



Systèmes de Référence Temps-Espace



Optical frequency combs and optical frequency measurements

Yann LE COQ, « HDR » defense

*The research work presented was done at:
NIST, Boulder, CO (USA) 2004-2006*



LNE-SYRTE (OP/CNRS/UPMC), Paris, France (2006-present)

Part of the work was done in collaborations with



Partial external Funding (at LNE-SYRTE) :



Curriculum Vitae

- **Engineering school:** SupOptique 1998
speciality : non linear optics
- **PhD in Physics (1999-2002): Institut d'Optique (Orsay)**
« Bose Einstein condensates and Atom Lasers »
supervised by A. Aspect and P. Bouyer
- **1st Post-doc (2003-2004): Institut d'Optique (Orsay)**
a new BEC apparatus for atom laser experiments
supervised by P. Bouyer
- **2nd Post-doc (2005-2006): NIST (Boulder)**
Neutral Ca optical clock and optical frequency combs
supervised by L. Hollberg, C. Oates, S. Diddams
- **Since 2007: LNE-SYRTE (Paris)**
Optical frequency combs (+ Eu:YSO based USL since 2013) ²

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Frequency metrology in a nutshell...

Oscillator : $s(t) = A_0 \cdot [1 + \alpha(t)] \cdot \cos[2\pi\nu t + \phi_0 + \phi(t)]$

ν : in GHz range : microwave oscillator
in 100's THz range : optical

$\alpha(t)$: amplitude noise
(generally neglected compared to ϕ -noise, bounded)

$\phi(t)$: phase noise
(not bounded, always divergent)

Frequency metrology in a nutshell...

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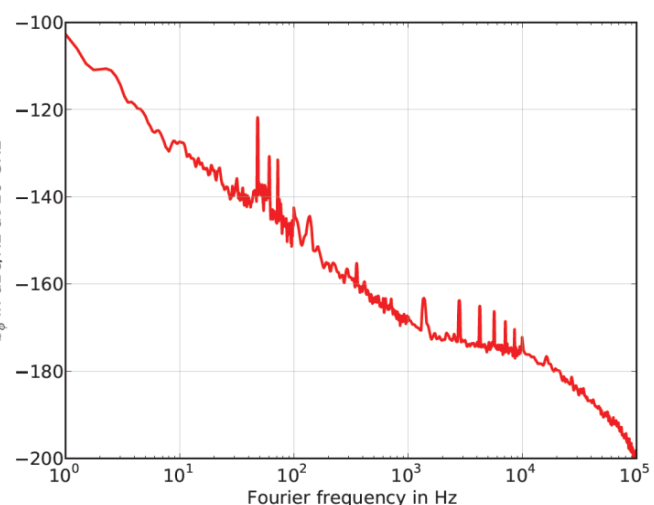
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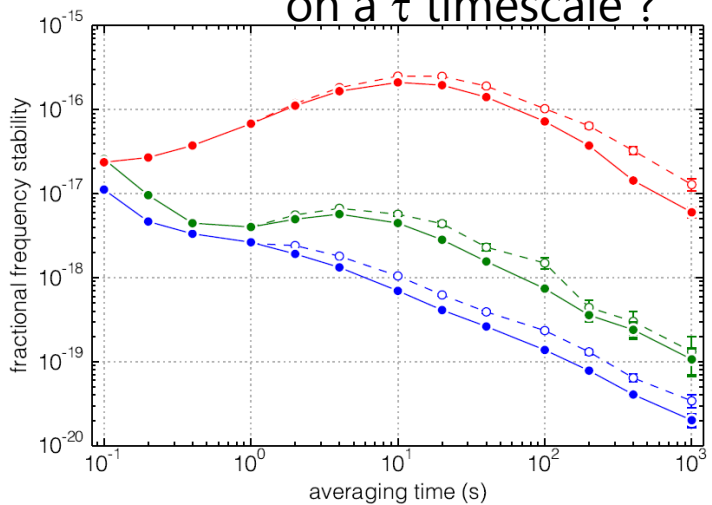
Fourier transform-based spectral analysis : $S_\phi(f)$

= noise distribution in F. freq.



Frequency stability based time domain analysis

How constant is $2\pi\nu + \phi'$ on a τ timescale ?



Accuracy assesment

How well is ν equal to what you think it is ?

→ Systematic errors evaluation from various parameters (all you can think about, and more)
 →NB: A good stability is very useful for such assesment

Fs-lasers and optical frequency combs

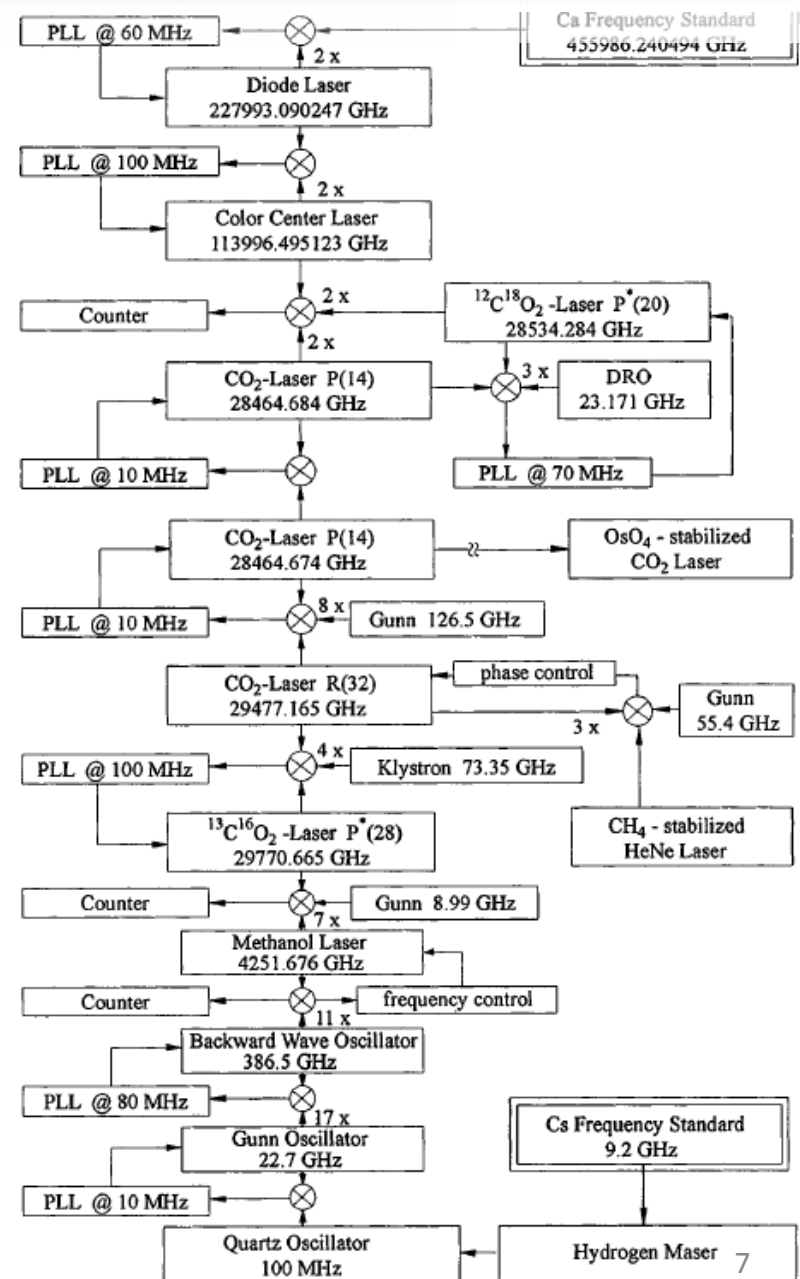
Optical Frequency Measurements (old technique)

Harmonic frequency chain: Ensemble of subsystems each allowing a frequency multiplication by a factor 2 or 3.

- Complexity.
- Inconvenient frequencies (THz, mid-IR).
- 3 or 4 chains in the world at PTB, SYRTE, NRC, JILA.
- Continuous operation <3h.

The setup has to be redesigned if one changes the frequency to be measured.

See for exemple Schnatz et al. PRL **76**, 18 (1996)



Optical frequency measurements with combs

Harmonic chain replaced with:

