The Oscillator IMP

A platform dedicated to the measurement of oscillators, frequency stability, and noise

Targets at being the world-leader facility dedicated to the measurement of noise and short-term stability of oscillators and devices in the whole radio spectrum (from MHz to THz), including microwave photonics, widely available to Agencies, to Research Institutions and to Private Companies

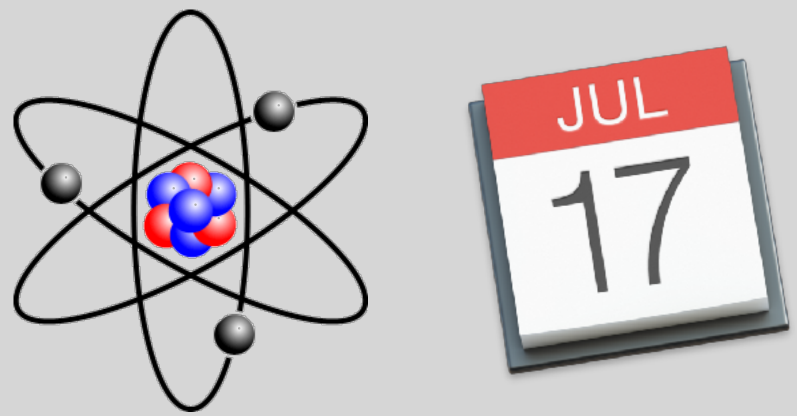
Oscillator Instability Measurement Platform

At your choice, P stands for Playground, Playstation or Platform
You can also read Oscillator IMPact

Short-Term Stability

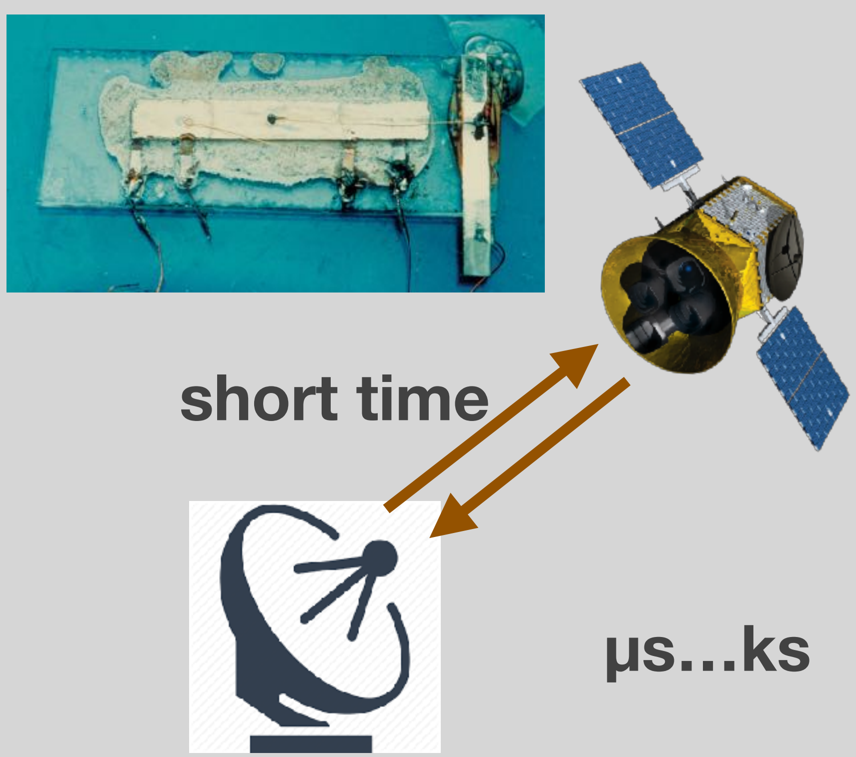
Plenty of ~~Room~~ Time at the Bottom – R. P. Feynmann, Pasadena, Dec 1959

Primary std –> Timekeeping



Boundary 1 day (+)
BIPM Circular

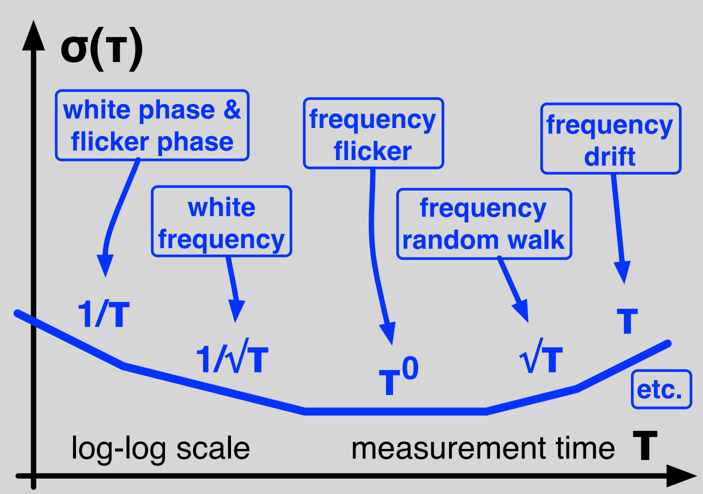
Oscillators –> Applications



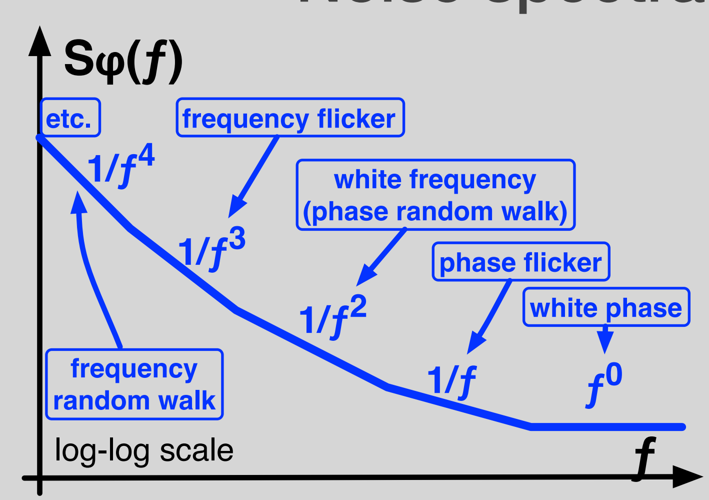
- Virtually all systems rely on time and frequency
  - Stable oscillator is stable for a short time τ
  - Accuracy from external reference (traceable)

