Tests of Quantum Mechanics

ECFA Detector & Roadmap Symposium
of Task Force 5
Quantum and Emerging Technologies

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The quantum superposition principle

It is the **building block** of Quantum Mechanics (and of QFT, QG, Strings, Loops …):

- Schrödinger's cat states
- Entanglement
- Plane waves

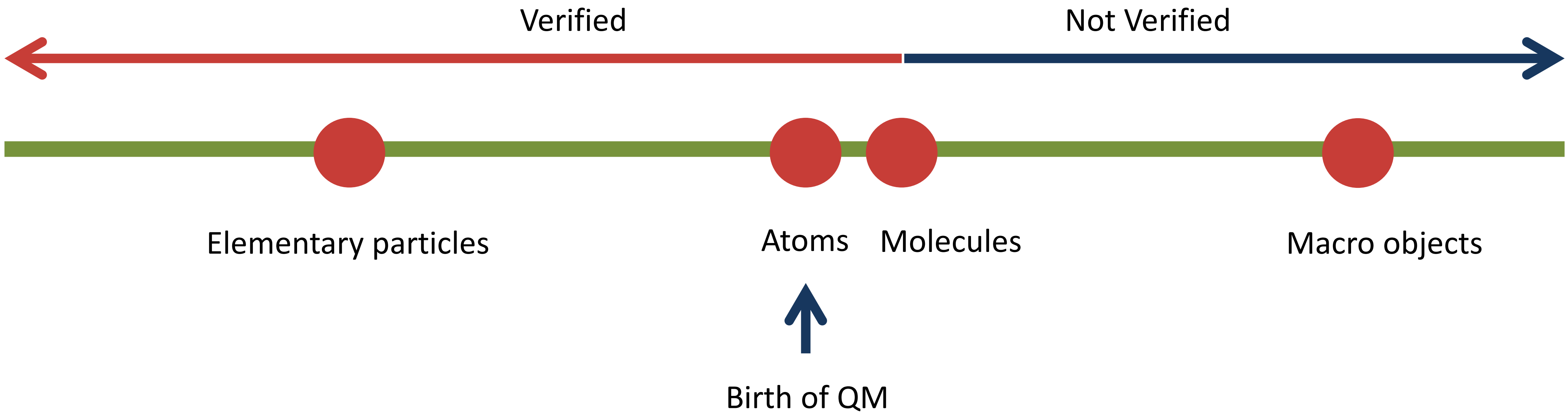
and in general everything that is related to **interference**.

A wave description of quantum phenomena was the very reason why Quantum Mechanics was formulated in the first place.

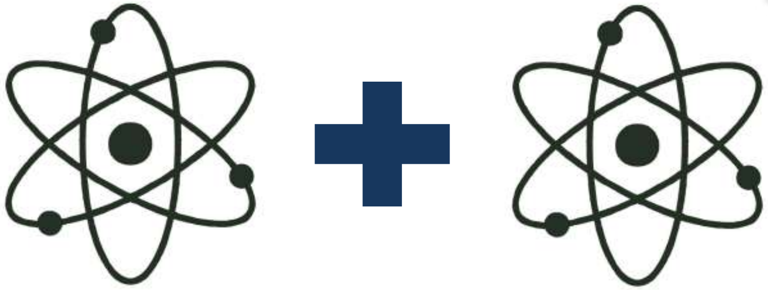
Quantization = waves = superposition principle

Why testing the quantum superposition principle?