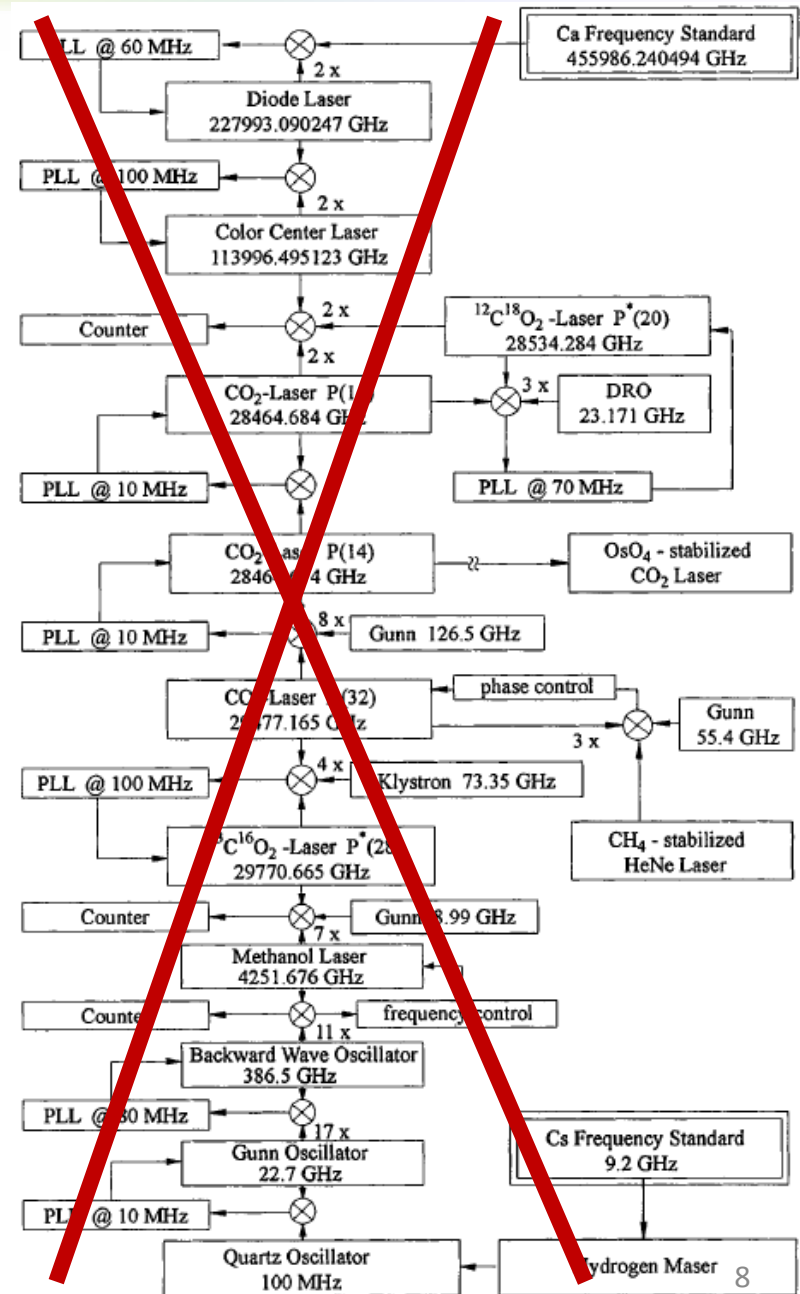
1 Laser

$$\nu_N = N f_{rep} + f_0 \quad N \text{ large !}$$

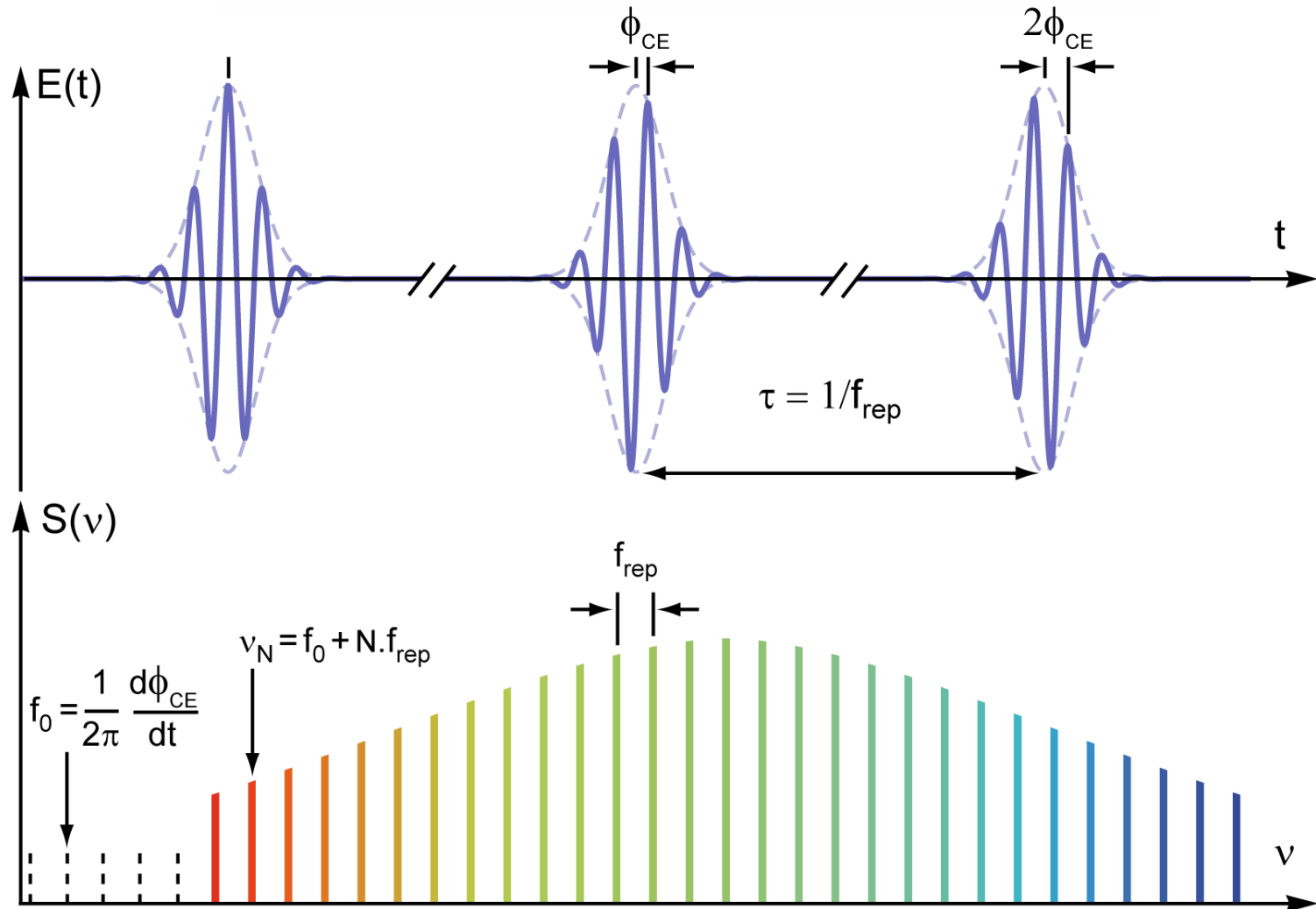
- Extremely simple and cost effective in comparison.
- No inconvenient frequency.
- Measurement of several frequencies at the same time.
- Continuous operation for weeks.
- Covers the visible-near IR range.
- Commercially available systems.

Nobel Lecture: Defining and measuring optical frequencies
J. L. Hall, *Rev. Mod. Phys.* 78, 1279 (2006)

Nobel Lecture: Passion For Precision
T. W. Hänsch, *Rev. Mod. Phys.* 78, 1297 (2006)



Output of a mode-locked Laser

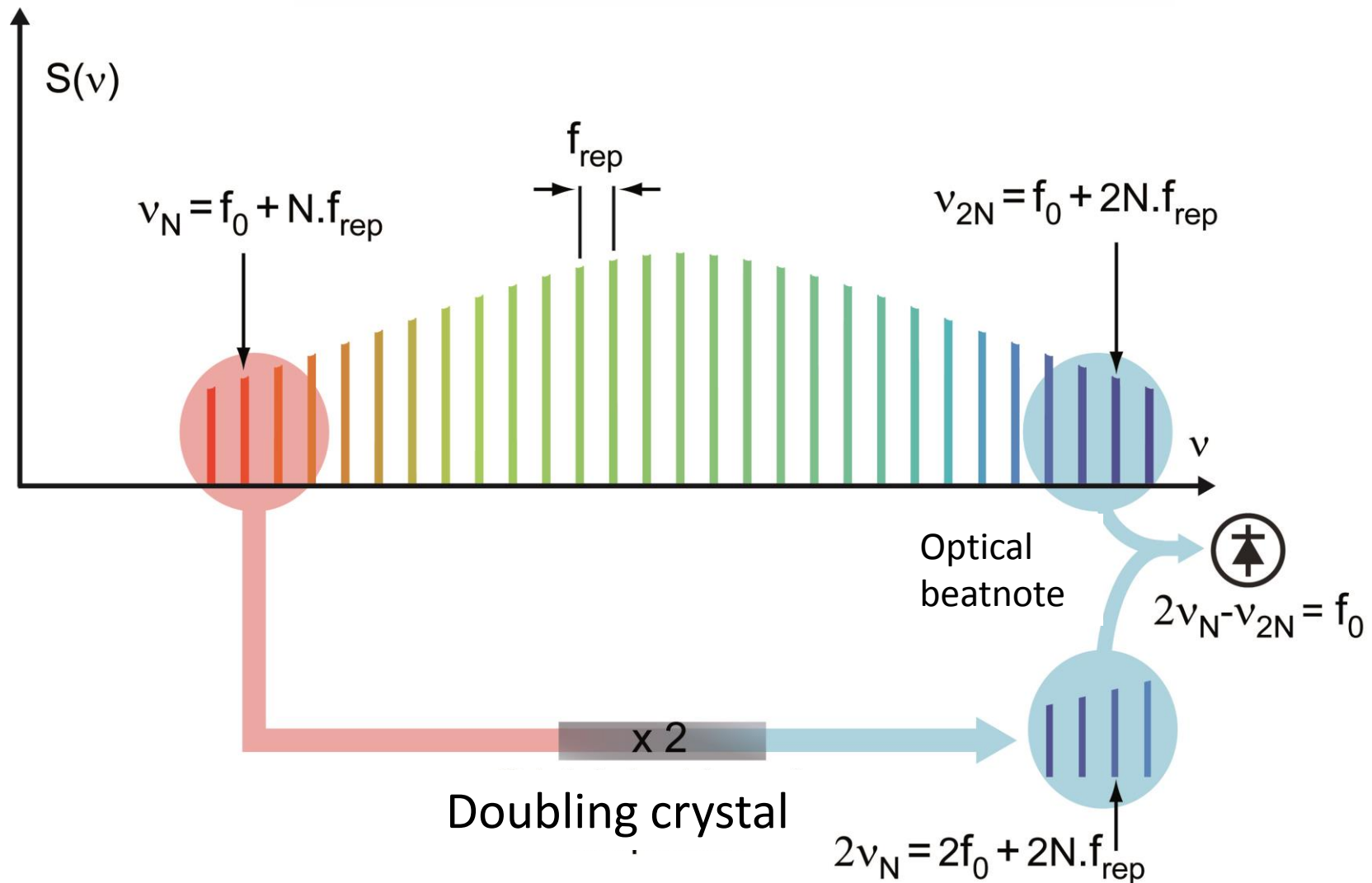


Inside the laser cavity : phase velocity \neq group velocity

→ ϕ_{ce} between successive pulses (in time domain)