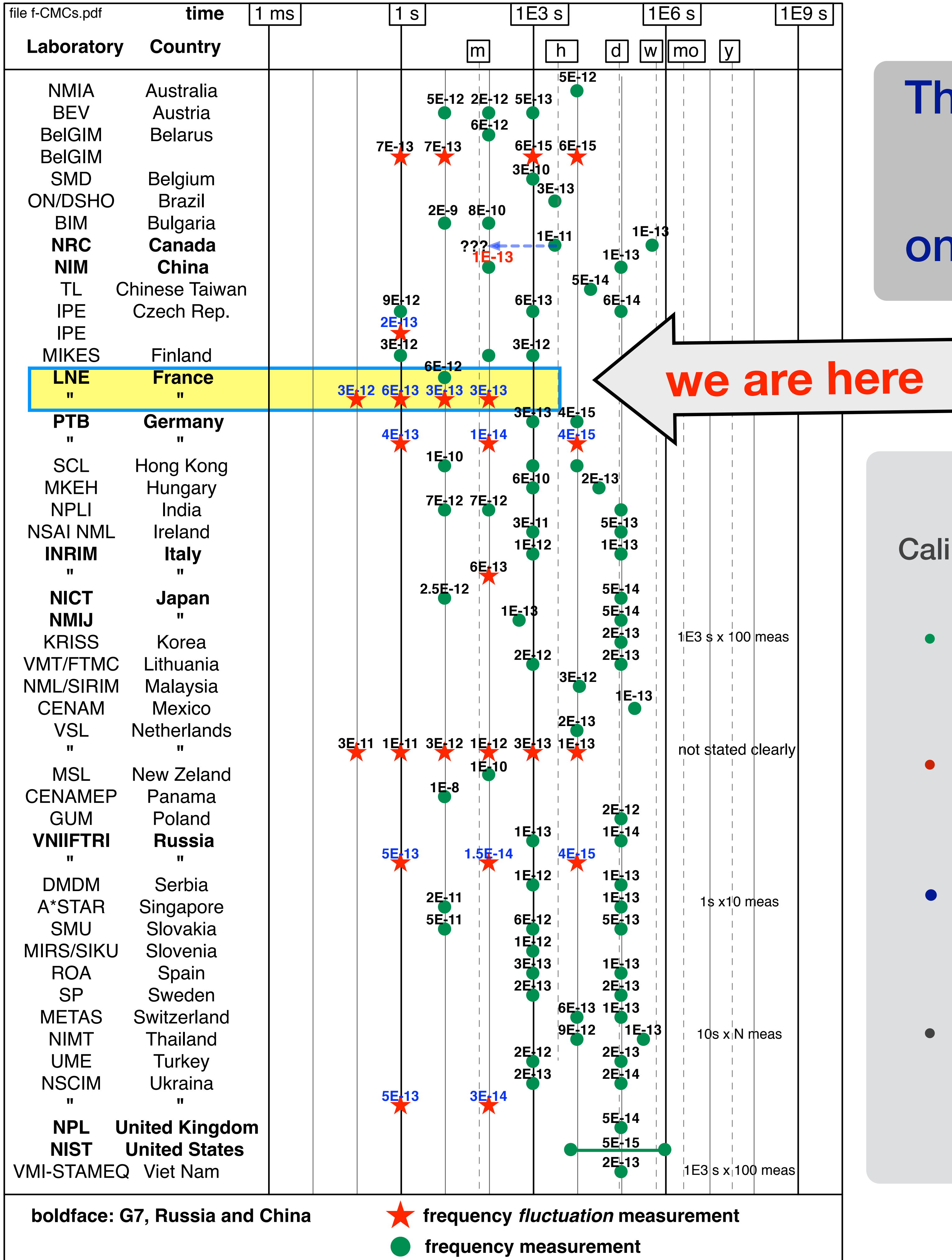
- Examples
  - Pendulum —> Earth rotation ($\tau \leq 10^1 \ldots 10^6$ s)
  - Radars ($\tau = 10^{-6} \ldots 10^{-2}$ s)
  - Telecom systems ($\tau \leq 0.1$ s … 10^5 s)
  - Computer boards ($\tau < \approx 1$ μs)
  - Particle accelerators ($\tau \leq \approx 100$ ms)
  - GNSS ranging (100 ms)
  - Very-Large Baseline Interferometry ($\tau = 10^{-1} \ldots 10^4$ s)
  - Space missions ($\tau = 1 \ldots 10^3$ s)
  - GNSS time scale ($\tau \leq 10^6$ s, i.e. ≈2 weeks)

Wavelet variances



Noise spectra



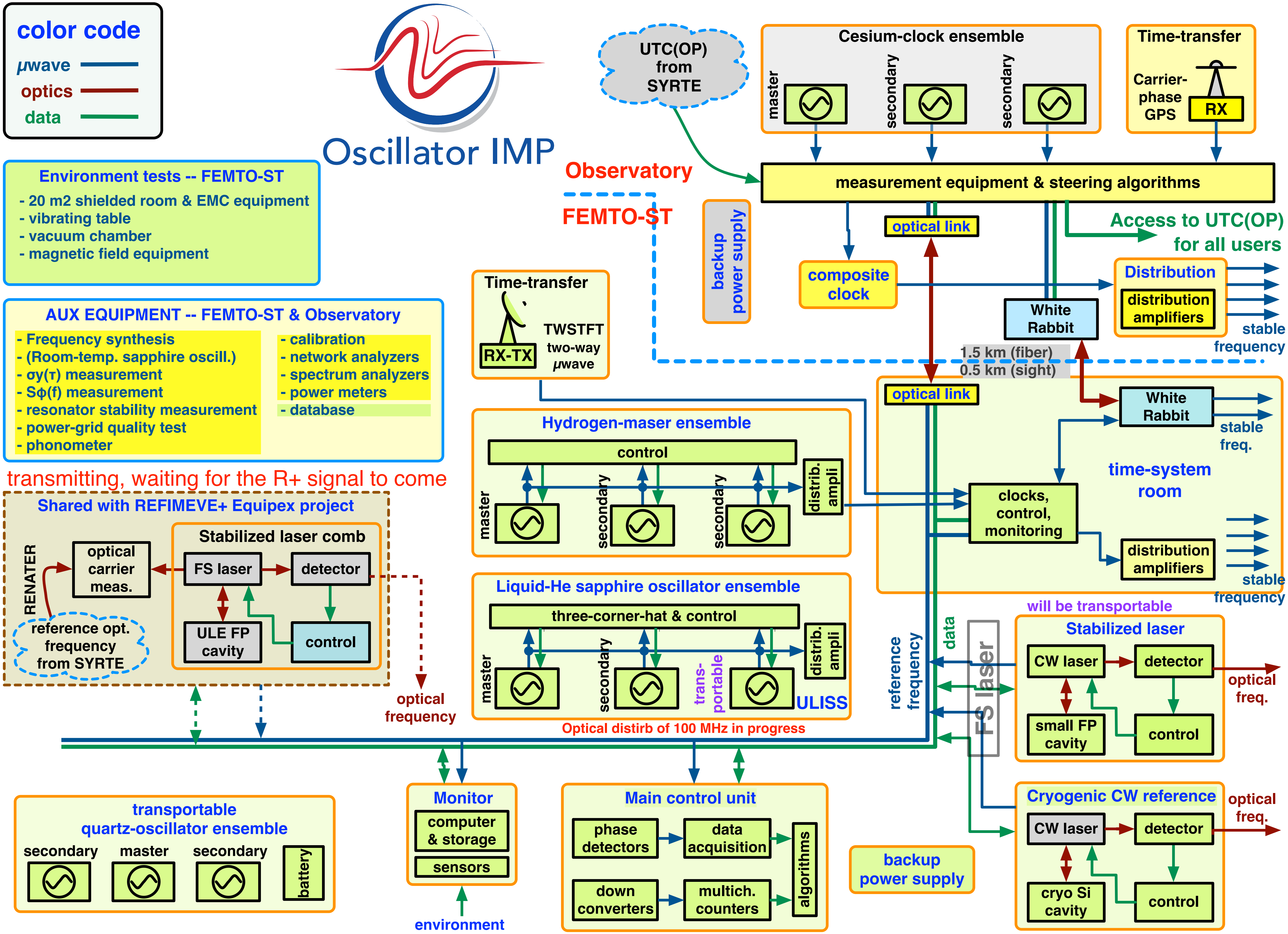


The BIPM is in charge of the "convention du mètre," on the top of the world metrology