- Like any theory, it is important to tests its limits of validity (like the EP with GR)
- Measurement problem in Quantum Mechanics
- Difficulties in combining Quantum Mechanics and General Relativity (Penrose)
- Possible limits to the scalability of Quantum Technologies



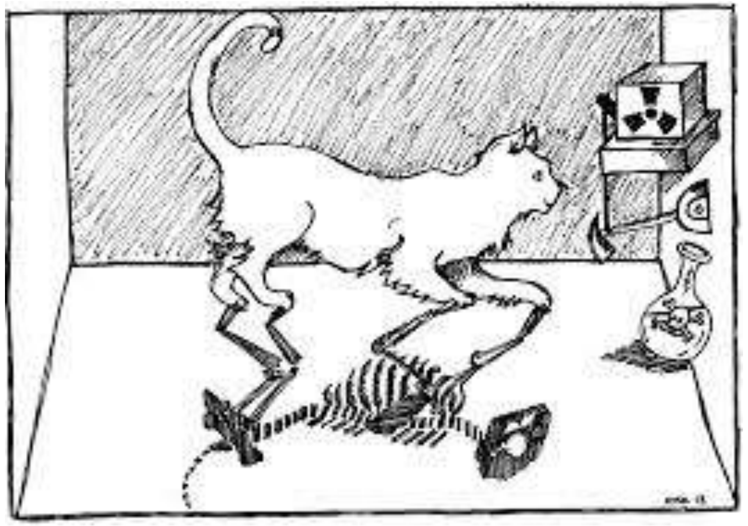
The measurement problem



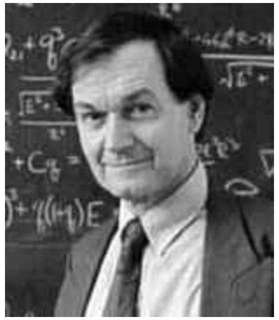
Microscopic superpositions
Experimentally verified

Cats are made of atoms + linearity of the theory

Macroscopic superpositions



If you push quantum mechanics hard enough it will break down and something else will take over – something we can't envisage at the moment.
Anthony J. Leggett



I believe that one must strongly consider the possibility that quantum mechanics is simply wrong when applied to macroscopic bodies
Roger Penrose

I'm not as sure as I once was about the future of quantum mechanics.
Steven Weinberg

Alternative models

- Models of spontaneous wave function collapse

  A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003), A. Bassi, K. Lochan, S. Satin, T.P. Singh and H. Ulbricht*, Rev. Mod. Phys.* 85, 471 (2013)

- Gravity induced collapse

  L. Diosi, Phys. Rev. A 40, 1165 (1989). R. Penrose, *Gen. Rel. Grav*. 28, 581 (1996)

- Gravity as a classical channel

  D. Kafri, J. M. Taylor, and G. J. Milburn, New J. Phys. 16, 065020 (2014). A. Tilloy and L. Diosi, Phys. Rev. D 96, 104045 (2017)

- Gravitational decoherence

  I. Pikovski, M. Zych, F. Costa, C. Brukner, Nature Physics 11, 668â��672 (2015)

- Semiclassical gravity (Schrödinger-Newton Equation)

  L. Diosi, Physics Letters A 105, 199 (1984).

New (quantum) physics

What described before can be used to describe **new physics, not necessarily non-quantum**, if it induces decoherence

- Stochastic gravitational wave background

  L. Asprea *et al.*, ArXiv 1912.12732 (to appear in PRL). L. Asprea *et al.,* ArXiv 1905.01121 (to appear in PRD)

- Gravitons

  M. P. Blencowe, Phys. Rev. Lett. 111, 021302 (2013). C. Anastopoulos *et al.,* Class. Quant. Grav. 30, 165007 (2013)

- Mark matter and more…

  J. Bateman *et al.,* Scientific Reports 5, 8058 (2015)

- Analog gravity

  A.r. Brown *et al.,* ArXiv 1911.06314. S. Plugge *et al.,* Phys. Rev. Lett. 124, 221601 (2020). T. Schuster *et al.,* ArXiv 2102.00010. S. Nezami *et al.,* ArXiv 2102.010064

\+ Precision tests of physics

T. Westphal *et al.,* Nature 592, 225 (2021)

Alternative models

In general, their predictions are mathematically expressed by

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \sum_{i=1}^{N^2-1} \gamma_i \left(L_i \rho L_i^\dagger - \frac{1}{2} \left\{ L_i^\dagger L_i, \rho \right\} \right).$$

