Call 2021

Mid-term Evaluation

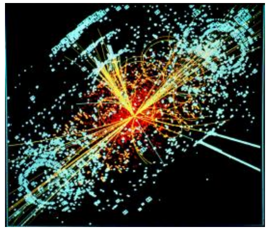
SQUEIS

SQUeezing-Enhanced Inertial Sensing

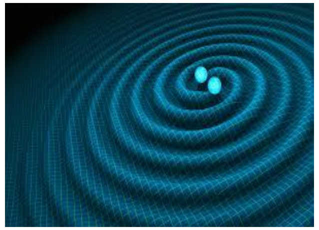
Luca Pezzè (coordinator)

COLLABORATION

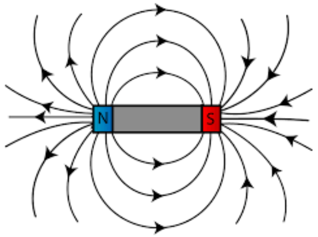
Atomic interferometry is a key technology in a broad range of application



tests of fundamental physics

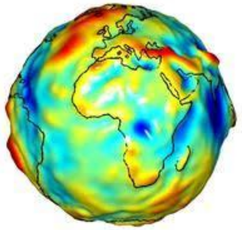


gravity-wave detection



magnetometry

underground composition



geophysics

engineering

navigation

SQUEIS wants to increae the sensitivity of inertial sensors based on atom interferometers (gravimeters, gradiometers, etc…) by developing protocols that exploit quantum correlations to overcome the standard quantum limit

COLLABORATION

Country	Institute	Principal investigator
Italy	CNR	L. Pezzè
Italy	INFN	G. Tino
Germany	LUH	N. Gaaloul
France	SYRTE	F. Pereira dos Santos
Poland	UV	J Chwedeńczuk

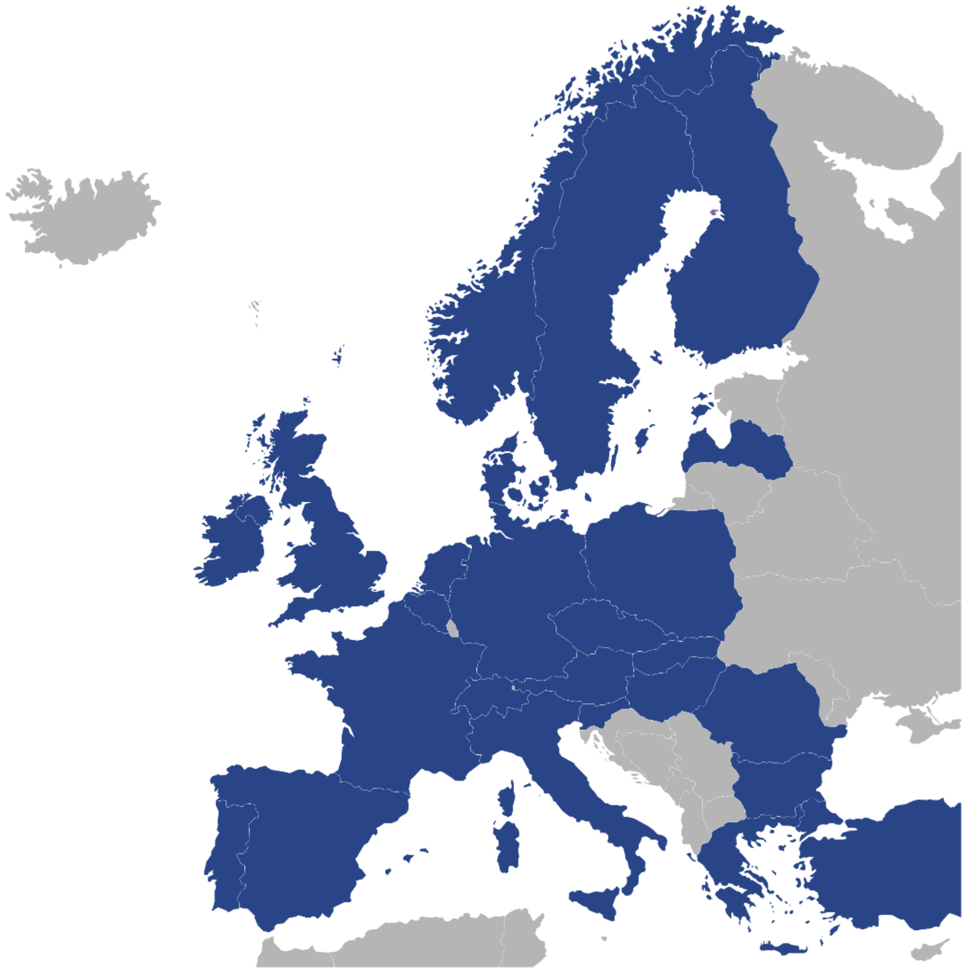
CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

