Q-Clocks

Cavity-Enhanced Quantum Optical Clocks

Motivations and Needs

Atomic clocks have been and will be a key technology in a broad range of applications spanning from tests of fundamental physical theories (e.g. general relativity, stability of fundamental constants), to daily use technologies (e.g. telecommunications, satellite navigation and radars). Optical clocks, in virtue of their higher accuracy, emerged as a strong candidate for the redefinition of the second.

Most advanced quantum technologies (QT) can surpass the classical noise levels present in optical clocks, allowing better and more stable clocks. To fully exploit the potential offered by QT, it is necessary to realize new quantum engineered states allowing in general to create cooperative behaviours of atomic ensembles. These advancements also support the development of quantum information processing and quantum simulation. These techniques have been proved in various quantum systems (mostly in the RF and microwave domains), but have not been employed at a metrologically relevant level yet.

The goal of the project is to study novel techniques for optical oscillators and quantum sensors, to achieve uncertainties of 10^{-18} in measurement time scales from minutes to hours.

This new generation of clocks will be used to perform test of fundamental physic, like relativity, physics beyond the standard model, more stringent limits on the variation of fundamental physical constants, search for dark matter, as well as in many innovative technological applications that are already appearing at the horizon, like chronometric geodesy,improved VLBI, and sensing.

Scientific Excellence

Atomic clocks today are still “first generation” quantum devices, where extremely accurate spectroscopic measurements are performed using incoherent ensemble of independent quantum particles. The possibility to realize a “second generation” clock, further exploiting the possibilities opened by quantum mechanics, represents a high level scientific goal, that combines scientific excellence and fundamental metrology.

Our goal is to realize a second generation quantum enhanced optical clocks, surpassing the most advanced optical clocks, using smart quantum techniques, to open the 10^{-19} accuracy range.

We will follow a three fold atom cavity system based on highly innovative elements:

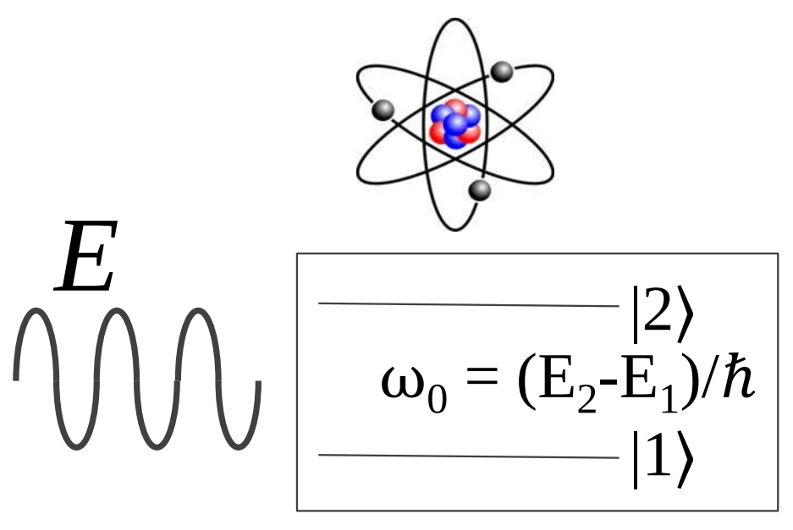
- Non dispersive quantum non demolition system in weak coupling regime to produce entanglement enhanced stability.
- Strong coupling regime to produce a high degree of spin squeezing, thus reducing the clock noise below the QPN limit.
- Narrow linewidth superradiant laser emission to overcome the cavity thermal noise.