↑ State of the system (density matrix)

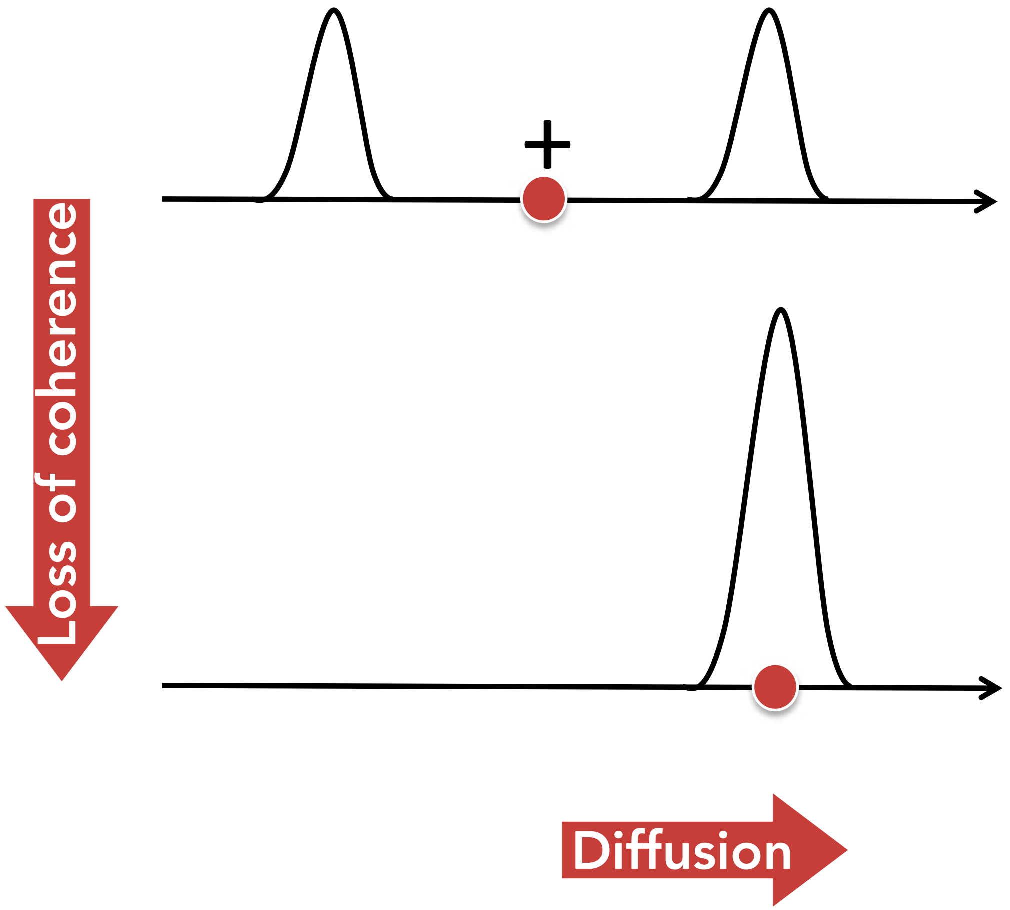
↑ Quantum Mechanics (unitary evolution)

↑ Additional effects (collapse, decoherence, …)

↑

Two fundamental predictions:
- **Loss of coherence**
- **Diffusion**

Loss of coherence & Diffusion



= center of mass

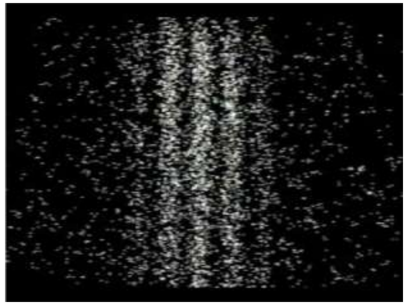
Every time **coherence** (in position) **is lost**, **diffusion** (in position) is associated to it.

Diffusion occurs also when the system **is not** in a quantum superposition.