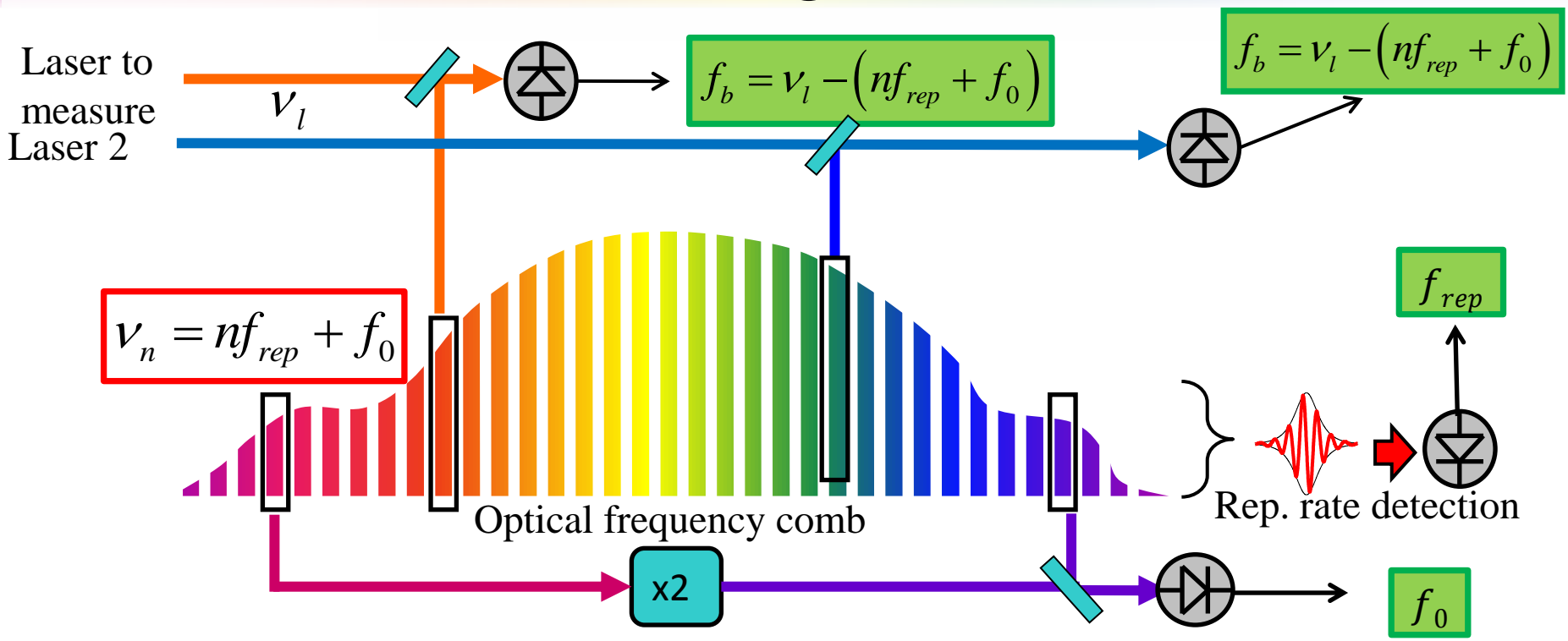
→ f_0 global offset of the frequency comb (in spectral domain)

Self-referenced comb : measuring f_0



- The doubling crystal acts on a set of « red » modes (over its efficiency BW)
- pairs of doubled red modes/blue modes beat (need to add coherently)
 - reasonably large SNR

Measuring scheme



If we know n (and we are sure of the signs in the equations),
 → the system is mathematically well determined

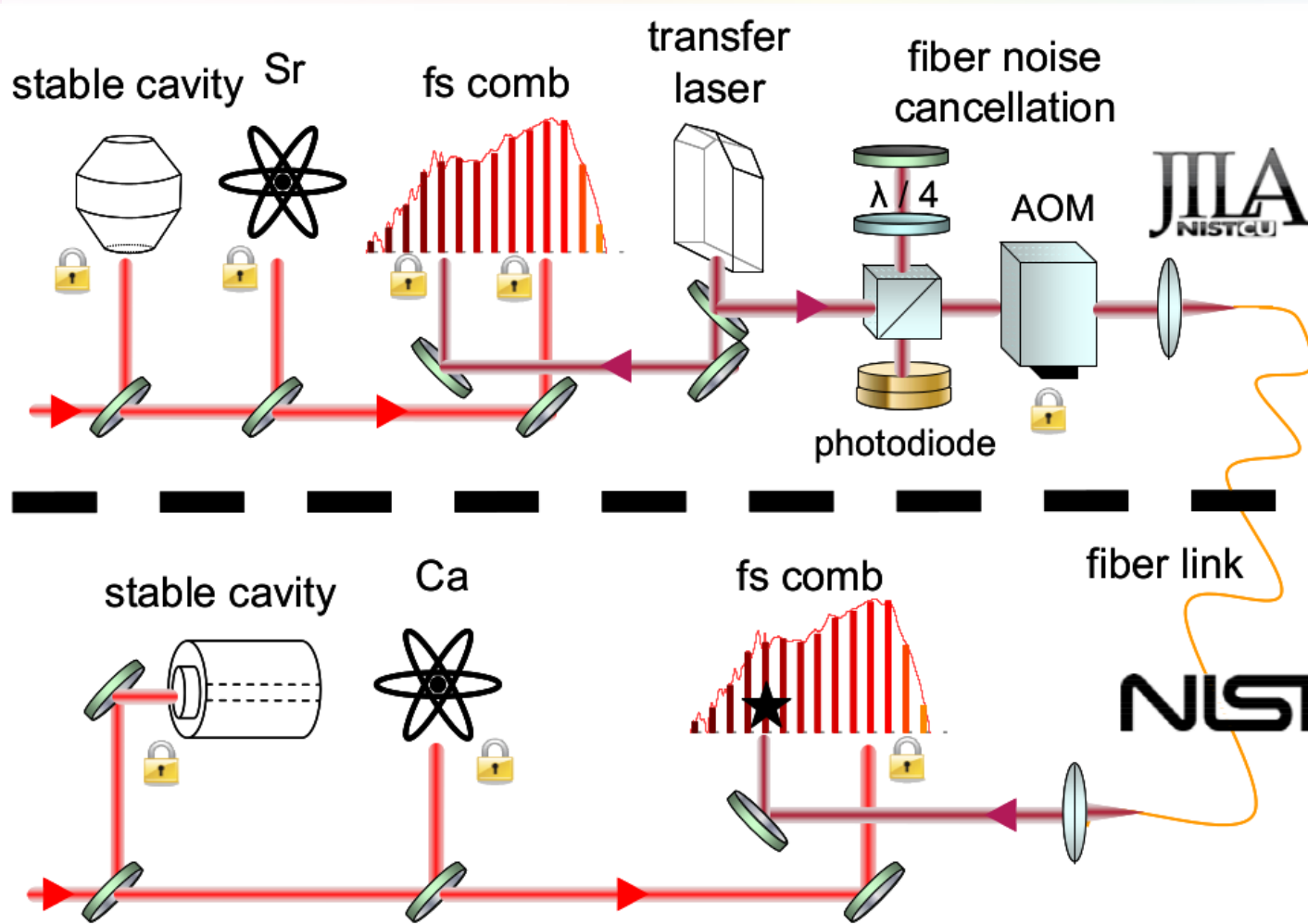
In practice, we may

- impose values to the different f with phase lock loops (multiplier scheme : ϕ -lock f_{rep} , divider scheme: ϕ -lock f_b) (narrow line...)
- measure them with frequency counters
- and/or use clever tricks (exemple : $f_b \otimes f_0 \rightarrow \text{BPF} \rightarrow v_l - nf_{rep} - f_0 + f_0 = v_l - nf_{rep}$)

Optical frequency measurements

Main players in the field (at the $\sim 10^{-15}$ level, mostly NMIs):
NIST/JILA, LNE-SYRTE, PTB/MPQ, NPL, NRC, NICT, NMIJ,
NMICChina/WIPM