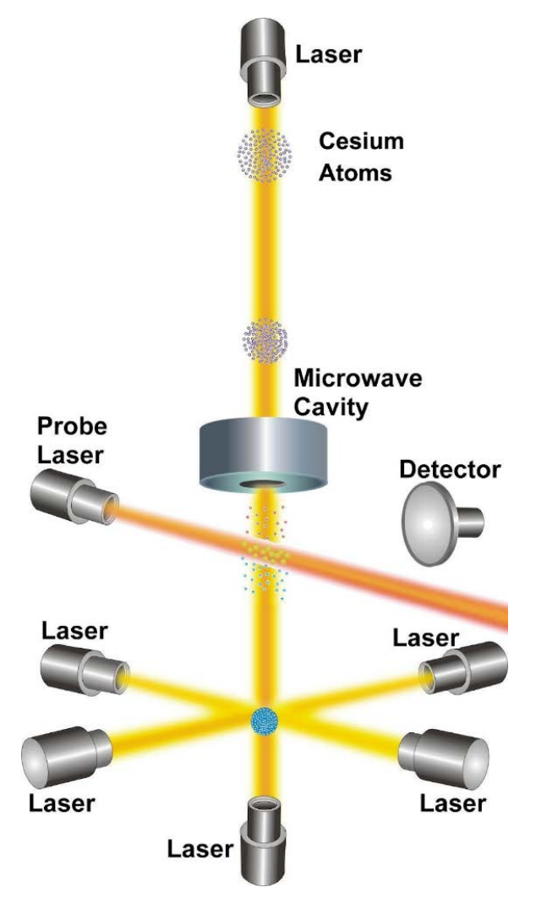
The project goal will be achieved through a joint effort between frequency metrologists and quantum technology experts, experimentalist and theoreticians, capable of introducing new quantum mechanical tools in clocks, and frequency metrology concepts and needs into quantum state engineering.

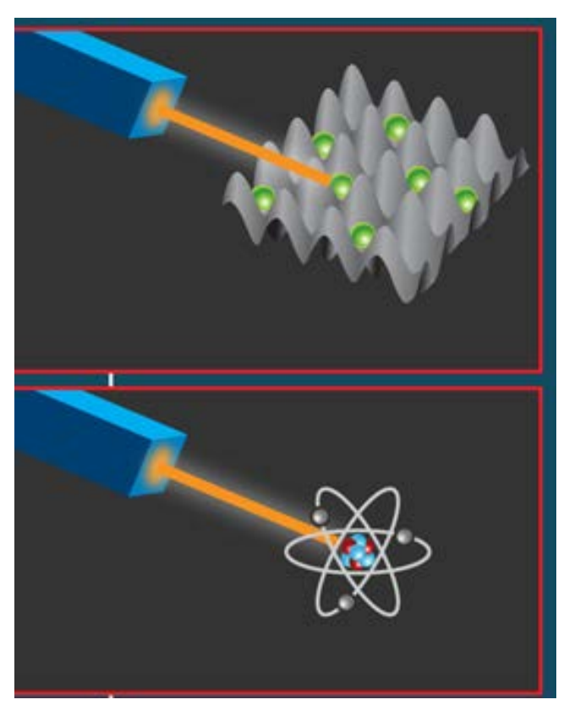
Semiclassical recipe

- *N* identical* & independent absorbers → laser cooled atoms
- A very-classical oscillating *E* field → high frequency, high-Q resonator-referenced *E* source
- A good device to count clock's ticks → Frequency comb

$$\sigma_y(\tau) = \frac{\Delta}{\omega_0}\sigma_{P_e}(T_c)\sqrt{\frac{T_c}{\tau}} \simeq \frac{1}{\pi Q\sqrt{N}}\sqrt{\frac{T_c}{\tau}} \sim 1\times 10^{-18}\,\tau^{-1/2}!!!$$