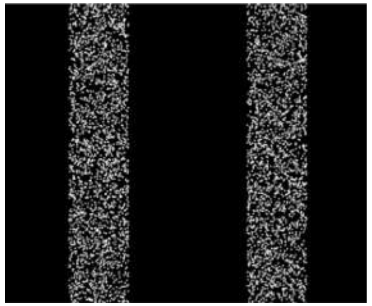
How to test these models

Interferometric experiments

Create a large superposition, in terms of mass, distance and duration, a perform a “double slit” experiment



Prediction of
quantum mechanics
(no environmental noise)

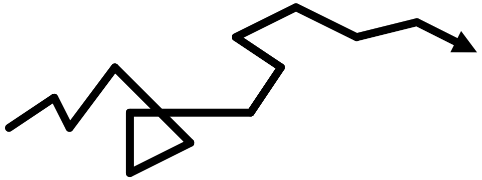


Prediction of
alternative models
(no environmental noise)

Non interferometric experiments

Reach the best possible control of the position of the (center of mass of the) system, and monitor it

Prediction of
quantum mechanics
(no environmental noise)



Prediction of
alternative models
(no environmental noise)

Advantages and disadvantages

Interferometric experiments

+ These are a **direct test** of the quantum superposition principle and of alternative models.

− They are **difficult**. The whole field of quantum optomechanics boomed also with the aim of creating macroscopic quantum states.

Non interferometric experiments

− They are a **direct test** of alternative models and an **indirect test** of the quantum superposition principle.

+ They are **easier** because **no quantum superposition** is needed to test the induced Brownian motion.

Interferometric Experiments (CSL)

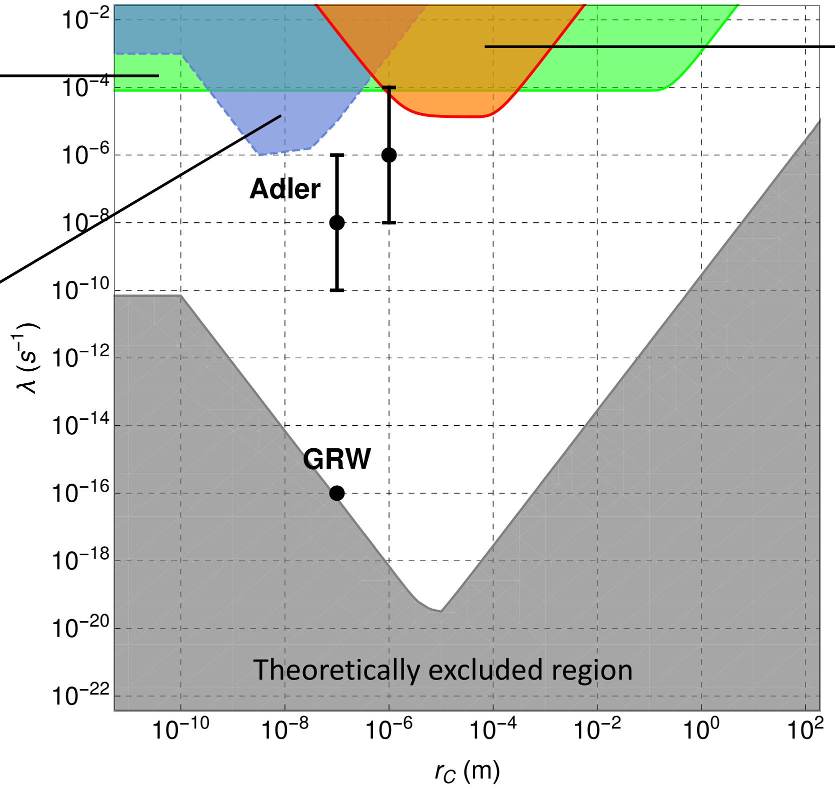
CSL is one of the reference collapse models in the literature