INFN Istituto Nazionale di Fisica Nucleare

l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace

Leibniz Universität Hannover

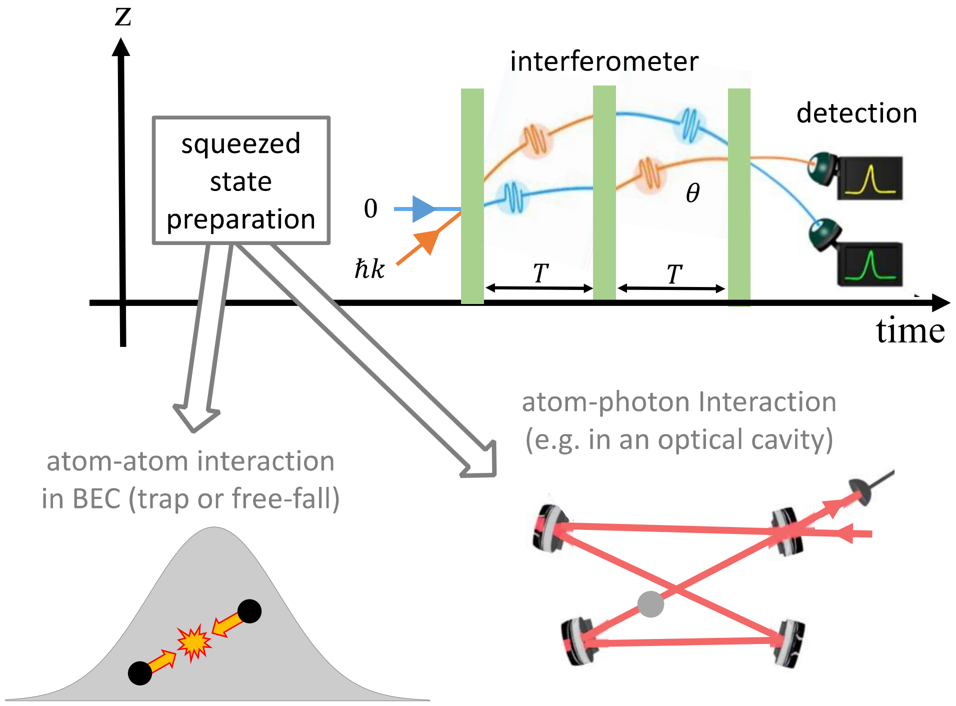
UNIVERSITY OF WARSAW



PROJECT PROGRESS

CHALLENGE:

The stringent constraints required for inertial sensing pose a very strong challenge when **incorporating quantum entanglement into high precision atom interferometers**, preserving both the entanglement and the high precision of the measurement device.



1) **Squeezed states engineering**
2) **Advanced detection schemes**
3) **Metrology using squeezed states**
4) **Squeezing-enhanced inertial sensing**

PROJECT PROGRESS

SOLUTION:

Exploration of different atomic platforms: free-fall and compact trapped sensors directly relevant to applications

Innovative squeezed-state generation methods: tunable atom-atom interaction in quantum gases, as well as non- demolition measurements via the coupling of atoms and light.

