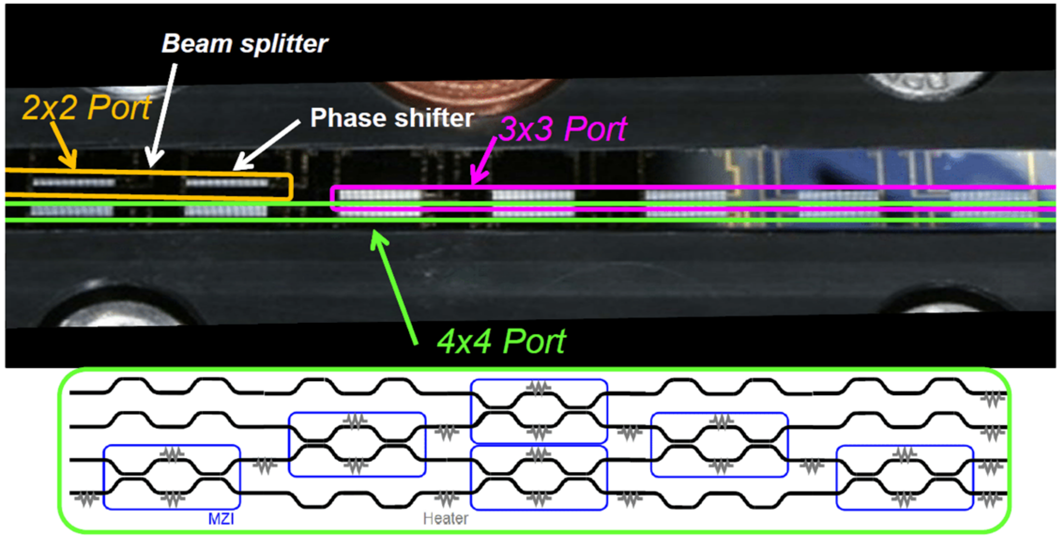

$$\Delta\tilde{\varphi} \geq \frac{\sqrt{1-\eta^2}}{\eta}\frac{1}{\sqrt{N}}$$

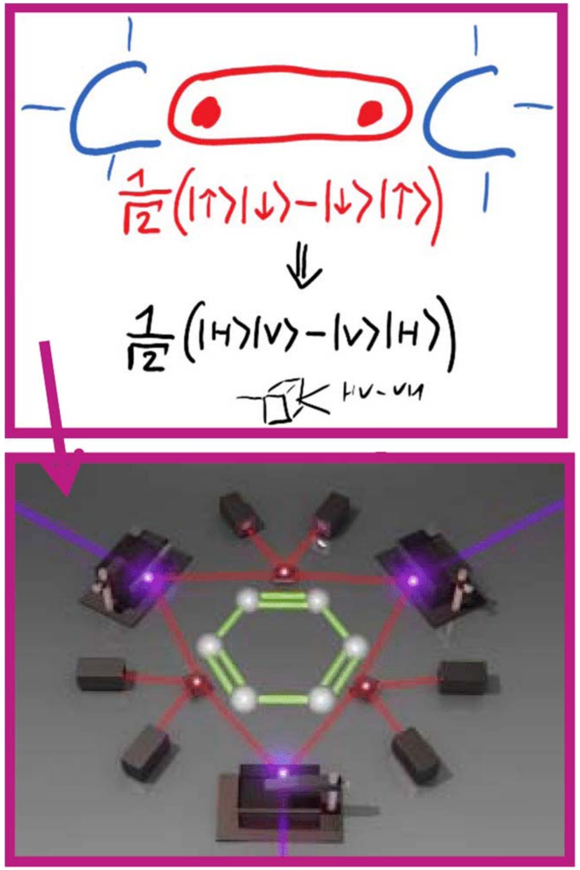
- Quantum simulation
  - bosonic – fermionic evolution with random walk in 3D-waveguides