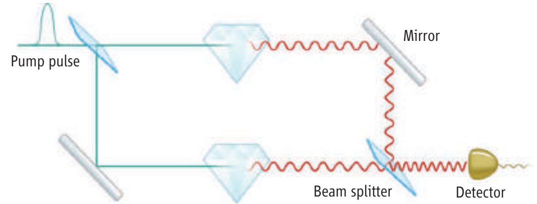
P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi et el., *Phys. Rev. A* 42, 78 (1990)

Atom Interferometry

T. Kovachy *et al.*, Nature 528, 530 (2015)

M = 87 amu
d = 0.54 m
T = 1 s

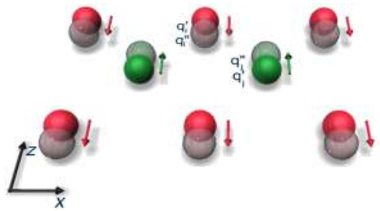




Entangling Diamonds (phonons)

K. C. Lee *et al.*, Science. 334, 1253 (2011).
S. Belli *et al.*, PRA 94, 012108 (2016)

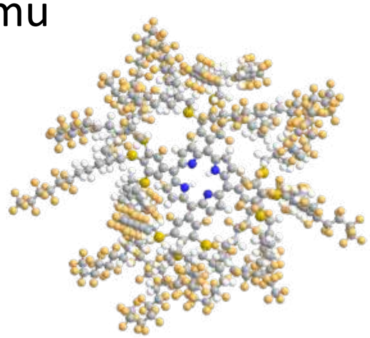
M = 10^{16} amu
d = 10^{-11} m → in reality, much smaller
T = 10^{-12} s



Molecular Interferometry

S. Eibenberger *et al.* PCCP 15, 14696 (2013)
M. Toros *et al.*, PLA 381, 3921 (2017)

M = 10^4 amu
d = 10^{-7} m
T = 10^{-3} s



About 1 order of magnitude improvement with the most recent experiment

Y.Y. Fein *et al.*, Nature Physics 15, 1242 (2019).

The Decoherence function (CSL)

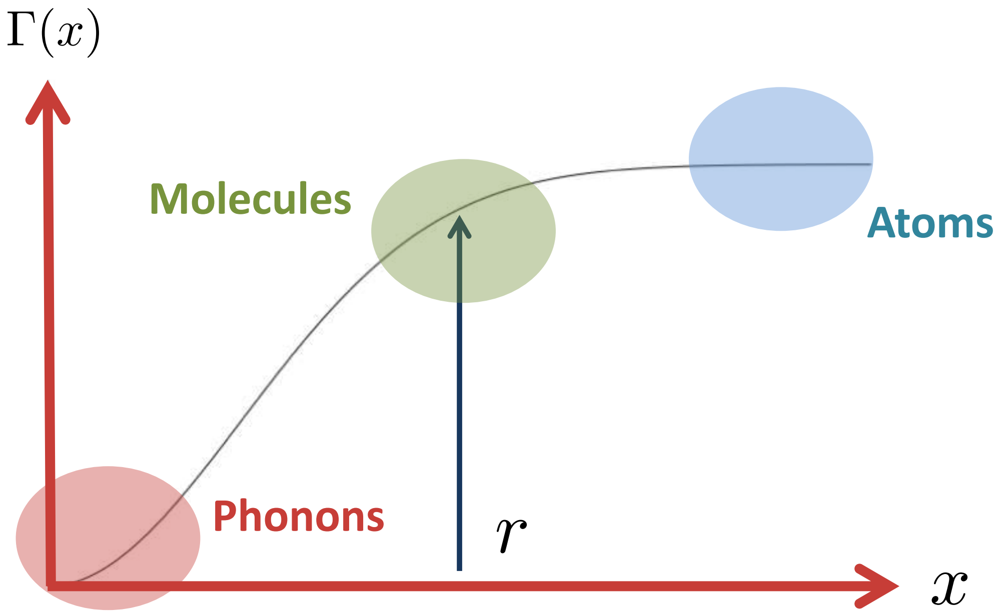
$$\text{Decoherence} \sim e^{-\Gamma(x-y)t}$$

