Quantum Devices & Systems

Congressino gruppo 5

03-02-2021

G. Rosi

Sommario

- Esperimenti «quantum» già presenti in sezione:
  - OLAGS
  - NaMaSSTE

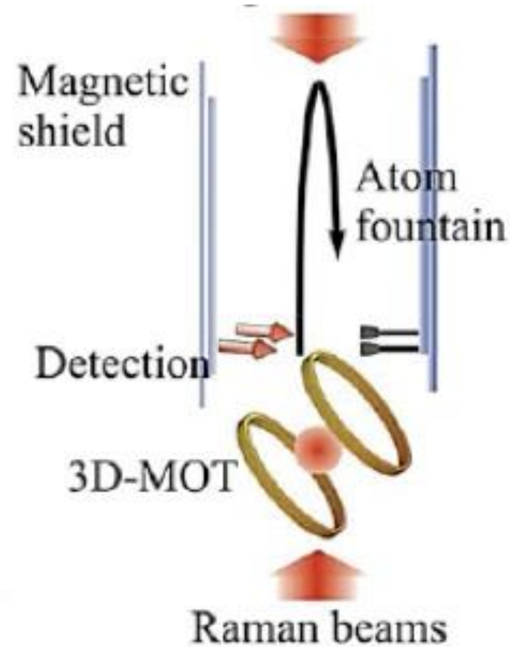
- «Idee» provenienti da attività Gruppo 2
  - Humor (tHEEOM-RD)
  - Supremo

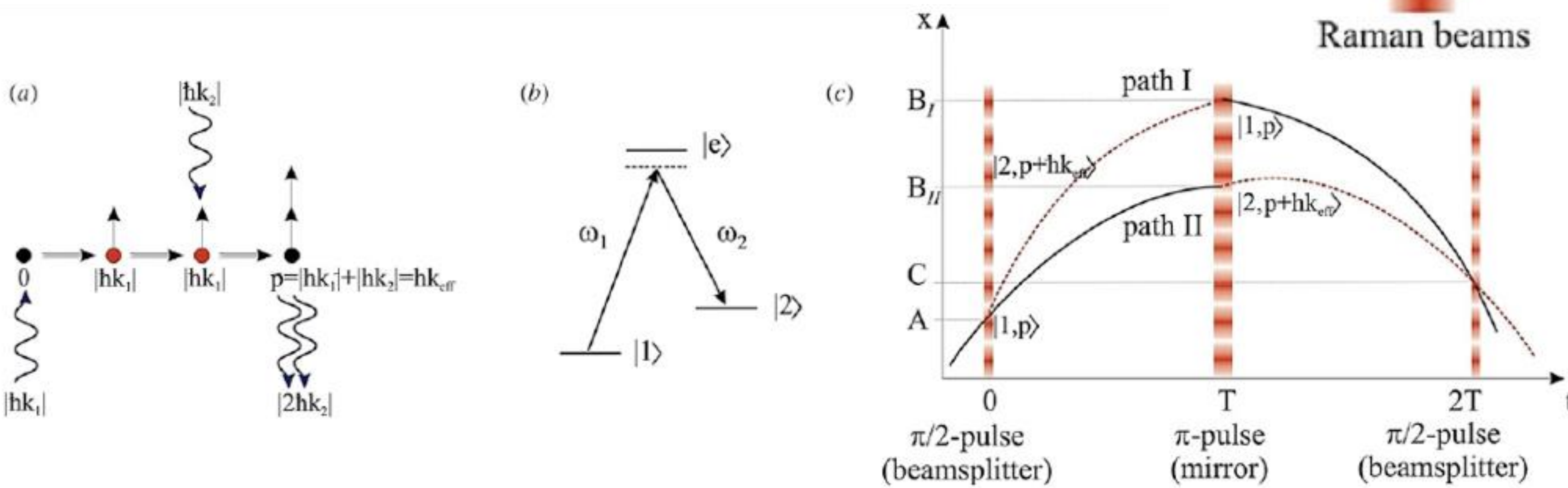
OLAGS COLLABORATION

Genova (1 FTE, coordination)
Firenze (1 FTE)
Pisa (2.5 FTE)
LNF (0.4 FTE)

Atomic gravimeters

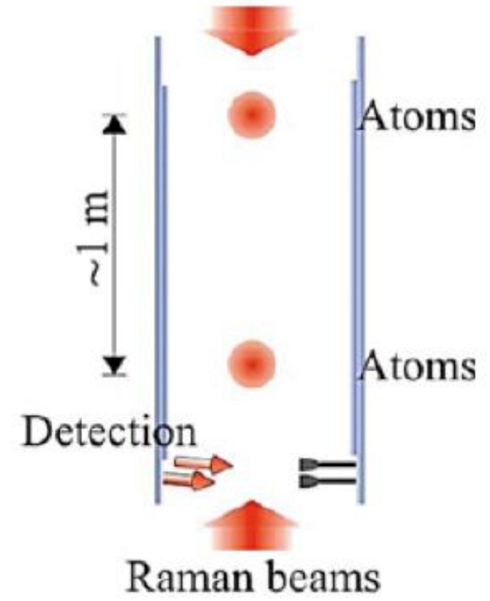
- They are based on atomic interferometry: laser cooling + coherent manipulation of atomic wave packets
- They are the best absolute gravimeters: sensitivity of the order of 10 μgal / √Hz demonstrated, accuracy ~ 1 μgal (1 μgal = 10^{-8} m / s^2)
- Seismic noise is one of the main sensitivity limits

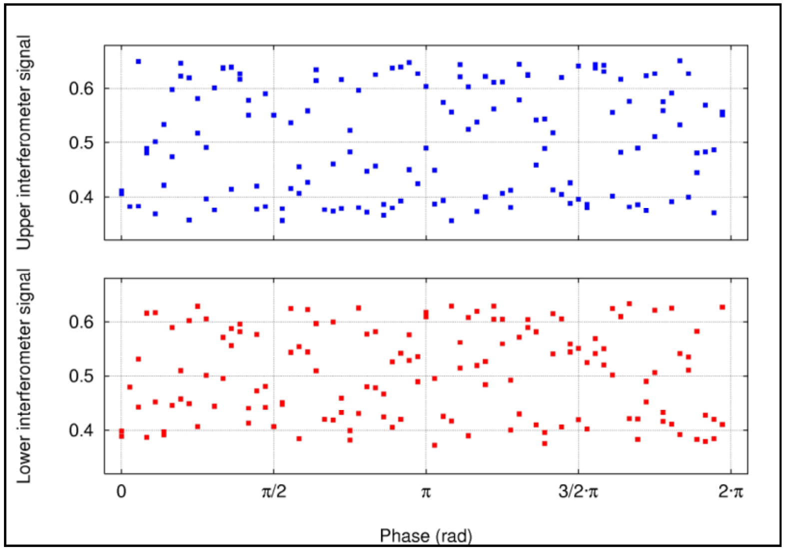


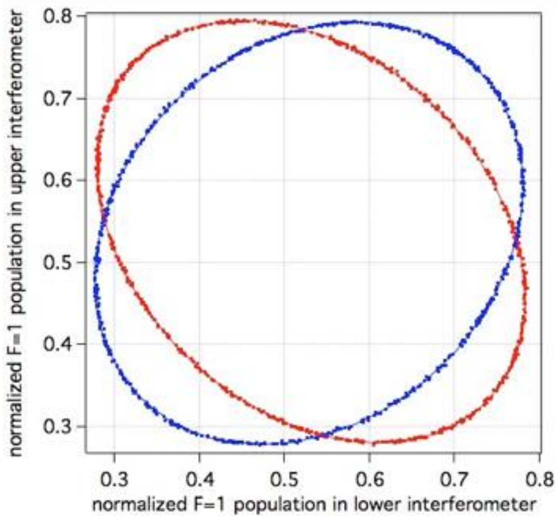


Atomic gravity gradiometer

- Two vertically separated atomic samples
- Interrogation with the same laser field for the manipulation of the atomic wave packet
- Demonstrated a CMRR better than 140 dB for seismic noise
- Demonstrated differential sensitivity of $5 \cdot 10^{-11}$ g @10000 s with baseline of 30 cm
  - [F. Sorrentino et al., Phys. Rev. A **89**, 023607 (2014)]