Advanced detection and control techniques: number counting measurements, control of interaction, manipulation of the wavepacket

synergy between experimental and theoretical experts in a consortium characterized by well-integrated collaborations

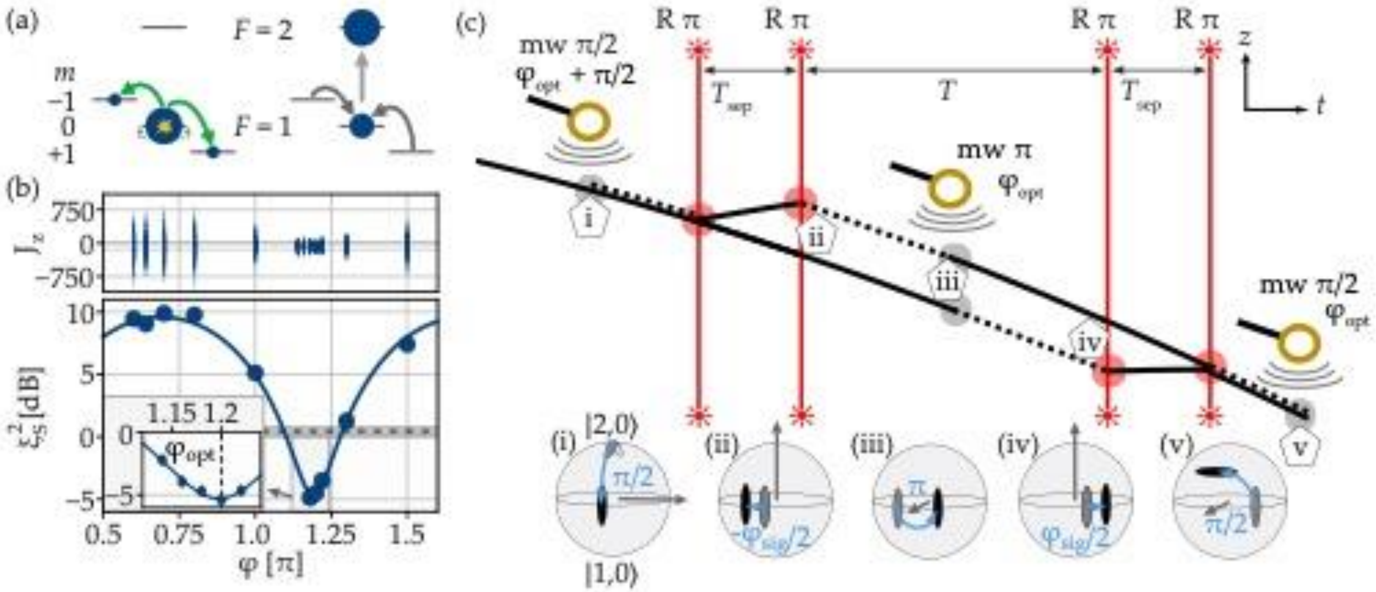
PROJECT PROGRESS

IMPLEMENTATION:

First realization of proof-of-principle squeezing-enhanced atomic gravimeter (LUH)

- Creation of spin squeezed state in ^{87}Rb-BEC via spin changing collisions
- Combined mw and Raman pulses for gravimeter sequence: transfer of squeezing from internal to external degrees of freedom
- First reported value for gravimetry below the SQL $\xi^2 = -1.7^{+0.4}_{-0.5}$ dB

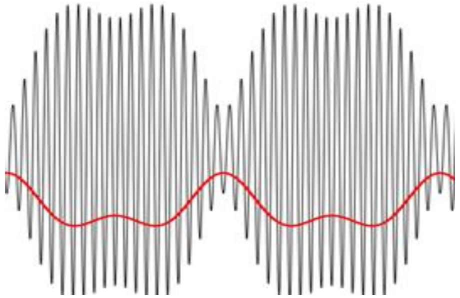
Cassens et al. arXiv:2404.18668



PROJECT PROGRESS

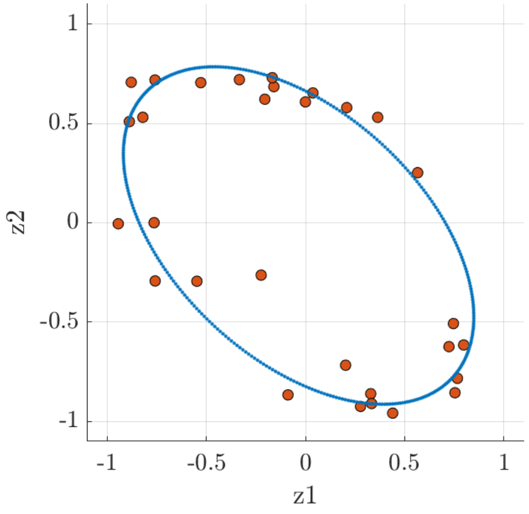
IMPLEMENTATION:

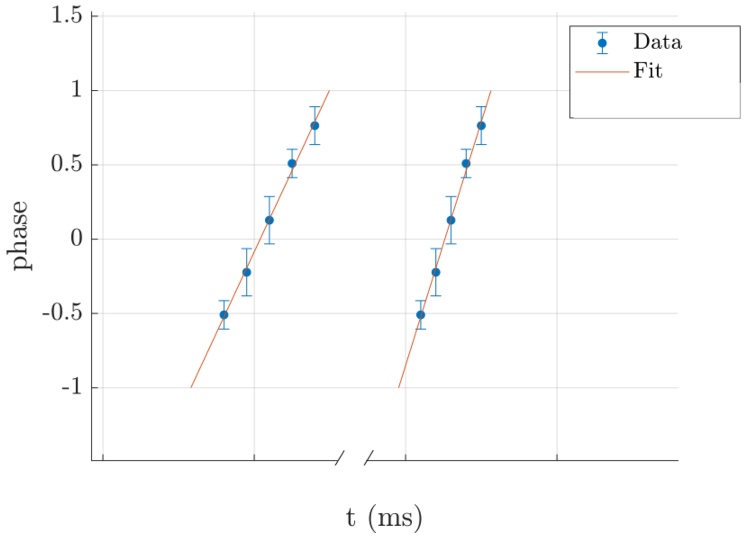
First realization of a trapped BEC gradiometer that benefits from noise rejection (CNR)



- two trapped interferometers (closed interferometer sequence) realized with a novel supert-lattice potential
- tunable scattering length (^{39}K atoms)
- novel beam splitting technique obtained tuning the potential barrrier