$$\Gamma(x-y) = \lambda\left[1 - e^{-(x-y)^2/r^2}\right]$$

Long times

Large mass - scales with geometry

Large separation



It helps to have larger masses

It helps to have longer times

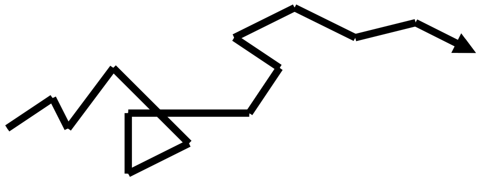
It does not help to have $|x-y| \gg r$

$r \sim 10^{-7}$ m for CSL

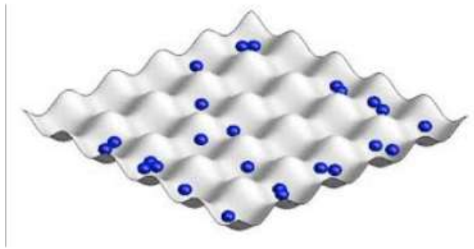
Non-interferometric platforms

Quantum Mechanics

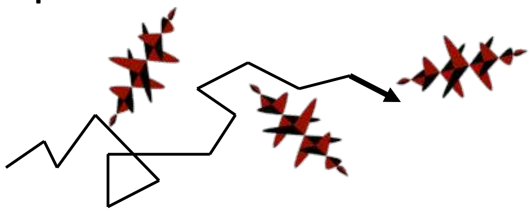
Alternative models



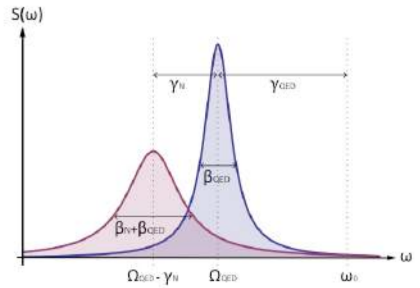
Cold atoms
A gas will expand (heat up) faster than what predicted by QM



Underground Experiments (DM detection)
Charged particles will emit radiation, whereas QM predicts no emission



Optomechanics
A cantilever's motion cannot be cooled down below a given limit



Non - Interferometric Experiments (CSL)