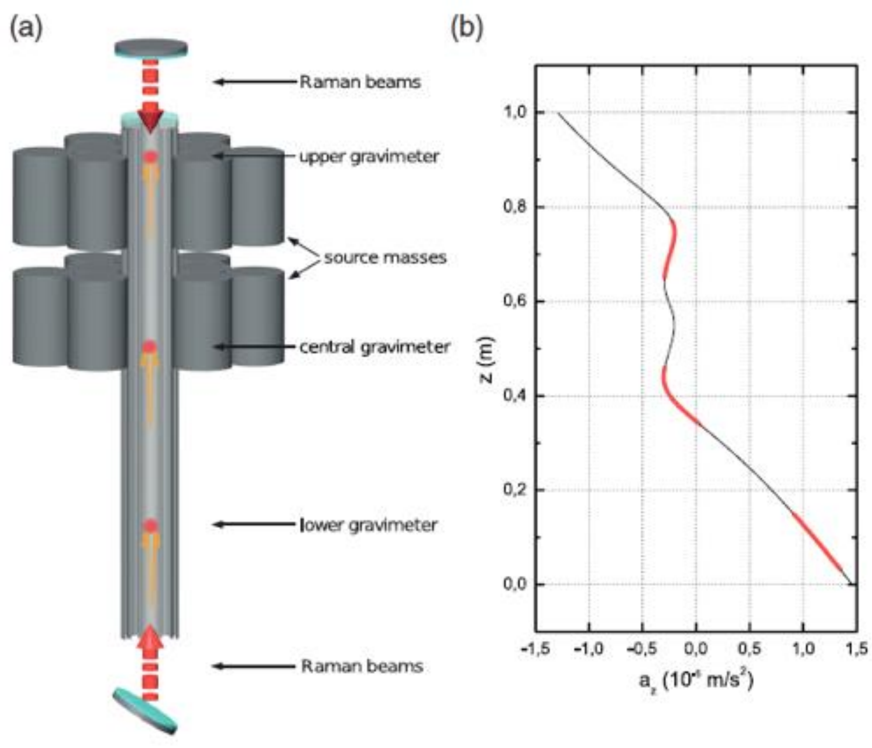


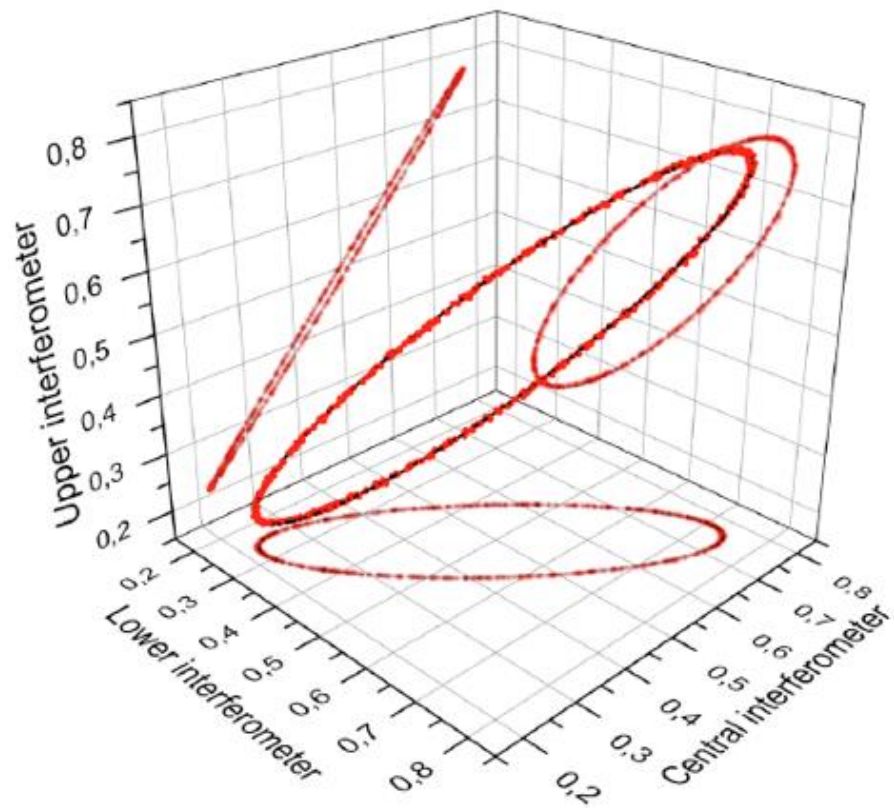




Gradiometer Scalability

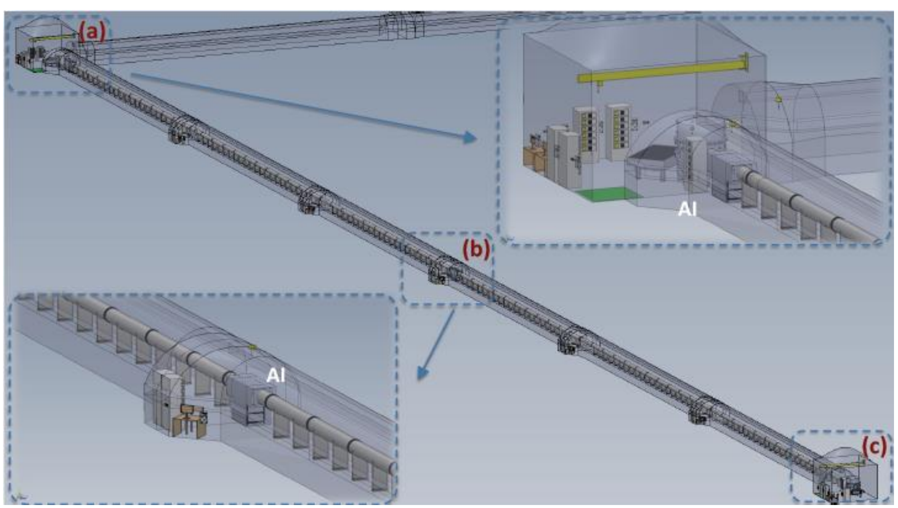
- With n+1 equally spaced atomic samples the nth spatial derivative of the gravitational field is measured
- Demonstrated eg. for measuring the curvature of the gravitational field (G. Rosi et al., PRL 114, 013001 (2015))