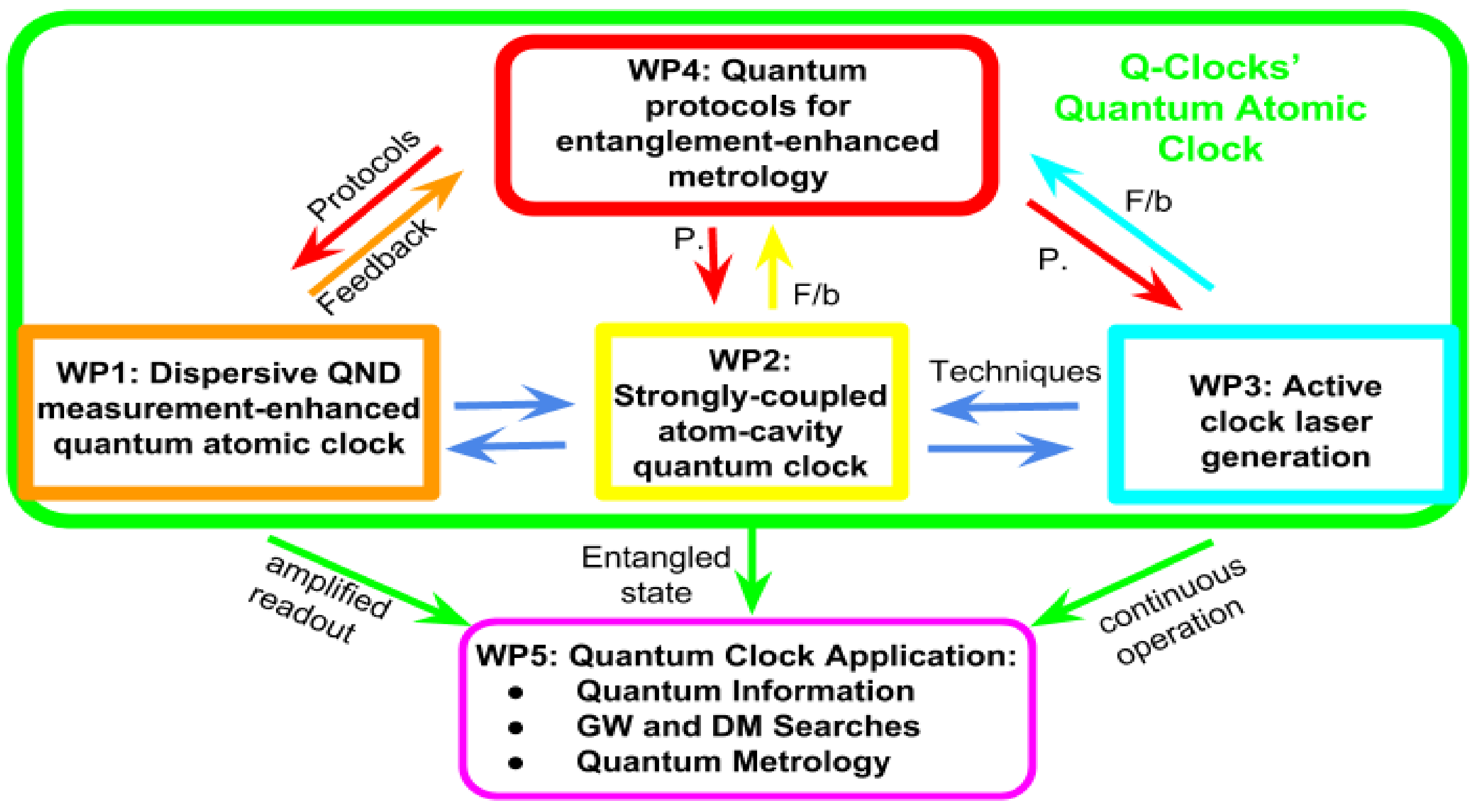




Quantum possibilities

1. Reduce the uncertainty (“**squeeze**”) of our clock' observable by increasing its conjugate observable error [1]
2. Increase the “lifetime” of our clock excited state to make a better reference: **subradiance** [2]
3. Increase/synchronize the radiative rate of our atoms to make a better laser: **superradiance** [2]
4. Keep atomic coherence as long as possible / make our clock “continuous”: **quantum non-demolition** [3], **nonlinear spectroscopy** [4]