Petrucciani et al.
in preparation



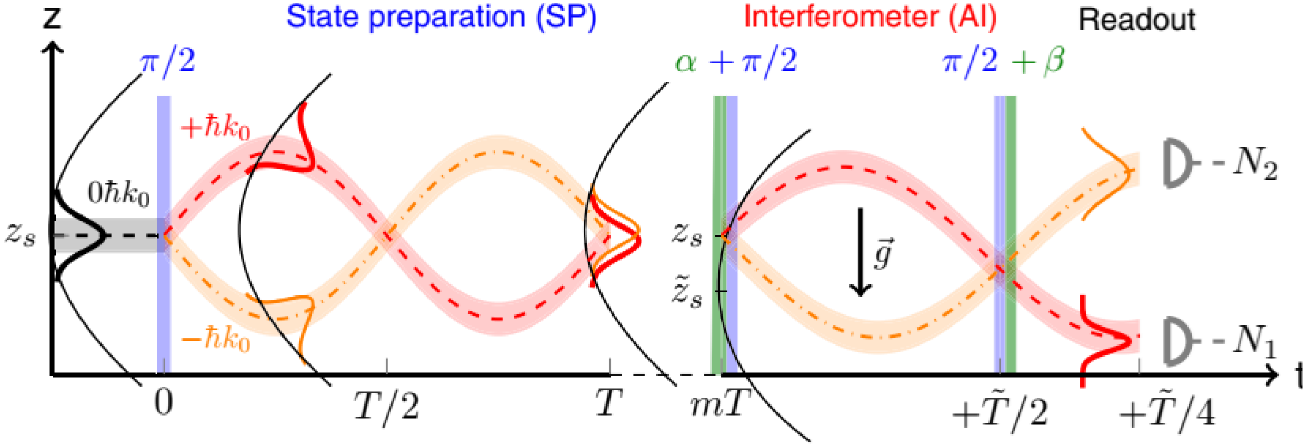


PROJECT PROGRESS

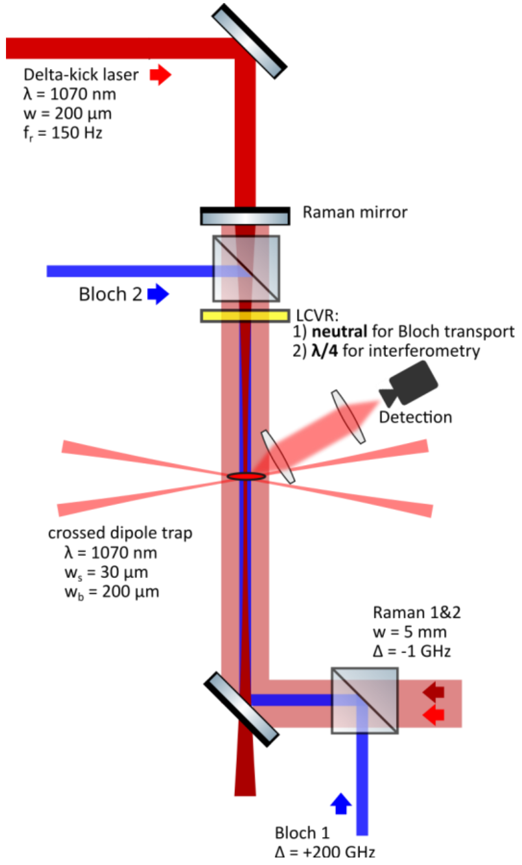
IMPLEMENTATION:

Progresses toward the realization of delta-kick squeezing (SYRTE and LUH)

(generate squeezing by controlling the density of a BEC wavepacket)



Corgier et al. PRL 2021



- LUH: operations with cancelling of interaction in a K BEC
- SYRTE: successsful Rb BEC, Bloch transport, new laser systems, demosntration of “focusing-lens” operations with a thermal cloud

PROJECT PROGRESS

IMPLEMENTATION:

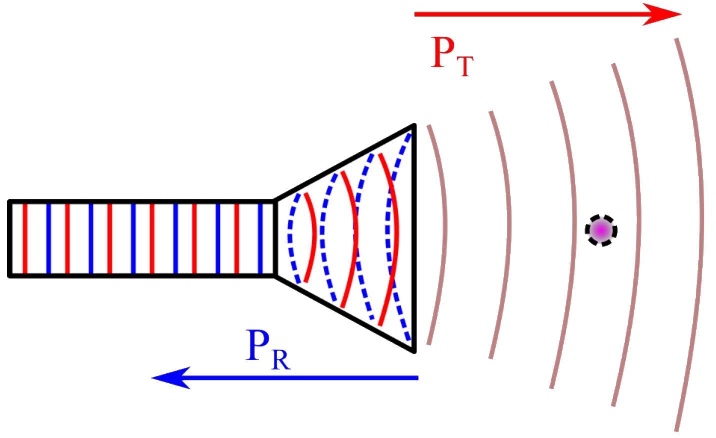
Implementation of ultra-precise measurement techniques

- Realization of number counting at the single-atom resolution (LUH-CNR) up to ~100 atoms: quantum tomography of the detector

  Hetzel et al. PRL 2023

- Realization of fluorescence imaging with detection noise of 20 atoms (SYRTE) for the detection of large atom numbers: this will allow the reduction of phase variance by 5 dB for 10^3 atoms and 15 dB for 10^4 atoms

- Experimental progress toward the implementation of non-destructive microwave detection methods from reflected mw signal to be used for detection and squeezed state engineering (SYRTE)



PROJECT PROGRESS

IMPLEMENTATION:

Theoretical studies stimulated by the experimental activity within the project

- Study of josephson dynamics in super-lattices (CNR-UW) and optimal wave-function control for the implementation of delta-kick squeezing (LUH-SYRTE)
- Impact and optimization of momentum width of Bragg pulses for metrological enhancement (LUH-CNR-SYRTE)

  Günter et al. arXiv:2409.4091
- Multiparameter estimation applied to inertial sensing with squeezed states (CNR)

  Corgier et al. QUANTUM 2023; Pezzè and Smerzi arXiv:2405.18404
- Optimal generation of spin-squeezing and Bell correlations in a double-well potentials (UW)

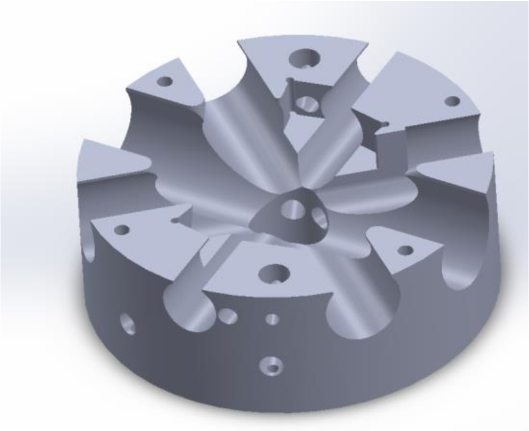
  Płodzień et al. PRL 2022; Sharma et al. arXiv:2406.14461
- Improved accuracy and precision in squeezing-enhanced differential measurements (SYRTE-CNR-INFN)