The first $\sim 1.10^{-16}$ lattice clock accuracy claim



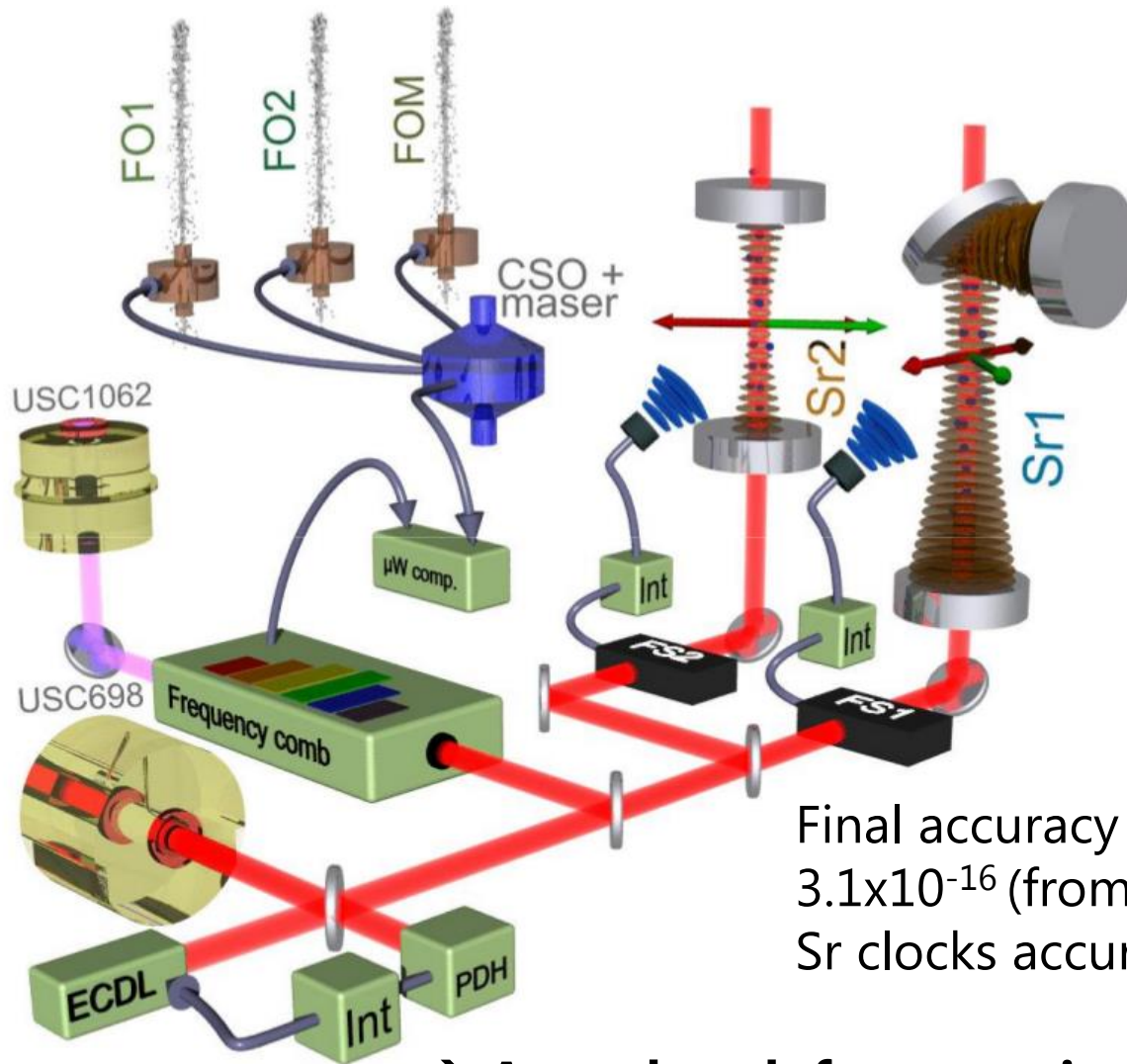
Ca clock facts:

- 2 SC lasers only (657nm clock, 423nm = 816nm x2 for cooling)
- 6×10^7 atoms at 1mK
- 5ms cycle time (3ms loading time)
- Ramsey-Bordé probing of $\sim 20\%$ for 10mW optical power
- 90% recapture
- $\sigma_y = 2 \times 10^{-15} \tau^{-1/2}$
- $\sigma_y(200s) = 3 \times 10^{-16}$
- OPTIMIZED FOR STABILITY, NOT ACCURACY

NIST Ca robust clock used as long term stability ref for remote (3km) Sr clock uncertainty evaluation at JILA

Final Sr uncertainty budget 1.5×10^{-16} (0.8 from Blackbody Radiation shift [BBR])

LNE-SYRTE 1.10^{-16} lattice clock accuracy and best absolute measurement



Measurement involves 2 Sr clocks (P. Lemonde, R. Le Targat, J. Lodewyck,...), 3 fountains, 1 CSO+H-maser referencing, 1 comb (and 1 extra $1\mu\text{m}$ USL for comb referencing)
+ tens of people
(and countless development efforts over many years)...

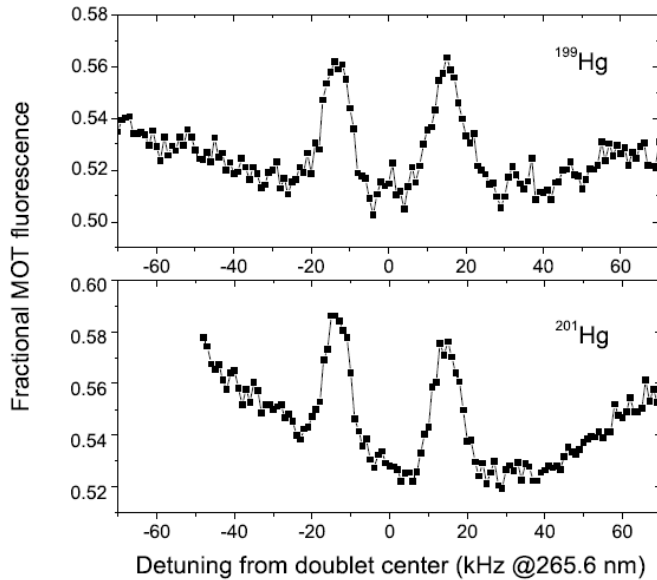
Final accuracy budget for the measurement :
 3.1×10^{-16} (from Cs fountains)
Sr clocks accuracy 1.1×10^{-16} (mostly BBR)

→ A test bench for an optical redefinition of the SI second

Measurements campaigns with Hg clock

Why Hg ? → lower BBR (but UV light everywhere...)

[S. Bize et al.]

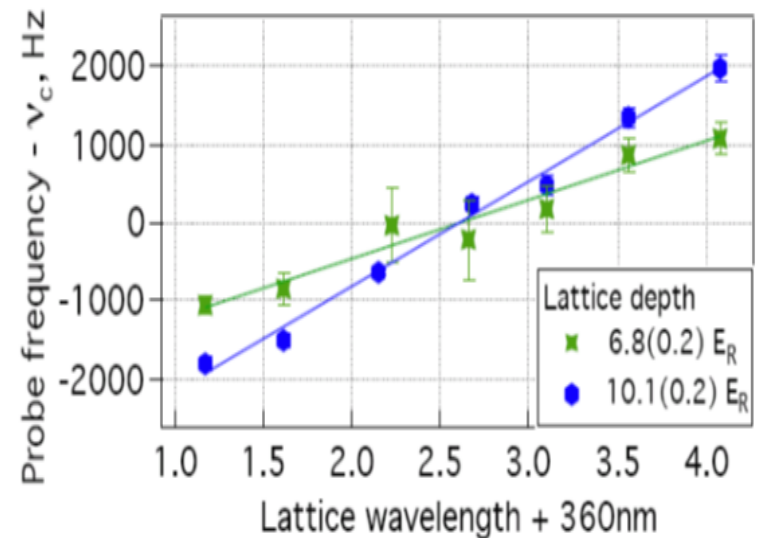


- First cold atoms spectroscopy and measurement of the clock transition

PRL 101, 1830054 (2008)

- First Hg magic wavelength lattice trap (measurement of trap and improved clock frequency)

PRL 106, 073005 (2011)



- First Hg « clock ». Accuracy budget at 5.7×10^{-15} , stability $5.4 \times 10^{-15} \tau^{-1/2}$

PRL 108, 183004 (2011)

Opt. Lett 37, 3477 (2012)

Low noise microwave generation (with optical frequency combs)

Main players in the field:
Photodiode: NIST, LNE-SYRTE,
BOM-PD : MIT, KAIST, NPL

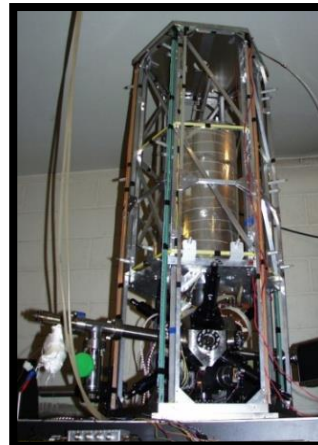
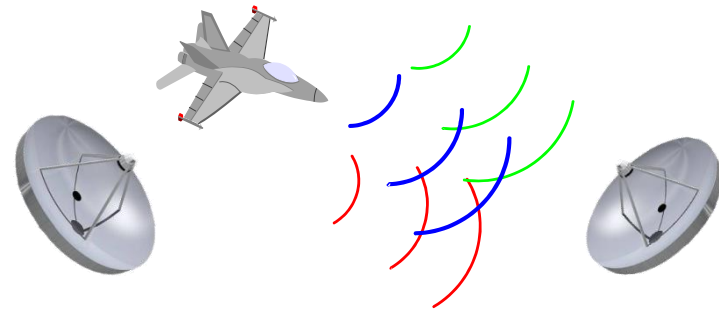
Low-noise μ wave: motivation (general)

Existing very low ϕ -noise μ -wave sources (~ 10 GHz):

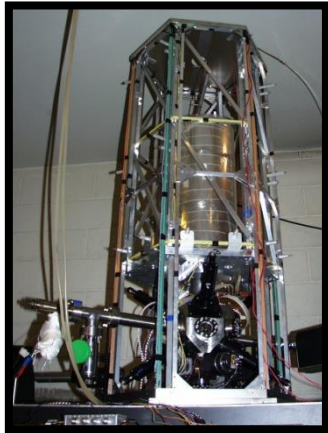
- **Room temp Sapphire osc.** (Raytheon, formerly Poseidon Australia):
 - 40dBc/Hz @ 1Hz, -170dBc/Hz @ 100kHz from carrier
- **Cryogenic Sapphire oscillator** (UWA, FEMTO-ST, ULISS):
 - 100dBc/Hz @ 1Hz, -140dBc/Hz @ 100kHz from carrier
- **Opto Electronic Oscillator** (JPL/OEwaves):
 - 40dBc/Hz@1Hz, -160dBc/Hz @ 10kHz (large resonances after that)

Applications:

- atomic frequency standards
- radar
- VLBI
- synchronization of particle accelerators
- time reference distribution
- telecommunication
- ...