QUASAR

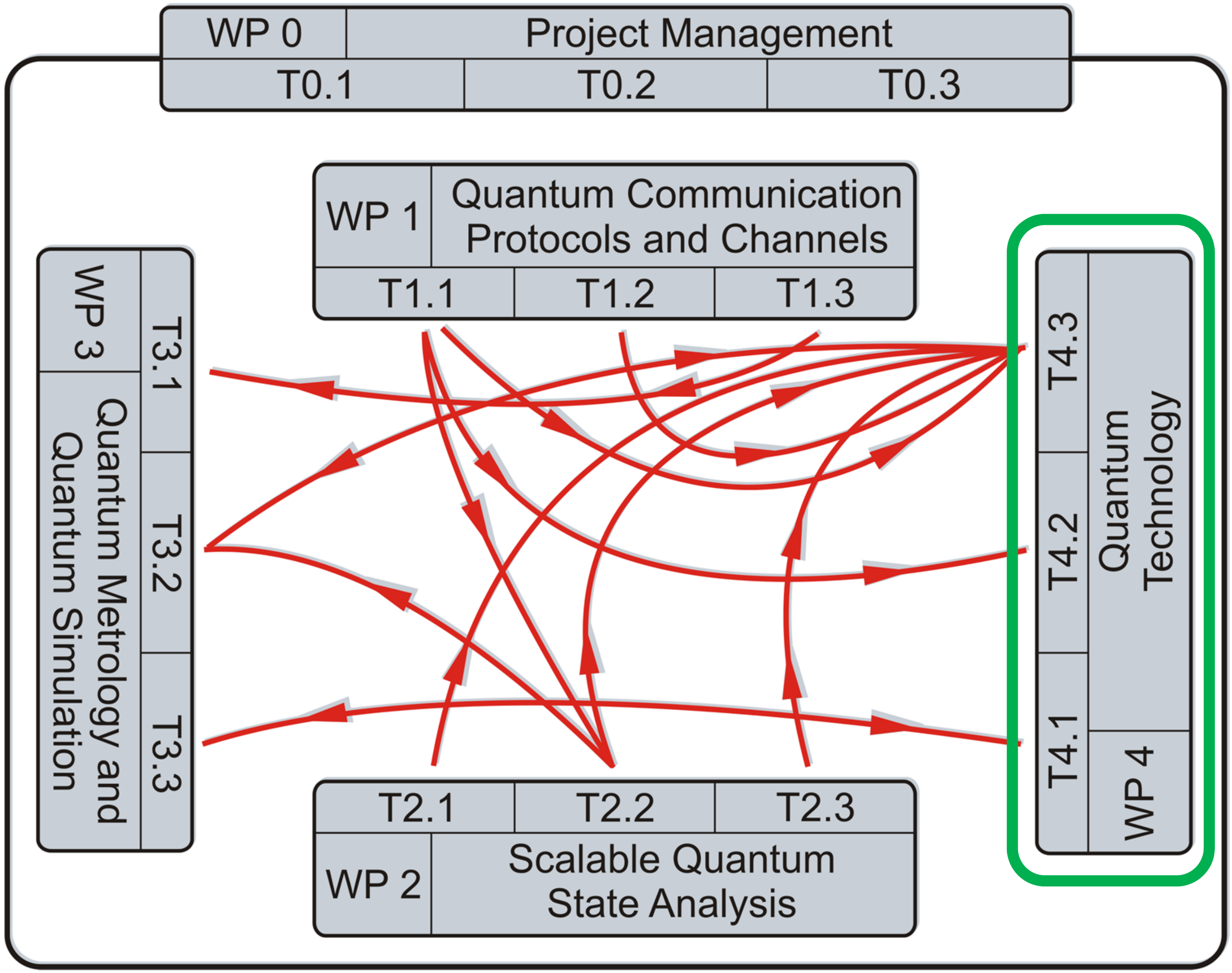
- Quantum simulation
  - quantum chemistry
  - photonic valence bond states



