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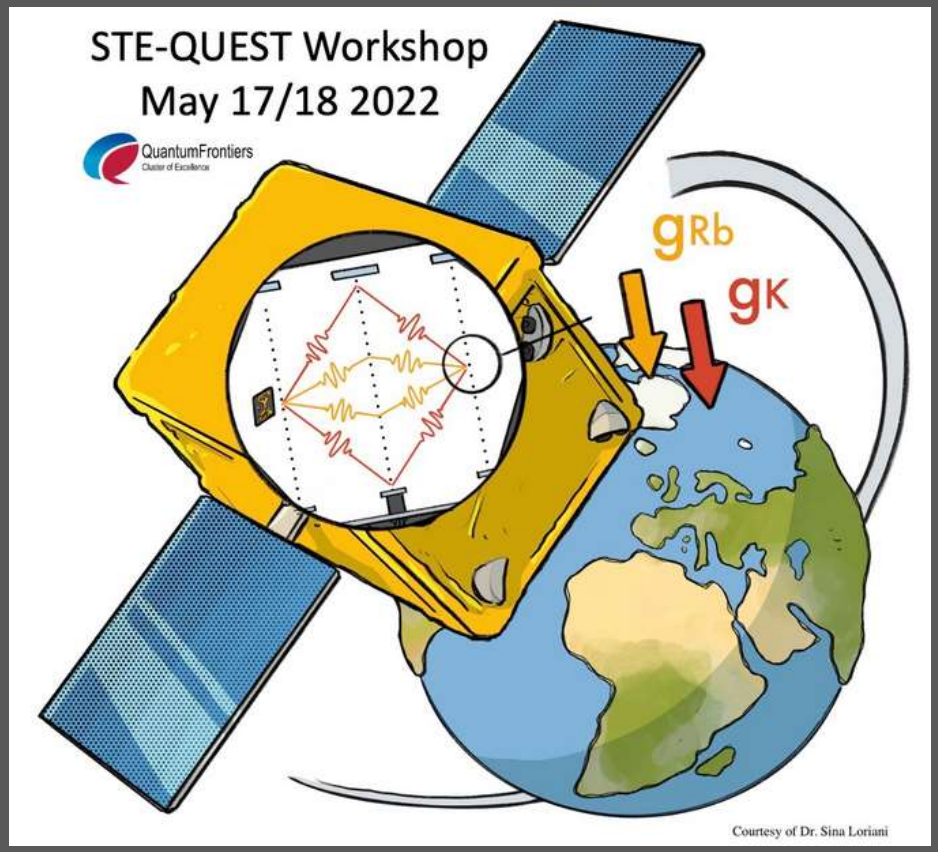
Universality of Free Fall & Einstein Equivalence Principle



STE-QUEST Core Team

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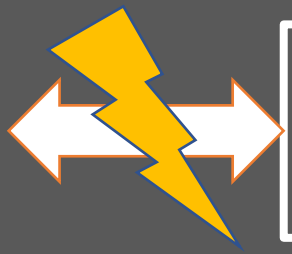
United Kingdom	Kai Bongs , Oliver Buchmueller, John Ellis
United States	Nan Yu

Lead proposer: Peter Wolf

ONE MOST CHALLENGING QUESTION

Quantum Field Theory (QFT) Standard Model of PP (SM)		General Relativity (GR) SM of Cosmology (SMC)

- Unifying GR with the other SM interactions?
- Accounting for Dark energy (DE) and Dark matter (DM) in the SM ?
- Why is vacuum energy density expected from the SM 40-120 orders of magnitude larger than observed (DE)?

Most proposed answers to these questions involve new fields that have no good reason to be universally coupled to the SM-fields

➡ Violation of Einstein Equivalence Principle

What is the Equivalence Principle (EP)?

Why testing it?

Why would EP be violated?

https://www.youtube.com/watch?v=xF8hEUKjauY

https://youtu.be/EtXIWYFEIIU?t=696

See e.g. recent review:

G. Tino, L. Cacciapuoti, S. Capozziello, G. Lambiase, F. Sorrentino, Precision Gravity Tests and the EEP, Progress in Particle and Nuclear Physics, 112, 103772 (2020)

GR OUR BEST THEORY OF GRAVITY

General Relativity (GR) addresses a wide range of phenomena: Galaxies dynamics, large-scale structures formation and dynamics, whole universe dynamics, ….

