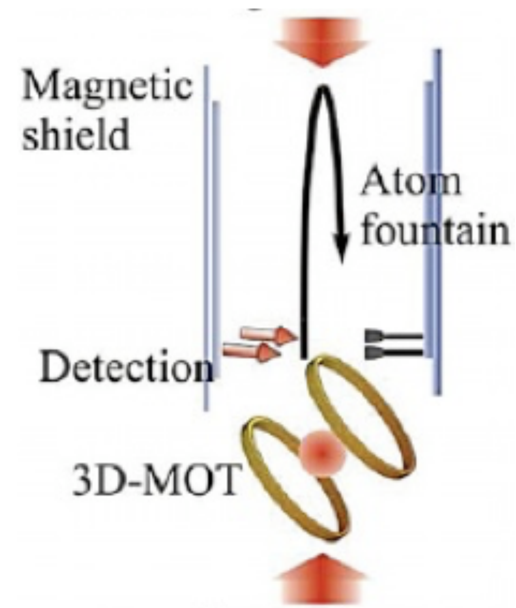
Optical Links for Atomic Gravity Sensors (OLAGS)

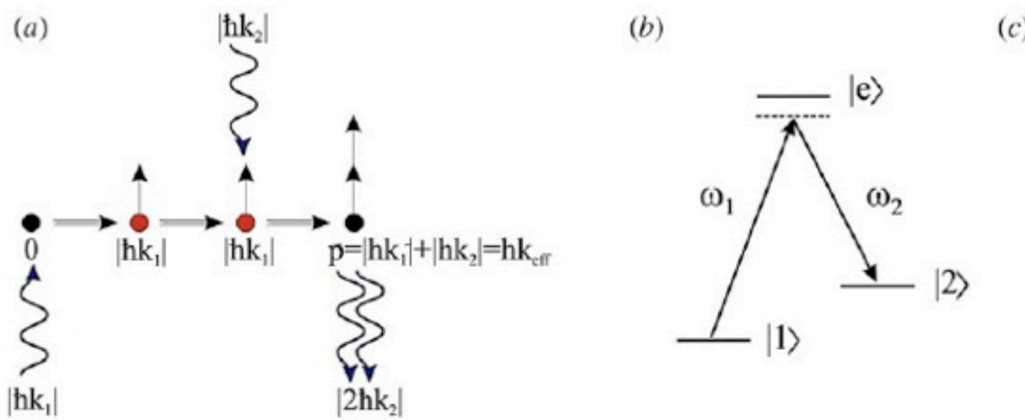
A new INFN-CSN5 experiment

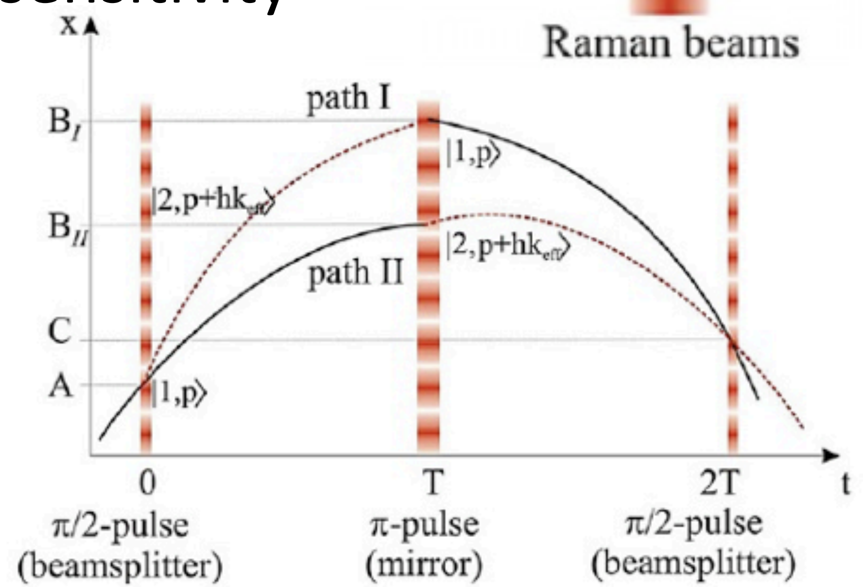
F. Sorrentino

Atomic gravity sensors

- Based on atom interferometry: laser cooling + coherent manipulation of atomic wavepackets
- Nowadays the best absolute gravimeters: demonstrated sensitivity of the order of 10 μgal/√Hz, accuracy ~1 μgal (1 μgal=10^{-8} m/s^2)
- Seismic noise is among the main sensitivity limitations