BIPM CMC-DB

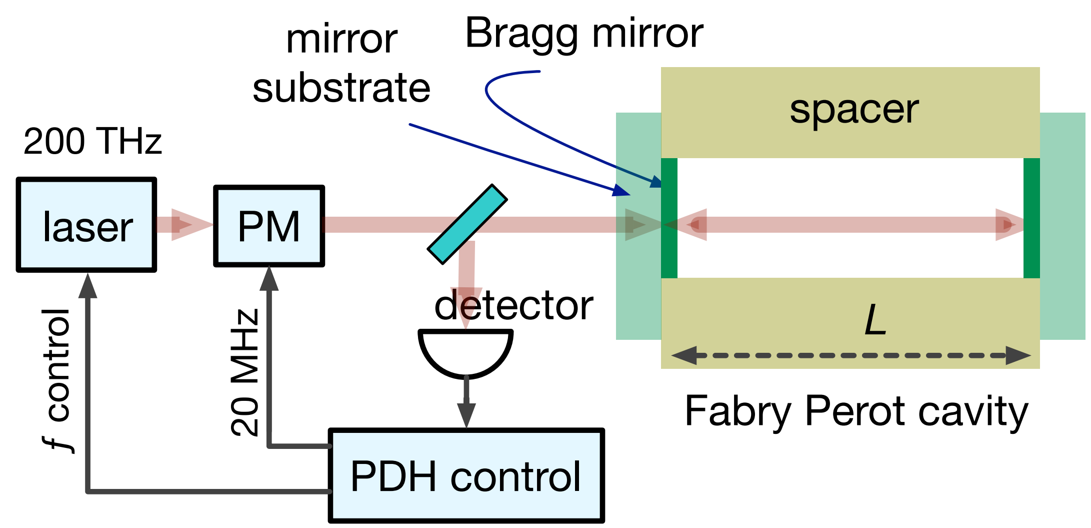
Calibration and Measurement Capabilities Data Base

- Green dots: absolute frequency measurements (70–80 nat'l labs)
- Red stars: frequency fluctuation measurements (8 nat'l labs)
- We are the one and only lab for spectral purity, $S_\phi(f)$ or $L(f)$
- Other labs (NIST, PTB, NPL) do well, but they did not do BIPM paperwork and peer review


color code
μwave
optics
data
Oscillator IMP
UTC(OP) from SYRTE
Observatory
FEMTO-ST
Cesium-clock ensemble
master
secondary
secondary
Time-transfer
Carrier-phase GPS
RX
measurement equipment & steering algorithms
backup power supply
optical link
composite clock
Access to UTC(OP) for all users
Distribution
distribution amplifiers
stable frequency
White Rabbit
1.5 km (fiber)
0.5 km (sight)
Environment tests -- FEMTO-ST
- 20 m2 shielded room & EMC equipment
- vibrating table
- vacuum chamber
- magnetic field equipment
AUX EQUIPMENT -- FEMTO-ST & Observatory
- Frequency synthesis
- (Room-temp. sapphire oscill.)
- σy(τ) measurement
- Sφ(f) measurement
- resonator stability measurement
- power-grid quality test
- phonometer
- calibration
- network analyzers
- spectrum analyzers
- power meters
- database
Time-transfer
RX-TX
TWSTFT two-way μwave
optical link
White Rabbit
stable freq.
time-system room
Hydrogen-maser ensemble
control
master
secondary
secondary
distrib. ampli
clocks, control, monitoring
distribution amplifiers
stable frequency
transmitting, waiting for the R+ signal to come
Shared with REFIMEVE+ Equipex project
RENATER
optical carrier meas.
Stabilized laser comb
FS laser
detector
ULE FP cavity
control
reference opt. frequency from SYRTE
optical frequency
Liquid-He sapphire oscillator ensemble
three-corner-hat & control
master
secondary
trans-portable
distrib. ampli
ULISS
Optical distirb of 100 MHz in progress
reference frequency
data
FS laser
will be transportable
Stabilized laser
CW laser
detector
small FP cavity
control
optical freq.
Cryogenic CW reference
CW laser
detector
cryo Si cavity
control
optical freq.
transportable quartz-oscillator ensemble
secondary
master
secondary
battery
Monitor
computer & storage
sensors
environment
Main control unit
phase detectors
data acquisition
down converters
multich. counters
algorithms
backup power supply

Microwave Photonics

Laser stabilized to FP etalon



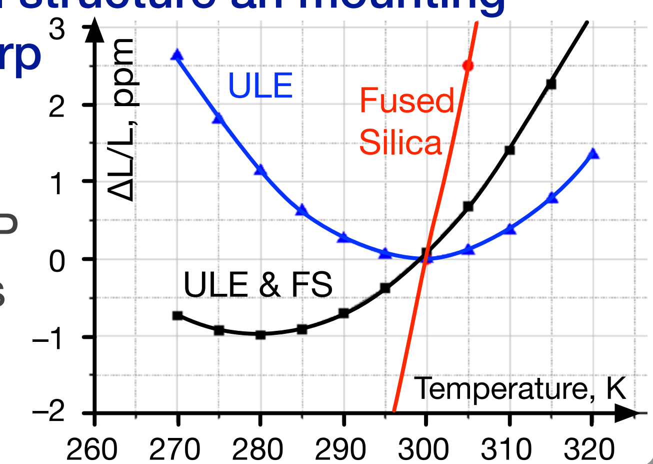
Typical values:

- $F = 2\ 10^5$
- $L =$ 10 cm
- $\Delta\nu =$ 7 kHz
- $\nu_l =$ 200 THz
- $\delta\nu/\nu = 10^{-15}$

Thermal stability

- **Even L(T) @T0 —> ΔL/L=0 at T_0**
- **ULE vitro ceramic $T_0 \approx 20$ °C**
- **Si crystal, 124 K and 17 K**
- **Challenges**
  - **Full structure an mounting**
  - **Warp**

2.5 cm FP
T_0 needs be fixed



Flicker is powered by thermal energy

Structural dissipation (hysteresis) turns white —> $1/f$ noise

$$S_{\delta L} = \frac{4 k_B T F(\dots)}{2\pi f Q}$$

Temperature T
Mechanical quality factor Q
Fourier frequency f

Fractional frequency stability

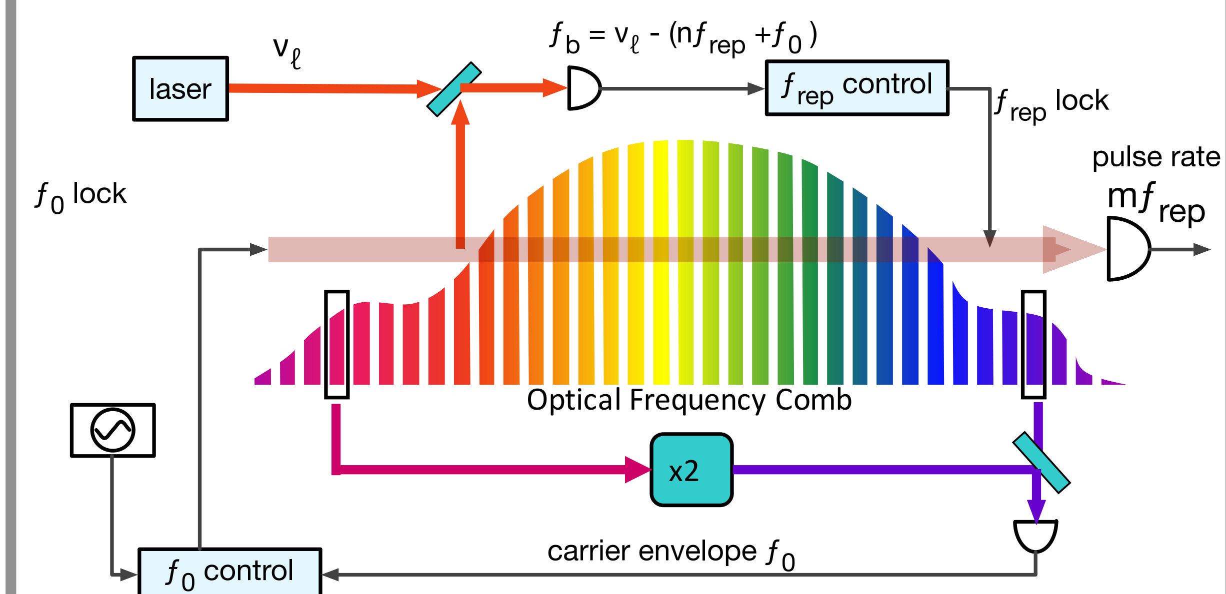
$$\sigma_y(\tau) = \frac{1}{L}\sqrt{2\ln(2)\, S_{\delta L}(1\ \mathrm{Hz})}$$

Stability of our cavities ($1/f$, laser stabilized to)