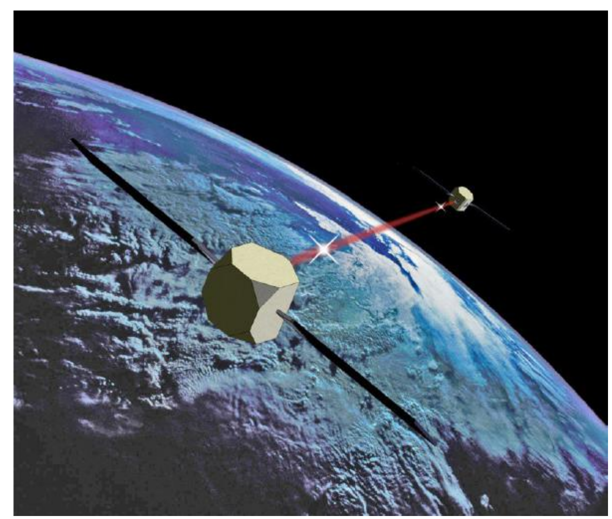




Gradiometer Scalability

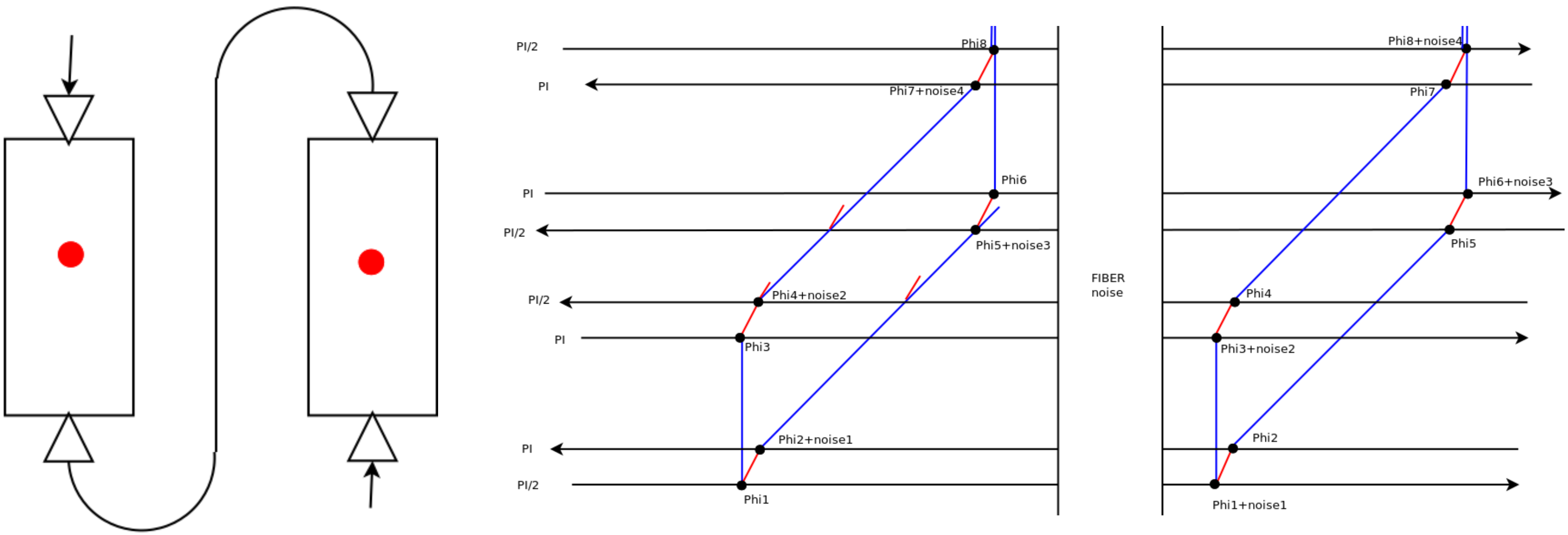
- With n+1 equally spaced atomic samples the nth spatial derivative of the gravitational field is measured
- Demonstrated eg. for measuring the curvature of the gravitational field (G. Rosi et al., PRL 114, 013001 (2015)
- The sensitivity in the gradient measurement depends on the distance between the sensors Ultra-sensitive measurements require large equipment
    - Large fountains ~10 m (Stanford, Hannover)
    - Horizontal optical cavity ~ 300 m, (LNBB, Francia, progetto MIGA)
    - Proposals for laser links between distant satellites : AGIS, AGIS-LEO, SAGE





OLAGS: base concept

- Demonstrate the possibility of measuring the gravitational gradient with two distant atomic sensors
- Use the same laser field to interrogate the two gravimeters, using a coherent optical link
  - Fiber optical link
    - Optical metrology methods for fiber-induced phase noise cancellation via two-way link



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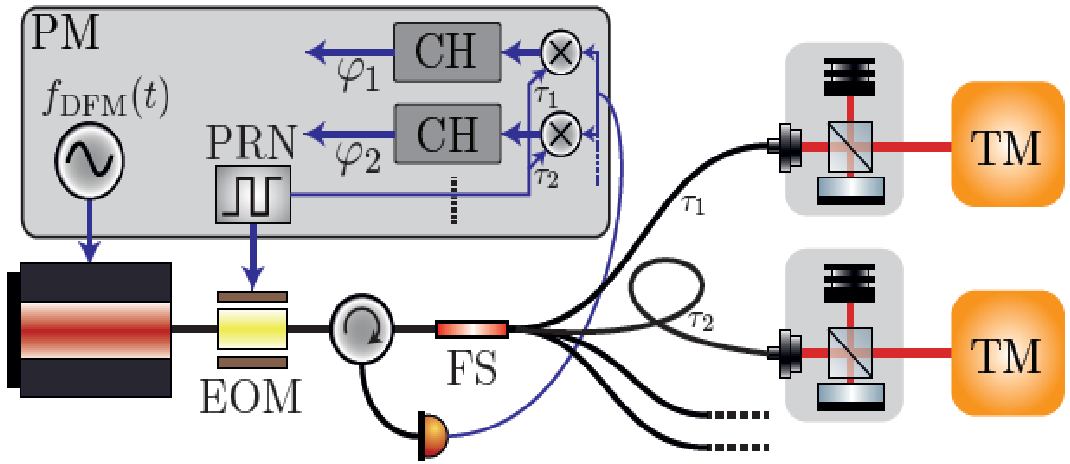


Application areas

- Earth and environmental physics
  - Solid earth physics
  - Fluid Earth Physics
- Detection of gravitational waves
  - Low frequency Newtonian noise measurement for 3rd generation detectors
  - Stochastic background measurement using normal earth modes
- Fundamental physics
  - Research of Dark Matter

NAMASSTE - Participants

INFN Istituto Nazionale di Fisica Nucleare CSN5

Pavia → Unit 1 **Firenze → Unit 2** **Milano → Unit 3**

Participants - Pavia, Firenze and Milano Units		FTE/year
Manuel Mariani – RU – UNIPV – PI	**Pavia**	**0.5**
Davide Cicolari – PhD – UNIPV	Pavia	0.3
Marta Filibian – Technician - UNIPV	Pavia	0.1
Elio Giroletti – Senior Member – INFN	Pavia	0.2
Alessandro Lascialfari – PO – UNIPV	Pavia	0.2
Lisa Rinaldi – PhD – UNIPV	Pavia	0.3
Fabio Cinti – RTDB – UNIFI	Firenze	0.2
Maria Fittipaldi – RU – UNIFI	Firenze	0.4
Giuseppe Latino – PA – UNIFI	Firenze	0.2
Angelo Rettori – PA – UNIFI	Firenze	0.2
Lorenzo Sorace – PA – UNIFI	Firenze	0.3
Diego Redigolo – INFN	Firenze	0.1
Giampaolo Tobia – INFN	Firenze	0.2
Paolo Arosio – RTDB – UNIMI	Milano	0.4
Francesco Orsini – Technician – UNIMI	Milano	0.3

External Participant:

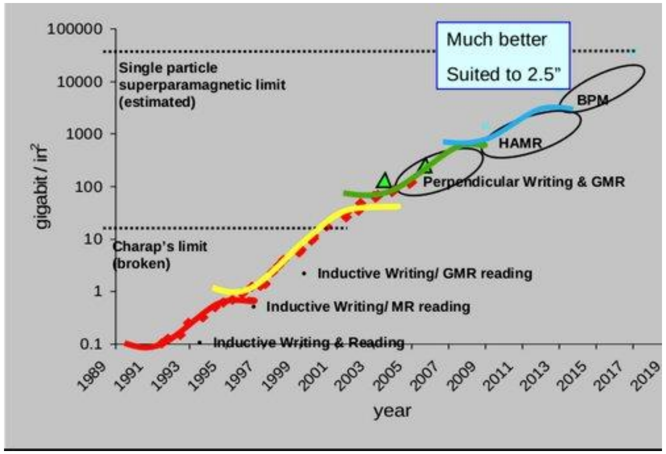
P. Santini – PO, Department of Mathematical, Physical and Computer Sciences, University of Parma

NAMASSTE: Aims

NAMASSTE project aims to design, synthesize, and characterize new molecular nanomagnets (MNMs) for two different applications

their use as

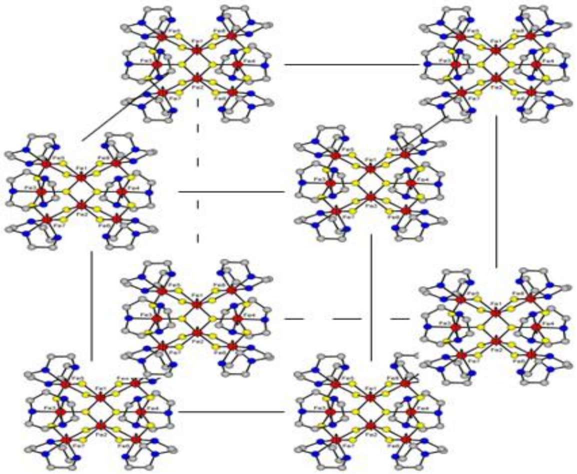
- high-density memory storage systems
- high-sensitivity sensors potentially suited for revealing dark matter



- World data generation: 25 Pbytes / day
- Generation is increasing faster than data storage capability

MNMs are crystalline materials composed by identical magnetically isolated molecules showing slow relaxation of the magnetization of pure molecular origin, and thus magnetic bistability, below a given temperature.