[1] D. J. Wineland et al., Spin squeezing and reduced quantum noise in spectroscopy, *Phys Rev A* 46, R6797-R6800 (1992)
[2] R. H. Dicke, Coherence in spontaneous radiation processes. *Phys. Rev.* 93, 99–110 (1954).
[3] V. B. Braginsky, Y. I. Vorontsov, K. S. Thorne, Quantum Nondemolition Measurements, *Science* 209, pp. 547-557 (1980)
[4] M. J. Martin et al., Extreme non-linear response of ultra-narrow optical transitions in cavity QED for laser stabilization, Phys Rev A 84, 063813 (2011)



Q-Clocks' Quantum Atomic Clock

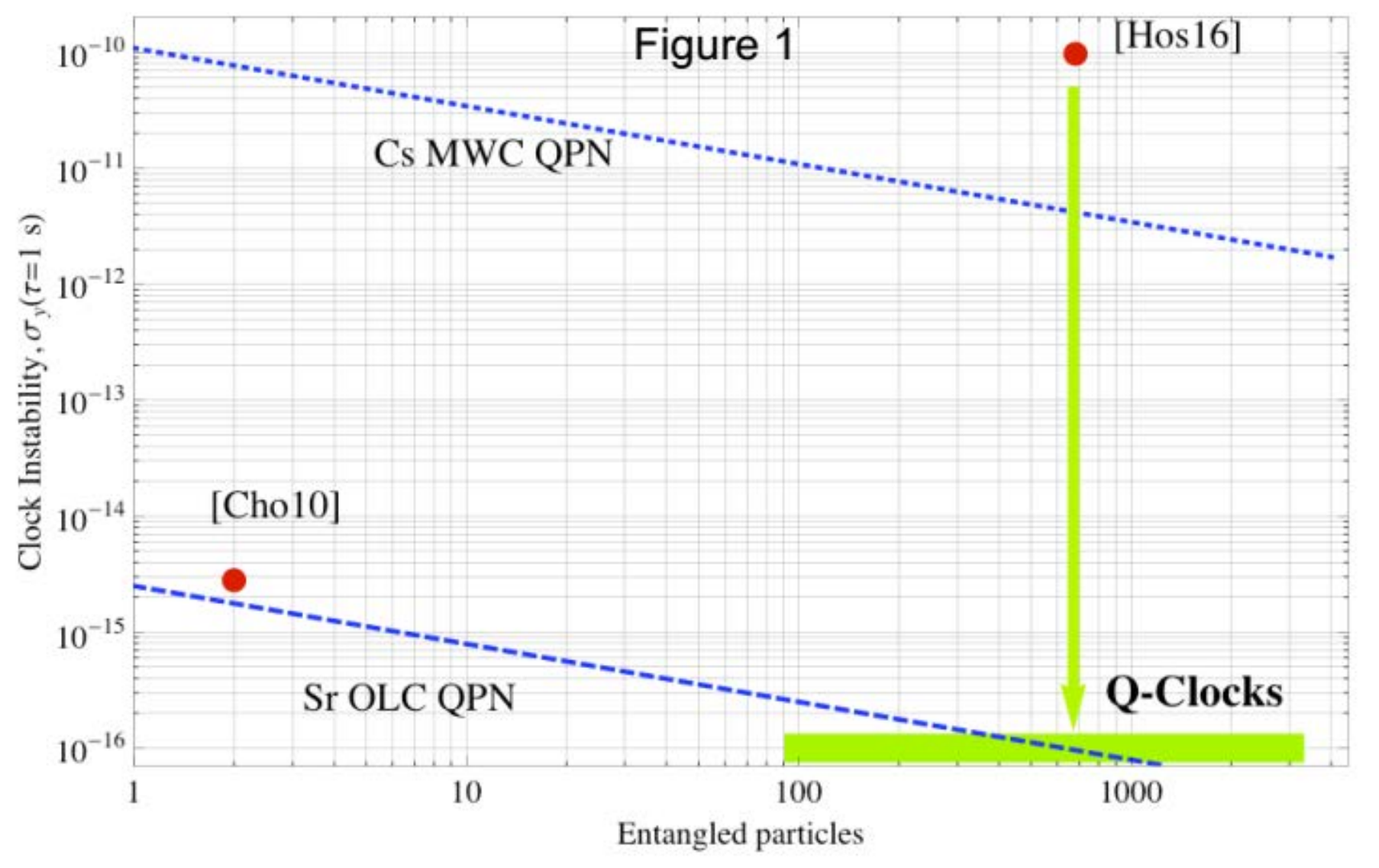
WP4: Quantum protocols for entanglement-enhanced metrology