2×10^{-15} 5 cm, ULE at room T (operational)
7×10^{-15} 2.5 cm, ULE at room T (got, more tests)
3×10^{-17} 14 cm, Si at 17 K expected (in progress)

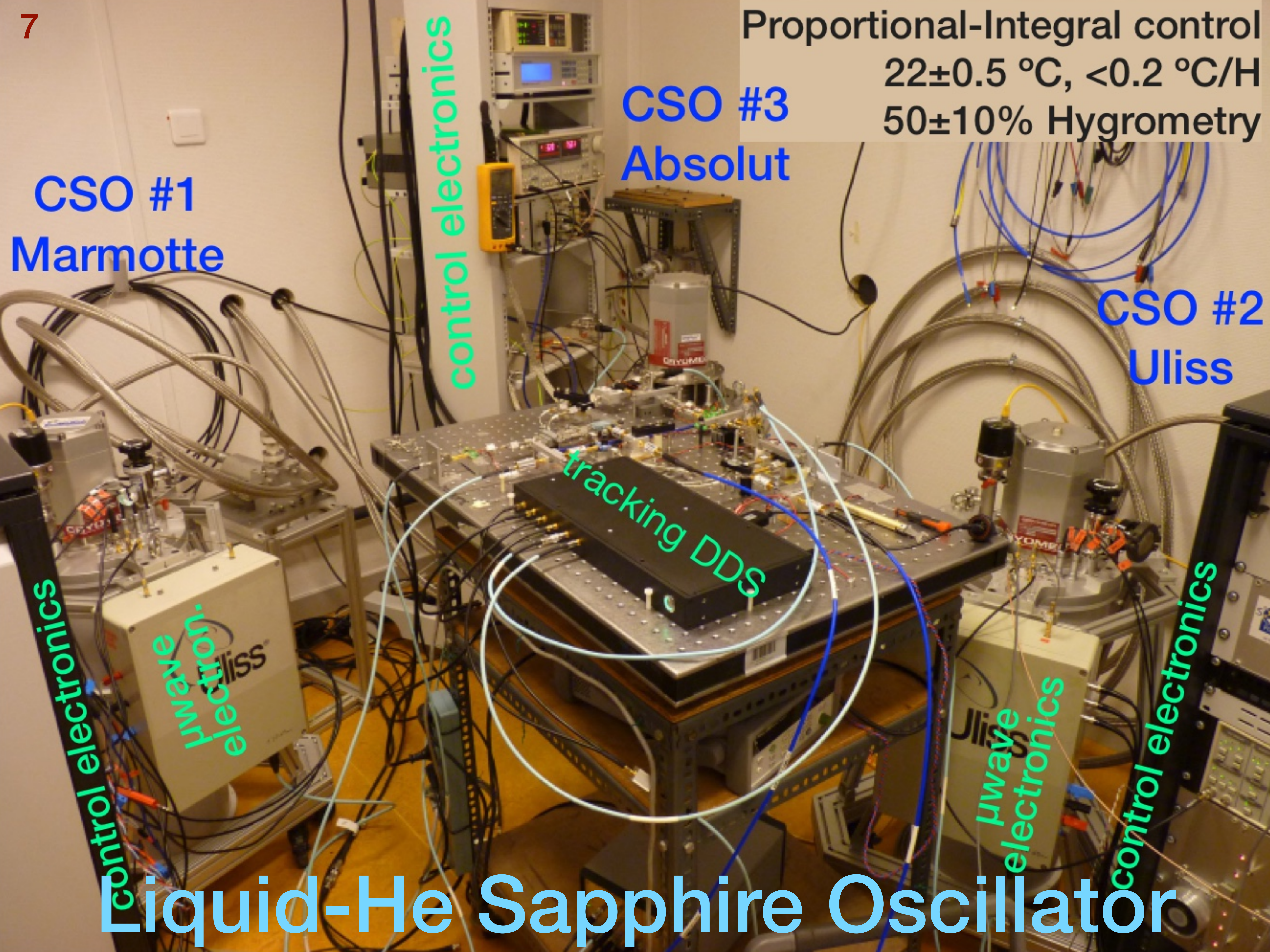
FS comb MENLO — RF/optics gearbox

SI second defined by 9.193 GHz NMR of ^{133}Cs



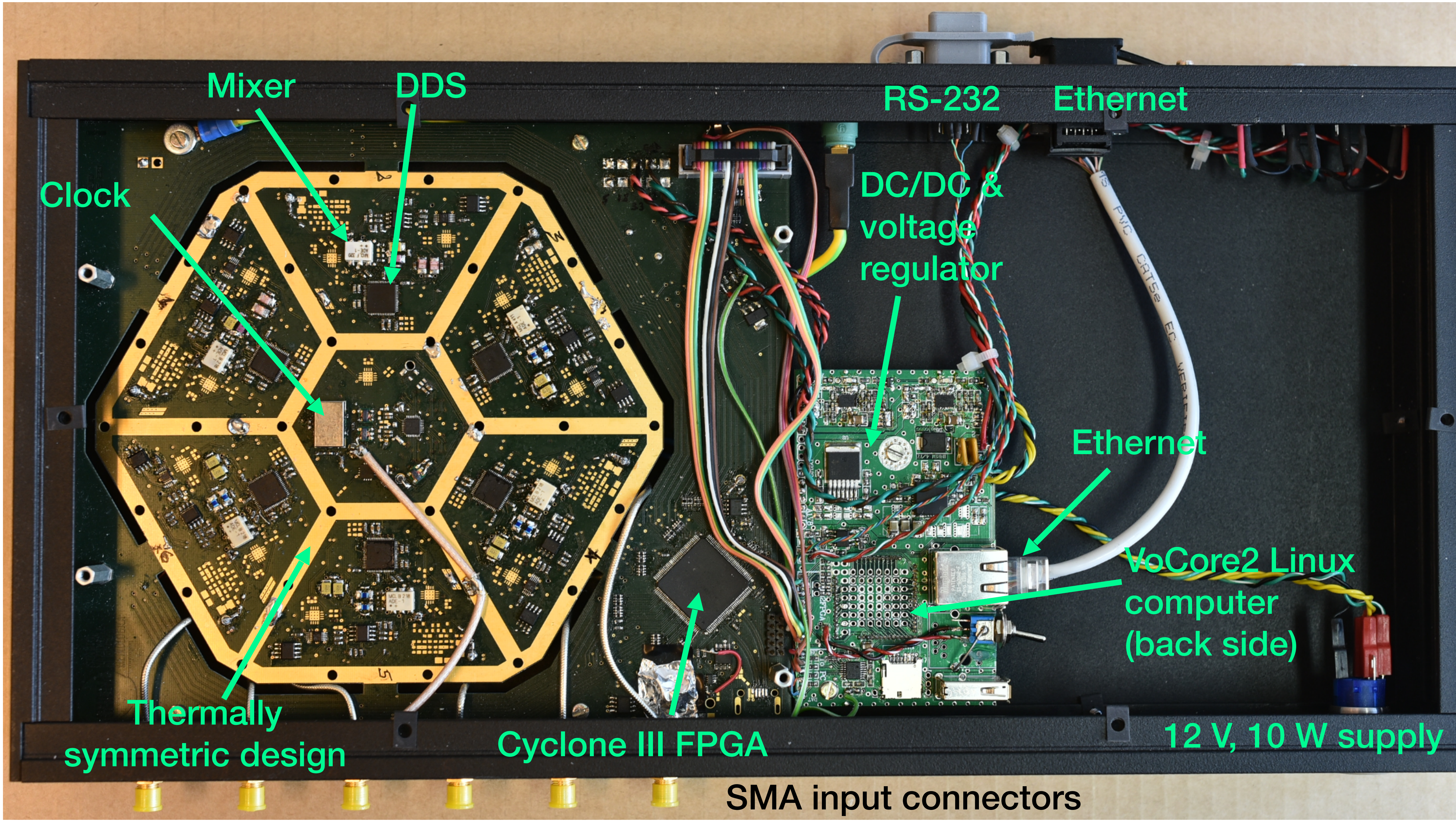
Microwave Photonics

- Room-temperature 5-cm ULE cavity
  - Operational, 2×10^{-15} flicker (8×10^{-16} projected), 10^{-16} τ drift
- Room-temperature 2.5-cm ULE cavity
  - Original design, help from CNES
  - Preliminary, 7×10^{-15} flicker (3×10^{-15} projected), 7×10^{-15} τ drift
  - Phase noise 0 dB at 1 Hz, $1/f^2$, still unexplained
  - Cannot set to the turning point, –40 ºC inferred
  - Prototype will fit in 8-unit, 19” rack (expected)
- Cryogenic (17 K) Si-monocrystal cavity
  - Original design
  - Very preliminary PDH, 10^{-14} flicker (3×10^{-17} projected)
  - Ready to test turning T, T stability, and PDH noise
- Optical path stabilization, path between laser and $\lambda/4$
  - Original method being tested