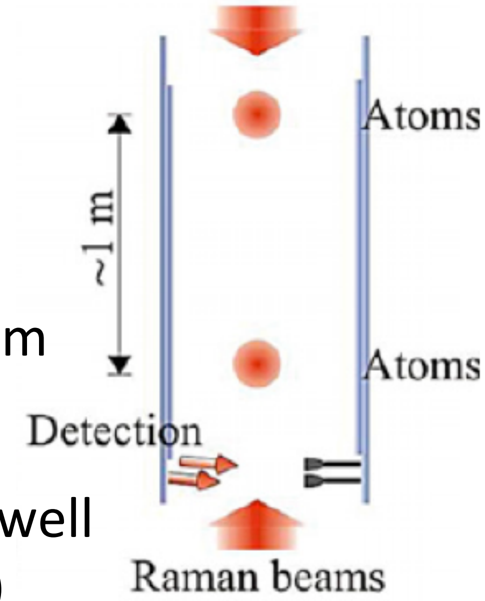


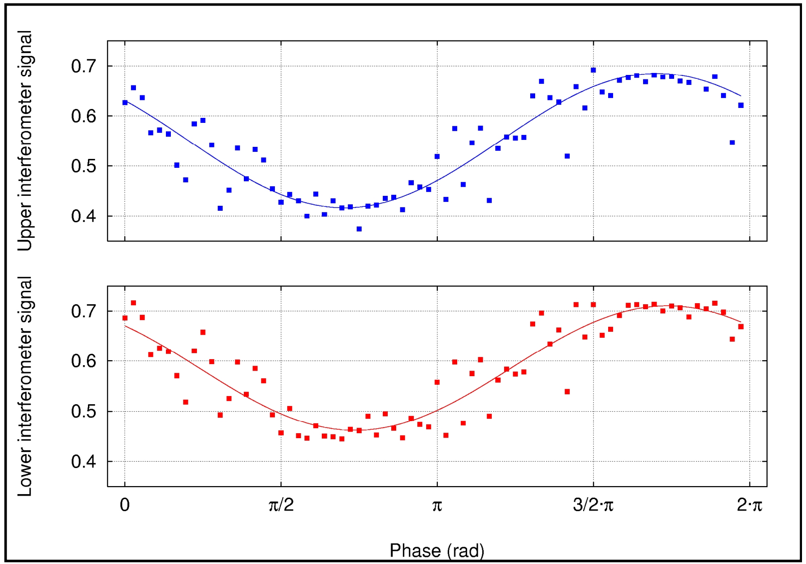


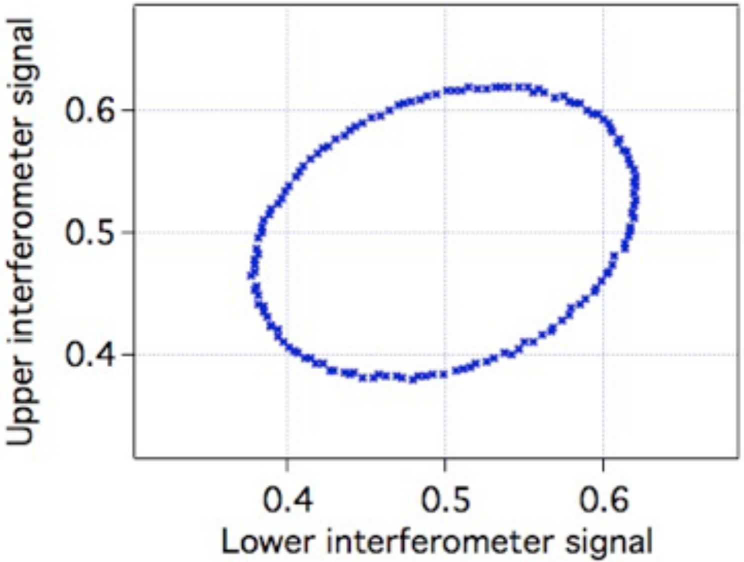


Gravity gradiometers

- Two vertically separated atomic samples
- Same interrogating laser field for atomic wavepacket manipulation
- More than 140 CMRR to seismic noise demonstrated
- Demonstrated sensitivity $5 \cdot 10^{-11}$ g @10000 s over 30 cm baseline [F. Sorrentino et al., Phys. Rev. A **89**, 023607 (2014)]
- Using two atomic clouds improves g measurement as well
  - F. Sorrentino et al., Appl. Phys. Lett. **101**, 114104 (2012)