GR is based on following principles:

- **Relativity principle: no preferred inertial frames, all (accelerated or no) frames are ok**
- **Equivalence Principle (EP): locally, inertial and gravitational effect are indistinguishable**
- **General covariance: field equations must be in covariant form**
- **Causality: each spacetime point has past, present, future**

EP: one of GR building blocks

Weak Equivalence Principle (WEP/Universality of Free Fall):

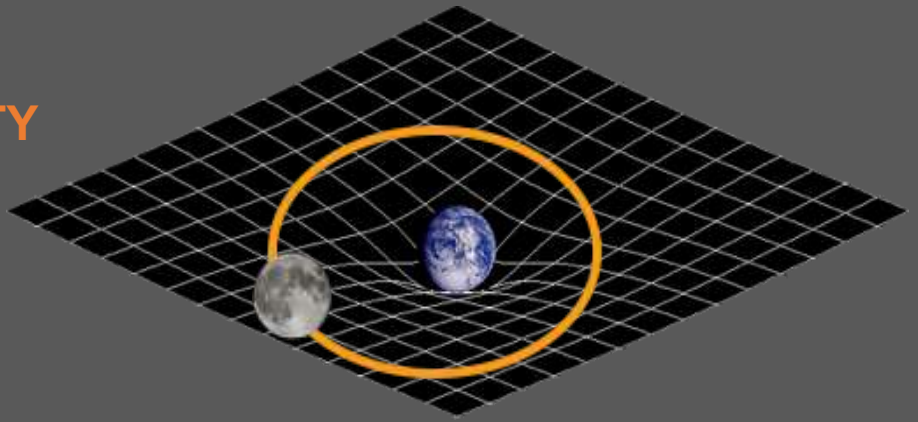
- Inertial and gravitational mass are equivalent. Thus:
- Locally, one cannot distinguish inertial and gravitational effects using the straightforward observation of physical objects free-fall
- Objects with different internal composition are subject to the same acceleration when moving in a gravitational field

Generalized, Einstein EP (EEP): Special Relativity is locally valid, Thus:

- **WEP** is valid
- **LLI**: Outcome of any "local non-gravitational" test is independent of frame velocity (of measuring apparatus) (Local Lorentz Invariance)
- **LPI**: and of where & when is performed (Local Position Invariance)

- **GRAVITY IS A CURVATURE OF SPACETIME: A UNIVERSAL PROPERTY**

- **EEP IS CRUCIAL FOR ALL METRIC THEORIES OF GRAVITY**



“Local non-gravitational exp”: performed in small-size free-falling lab:

- **Gravitational interactions depend on spacetime curvature**
- **Metric constitutes dynamic variables**
- **World lines of test bodies are geodesics of the metric**
- **In local Lorentz (free falling) frames, non-gravitational laws of physics (e.g. driven by strong+electroweak forces) are SR ones. E.g. gravitational redshift**

Strong Equivalence Principle (SEP): EEP with gravitational energy in!

EEP encodes the local Lorentz invariance:

1. **Clock rates are independent of the clocks velocities**
2. **Local position invariance, i.e. the universality of red-shift**
3. **Universality of free fall: all free falling point particles follow the same trajectories independently of their internal structure and composition**
   - **1 and 2 can be tested with e.g. atomic clocks**
   - **3 can be tested by tracking trajectories**

What is the Equivalence Principle (EP)?

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G. Tino, L. Cacciapuoti, S. Capozziello, G. Lambiase, F. Sorrentino, Precision Gravity Tests and the EEP, Progress in Particle and Nuclear Physics, 112, 103772 (2020)

IT REMAINS A HEURISTIC HYPOTHESIS:

- **BASED ON OBSERVATIONS: BODIES FALL WITH SAME ACCELERATION IN A GRAVITATIONAL POTENTIAL**
- **NOT BASED ON ANY UNDERLYING PRINCIPLE OR FUNDAMENTAL SYMMETRY (as e.g. gauge sym in SM)**
  - **WHY UNIVERSAL CHARACTER OF GRAVITATION SEEMS ANOMALOUS COMPARED TO OTHER INTERACTIONS?**