Proportional-Integral control
22±0.5 °C, <0.2 °C/H
50±10% Hygrometry
CSO #3
Absolut
CSO #1
Marmotte
CSO #2
Uliss
control electronics
tracking DDS
µwave electron.
µwave electronics
control electronics
control electronics
Liquid-He Sapphire Oscillator

Coming: Multi-Channel TDDS

IEEE T UFFC, DOI 10.1109/TUFFC.2018.2870593



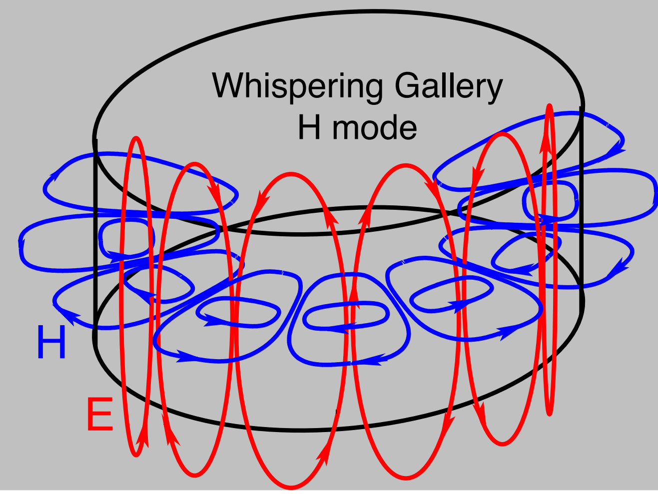
6 TDDSs, control unit, and interface in a small instrument

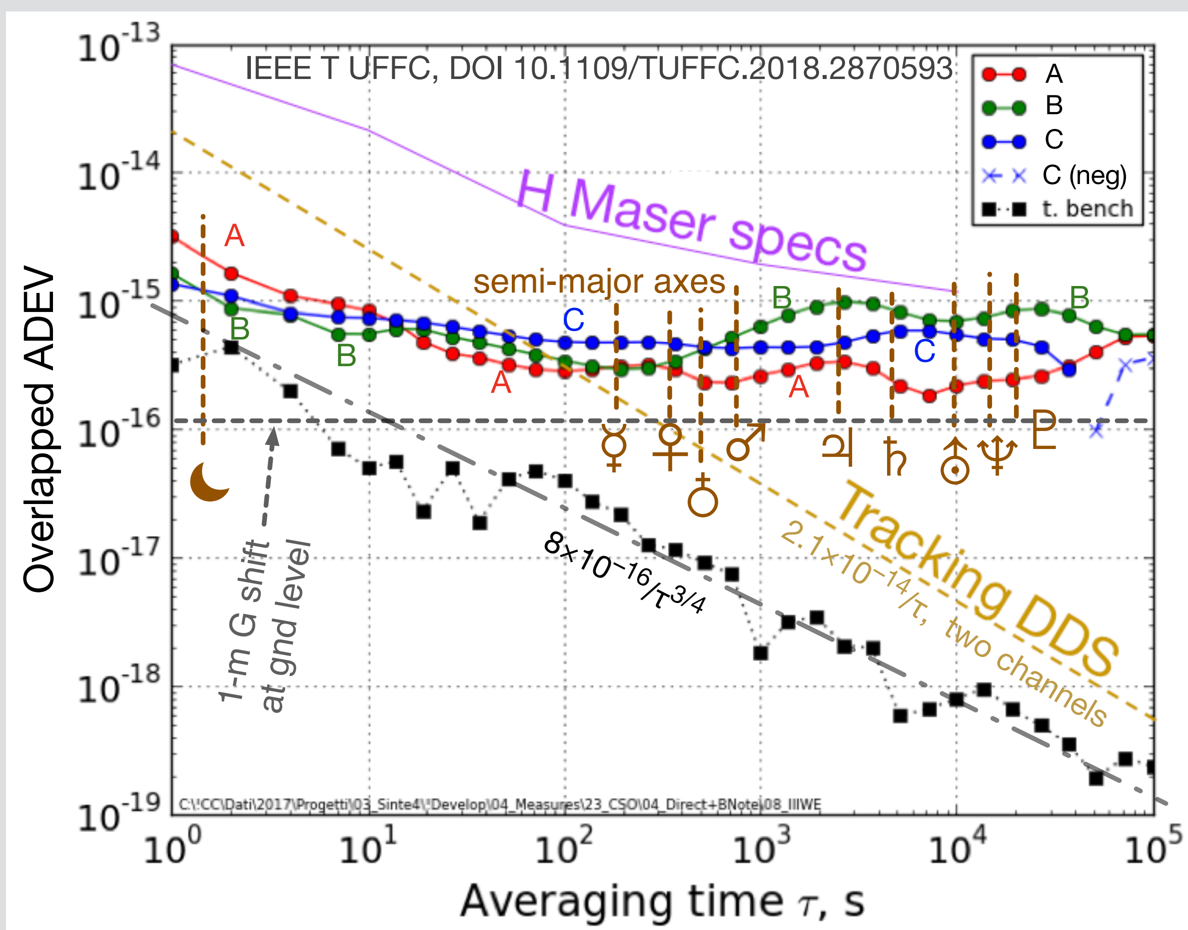
Developed by C. E. Calosso, INRIM, Italy – Next version will have arbitrary frequency output

Liquid-He Sapphire Oscillator

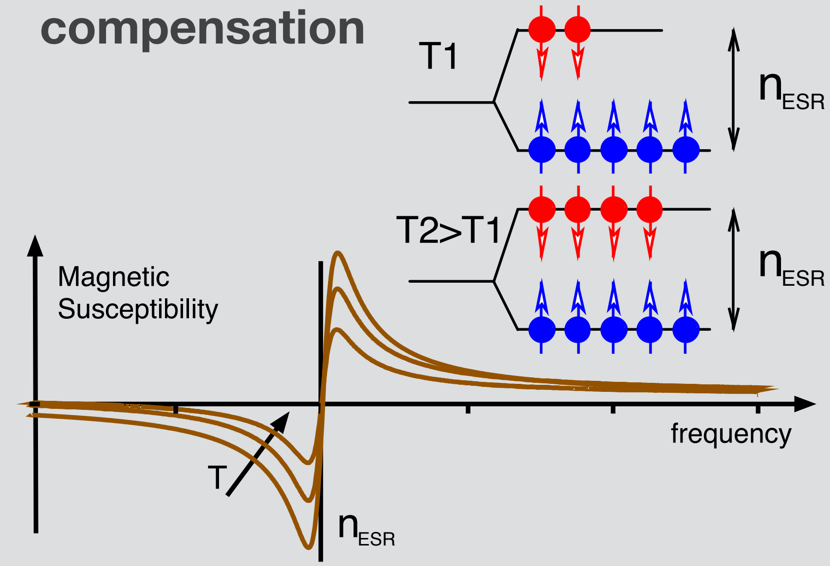
Cr^{3+} Fe^{3+} doped
Al_2O_3 mono crystal
ϕ ≈ 5 cm, H ≈ 3 cm