WP1: Dispersive QND measurement-enhanced quantum atomic clock

WP2: Strongly-coupled atom-cavity quantum clock

WP3: Active clock laser generation

WP5: Quantum Clock Application:
- Quantum Information
- GW and DM Searches
- Quantum Metrology

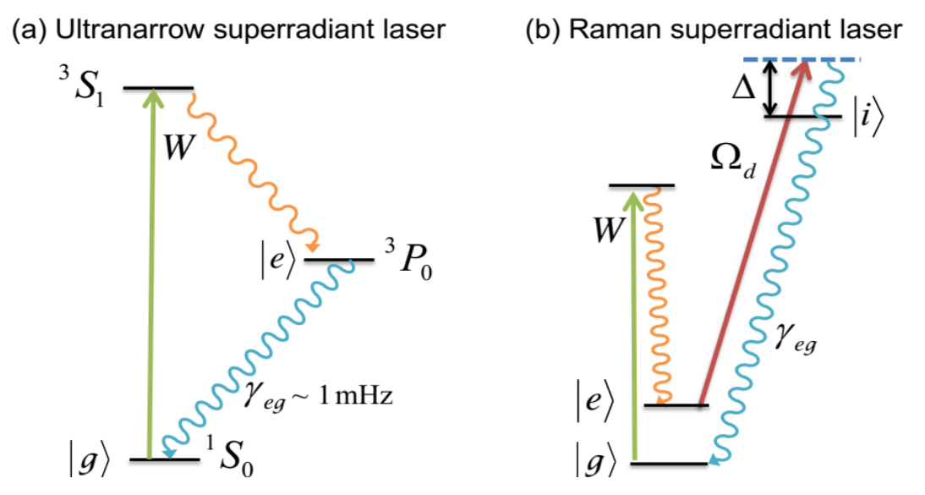


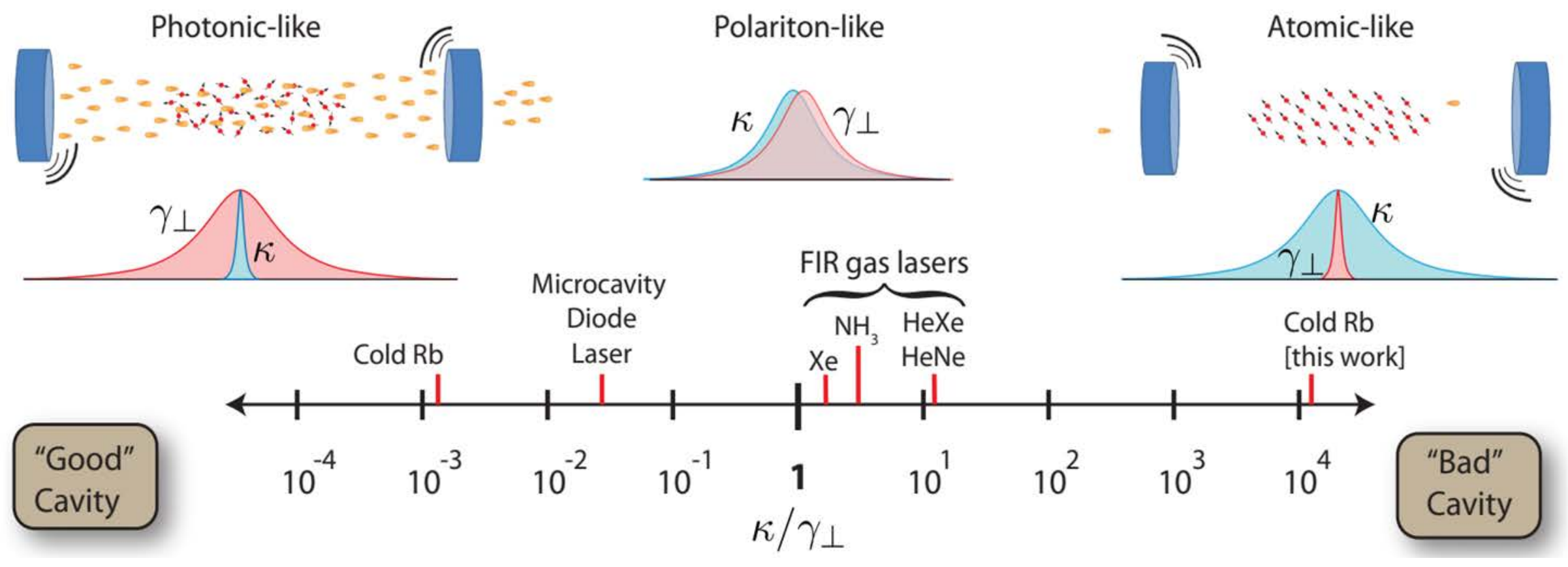
Experiments exploiting entangled states to beat the projection-noise limit have been restricted to microwave transitions [Hos16] and strongly confined systems [Cho10], with performance far from state-of-the-art.