    (e.g. it does not rely on internal charges)
  - **WHY IS GRAVITATION SO DIFFERENT?**

Despite successes of GR, a number of issues:

- **@ infrared scales (cosmology) Big Bang singularity, flatness, monopoles: SMC and SM-PP inadequate at extreme energy curvatures regimes**

- **@ ultraviolet scales (quantum field theory): GR cannot work as a fundamental theory of gravity with a quantum spacetime**

- **Act on the sources of Einstein field equations: introduce exotic forms of matter (Dark Matter) and energy (Dark energy) – in fact making up to 95% of total matter + energy**

- **Act on geometric view:**
  - **Effective theories with GR recovered in some limit (e.g. @solar system scales)**
  - **Extended Theories of Gravity based on adding higher-order curvature invariants and (non/)minimally coupled scalar fields (maybe due to field quantization of spacetime?)**

What is the Equivalence Principle (EP)?

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- Several DM and DE models break EP due to the introduction of new fields expected to non-universally couple to SM
- Same with several unification scenarios (strings, branes, …)
- Some attempts to develop a quantum theory of gravitation lead to a breaking of Lorentz symmetry
- EP breaking can explain the values of some arbitrary SM constants
- WEP and LLI can be violated in extended SM theories, e.g. due to coupling to generalized charges
- SEP can be violated in extended GR theories, e.g. in presence of a scalar field non-minimally coupled to geometry
- EP can be violated at finite T: fraction of particle mass might arise via finite-T radiative corrections spoiling Lorentz-invariance of vacuum

For a detailed discussion, see also T. Damour, Class. And Quantum Grav., 2012

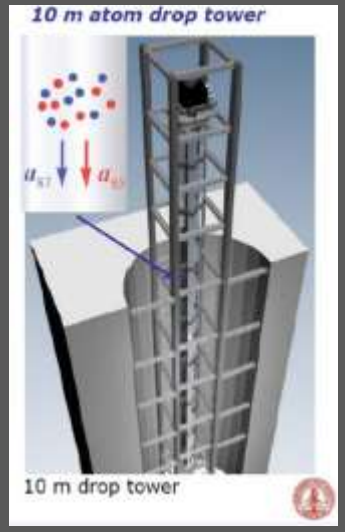
- EEP crucial question for any self-consistent theory of gravity and can discriminate competing theories
- EEP Can hold at classical level but be violated at quantum level
- If violated at fundamental level, causal and geodesic structures could be independent

Natural question is not

"why should EEP be violated?"

but rather

"WHY HAVEN'T WE SEEN A VIOLATION YET?"
"TO WHAT EXTENT DOES IT HOLD?"



$$\eta_{AB} = 2\,\frac{a_A - a_B}{a_A + a_B}$$

Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
Quantum	^{39}K - ^{87}Rb	3×10^{-7}	2020	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020	10 m tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2023+	under construction at CERN

STE-QUEST: 3 orders of magnitude better !!!

Next generation of UFF tests will be in space

- Space exp: long free fall times and quiet +well controlled environment
  Demonstrations: MICROSCOPE and LISA-Pathfinder missions

- Ground exps: ultimately limited by local gravity gradients and uncertainties in the positioning of the test masses
  Not the case in space as demonstrated by MICROSCOPE

- Europe has a clear lead in the field
  MICROSCOPE, LISA-Pathfinder, ACES/PHARAO