Cold atom gas

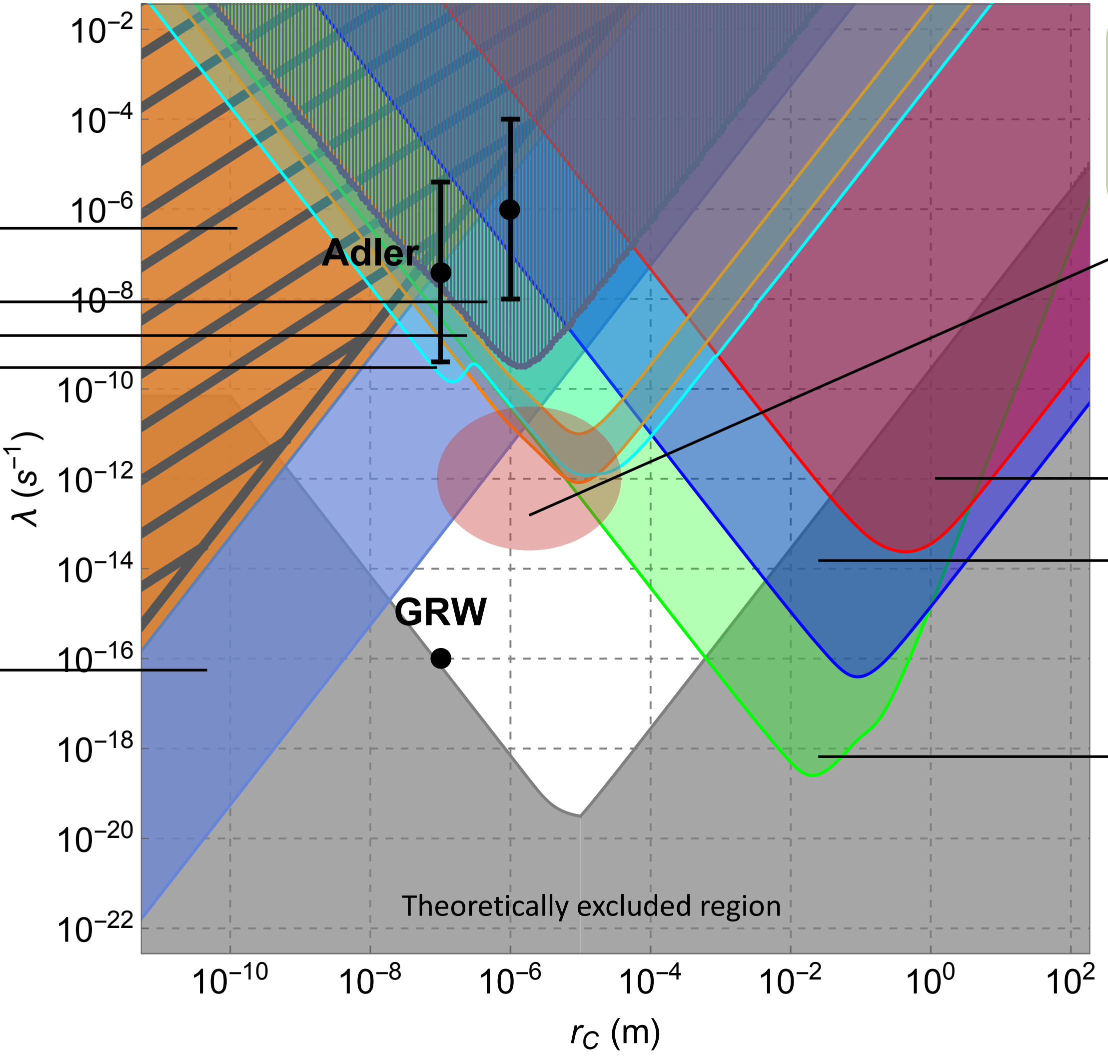
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)
T. Kovachy *et al.*, Phys. Rev. Lett. 114, 143004 (2015)
M. Bilardello *et al.*, Physica A 462, 764 (2016)

Cantilever

A. Vinante *et al.*, Phys. Rev. Lett. 116, 090402 (2016)
A. Vinante *et al.*, *Phys. Rev. Lett.* 119, *110401 (2017)*
A. Vinante *et al.*, *Phys. Rev. Lett.* 125, *100404 (2020)*

X-ray emission

K. Pisicchia *et al.*, *Entropy 19, 319 (2017)*
S.L. Adler *et al.*, Jour. Phys. A 40, 13395 (2009)
S.L. Adler *et al.*, Journ. Phys. A 46, 245304 (2013)
A. Bassi & S. Donadi, Annals of Phys. 340, 70 (2014)
S. Donadi & A. Bassi, Jounr. Phys. A 48, 035305 (2015)
C. Curceanu *et al.*, J. Adv. Phys. 4, 263 (2015)