These aims will be pursued by combined experimental and theoretical approach involving the synergic work of Physicists and Chemists



Fe_8 crystal

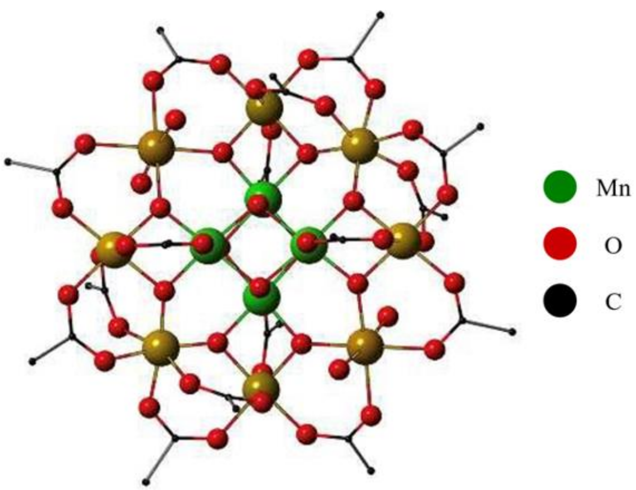
NAMASSTE – Employed systems

Molecular Nanomagnets (MNMs) **(systems size of the order of nanometers):**

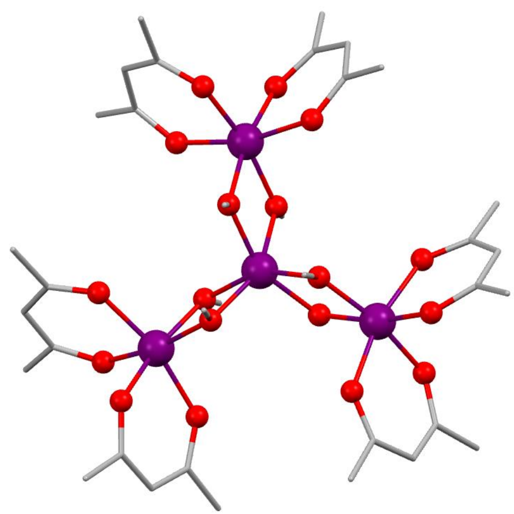
- regular crystalline structure with a magnetic core of a finite number ($n \geq 1$) paramagnetic centers (strong intramolecular exchange interactions)
- molecules shielded by organic ligands → weak intermolecular interactions

SMMs: 3d Single - Molecule Magnets (**Mn_{12}**, **Fe_4**)

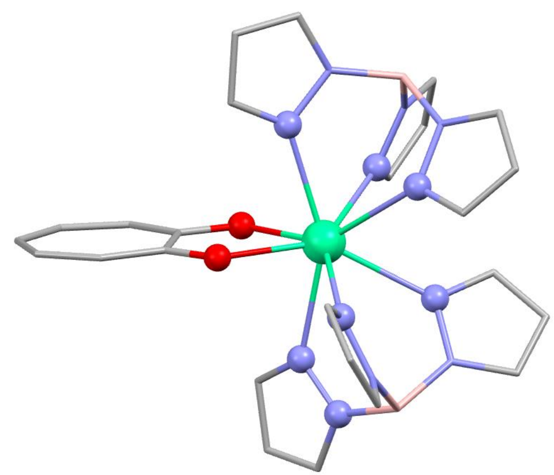
SIMs: 4f Single - Ion Magnets (Ln – Zn and **Ln – tropolonato systems**)