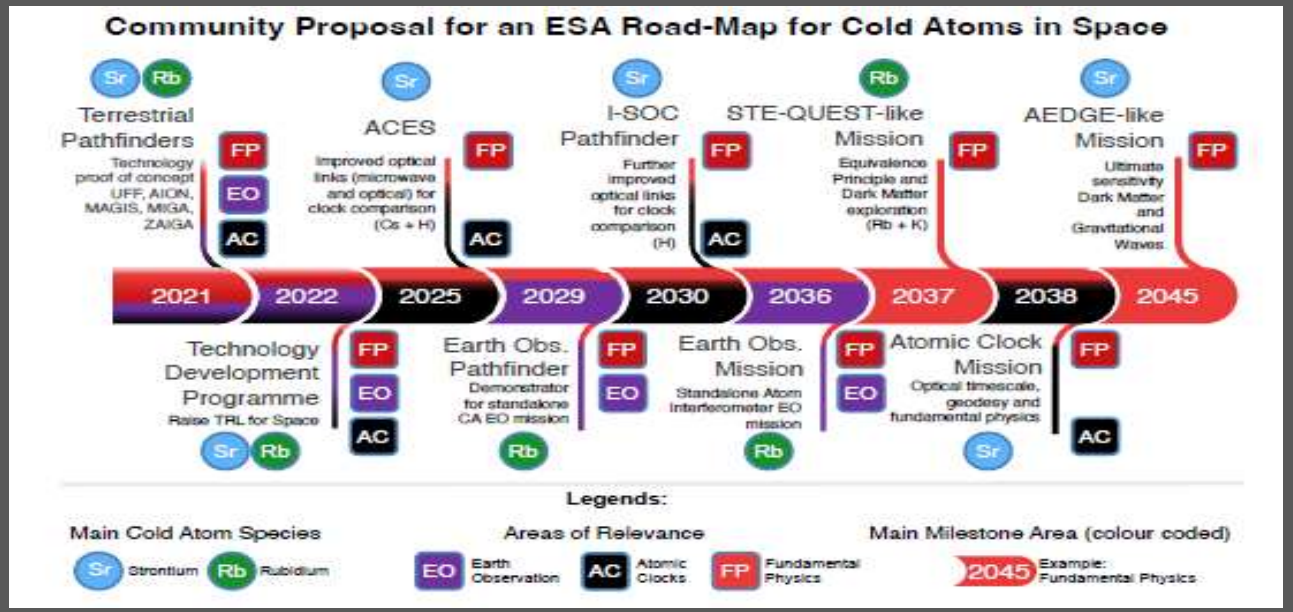
- Available technological heritage offered by space-accelerometers (classical or cold-atoms) for applied fields:
  - gravity field recovery (GRACE, GOCE, GRACE-FO)
  - navigation
  - planetary and lunar exploration

STE-QUEST: Quantum Space Test of UFF at 10^{-17}

- Double Atom Interferometer (AI) with Rb and K "test masses" in non-classical states (quantum superpositions)
- Optimized for UFF test (local g, atm drag, gravity grad, eclipses): assumes 700 km Sun Syn circular orbit
- Applies recent results on controlling gravity gradient shifts by laser freq offset: atom positioning requirements relaxed by factor >100
- Uses last decade tremendous tech development for AI in space

➡ Reaches 10^{-17} target after 18 months of operation

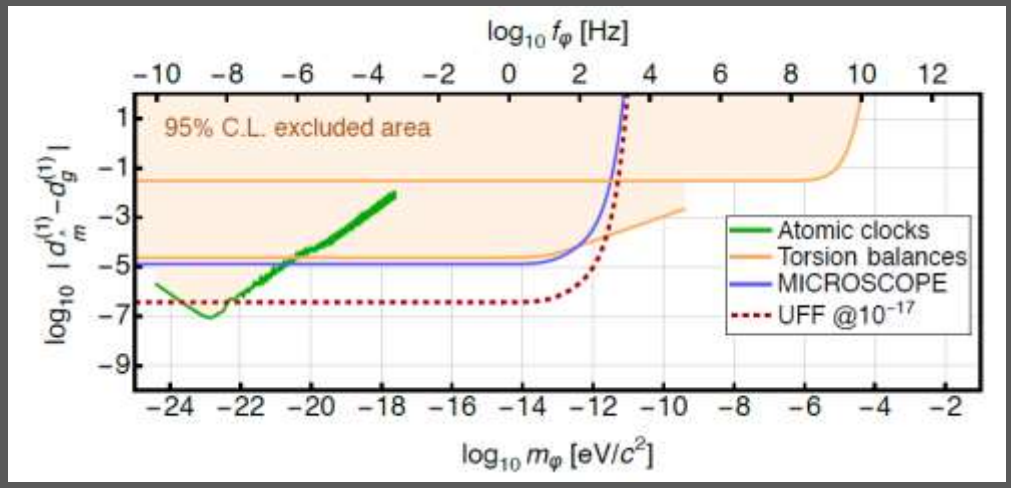
- Milestone for future more ambitious missions
- Integral part of recent AEDGE community roadmap for cold atoms in space [arXiv: 2201.07789]