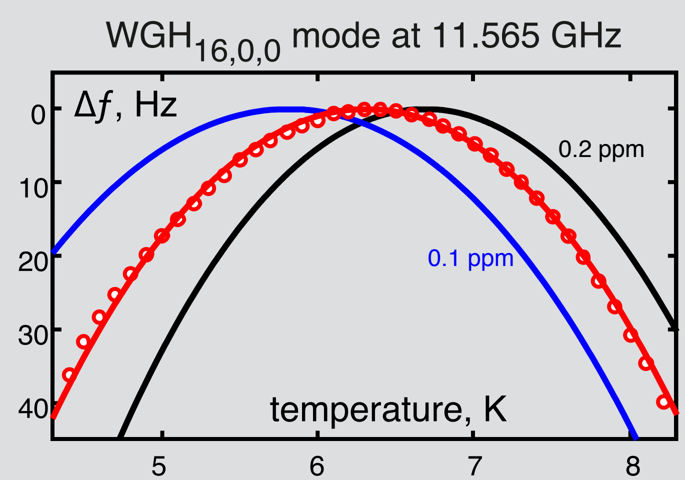
10 GHz resonance
Q ≈ 2×10⁹ at 5–7 K





paramagnetic temperature compensation



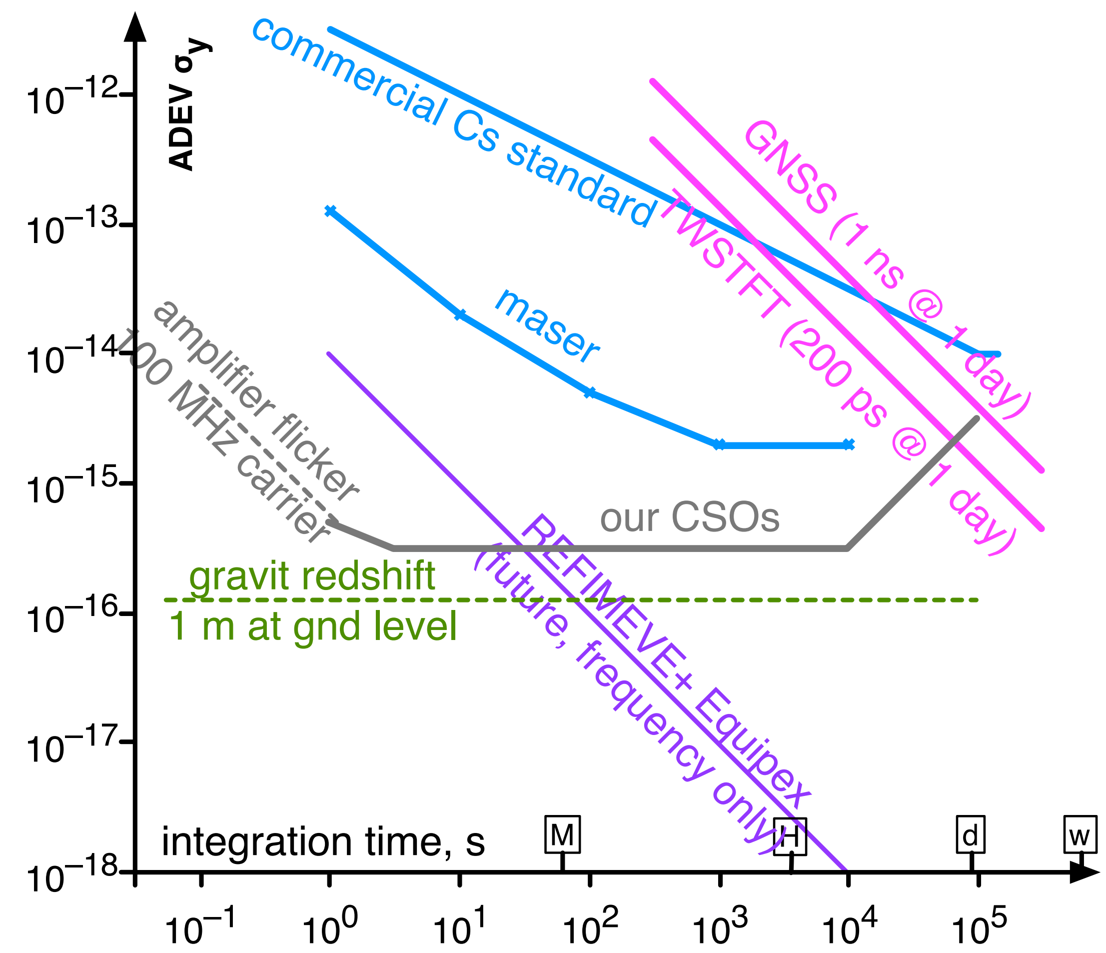


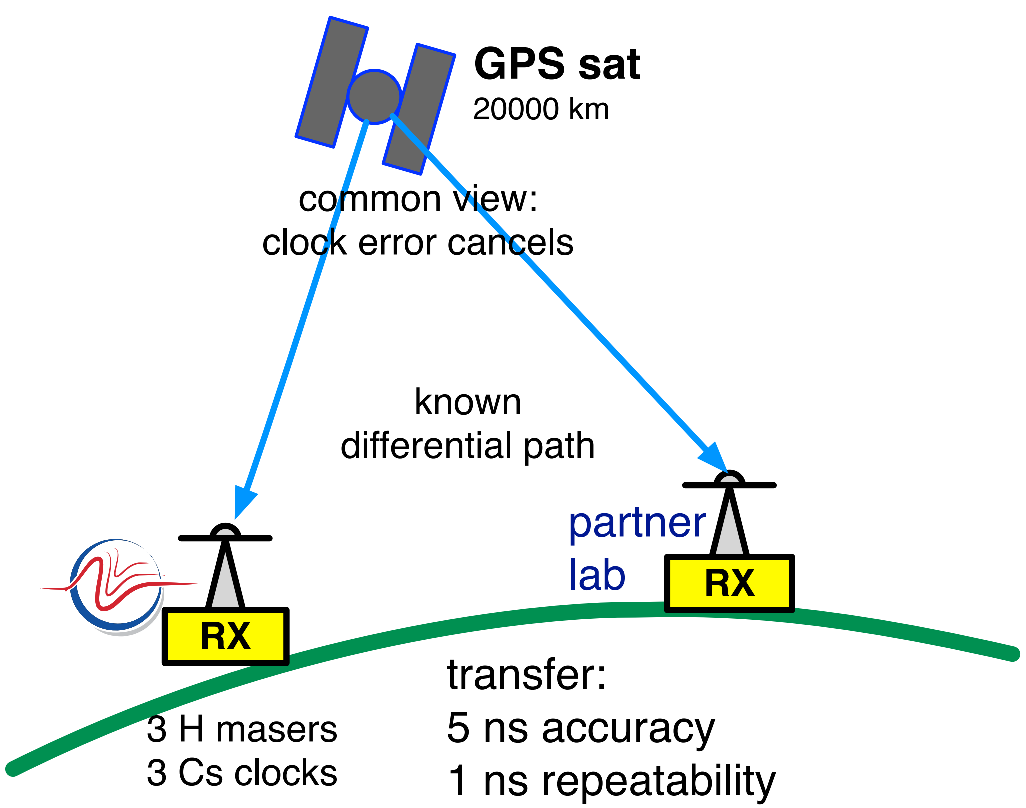
- 3 units operational –> covariances
  - Transportable unit –> stability & noise validated after roundtrip
- μHz-resolution synthesis