Mn_{12} SMM

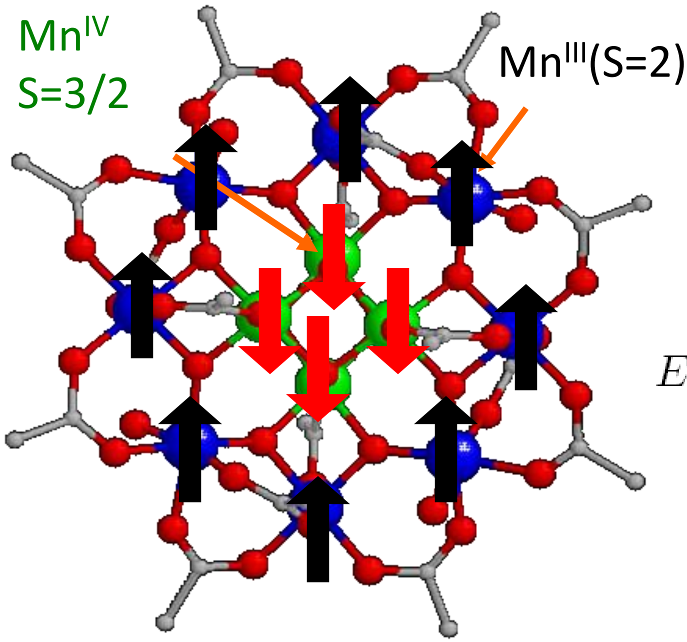


Fe_4 SMM

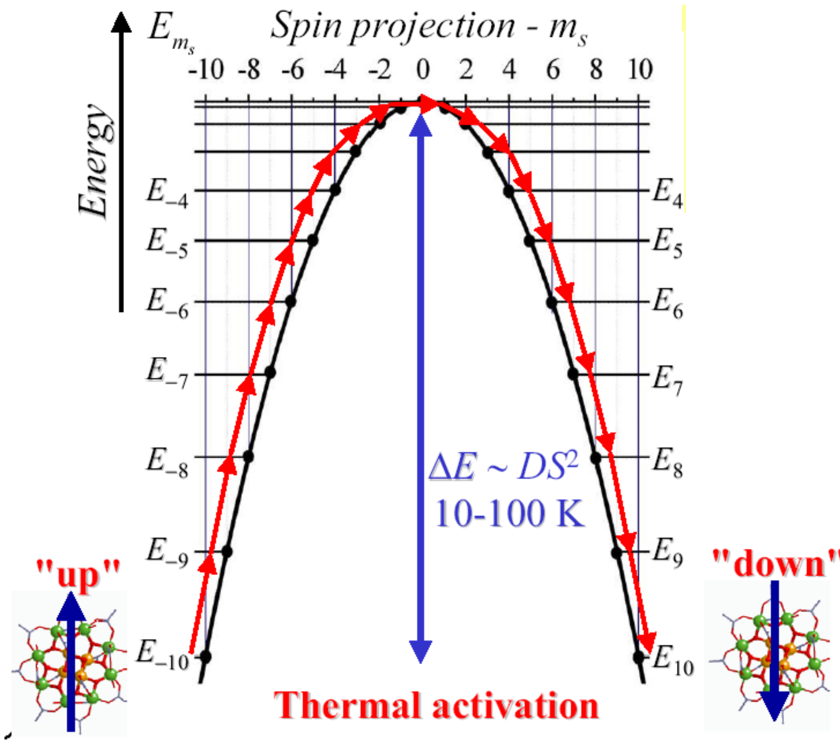


Ln – tropolonato

NAMASSTE – SMM state of art

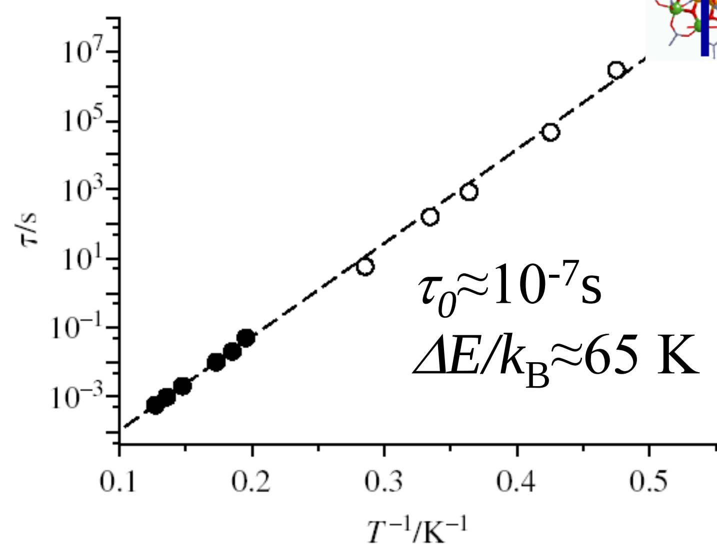


$$E_m = -|D|m^2$$

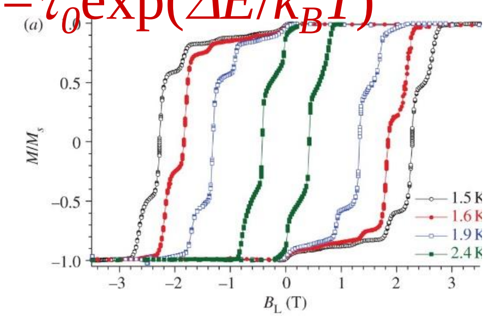


S_{tot}=10

D≈-0.7 K



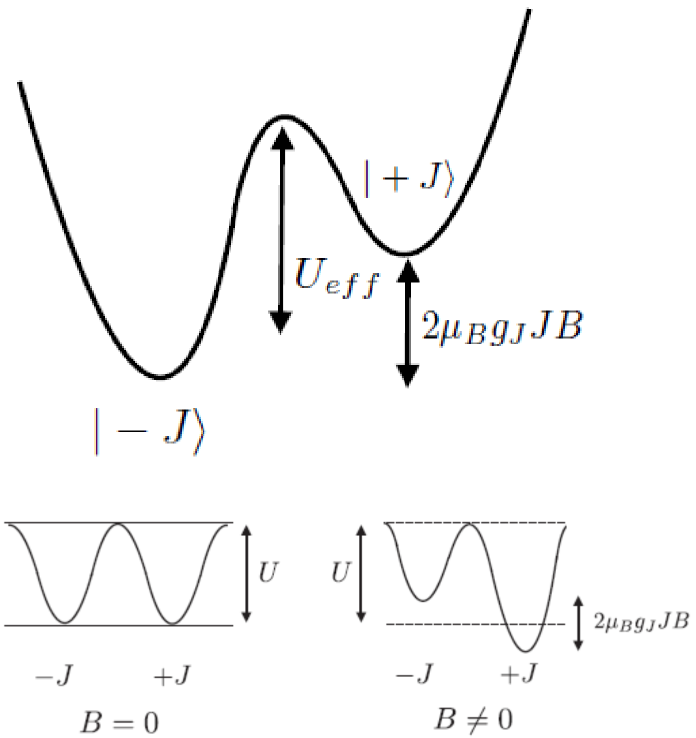
$$\tau = \tau_0 \exp(\Delta E/k_B T)$$



Sessoli et al. Nature 1993

Christou et al. MRS Bull. 2000

NAMASSTE: MNMs as sensors



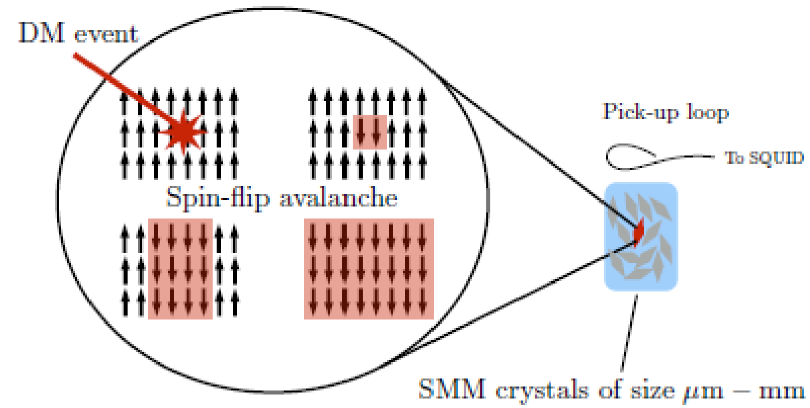


FIG. 1. DM detector concept based on magnetic deflagration in molecular nanomagnet crystals. A DM event that deposits energy in the form of heat ignites a spin-flip avalanche in the crystal which is detected by the change in magnetic flux through a pick-up loop.

PHYSICAL REVIEW D 95, 095001 (2017)

Molecular spins in MNMs represent a possible interesting alternative, with respect to other spins systems currently investigated (NV centers in diamonds).

Their potentialities as quantum probes for external electric and magnetic fields are still largely unexplored.

NAMASSTE: Methods

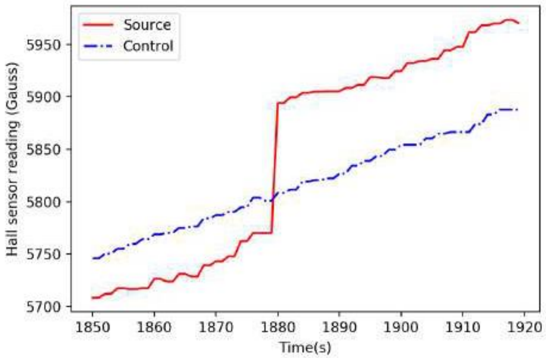
Theoretical and experimental investigations of the spin dynamics of SIMs to find relationships between chemo-physical properties and the magnetic properties → to conceive new design principles for improving their working temperatures **as magnetic molecular memories**

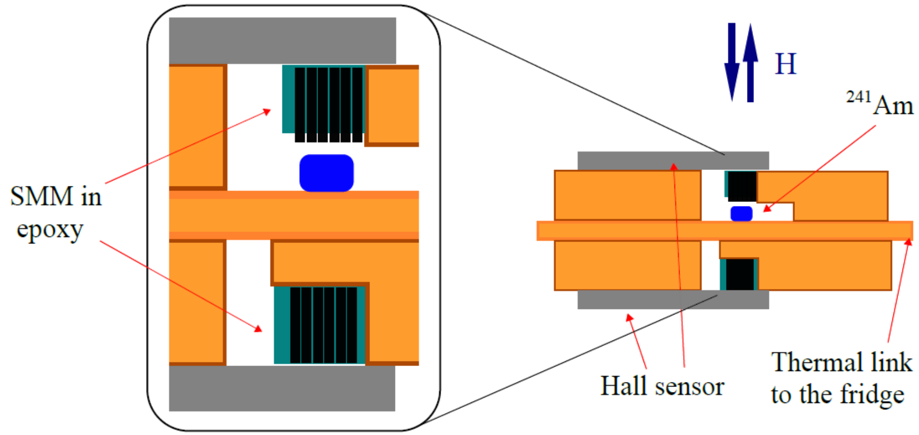
Experimental studies to identify the best SMM with the highest sensitivity as particle sensors.

Experiments of MNMs as Sensors

CSN5

For the first time, recent experiments validated SMMs as quantum sensors





*arXiv:2002.09409v2 21 Feb 2020

We will compare, through NMR, ESR, and SQUID Magnetometry as a function of the magnetic field, the experimental results obtained on SMMs in **normal conditions** and **in presence of a low-activity radioactive source**, in order to:

a. increase the overall detection sensitivity thank to the use of more sensitive techniques than that used by Chen et al.*

b. increase the temperature of use of SMMs as sensors (higher energy barriers and T_B)

tHEEOM-RD

techonology for High Efficiency Electro Optical Modulator

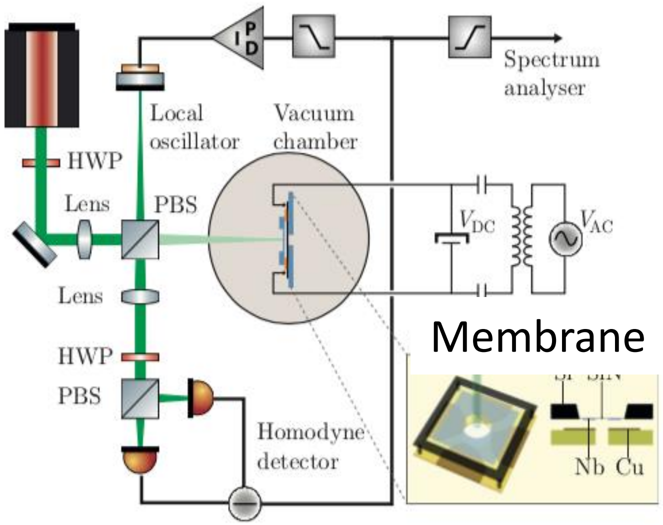
Responsabile nazionale: Enrico Serra TIFPA