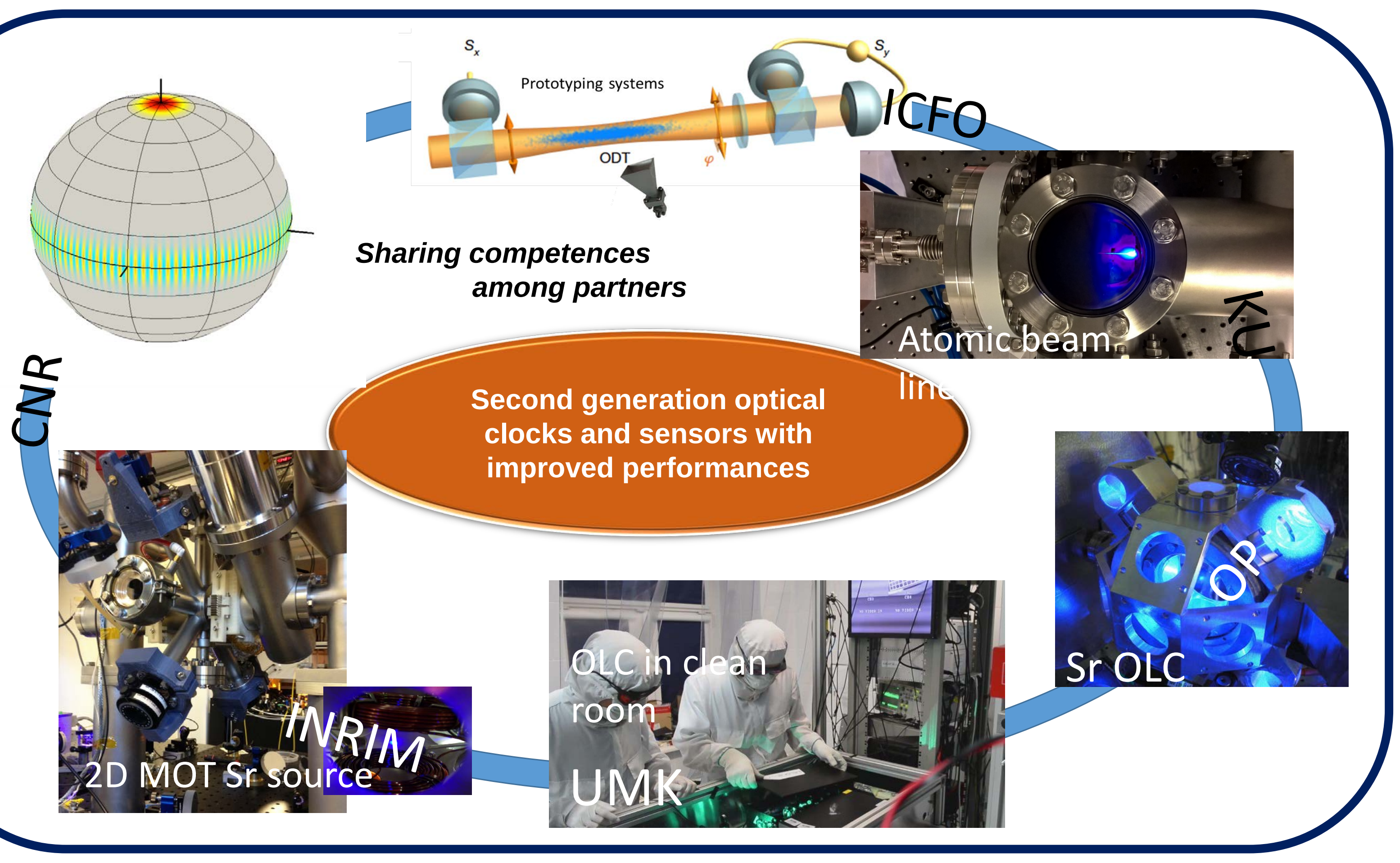
Q-Clocks has the ambition to operate a OLC with thousands of entangled atoms with an atom-light coherence time of the order of 1 s (blue dashed line) to demonstrate both feasibility and advantage with respect to classical measurement techniques.

Superradiant laser as active optical clock

- Spontaneous emission in a high-cooperativity optical cavity enables dipoles' phase lock → superradiant laser
- Dicke state radiance: $P \propto N^2$
- Steady-state: optical pumping *W*