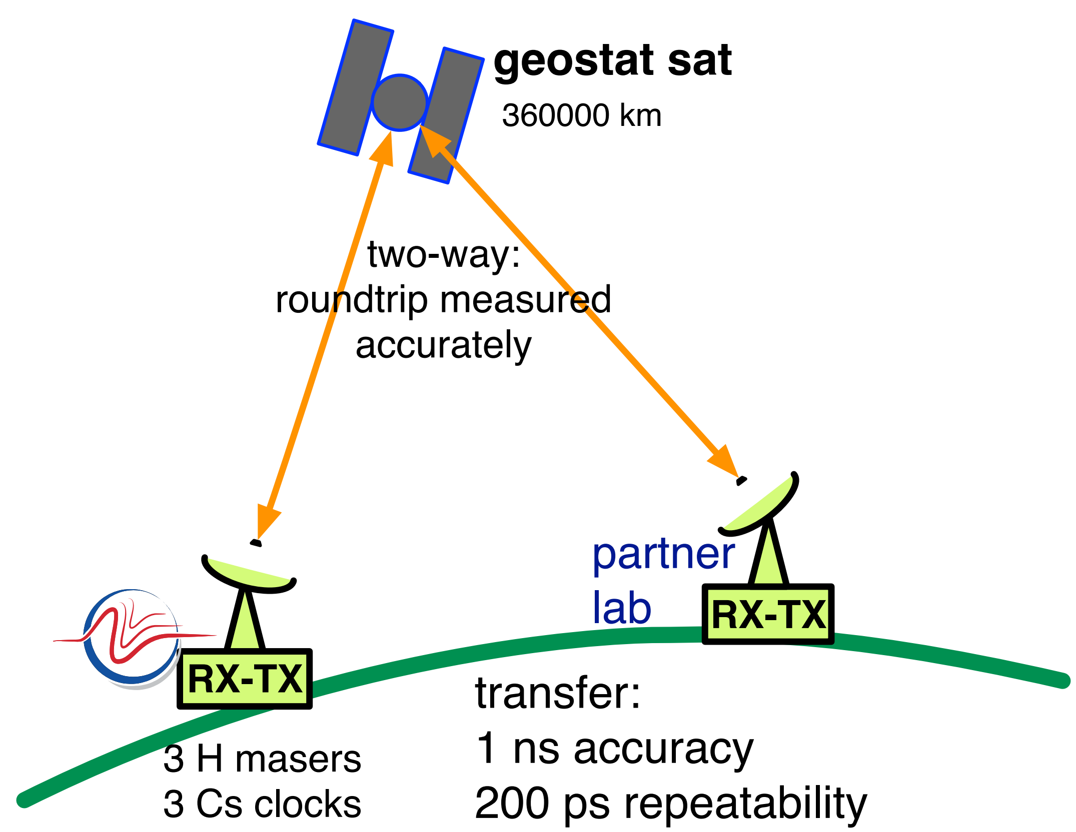
ELISA –> ESA, Argentina / ULISS available for rental / 3 units for GPS @ USNO

Time System

- 3 H masers & 3 Cs clocks operational
- Common view GPS operational
- TWSTFT operational, calib in progress
- REFIMEVE+ Equipex in progress
- On-site White Rabbit (CERN design)
- On-site frequency distribution on fibers
- 3rd time site in France



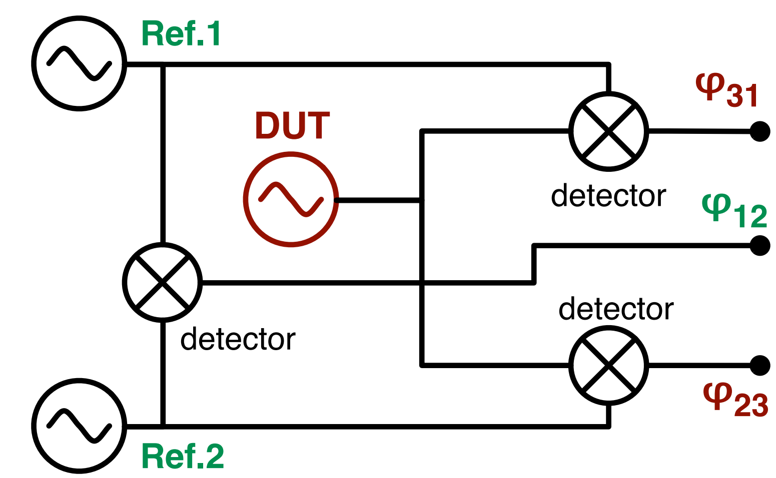




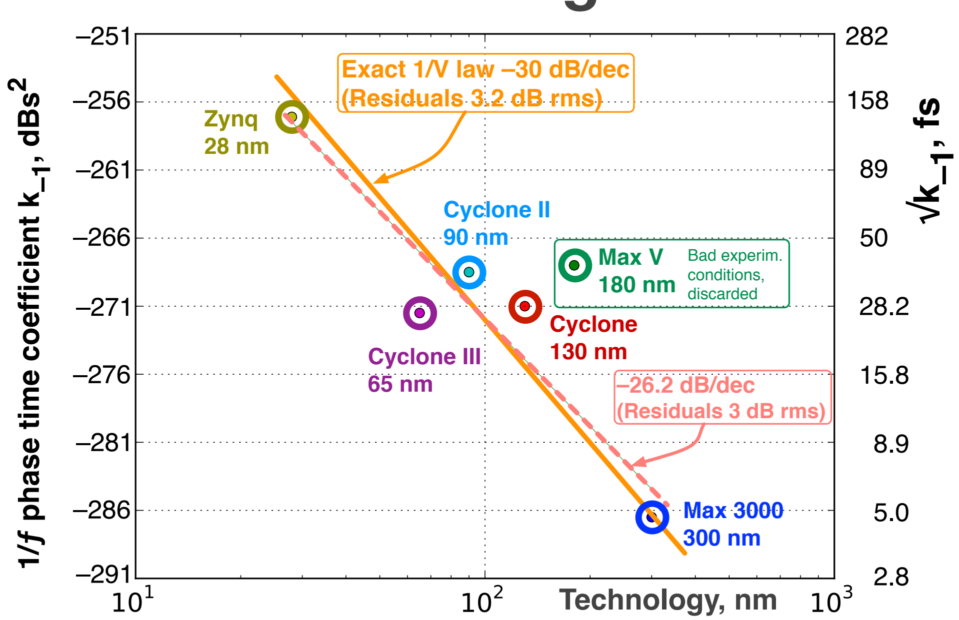
Metrology & Digital Electronics

- Shielded chamber & EMI lab
- Transportable oscillators (quartz, CSO)
- Phase noise in digital devices and ADCs
- Digital methods for PM noise measurement
- Three-cornered hat measurements (covariances and cross spectra)
- Ω (LinReg) frequency counter
- PVAR, LinReg wavelet variances
  detects noise phenomena with the shortest data record
- AM noise and laser RIN