Unità partecipanti: Trento, Perugia (+Firenze)

- **Francesco Marin** – Professore Associato – Università di Firenze - **FTE 0.2**
- **Francesco Marino** – Ricercatore CNR-INO – **FTE 0.3**

Spin-off della tecnologia sviluppata per **HUMOR**

Development of Electro-Optical-Modulators (EOM) for transduction of the weak RF signals



Membrane + ed electrode

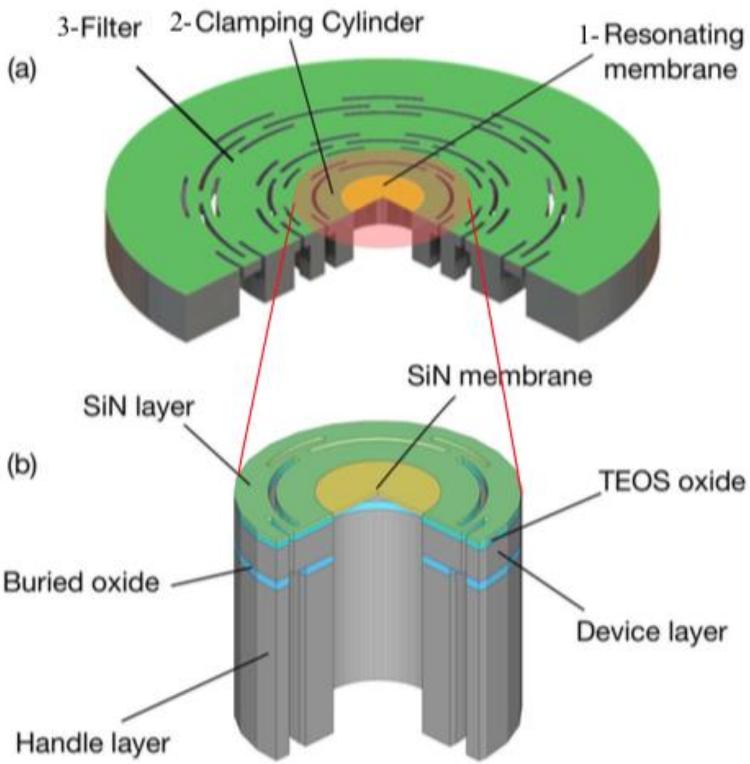
$$H = \sum_{i=1}^{2} \left[\frac{p_i^2}{2m_i} + \frac{m_i \omega_i^2 x_i^2}{2} \right] + \frac{\phi^2}{2L} + \frac{q^2}{2C(\{x_i\})} - qV$$

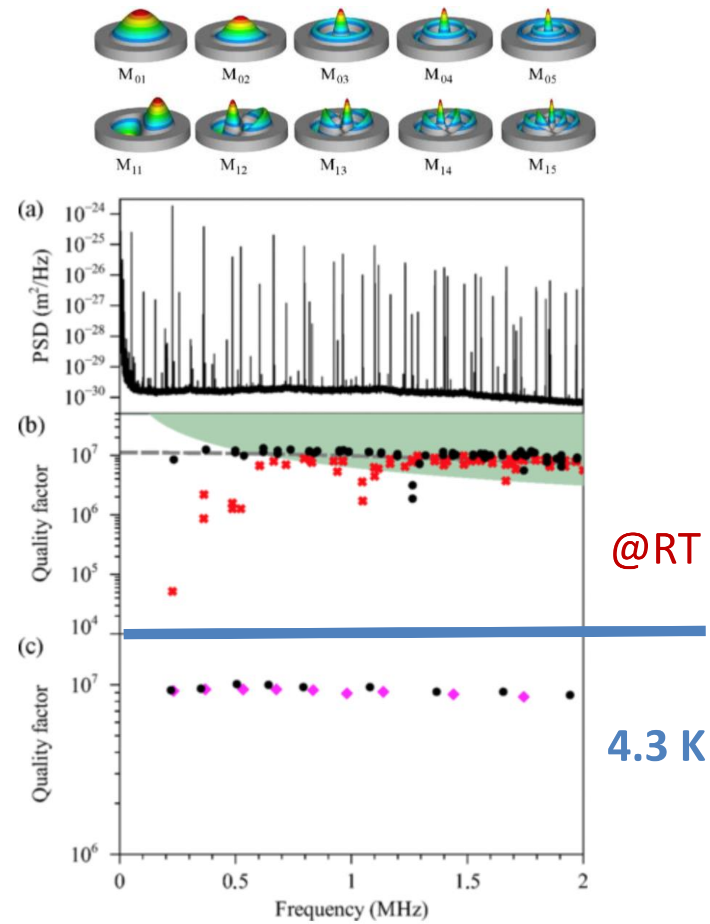
Electro - mechanical coupling constan

$$G_i \simeq -\frac{V_{\mathrm{dc}}}{C_0} \frac{\partial C_{\mathrm{m}}(\{x_i\})}{\partial x_i} \bigg|_{x_i = \bar{x}_i}$$

Circular-shaped resonator developed for HUMOR

Resonator base on high-stressed 1 GPa 100 nm - Si_3N_4 membrane – D=1.560 mm





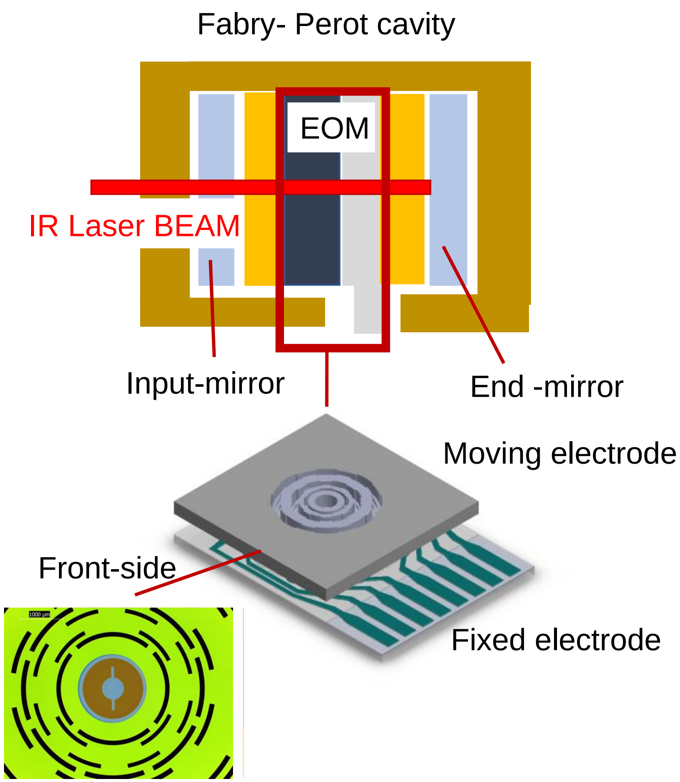
AIP Advances 2016-06; Phys. Rev. B 94, 121403(R);

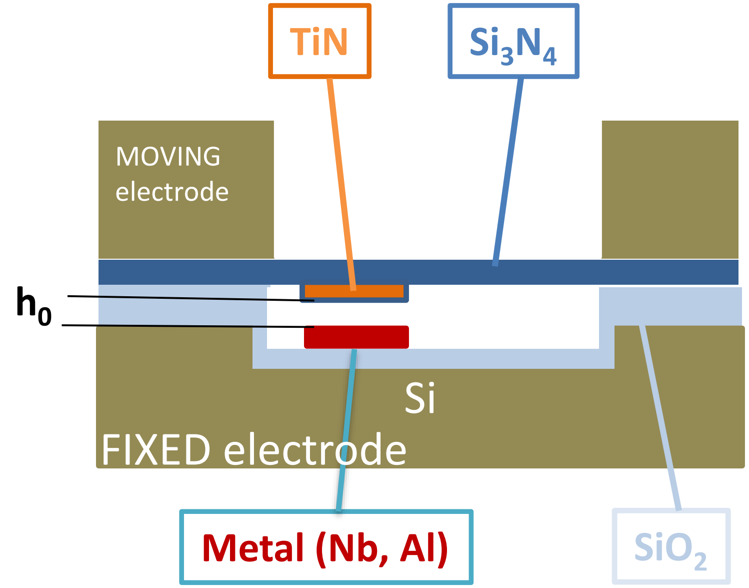
- High-Q factor > 10^7 over a [1-5] MHz bandwidth and good separation between mode