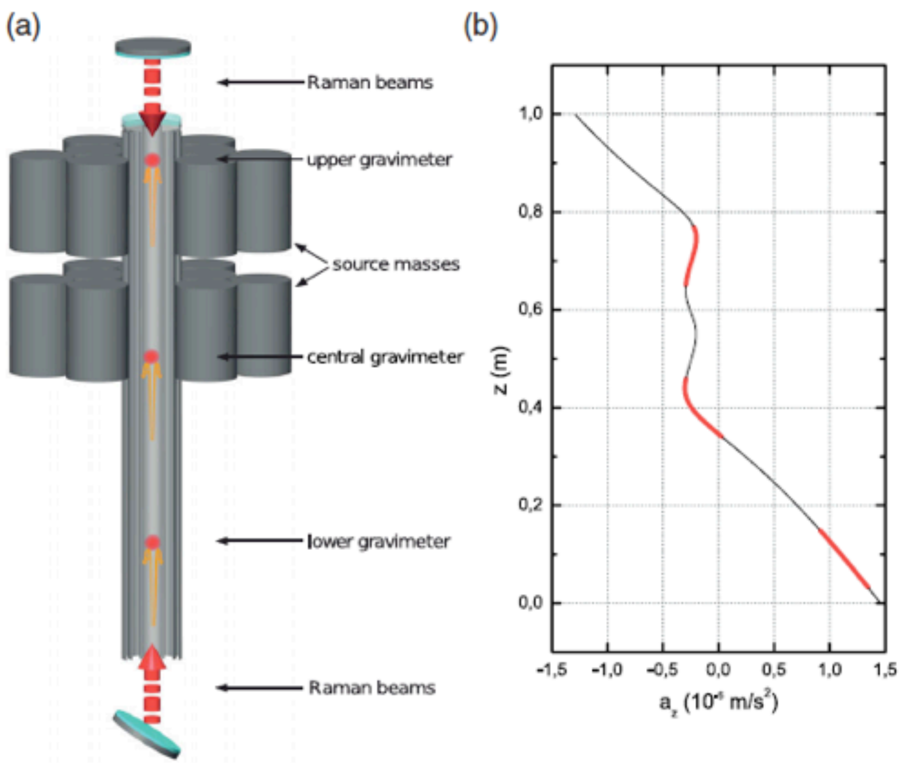


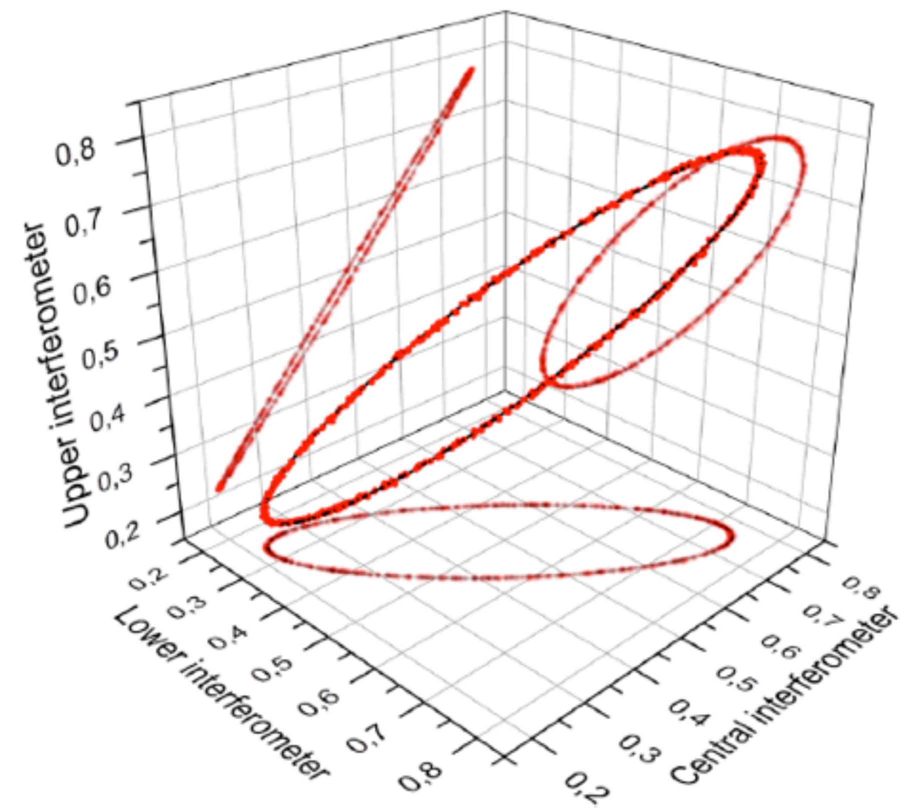




Scalability of gradiometers

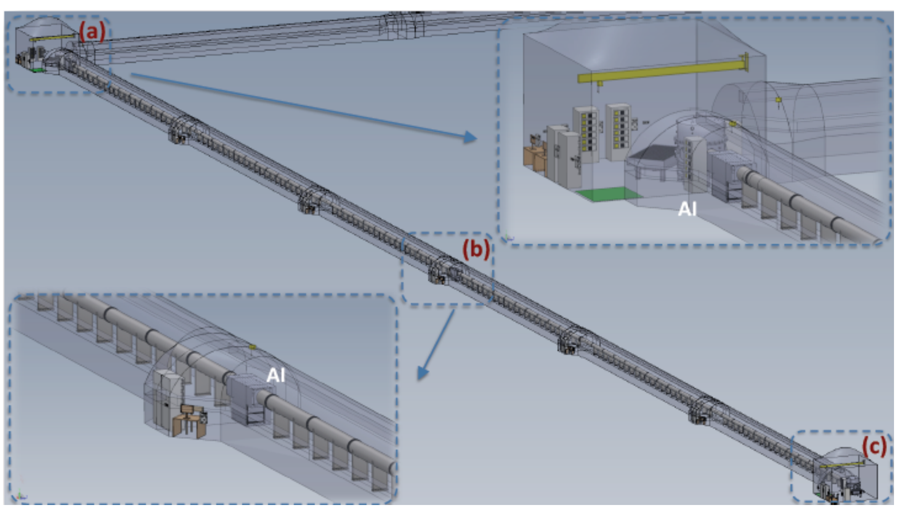
- With n+1 equally spaced atomic samples one can measure the n-th spatial derivative of the gravitational field
- Demonstrated e.g. by measuring the curvature of gravitational field
  - F. Sorrentino et al., Appl. Phys. Lett. **101**, 114104 (2012)

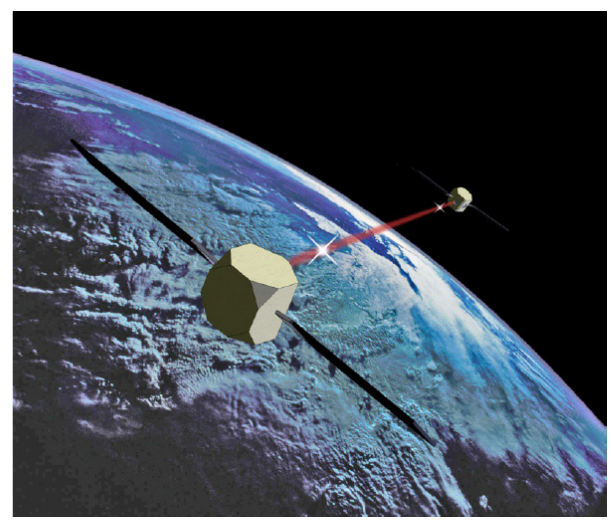




Scalability of gradiometers

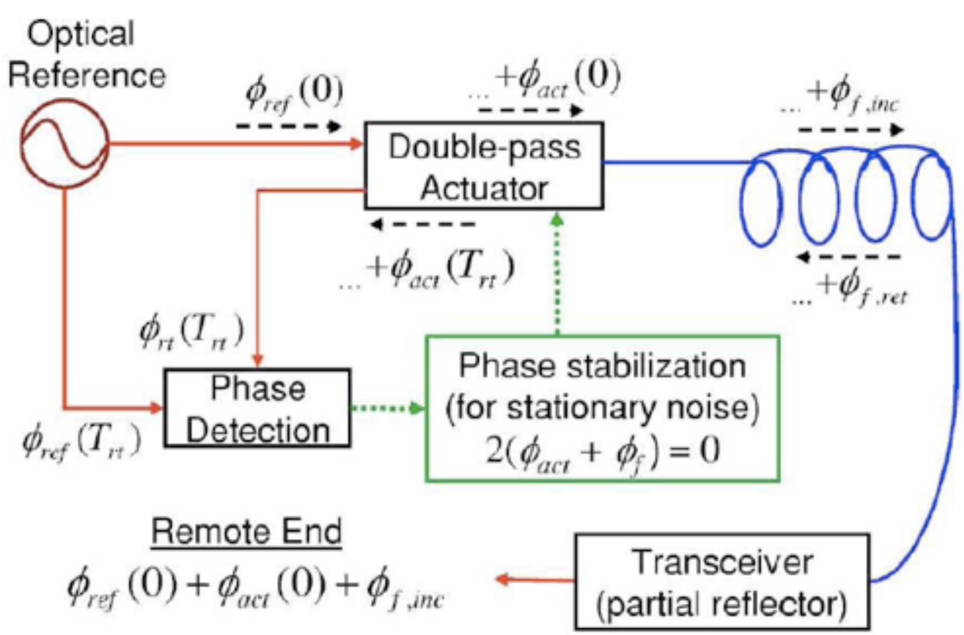
- With n+1 equally spaced atomic samples one can measure the n-th spatial derivative of the gravitational field
- Demonstrated e.g. by measuring the curvature of gravitational field
  - F. Sorrentino et al., Appl. Phys. Lett. **101**, 114104 (2012)
- The sensitivity of gradient measurement depends on the distance among test masses (atomic samples)
  - Ultra-sensitive measurements require an extremely large apparatus
    - Vertical ~10 m atomic fountains in lab (Stanford, Hannover, Firenze)
    - Underground cavities 0.1÷1 km (MIGA: LNBB, FR; MAGIS: Stanford & Fermilab, USA)
    - Proposals for laser links among distant satellites (AGIS, AGIS-LEO, SAGE, AEDGE)