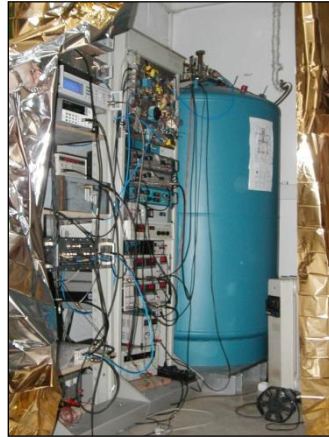


Low-noise μ wave : motivation (LNE-SYRTE and other NMIs)



Atomic fountain clock

+



Cryogenic Sapphire oscillator **carrier**

Fountain clock stability limited by QPN:
 $1,4 \times 10^{-14} \tau^{-1/2}$

See Santarelli et al. Phys. Rev. Lett 82, 4619 (1999)

Need a backup/replacement for CSO with low F-noise near 1Hz from 9.2GHz carrier

→ **USL+comb** can have **very low ϕ -noise BOTH near (1Hz) and far (100kHz) from carrier** (+natural connection to opt. freq. std.)

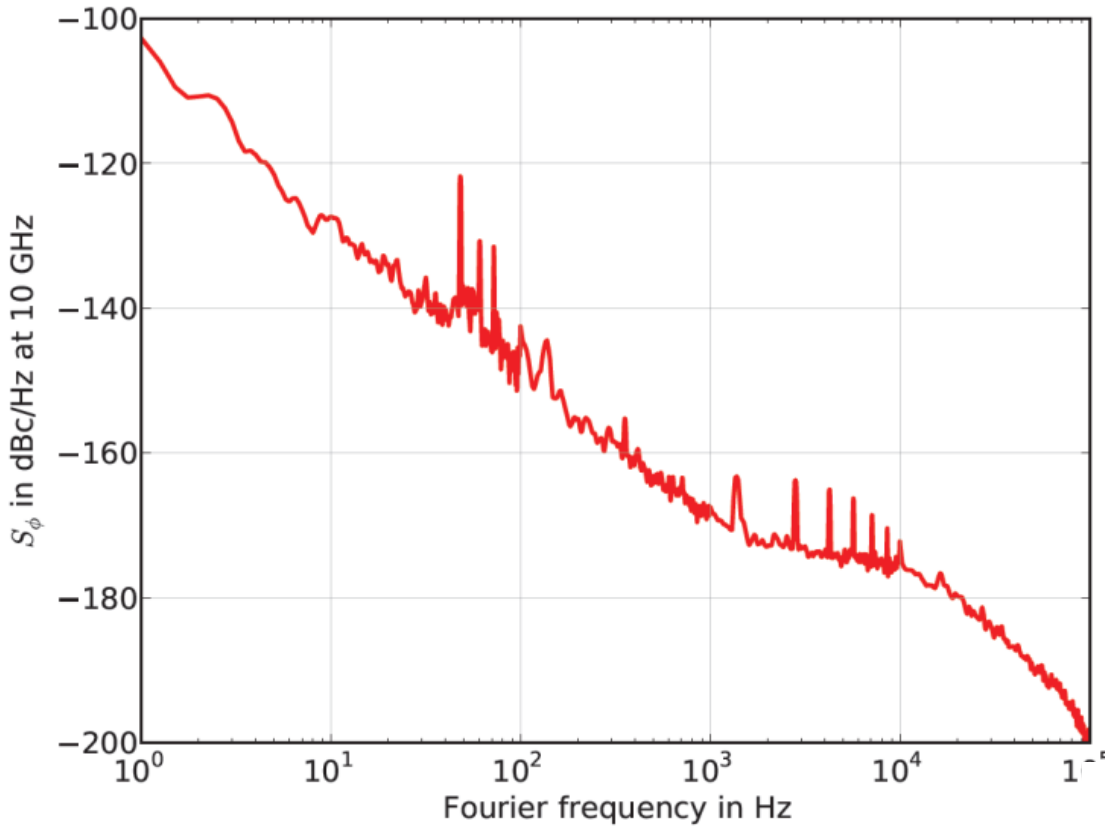
→ Demonstration of QPN limited fountain clock at LNE-SYRTE realized in 2009 (now getting 100% operational)

Applied Physics Letters 94, 141105 (2009)

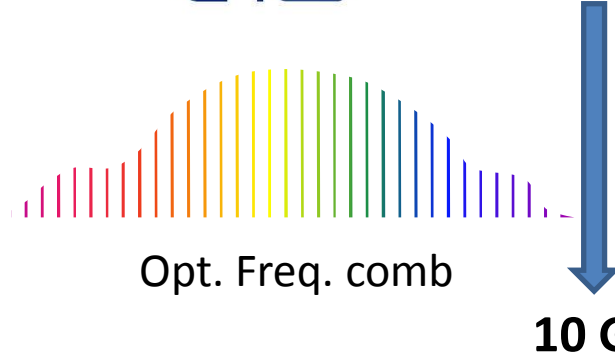
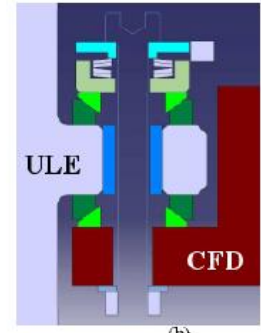
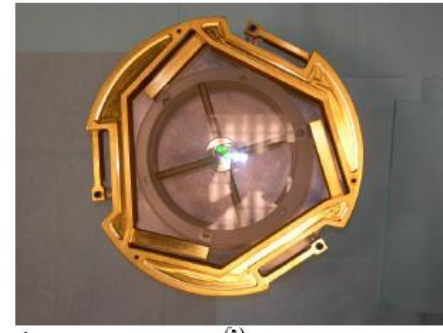
Note: further characterization in collaboration with FEMTO-ST reported in :

Opt. Letters 34, 3707 (2009)
App. Phys. Lett. 96, 211105 (2010)

USL transferred to μ -wave (objective)



- A robust 4.5×10^{-16} (@1s) level USL cavity (designed following space industry standards and methods)
- 10cm long cavity with rings
- Prototype designed for transport +/-10g and operation at zero-2g
- Currently existing lab prototype