Requirements for tHEEOM-RD:

- Geometrical optimization of the electrodes exploiting circular symmetry
- Controlling possible increase of dissipation due to the metal layer
- Bonding strategy for reducing electrode gap to 3-8 um

Optimizing the electro-mechanical coupling





$$G_i = \frac{V_{\mathrm{DC}}\,\epsilon_0}{C_0 h_0^2} A_i^{\mathrm{eff}}$$

Fundamental requirements:

1) minimizing the gap h_0 (3 - 8 um)

2) maximizing A_i^{eff}

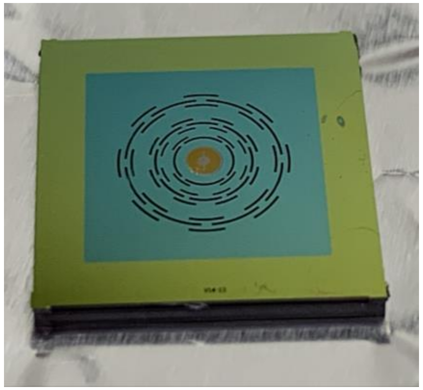
3) plane alignment (< 50 um accuracy)

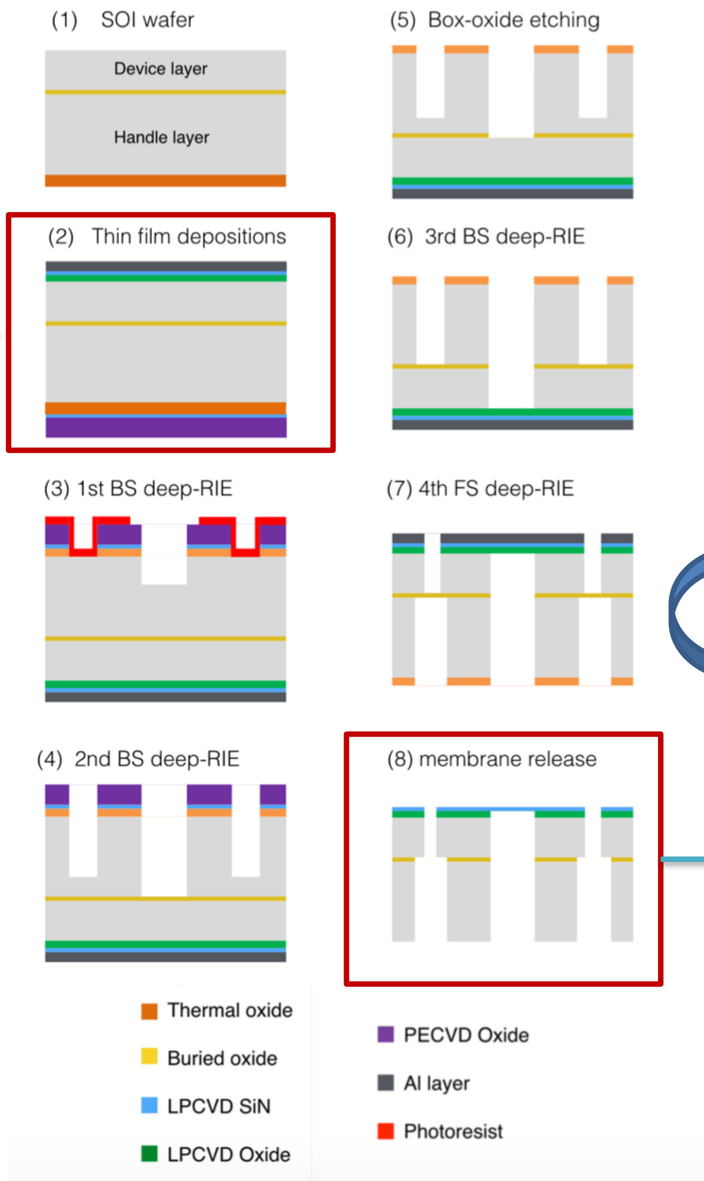
4) best parallelism between the electrodes (< 1 mrad)

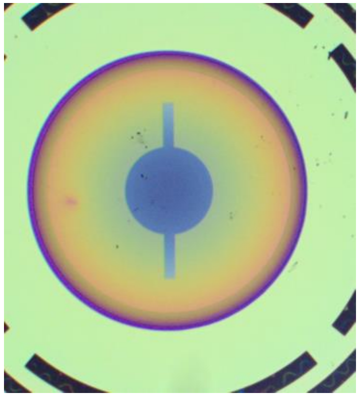
Technology for integrating the TiN electrode (2019-2020)

Electrode integration:
sputtering of 25 nm
TiN film @ 350 °C

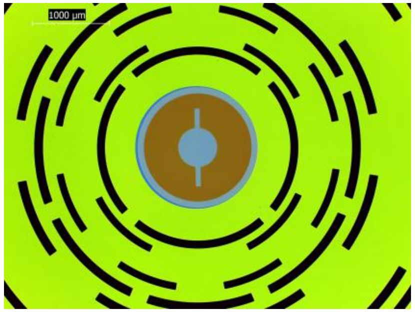
TiN is CMOS compatible
& cryogenically compatible



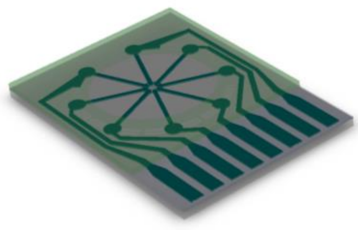


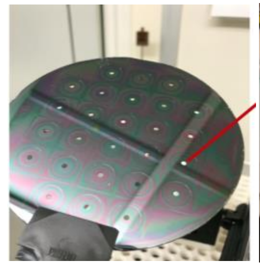


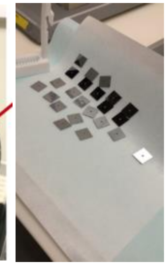
After HF wet etching
release and cleaning



Technology development for the fixed electrode (2020)







Starting from the PREVIOUS technology for microfabricated spacers (developed for HUMOR).

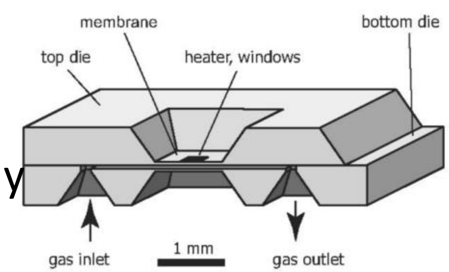
Microfabricated fixed electrode has the required planarity for minimizing optical losses

- **KOH wet-etching/ DRIE recession H** to reach a 3-8 um **gap**
- Patterning metal lines over a thick **SiO_2 (3 um) thermal oxide. Very good i**nsulation from the silicon substrate is needed.