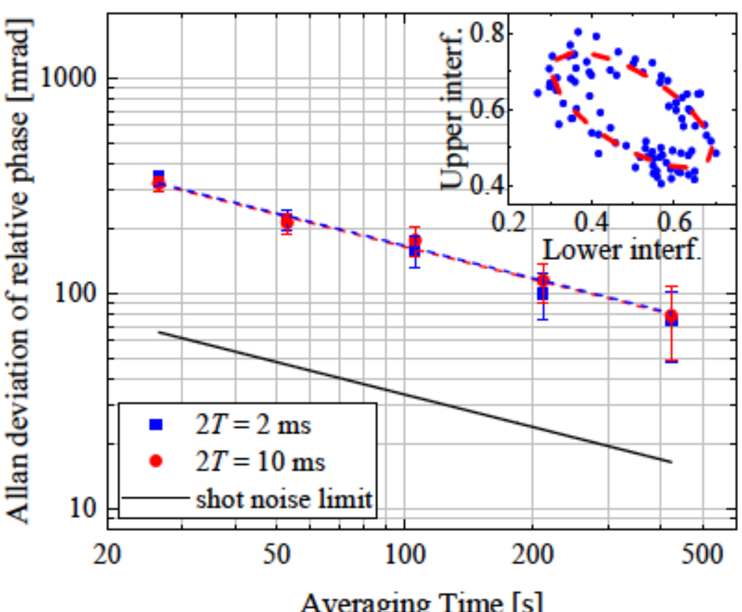
Coherent optical links

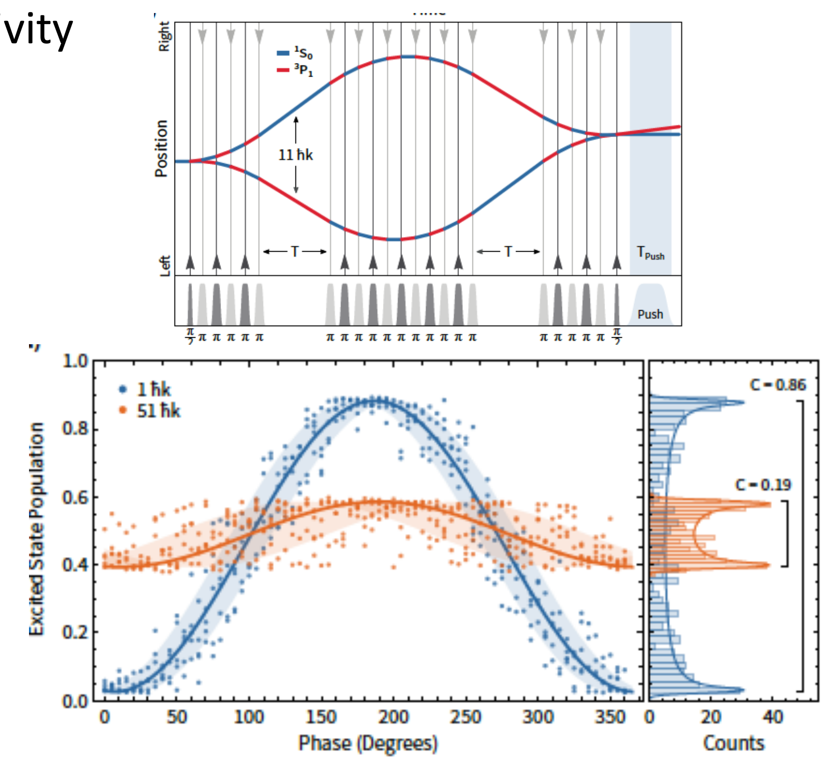
- Cancellation of phase noise introduced by the optical fibre (due to thermal and mechanical effects) through active control of the laser field
- Optical frequency comparison over ~100s km is nowadays possible with precision better than 10^{-20}
- Several links already developed worldwide, based on existing telecom fibre infrastructure