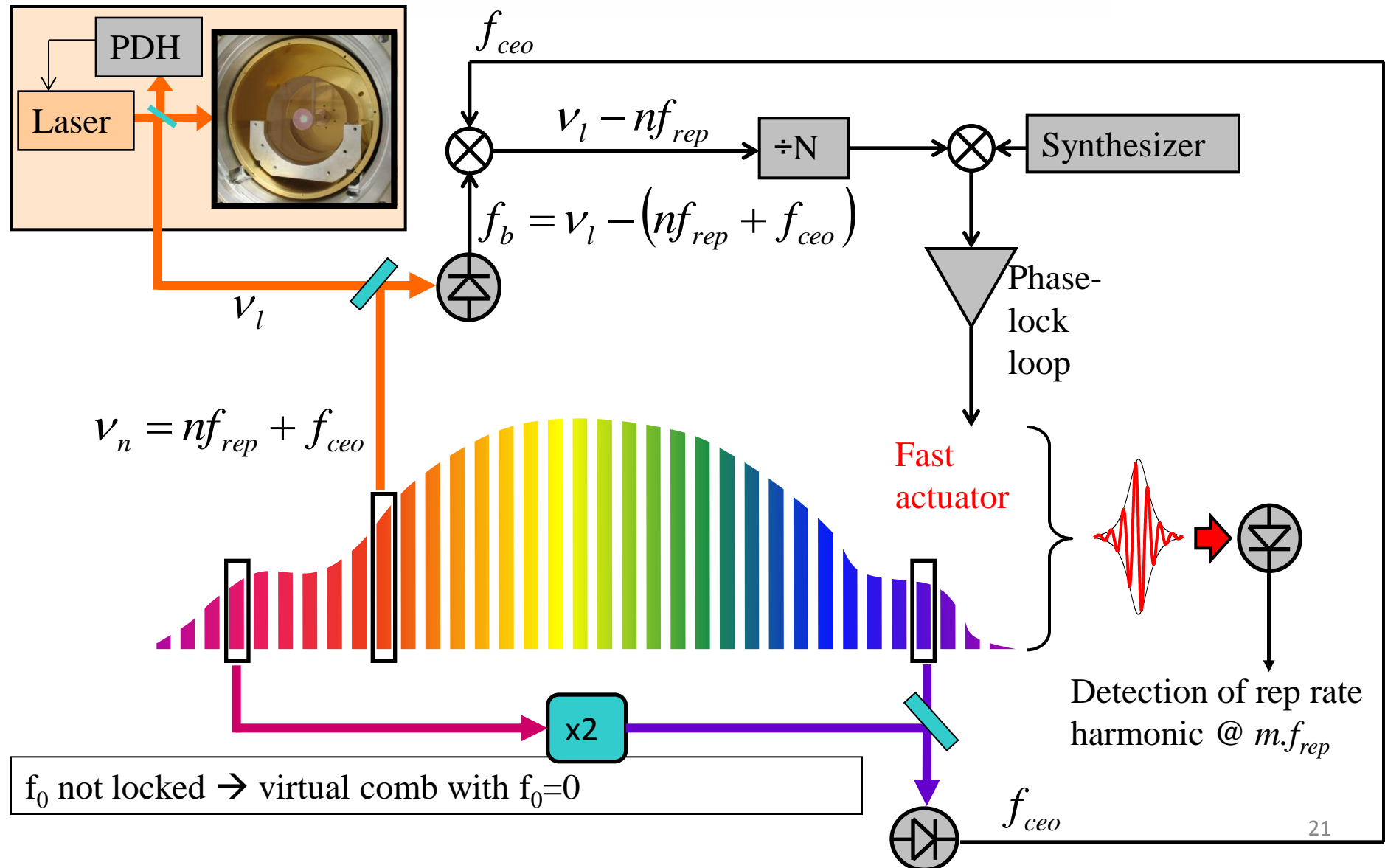


Φ -noise
 → $-20 \cdot \log(20000)$
 = -86dB (!!!)

Φ -noise of a 10 GHz carrier obtained by frequency division of the space-prototype USL at 200THz (SODERN/CNES/SYRTE), by a frequency comb, assuming perfect division

Note : data from Argence et al. Opt. Express 20, 25409 (2012), work realized at LNE-SYRTE

μ -wave generation with comb (divider scheme)



Er-fibre comb with intra-cavity EOM

WHY ?

large feed-back BW difficult for Er fs lasers

→ pump diode current : rather low response, $\sim 100\text{kHz}$ max BP (with good phase-advance electronics...)

→ PZT : resonances $\sim 40\text{kHz}$ BW

Free-running high Fourier frequency phase noise is hard to kill with phase-locking

HOW ? (in coll. with **MenloSystems** GmbH)

-Add a fast actuator (EOM) in the fs laser cavity

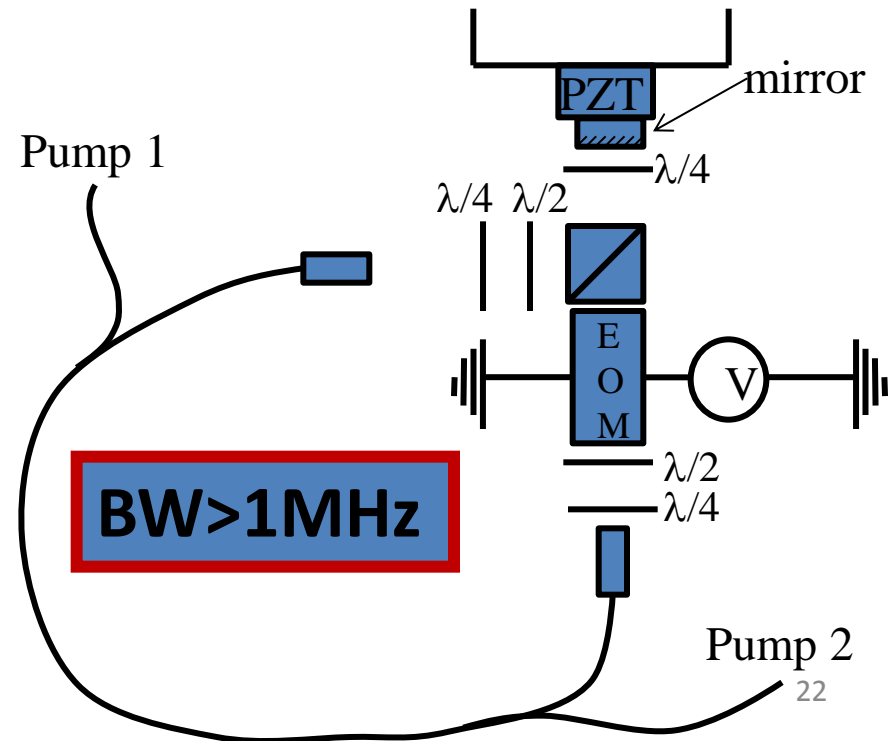
-Used as a voltage-controlled group delay actuator

(index $\langle n \rangle$ controlled by V ; linear polarization)

- Good alignment to ↘ cross-talks (via polarization and amplitude)

Zhang et al. IEEE UFFC 59


also NIST
also NMIJ

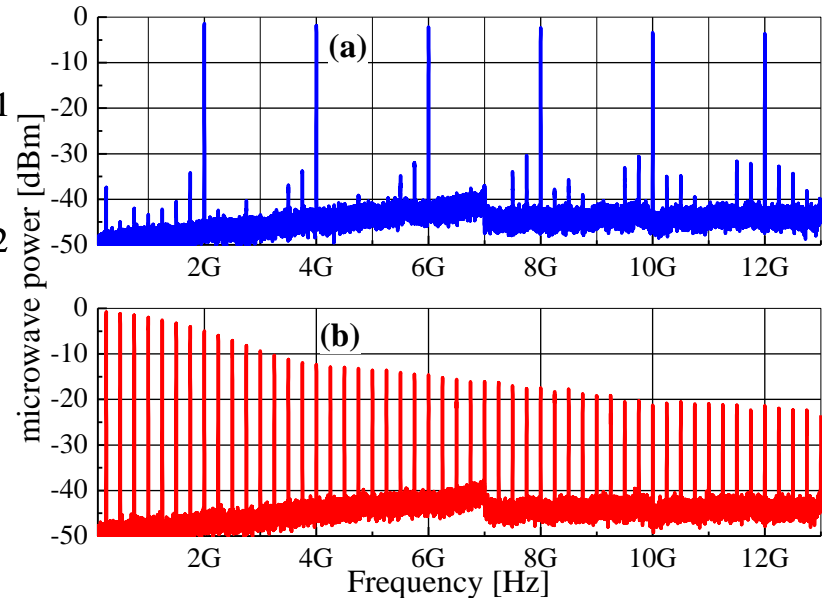
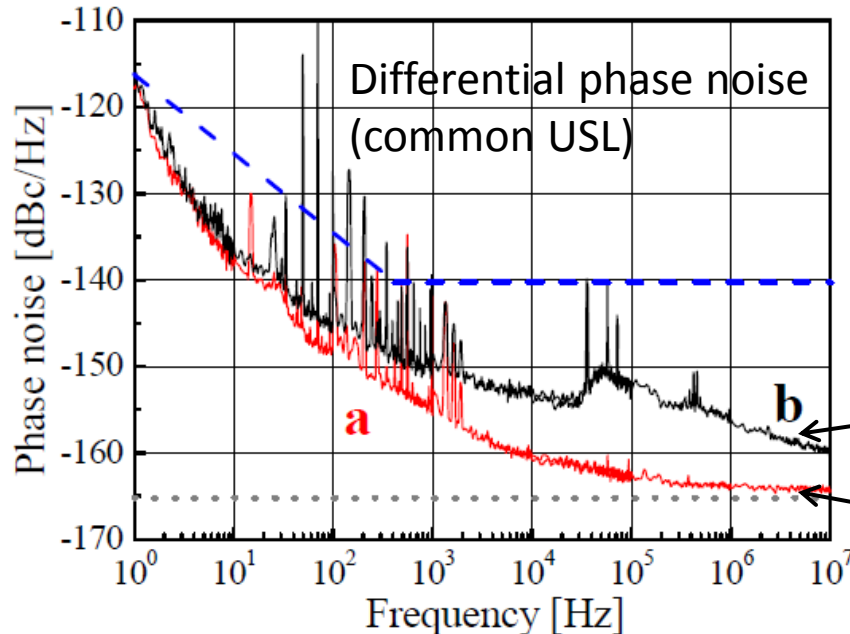
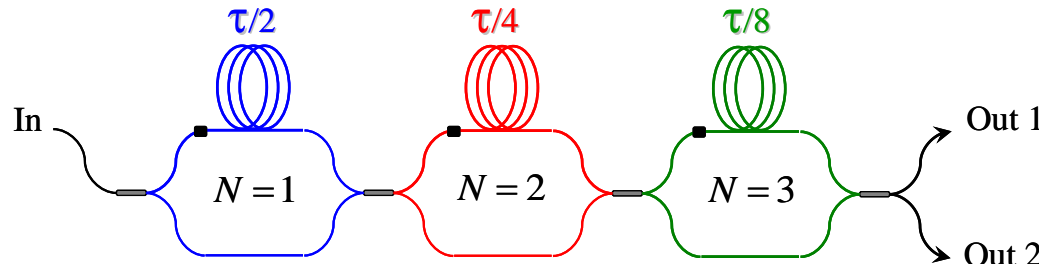


(Note : no output coupler represented here)

Increase SNR for lower white phase noise floor

Thermal noise (Johnson-Nyquist) :