H2020 FET project
www.tequantum.eu

In progress

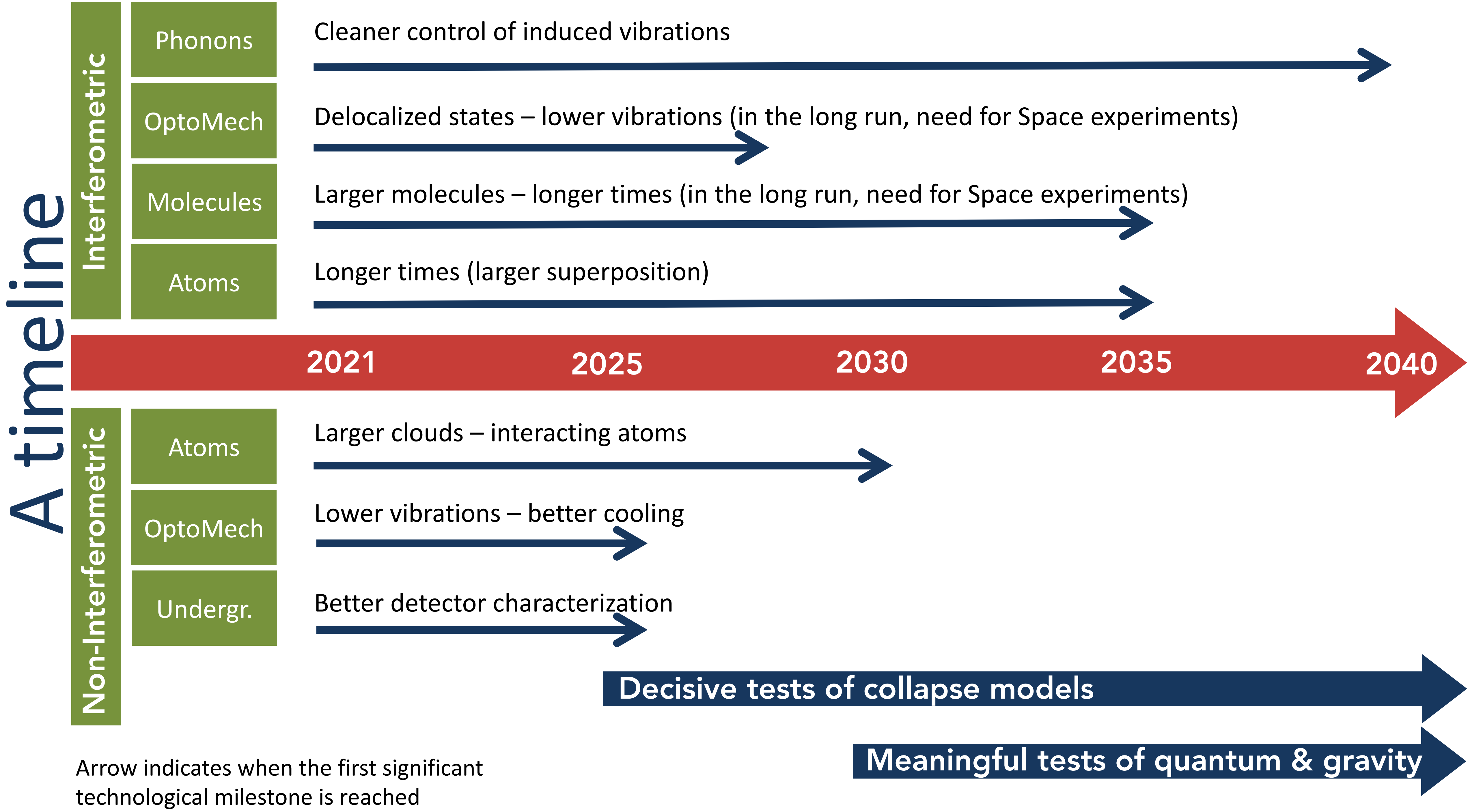
Auriga

Ligo

M. Carlesso *et al.* Phys. Rev. D 94, 124036 (2016)

Lisa Pathfinder

M. Carlesso *et al.*, *N. Journ. Phys 20, 083022 (2018)*


A timeline
Interferometric
Phonons
Cleaner control of induced vibrations
OptoMech
Delocalized states – lower vibrations (in the long run, need for Space experiments)
Molecules
Larger molecules – longer times (in the long run, need for Space experiments)
Atoms
Longer times (larger superposition)
2021
2025
2030
2035
2040
Non-Interferometric
Atoms
Larger clouds – interacting atoms
OptoMech
Lower vibrations – better cooling
Undergr.
Better detector characterization
Decisive tests of collapse models
Meaningful tests of quantum & gravity
Arrow indicates when the first significant technological milestone is reached