Atom interferometers and optical clocks

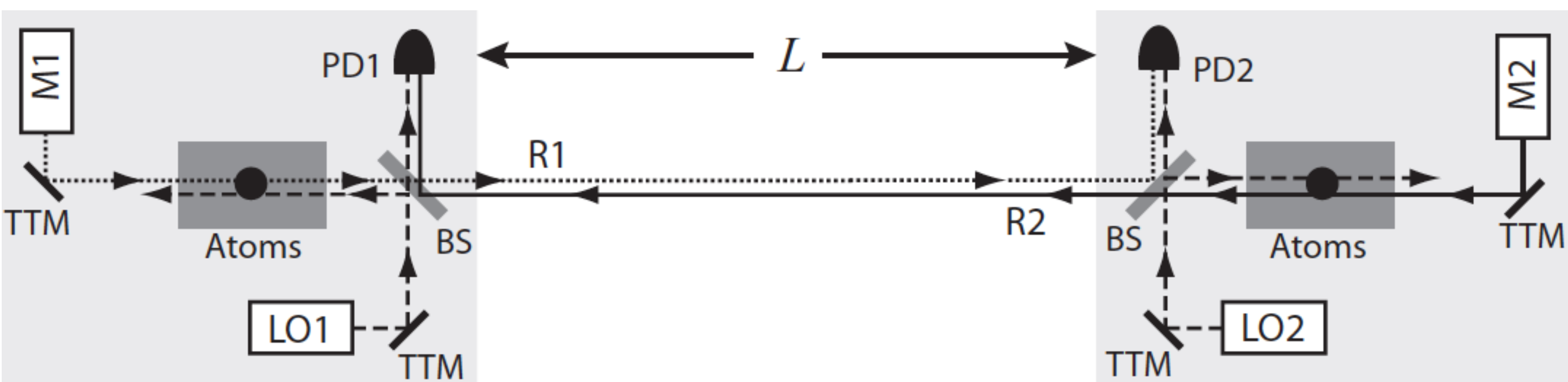
- Inertial sensing with single photon transitions, to reduce the impact of laser frequency noise on long baselines due to finite propagation time.
  - Theoretical proposal for differential scheme: N. Yu and M. Tinto, Gen. Relativ. Grav. 43, 1943(2011); S. Dimopoulos et al., Phys. Rev. D 78, 122002 (2008)
  - Experimental evidence of atom interferometer with single-photon transition on Sr clock line: L. Hu et al., PRL 119, 263601 (2017)
  - High sensitivity sensing with large-momentum transfer using the 689 nm intercombination line in Sr: J. Rudolph et al., arXiv:1910.05459v1 (2019)
  - OLAGS will develop this method for differential measurements over variable baseline up to state-of-the-art sensitivity





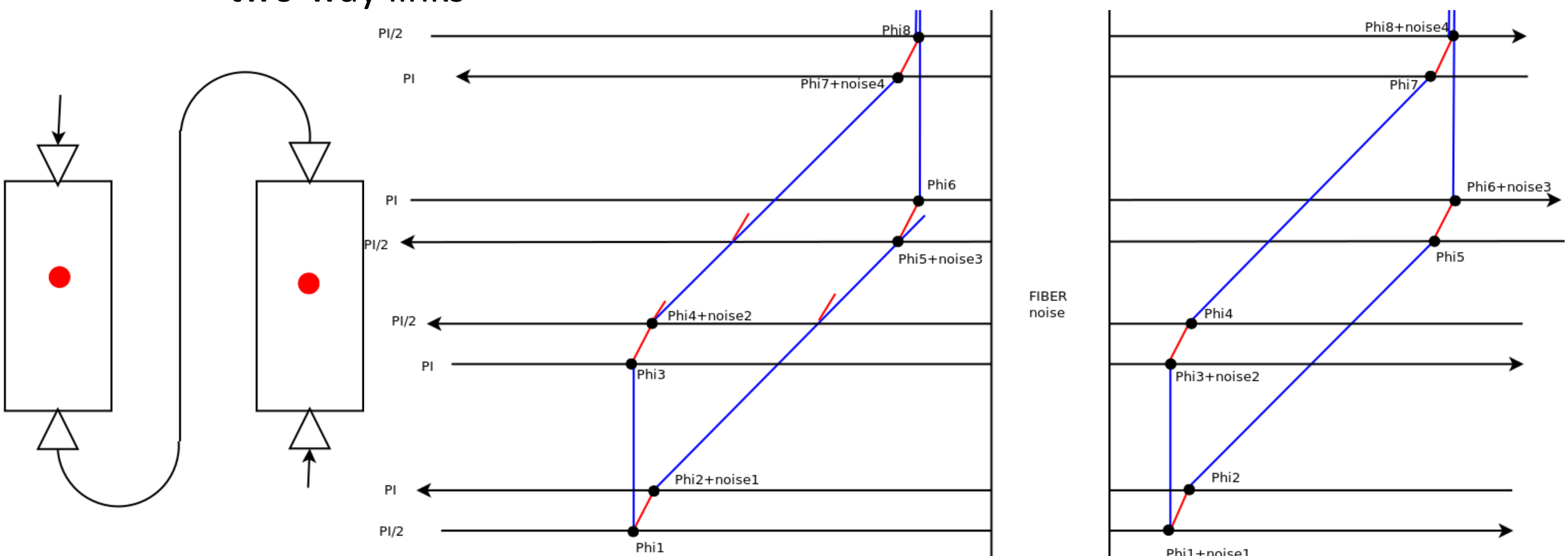
OLAGS: base concept

- Demonstrating the possibility to measure the gravitational gradient with two distant atomic sensors
- Same laser field to interrogate the two atom gravimeters, through a coherent optical link
  - Link in vacuum
    - High CMRR on large distances (~km)
    - control of laser wavefronts
    - Heterodyne link [J. M. Hogan and M. A. Kasevich, Atom interferometric gravitational wave detection using heterodyne laser links, Phys. Rev. A 94, 033632 (2016)]



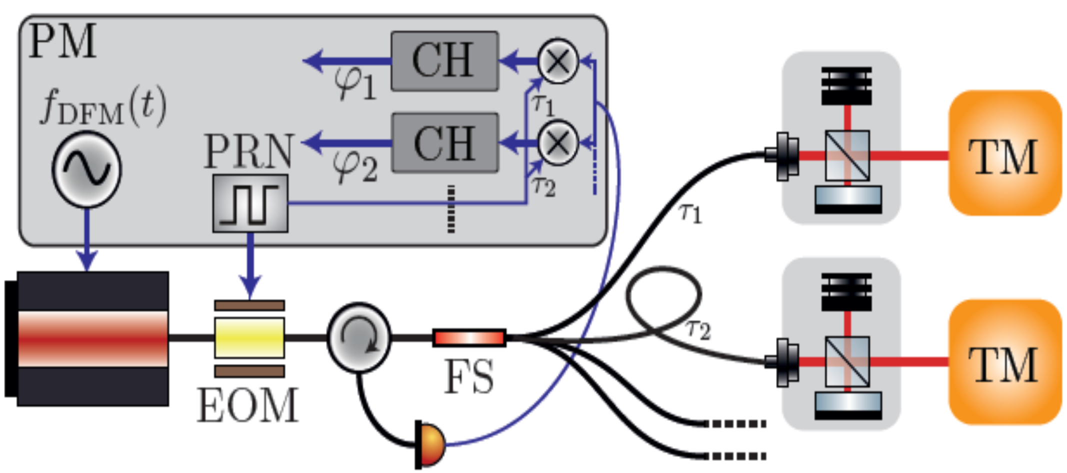
OLAGS: base concept

- Demonstrating the possibility to measure the gravitational gradient with two distant atomic sensors
- Same laser field to interrogate the two atom gravimeters, through a coherent optical link
  - Link in vacuum
  - Optical fiber link
    - Optical metrology methods to cancel the phase noise induced by the fiber: two-way links