- ➔ A -20dBm μ -wave signal cannot have a white phase noise limit better than -157dBc/Hz
- ➔ Solution : increase μ -wave power
 - higher optical power+more linear PD
(in coll. with  *Discovery Semiconductors, Inc.*[®])
We Chip the Future[®]
 - high rep rate fs laser / external rep rate multiplication
➔ less power in undesired harmonics,
more in the harmonic of interest

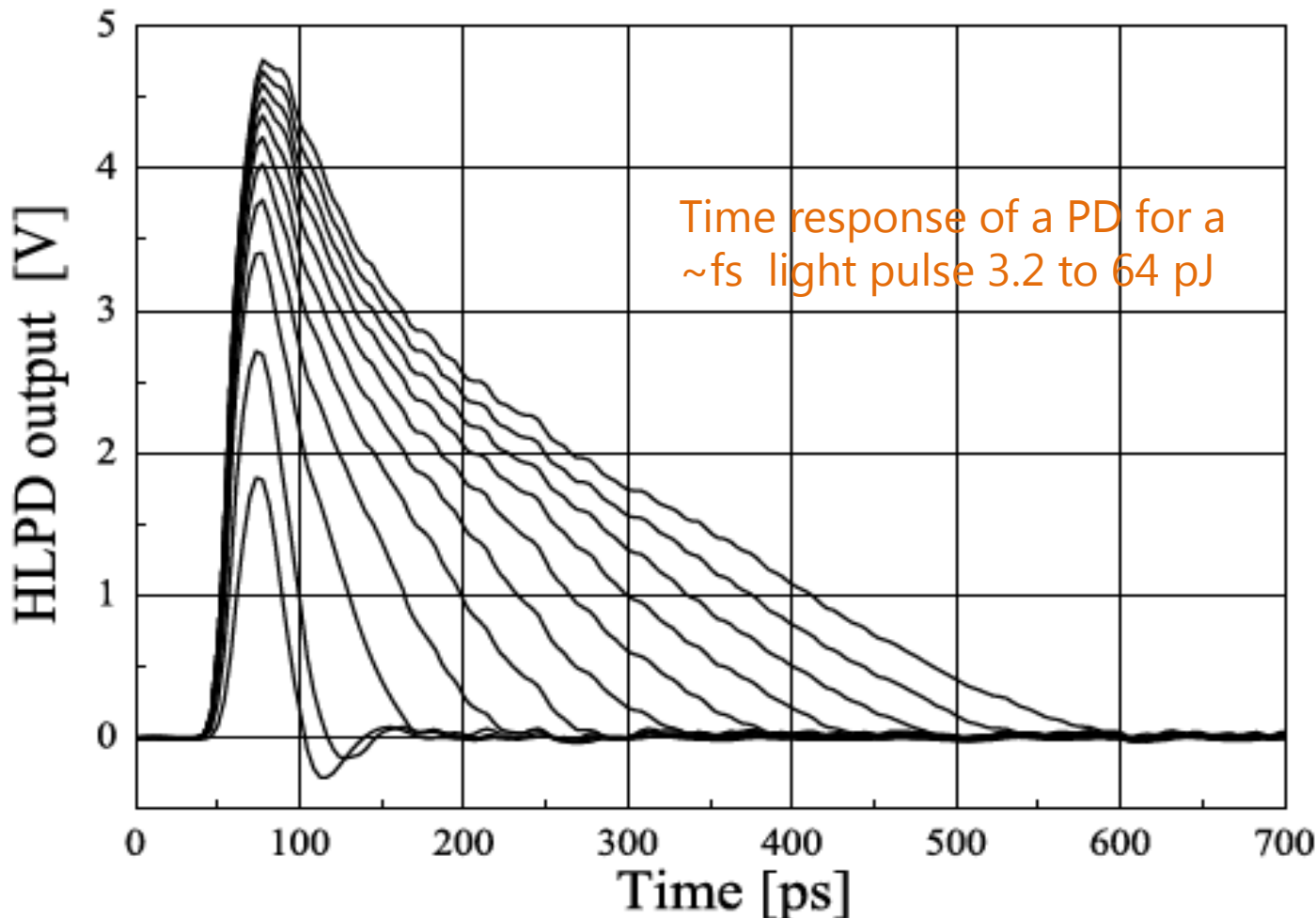


2 combs 2 MZM 2 PD
(excess phase noise to investigate)

1 combs 2 MZM 2 PD

AMPM conv. in f_{rep} and harmonics photodetection

- amplitude fluctuations of the fs laser induce fluctuations of phase of f_{rep} (and its harmonics)
 - possible to lock amplitude (but only at low Fourier frequencies)
 - or analyze carefully the physics...

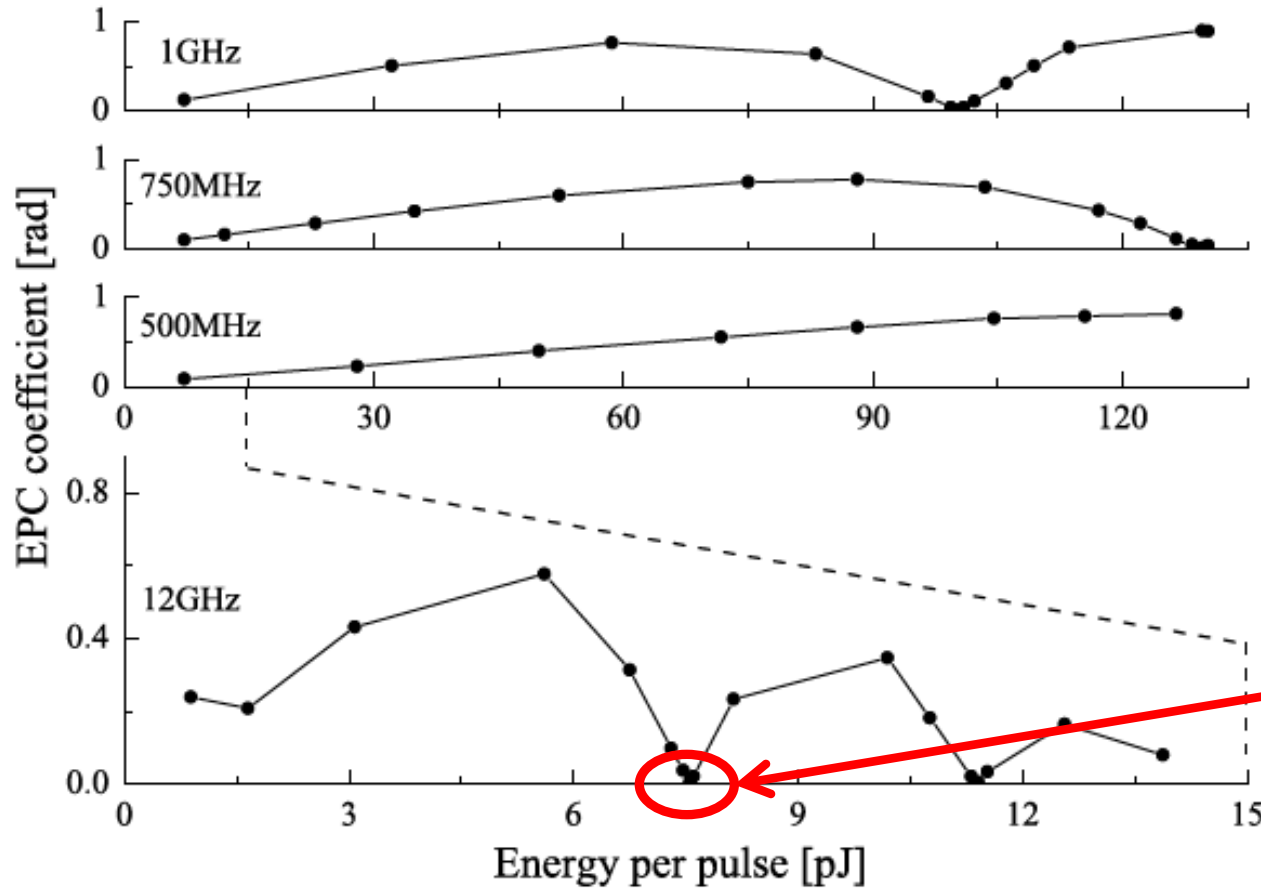


By **space-charge screening effect**, close to saturation, the PD response is **asymmetric**

→ AM noise produces PM noise

For harmonic order >1 there are special situations...