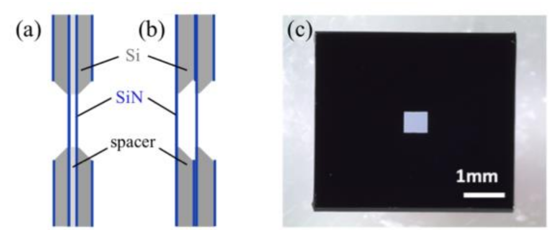
Chip-to-chip bonding + Cavity assembly (2021)

EXAMPLES of assembly

TEM SiNx nanoreactor assembly



Optomechanical SiN two membrane sandwich



SUPREMO:

using molecular spectroscopy to measure variations of β.

$$\frac{1}{\dfrac{\nu(\mathrm{S})}{\nu(\mathrm{Cs})}} \frac{\partial \left[\dfrac{\nu(\mathrm{S})}{\nu(\mathrm{Cs})}\right]}{\partial t} \simeq -\frac{1}{2\beta}\frac{\partial \beta}{\partial t}$$

$$\frac{\nu(\mathrm{S})}{\nu(\mathrm{Cs})}$$

Frequency of a given molecular ro-vibrational transition relative to the clock hyperfine transition in the Cs atomic clock

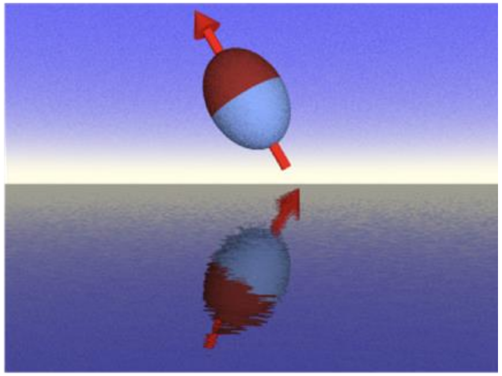
Florence Group Members:

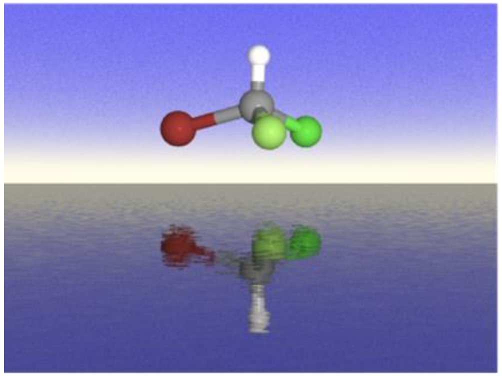
Simone Borri (INO-CNR)
Giacomo Insero (INO-CNR)
Gabriele Santambrogio (INRIM)

Napoles Group Members:

Pasquale Maddaloni (INO-CNR)
Valentina Di Sarno (INO-CNR)
Roberto Aiello (INO-CNR)

The electric dipole moment (EDM)
of fundamental particles

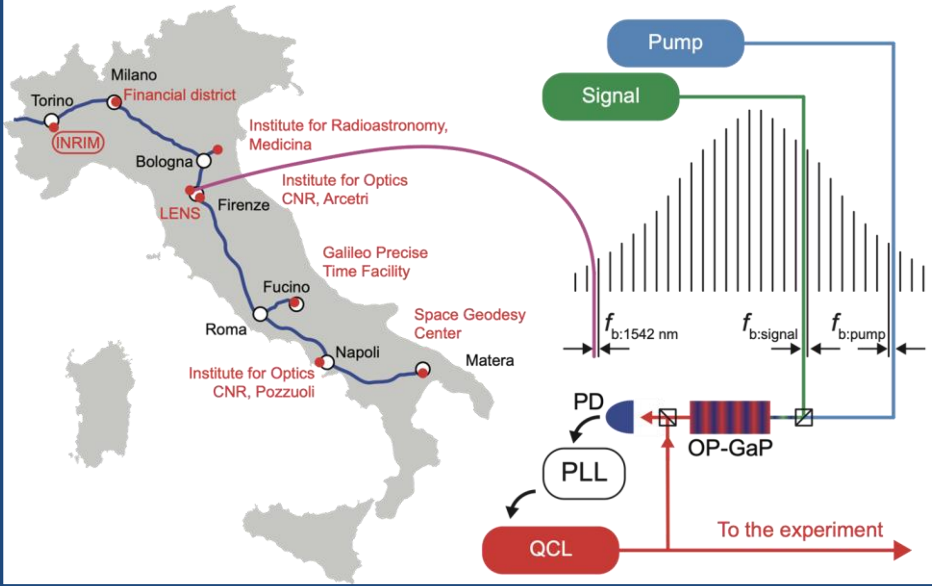




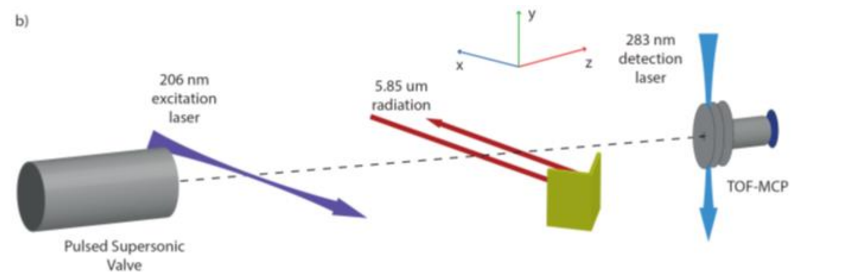
Parity violation

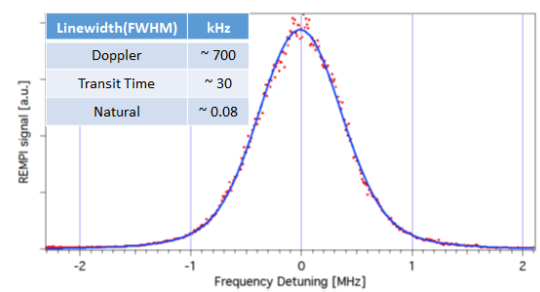
- Variations of fundamental constants
- Test of QED and search for a fifth force
- Determination of the Boltzmann constant

Instrument: a mid infrared laser referenced to the primary frequency for molecular spectroscopy



Usage: CO ro-vibrational transition measured with ***<u>11-digit accuracy on a molecular beam</u>***



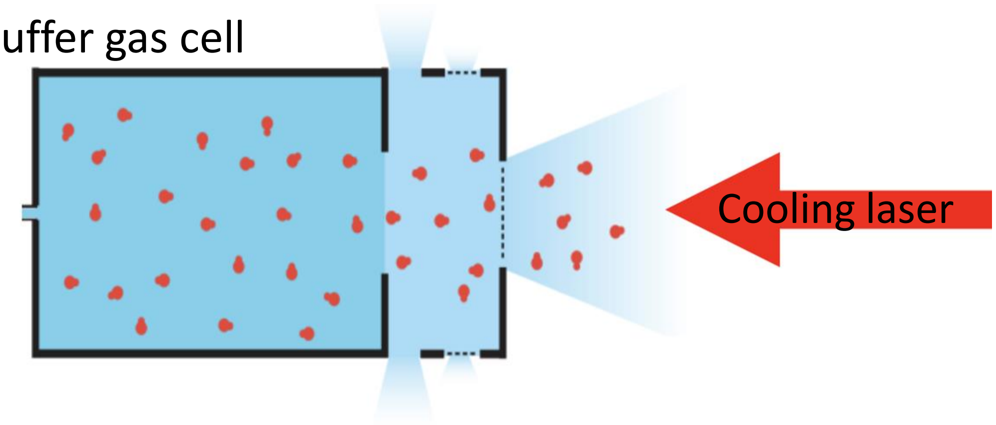


Linewidth(FWHM)	kHz
Doppler	~ 700
Transit Time	~ 30
Natural	~ 0.08

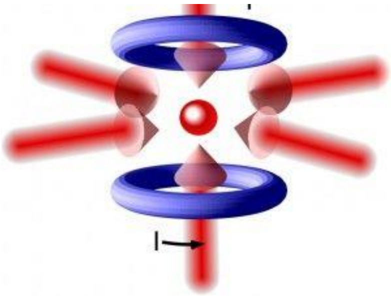
Temperature of the molecules is the current limit.

→ Colder molecules by buffer gas cooling + laser cooling

Buffer gas cell



<u>Towards ultra-cold molecules</u>



Lowest temperature of "real molecule" is currently tens of uK (ultra-cold atom experiment few nK)

Ultra-cold molecules would allow:

- Extremely precise transition energy measurement
- Discovery of new physics based on low-energy scale experiments
- Precise sensors to external fields
- Quantum simulation with long-range interaction

Conclusioni

- Le tecnologie quantistiche possono essere utilizzate per lo sviluppo di strumenti sia per impieghi in fisica fondamentale sia per applicazioni tecnologiche.

- Le recenti attività/sigle di gruppo 5 nate da esperimenti «quantum» di gruppo 2 (e non solo) mostra come sia presente la volontà da parte dei gruppi di ricerca in sezione di rendere fattuale tale trasferimento tecnologico.

GRAZIE DELL'ATTENZIONE!