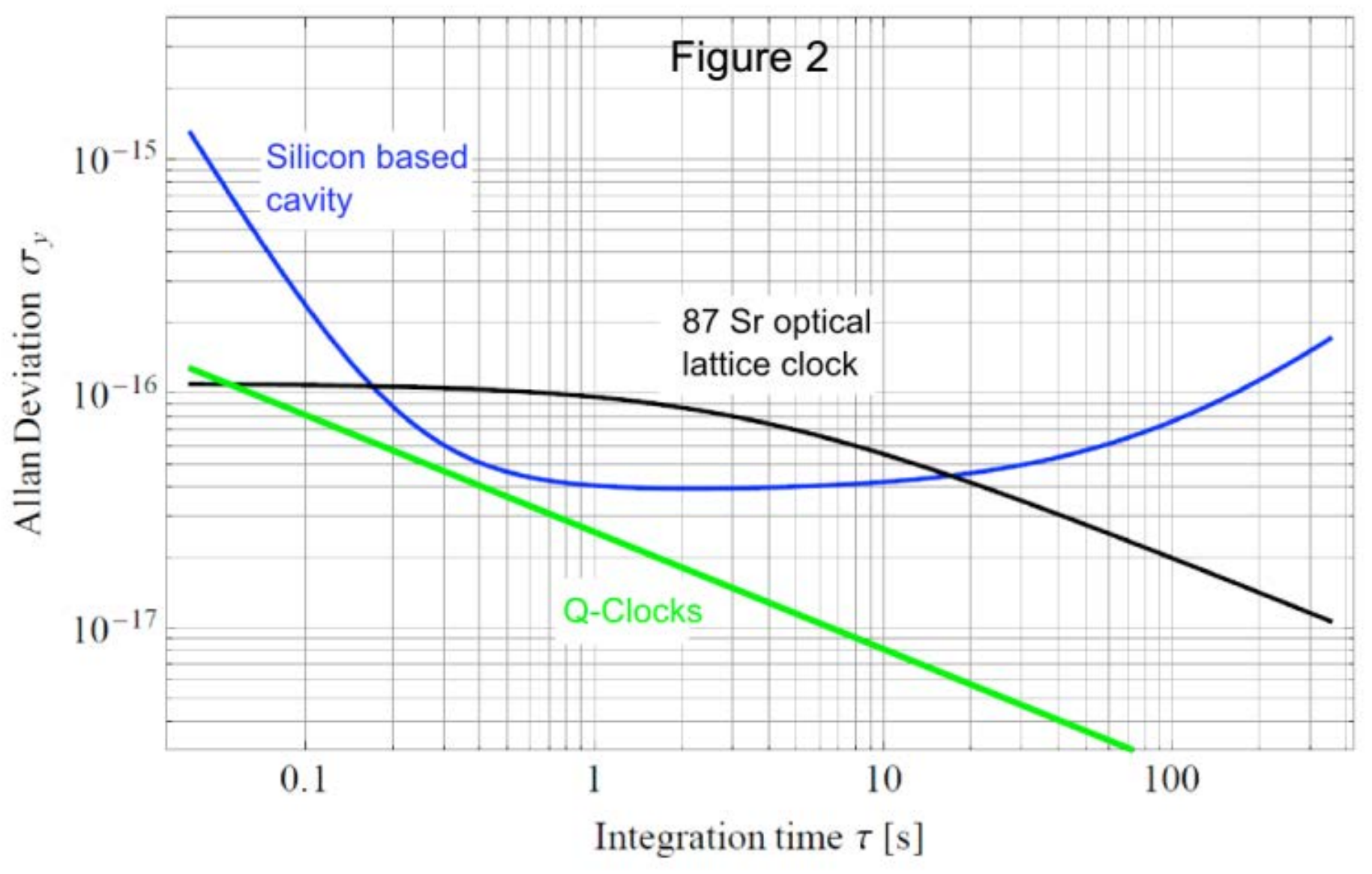

(a) Ultranarrow superradiant laser
(b) Raman superradiant laser





Sharing competences among partners

Second generation optical clocks and sensors with improved performances



Improvements can be achieved by a quantum-enhanced active clock approach. A superradiant laser operating in the “bad” cavity regime has been recently demonstrated [Nor16]. Introducing methods that allow for genuine zero dead-time operation of the clock such as replenishing atoms by conveyer belt techniques will enhance considerably superradiant sources. A related, complementary approach uses of atom-cavity cooperativity to generate nonlinear-optical spectral features showing narrow, atomically-defined linewidths unaffected by cavity noise [Mar11].

[Cho 10] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband, “Frequency Comparison of Two High-Accuracy Al+ Optical Clocks”, Phys. Rev. Lett. 104, 070802 (2010)
[Hos 16] Onur Hosten, Nils J. Engelsen, Rajiv Krishnakumar & Mark A. Kasevich, ”Measurement noise 100 times lower than the quantum-projection limit using entangled atoms”, Nature 529, 505 (2016)
[Mar11] M. J. Martin, D. Meiser, **J. W. Thomsen**, Jun Ye, and M. J. Holland, “Extreme nonlinear response of ultranarrow optical transitions in cavity QED for laser stabilization”, Phys. Rev. A 84, 063813 (2011)