# WP4 Quantum Technology

QUASAR



# WP4 Quantum Technology

QUASAR

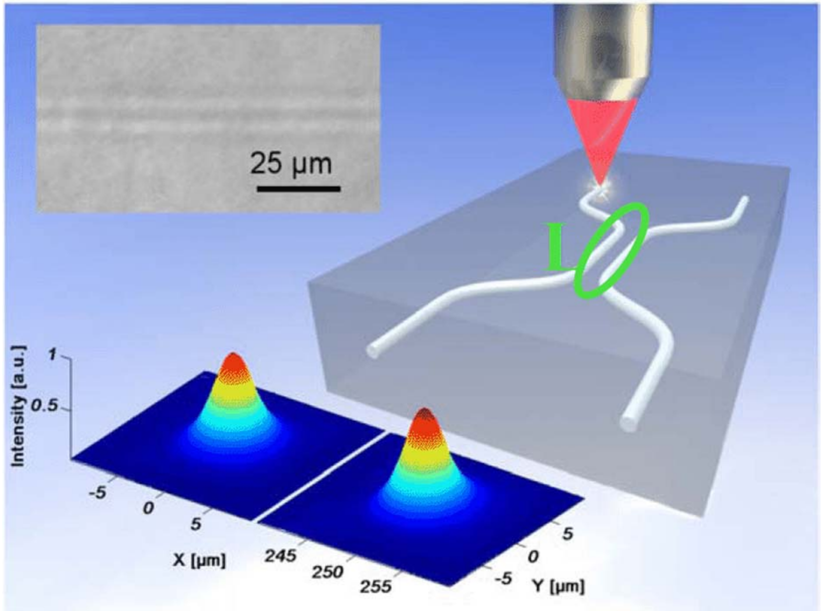
develop new technologies

micro- waveguide- adaptic optics

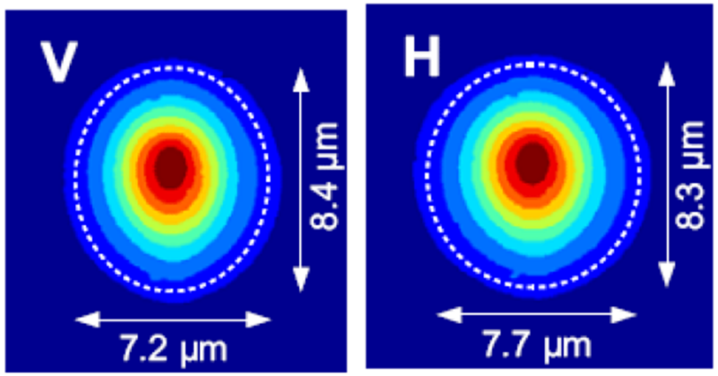
(UNIROMA1, UWAW, OEAW, LMU, OPTOTEC)

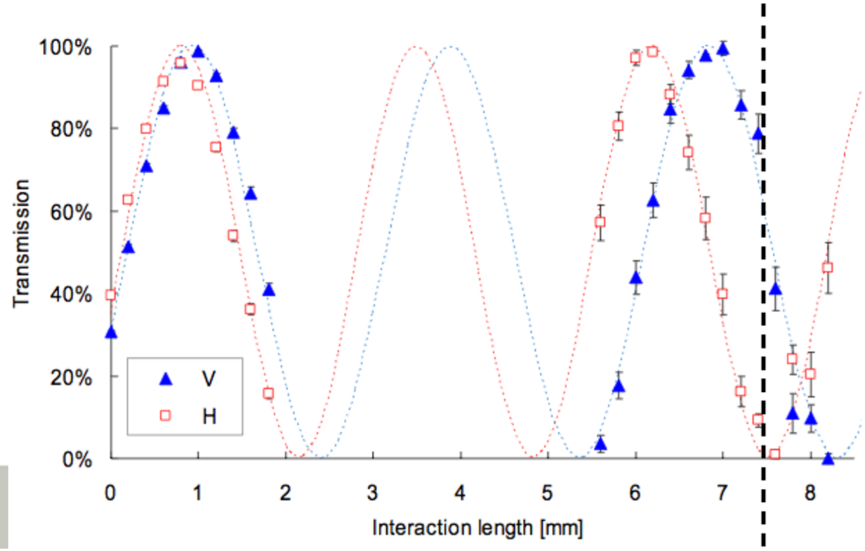
- integrated quantum optics
- adaptive optics for long-distance quantum communication to moving observers