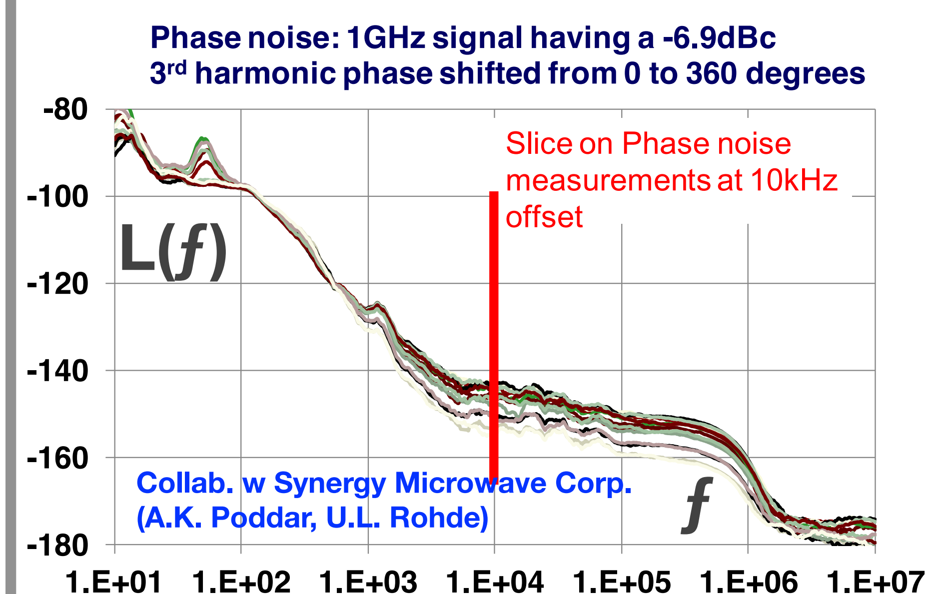
Three-cornered hat noise measurements



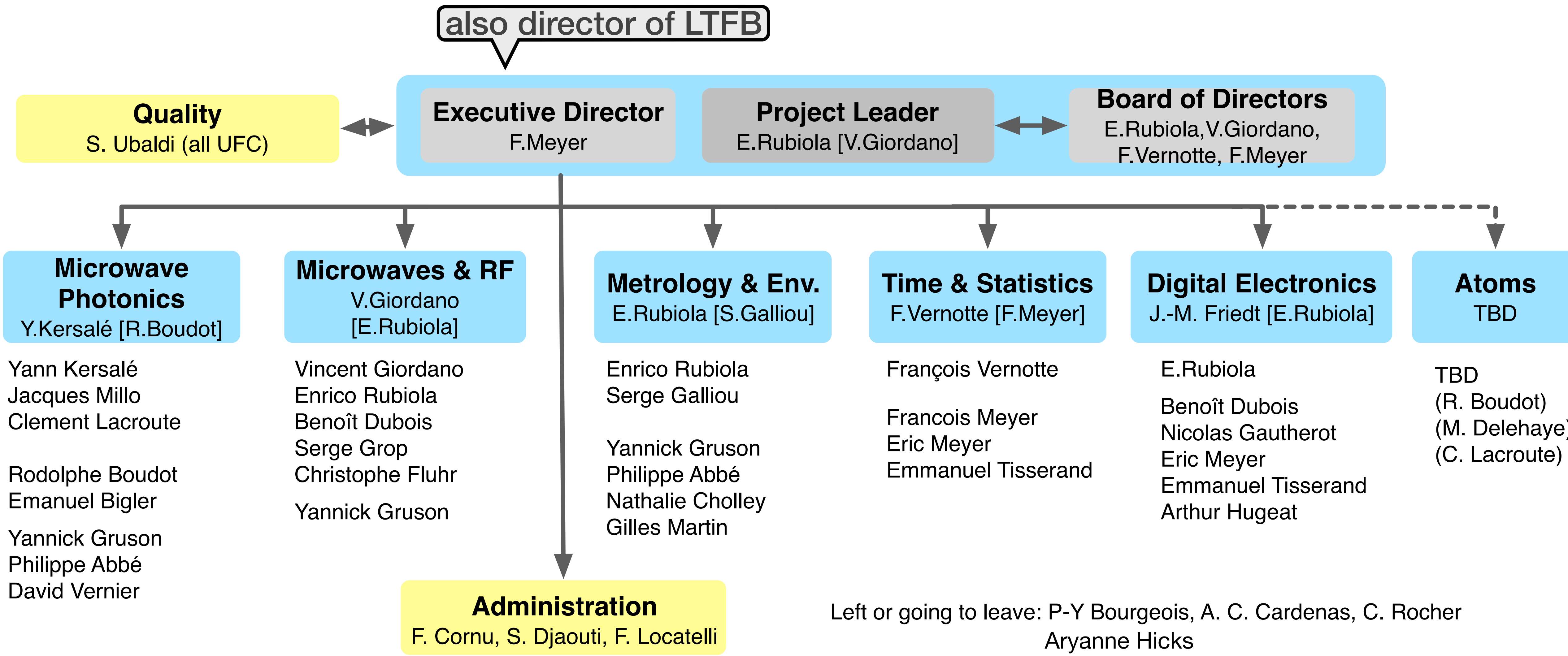
Volume Law <–> Digital Electron.



Inconsistent PM noise measurements



Organization and Manpower



New WP “Atoms” will proposed soon

Partnership with LTFB

- Oscillator IMP and LNE-LTFB operate in the same domain with different purposes
- LTFB —> most routine calibrations and services
- Oscillator IMP —> research & more

	Oscillator IMP	LTFB
Recherche	●●●	
Services pour la	●●	●
Métrologie pour la	●●	●
Services pour	●	●●
Métrologie accréditée		●●●
Designated Institute		●●●

Formalisation en cours

FastLab

Censored 🤬

Maurice and Fabrice already talked

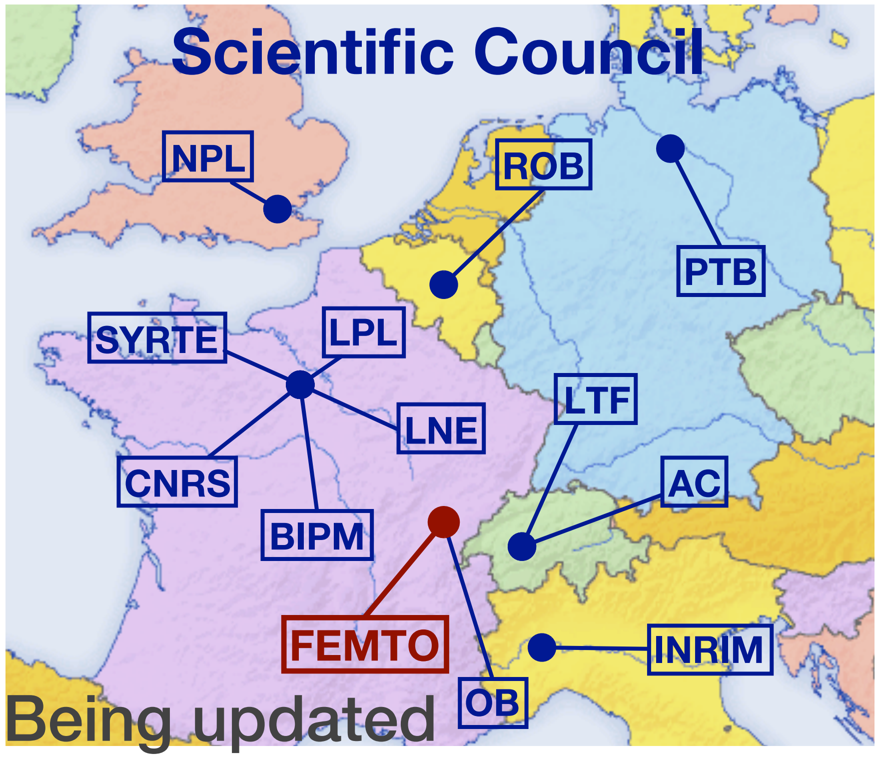
- I have seen recently
  - Measurement of VLF signals, highly resistant to EMI
  - Spoofing GPS, time and position

Some Milestones

- Official start, November 1, 2012
- Kickoff, May 31, 2013
- International evaluation, June 27, 2017
    - Collaborations welcome!
- FastLab, March 1, 2018
- Inauguration, March 28, 2018
- EFTS, created in 2013, 7th edition July 2019
- Cross-spectrum measurement of L(f), three workshops (Paris 2014, Denver 2015, Besancon 2017)

EFTS
European Frequency and Time Seminar

Next: July 1-5, 2019
Registrations open end January



- Joint effort of FIRST-TF & Oscillator IMP
- Crash course on T&F for newcomers
- Fair competition with the NIST T&F Seminar
- Topics: Oscillators, Measurement, Atomic standards, Time scales, and general
- Broad target audience
- Balance between academic and applied issues
- Instructors from leading European institutions
- 5 days, 23 H lectures, 12 H labs in small groups

Lives on 20 k€/y (3/4 registrations, 1/4 public) plus volunteer work