OLAGS: base concept

- Demonstrating the possibility to measure the gravitational gradient with two distant atomic sensors
- Same laser field to interrogate the two atom gravimeters, through a coherent optical link
  - Link in vacuum
  - Optical fiber link
    - Optical metrology methods to cancel the phase noise induced by the fiber: two-way links
    - Optical interferometry methods to transfer an inertial reference to a test mass [O. Gerberding, Opt. Expr. 14753, 234267 (2015)]



OLAGS: base concept

- Demonstrating the possibility to measure the gravitational gradient with two distant atomic sensors
- Same laser field to interrogate the two atom gravimeters, through a coherent optical link
  - Link in vacuum
  - Optical fiber link
    - Optical metrology methods to cancel the phase noise induced by the fiber: two-way links
    - Optical interferometry methods to transfer an inertial reference to a test mass [O. Gerberding, Opt. Expr. 14753, 234267 (2015)]
- Studying the network scalability in terms of:
  - Number of sensors
  - Distance among sensors
  - Size and sensitivity of individual sensors

OLAGS: base concept

- Demonstrating the possibility to measure the gravitational gradient with two distant atomic sensors
- Same laser field to interrogate the two atom gravimeters, through a coherent optical link
  - Link in vacuum
  - Optical fiber link
    - Optical metrology methods to cancel the phase noise induced by the fiber: two-way links
    - Optical interferometry methods to transfer an inertial reference to a test mass [O. Gerberding, Opt. Expr. 14753, 234267 (2015)]
- Studying the network scalability in terms of:
  - Number of sensors
  - Distance among sensors
  - Size and sensitivity of individual sensors
- Studying optimal configurations for specific application fields
  - Network topology
  - Cost/performance trade-off

Application fields

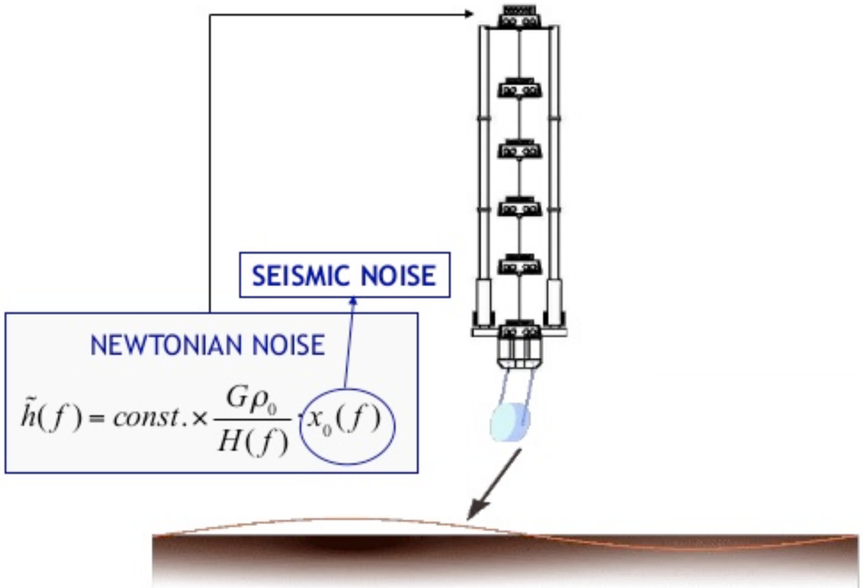
- Geophysics and environmental physics
  - Physics of solid Earth
  - Geophysics of fluids
- GW detection
  - Low frequency Newtonian noise measurement for third generation detectors
  - Measurement of GW stochastic background through Earth normal modes
- Fundamental physics
  - Ricerca di Dark Matter
  - Dark energy

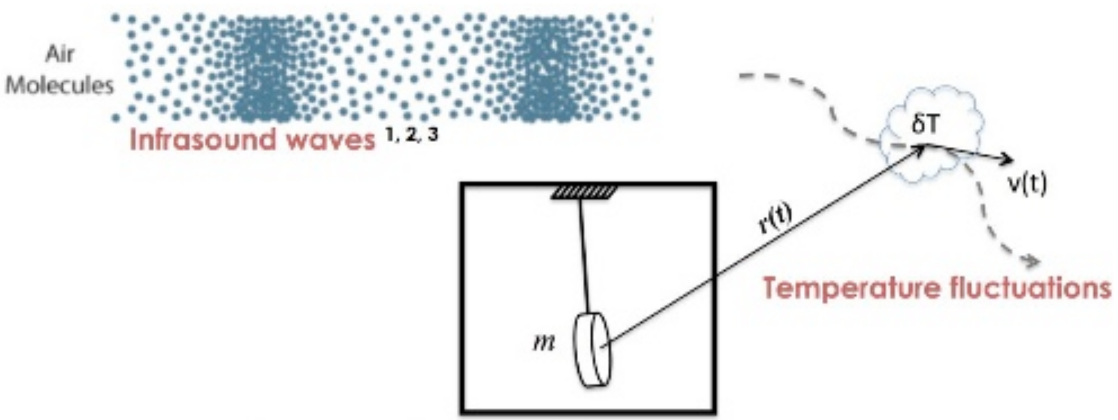
Geophysical applications

- Physics of solid Earth
  - Global scale
    - Detection of Slichter modes
    - Observation of Earth Hum
  - Local gravitational anomalies
    - Hydrology of aquifers
    - Elastic deformation of rock bodies
    - Migration of magmatic-hydrothermal fluids in volcanic or geothermal systems
  - Seismic phenomena
    - Deformation of underground rock bodies
    - Physical processes in dislocation of seismogenetic structures
- Physics of fluid Earth
  - Oceans
    - Sources and propagation of tsunami events
    - Ocean dynamics (benthic structures, thermoalyne circulation)
  - Atmosphere
    - Physics of clouds, coalescence in water vapour phase transitions
    - Atmospheric dynamics in stratified atmosphere
  - Endogenous fluids
    - Natural gas reservoirs
    - hydrology