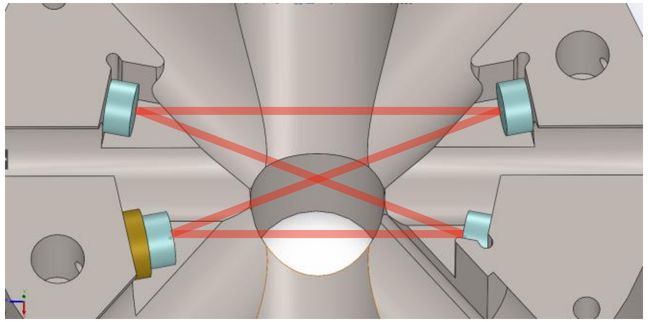
  Corgier et al. *in preparation*

PROJECT PROGRESS

HURDLES:

- Vibrational noise and difficulties in stabilization prevented the realization of cavity squeezing (INFN): a new monolitic cavity - with high rigidity, high thermal control and low thermal expansion – has been designed and is ready to be implemented.





- General delay in some of experiment activity due to hiring delay, technical difficulties (heating), uncontrolled sources of noise, etc. (LUH, CNR, SYRTE)

PROJECT PROGRESS

CROSS FERTILIZATION:

- Theoretical studied on Josephson dynamics in novel trapped systems: supersolids and ring Fermi superfluids

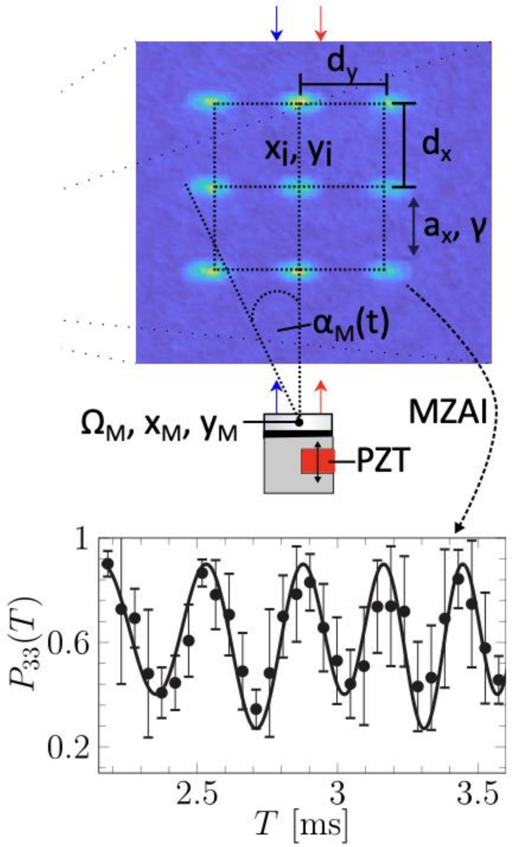
  Biagioni et al. NATURE 2024; Pezzè et al. NAT COMM 2024

- Realization of a multi axis multi-axis inertial sensor with 2D arrays of Bose Einstein condensates: 9 coupled interferometers operating in parallel

  K. Stolzenberg, et al. arXiv:2403.08762 (2024)

- Realization of a free-fall gradiometer operated on blue transitions around 420 nm (convenient cancellation of systematic effects) close to the shot noise sensitivity (INFN).

  Salvi et al. PRL 2023



IMPACT

SCIENCE EDUCATION:

9 fellowships/contracts have been created within SQUEIS:

- 2 are female (22%)
- 2 are from widening countries (Poland, Albania) (22%)

OPEN SCIENCE:

22 research papers acknowledge SQUEIS so far:
1 Nature; 1 Nature Communications; 4 PRL; 1 Quantum; 4 PRA/PRR
11 submitted manuscripts

all publications and preprints are available as open source (arXiv)

PUBLIC ENGAGEMENT:

more than 50 public presentations acknowledge SQUEIS
(national/international conferences; workshops; seminars)

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 101017733