Expected scientific outcome from STE-QUEST

- 2-3 orders of magnitude improvement in test of EP: pushing the limit of fundamental physics into a totally unexplored region with possible groundbreaking discovery or stringent constraints theo scenarios

- Extend parameters search for various DM candidates by 1-2 orders of magnitude: scalar Ultra Light Dark matter, new U(1) gauge boson, …

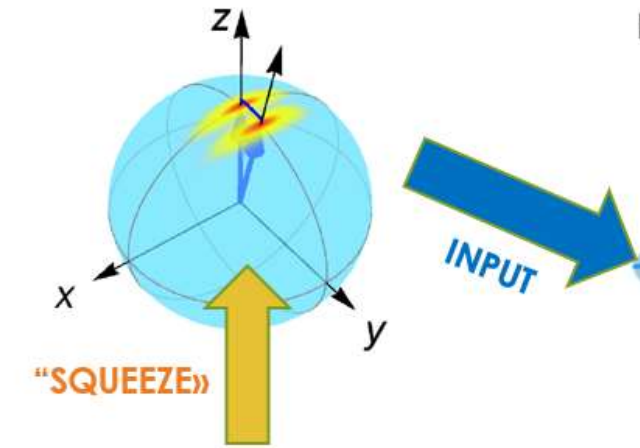


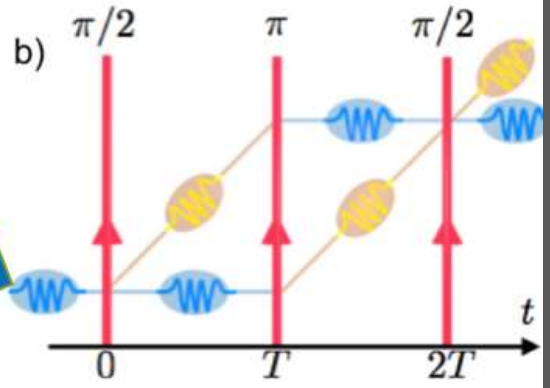
- Extend the parameter search for a violation of Lorentz or CPT symmetry (dedicated analysis) by 3 orders of magnitude. Test for SM Extended and QG Theo

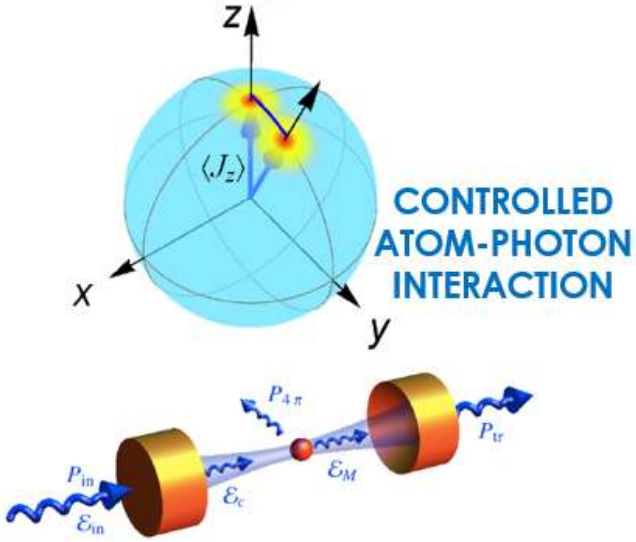
- Test foundations of Quantum Mechanics: the validity and the breakdown of the superposition principle. Expected improvement by up to 4 orders of magnitude