GW detection

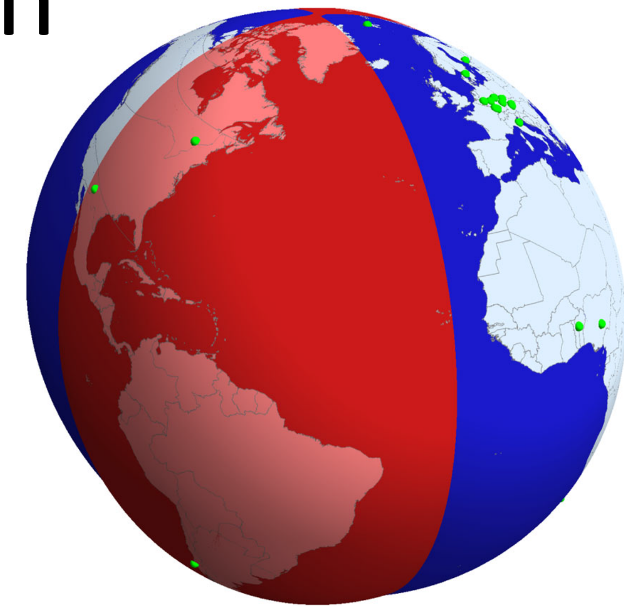
- Measurement of low-frequency Newtonian noise (sub-Hz) for third generation GW detectors
  - Current protocols for NN mitigation require a network of seismometers & microphones + a reliable model to compute NN from ground vibration and air pressure fluctuations
  - Gravity gradiometry would allow direct NN sensing

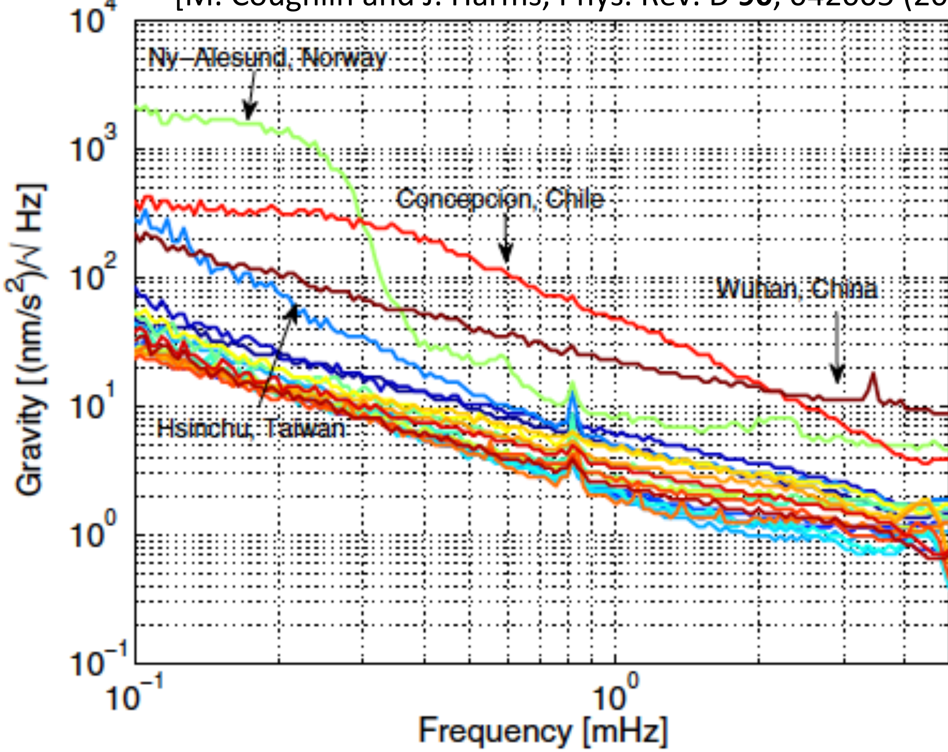


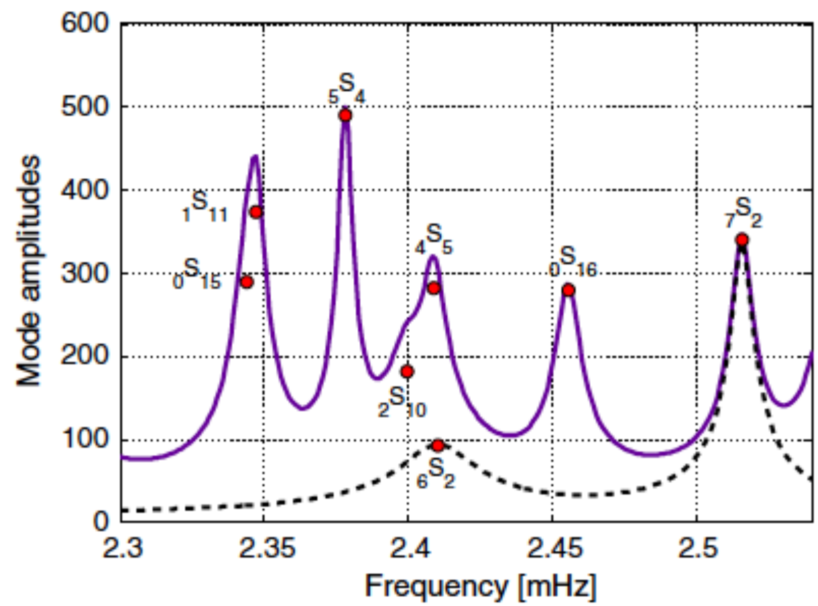


GW detection

- Measurement of low-frequency Newtonian noise (sub-Hz) for third generation GW detectors
  - Current protocols for NN mitigation require a network of seismometers & microphones + a reliable model to compute NN from ground vibration and air pressure fluctuations
  - Gravity gradiometry would allow direct NN sensing
- Measurement of GW stochastic background through Earth normal modes
  - [M. Coughlin and J. Harms, Phys. Rev. D **90**, 042005 (2014)]