- wave guides by fs-laser writing



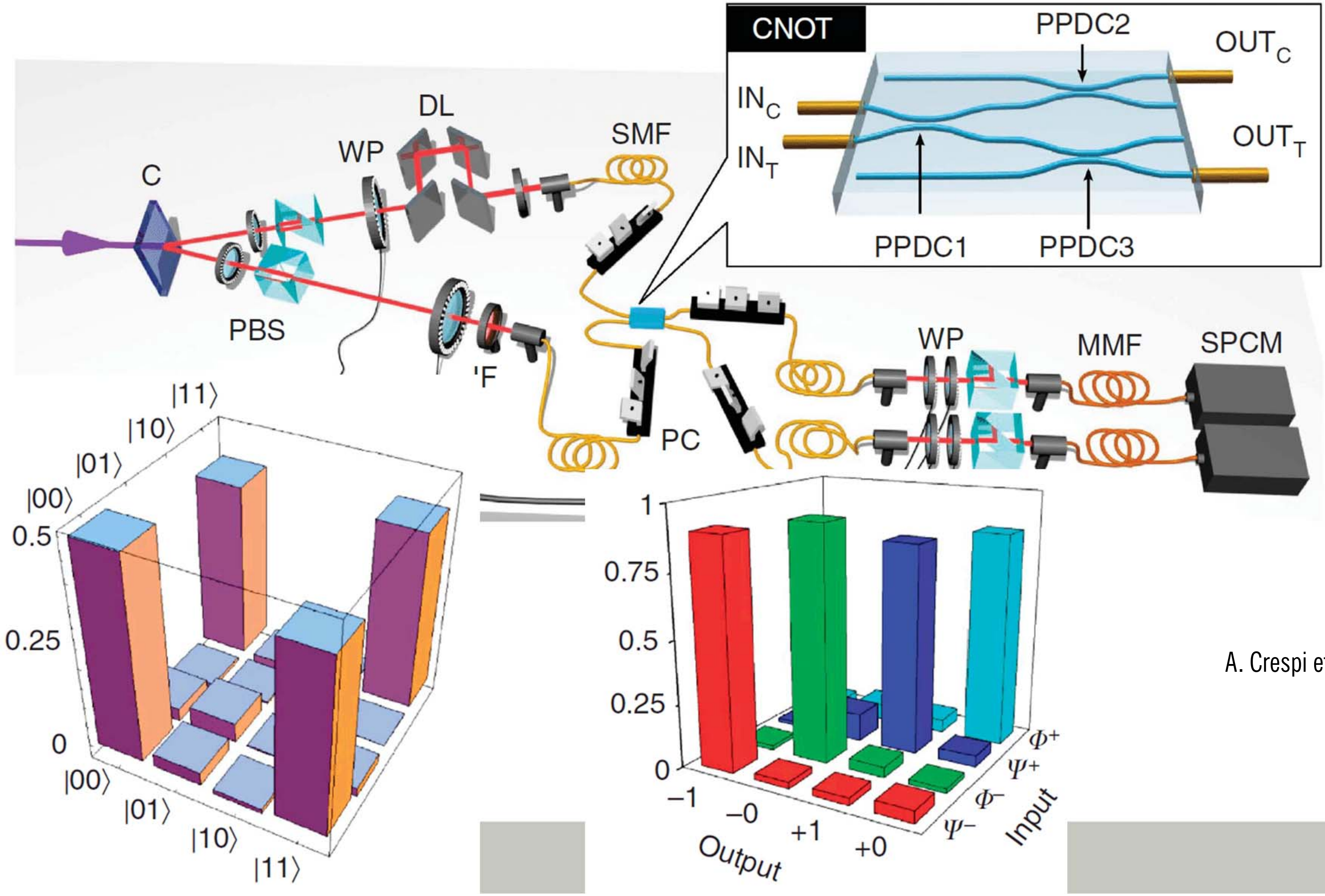

polarisation anisotropy



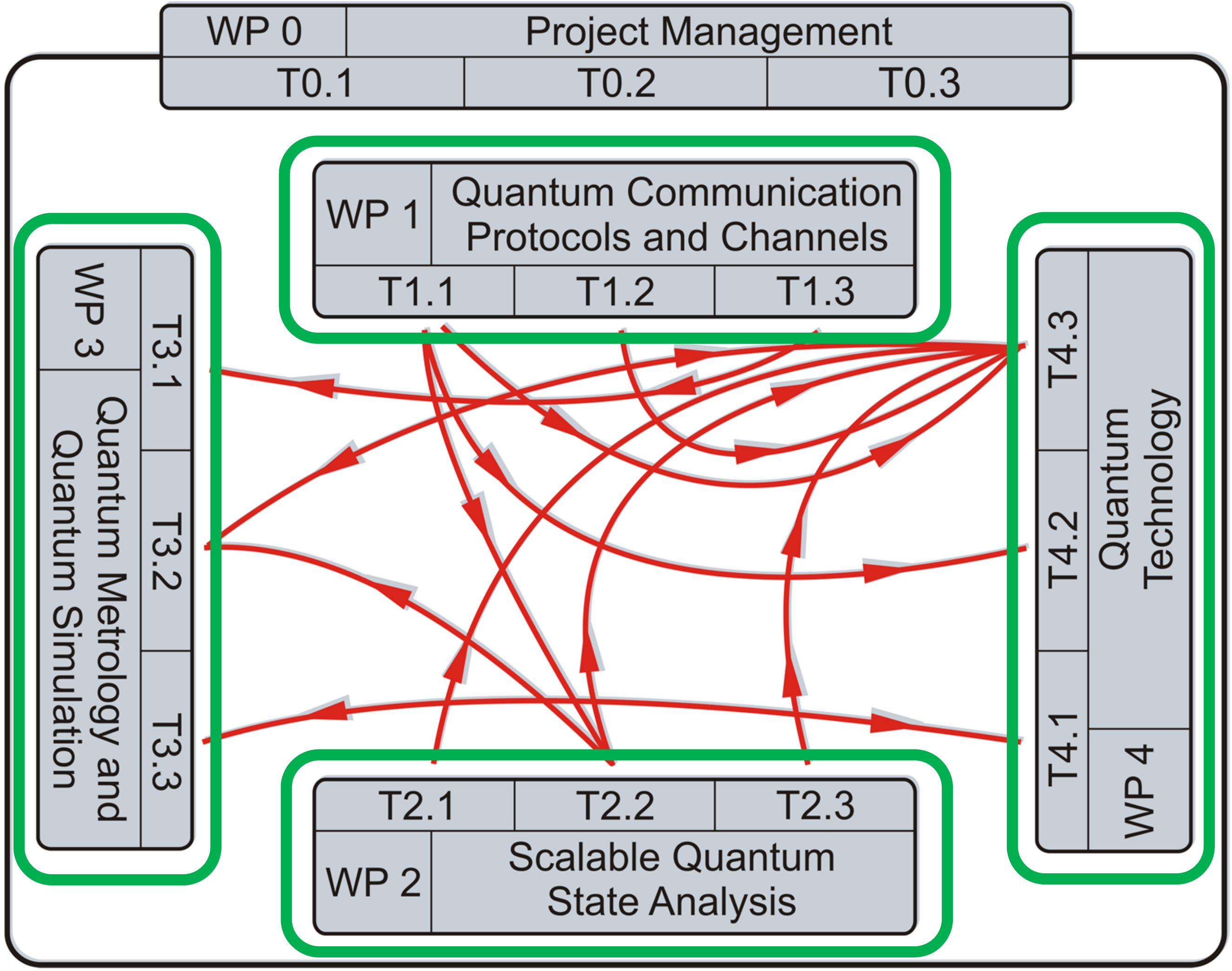

polarisation components!

- waveguide structure for quantum logic




A. Crespi et al., Nature Comm. 2, 556 (2011)

QUASAR


WP 0
Project Management
T0.1
T0.2
T0.3
WP 1
Quantum Communication Protocols and Channels
T1.1
T1.2
T1.3
WP 3
Quantum Metrology and Quantum Simulation
T3.1
T3.2
T3.3
WP 4
Quantum Technology
T4.3
T4.2
T4.1
T2.1
T2.2
T2.3
WP 2
Scalable Quantum State Analysis