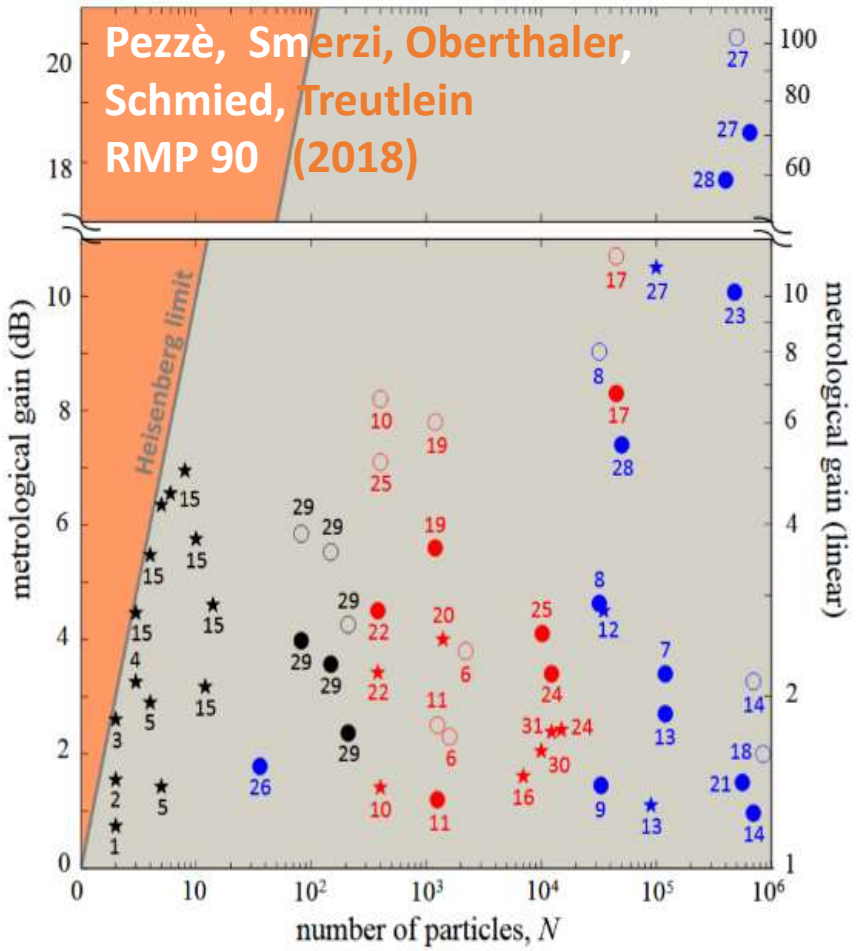
NEW PARADIGMS FOR METROLOGY

[Shankar, Salvi, Poli,Chiofalo, Holland, QST (2019)]









TRAPPED IONS
[1] Sackett *et al.*, 2000
[2] Meyer *et al.*, 2001
[3] Leibfried *et al.*, 2003b
[4] Leibfried *et al.*, 2004
[5] Leibfried *et al.*, 2005
[15] Monz *et al.*, 2011
[29] Bohnet *et al.*, 2016

BOSE-EINSTEIN CONDENSATES
[6] Estève *et al.*, 2008
[10] Gross *et al.*, 2010
[11] Riedel *et al.*, 2010
[16] Lücke *et al.*, 2011
[17] Hamley *et al.*, 2012
[19] Berrada *et al.*, 2013
[20] Ockeloen *et al.*, 2013
[22] Strobel *et al.*, 2014
[24] Muessel *et al.*, 2014
[25] Muessel *et al.*, 2015
[30] Kruse *et al.*, 2016
[31] Zou *et al.*, 2018

COLD THERMAL ATOMS
[7] Appel *et al.*, 2009
[8] Leroux *et al.*, 2010a
[9] Schleier-Smith *et al.*, 2010b
[12] Leroux *et al.*, 2010b
[13] Louchet-Chauvet *et al.*, 2010
[14] Chen *et al.*, 2011
[18] Sewell *et al.*, 2012
[21] Sewell *et al.*, 2014
[23] Bohnet *et al.*, 2014
[26] Barontini *et al.*, 2015
[27] Hosten *et al.*, 2016a
[28] Cox *et al.*, 2016

Q-TECHNOLOGY

FOR Q-METROLOGY

Thanks Everyone

for your attention

Nanchi

https://youtu.be/EtXIWYFEIIU?t=696

Episode III: Pisa 26-28 October 2022

https://agenda.infn.it/event/QFC2022

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KEYNOTE SPEAKERS

T1- Equation of state:
Francesca Ferlaino (Q)
Isaac Vidana (F)
Samaya Nissanke (C)

T2-Tests of GR:
Mark Kasevich (Q)
John Ellis (F)
Eleonora Di Valentino (C)

T3-Analog quantum sims for F and C:
Monika Schleier-Smith (Q)
Massimo Mannarelli (F)
Ivette Fuentes (C)

TRANSVERSAL KEYNOTE SPEAKER:
Gordon Baym