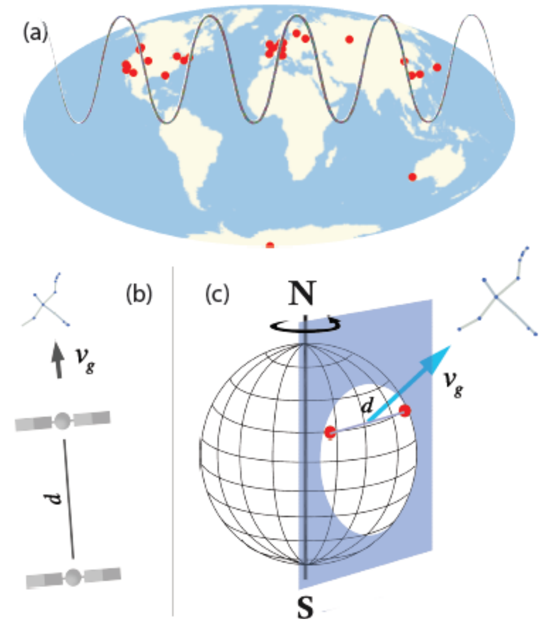


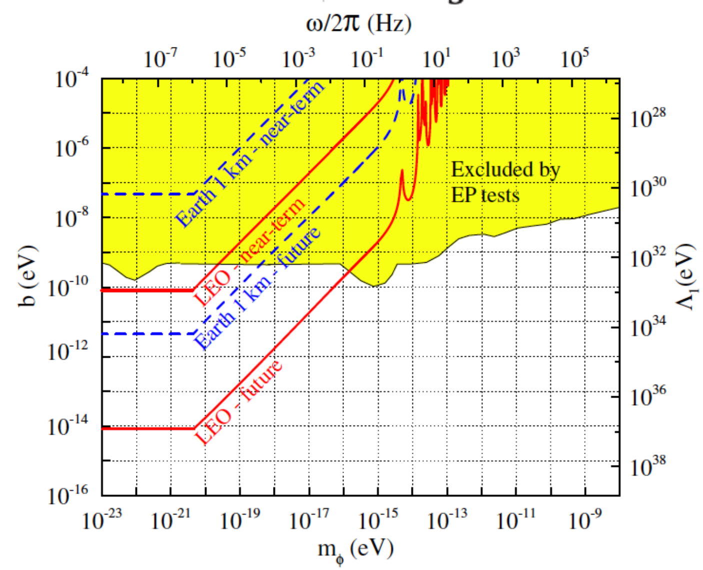




Fundamental physics

- Dark Matter search
  - A. Geraci and A. Derevianko, Sensitivity of Atom Interferometry to Ultralight Scalar Field Dark Matter, PRL 117, 261301 (2016)
  - A. Derevianko, Detecting dark matter waves with a network of precision measurement tools, arXiv:1605.09717 (2016)
  - P. W. Graham et al., Dark Matter Direct Detection with Accelerometers, arXiv: 1512.06165 (2016)
  - A. Arvanitaki et al., Search for light scalar dark matter with atomic gravitational wave detectors, arXiv:1606.04541 (2016)
- Dark Energy search
  - C. Burrage and E. J. Copeland, Using Atom Interferometry to Detect Dark Energy, arXiv: 1507.07493 (2015)
  - P. Hamilton et al., Atom-interferometry constraints on dark energy, Science 349, 849 (2015)





OLAGS: the team

- INFN-GE
  - coordination, optical fibre link, magnetic noise control, Newtonian noise models
- INFN-FI
  - Atom interferometry on optical clock line, atom optics tools, vacuum fiber link and laser wavefront control, integration of optical link and seismic isolation system on atom interferometer
- INFN-PI
  - Seismic isolation, angular controls, Newtonian noise models, atom optics models for interferometry with trapped atoms
- INFN-LNF
  - Control electronics

Structure of the project

- **Technology for optical links** (GE + FI)
  - Development of the optical fiber link; study of optimal topologies; *test* of measurement principle on variable baseline; integration with atomic sensors.
  - Development of the vacuum optical link; methods for laser wavefront control over long distances.
- **Atom optics technologies** (FI + PI)
  - Atom interferometry on optical clock line; LMT atomic splitters; interferometry with trapped Sr atoms.
  - Integration of seismic isolation system, wavefront control systems, and fiber link on differential atom interferometry sensor
- **Seismic isolation** (PI)
  - Vertical acceleration filter for single atom interfeormeter
  - Pointing control system for atomic beam splitting laser
- **Other technological develoments** (LNF + GE)
  - Magnetic noise control system
  - Network control electronics
- **Models for network data analysis** (PI+GE)
  - Models for measurement of geophysical observables
  - Models for NN sensing
  - Seismic isolation of GW test masses via Inertial reference transfer

Program

- 1° year
  - Design of the atomic sensor network topology
  - Design and development of fiber link
  - Development of wavefront control methods for vacuum link
  - Design and basic prototyping of seismic isolation and angular control system
- 2° year
  - Test of optical link on lab scale
  - Development and test of seismic isolation and angular control system
  - Test of critical atom optics tools.
- 3° year
  - Integration of seismic isolation system atomic sensor
  - Integration of wavefront control system on atomic sensor
  - Integration of optical fiber link on differential atomic sensor
  - Test of differential atomic sensor
  - Study and mitigation of noise sources
- Models to extract data of physical interest from the sensor network (geophysical applicaitons, NN, GW, DM,…) to be developed along the project, will contribute to define the network topology during the secon year