Suppression of AMPM conversion



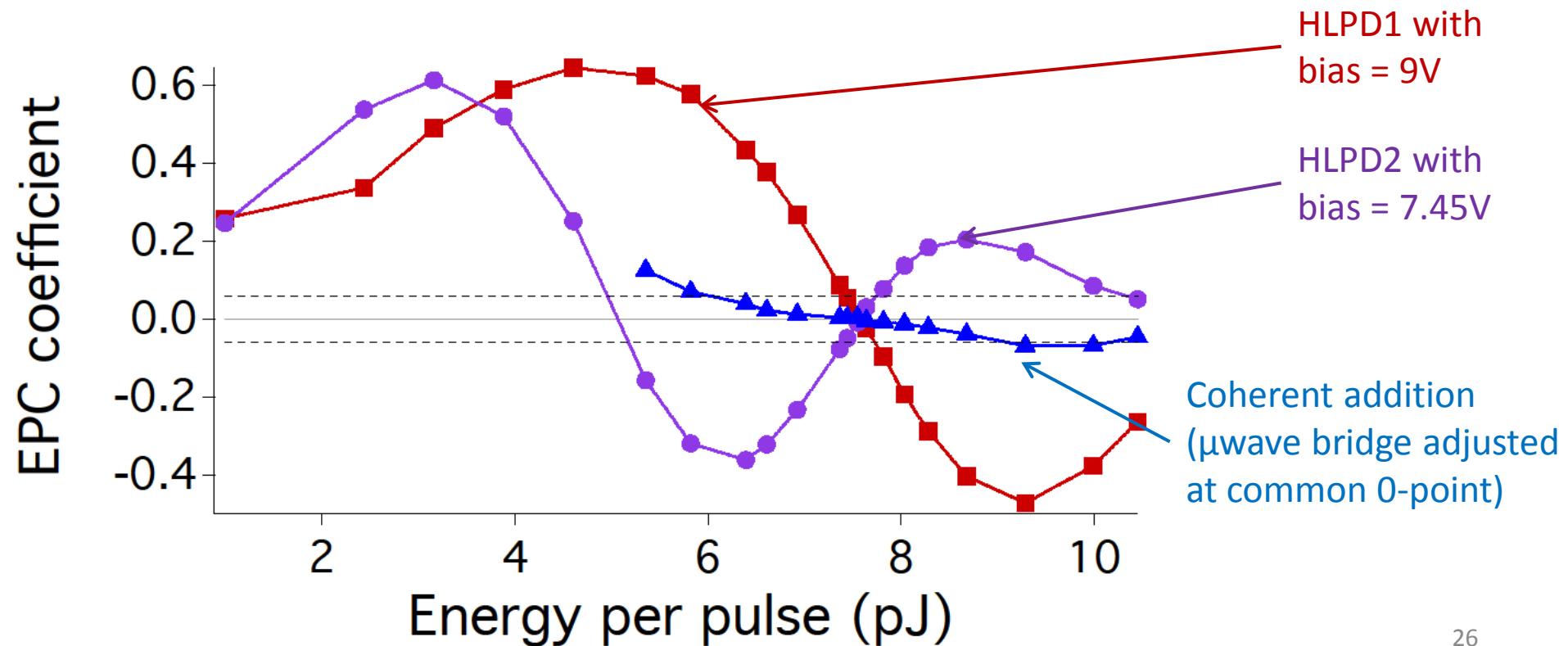
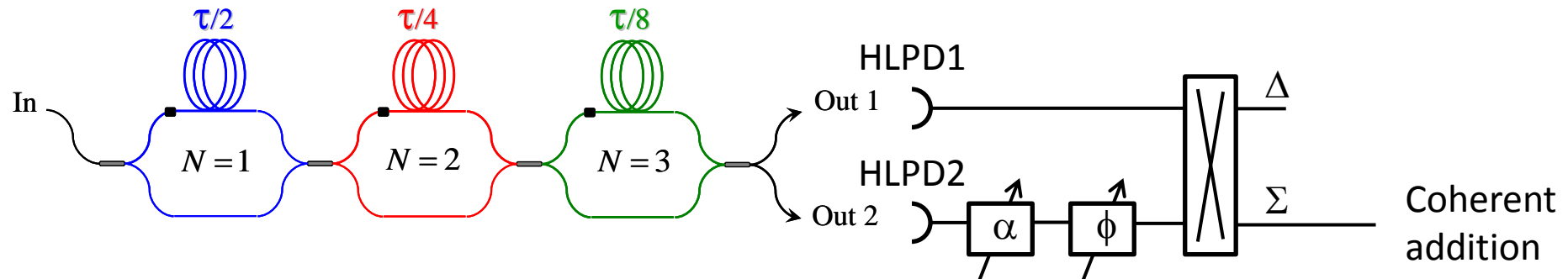
Note : EPC coeff. is really alternatively >0 and <0 , only $|EPC|$ is plotted here...

In this area
→ low EPC

Reasonable to **passively** keep the laser power at $\sim 0.1\%$
→ From slope of EPC vs. Energy per pulse → EPC < 0.003 rad
→ AMPM-induced excess phase noise = RIN – 50dB !!!

Easy low AMPM with MZM & Dual PD

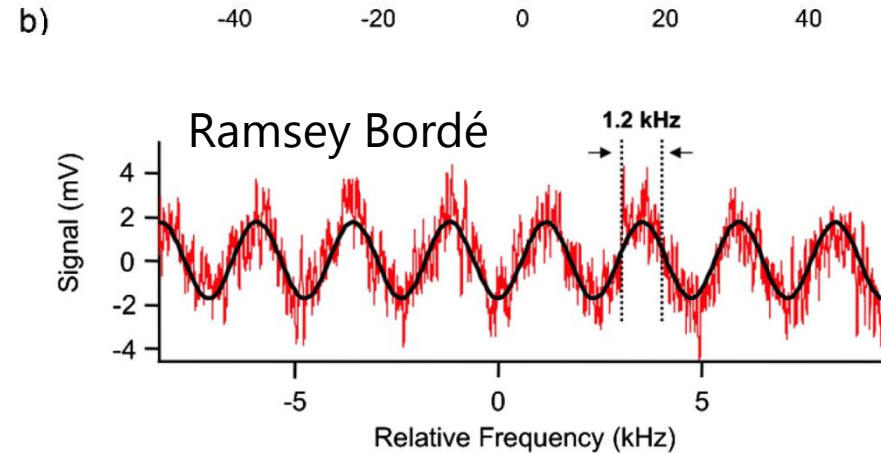
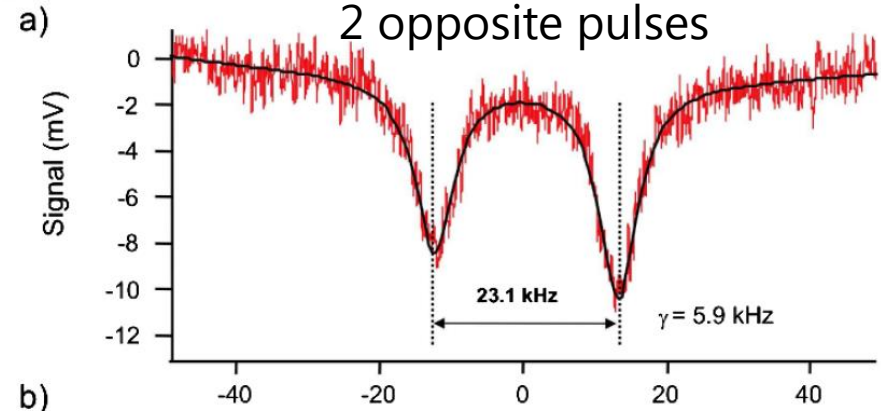
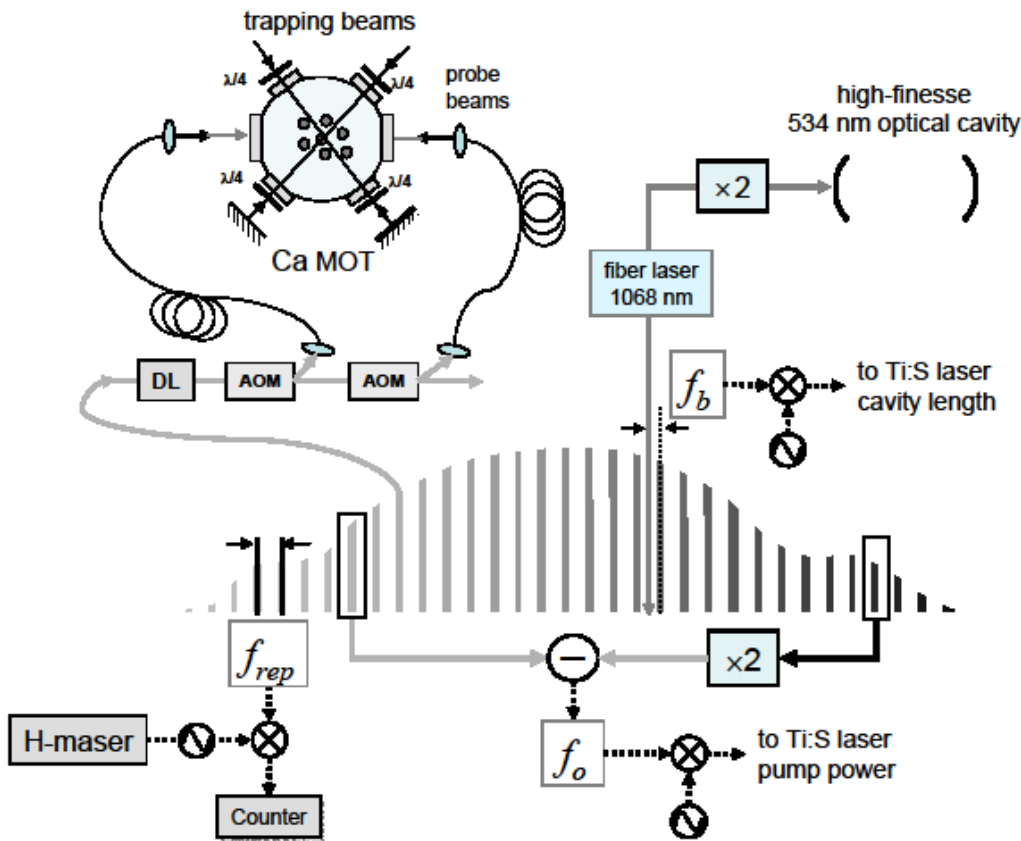
(with  *Discovery Semiconductors, Inc.*
We Chip the Future®)



New applications of frequency combs in the optics domain

Main players in the field:
NIST(+JILA)), LNE-SYRTE(+LPL),
MPQ/PTB, MIT, NMIJ,...

Direct frequency comb spectroscopy



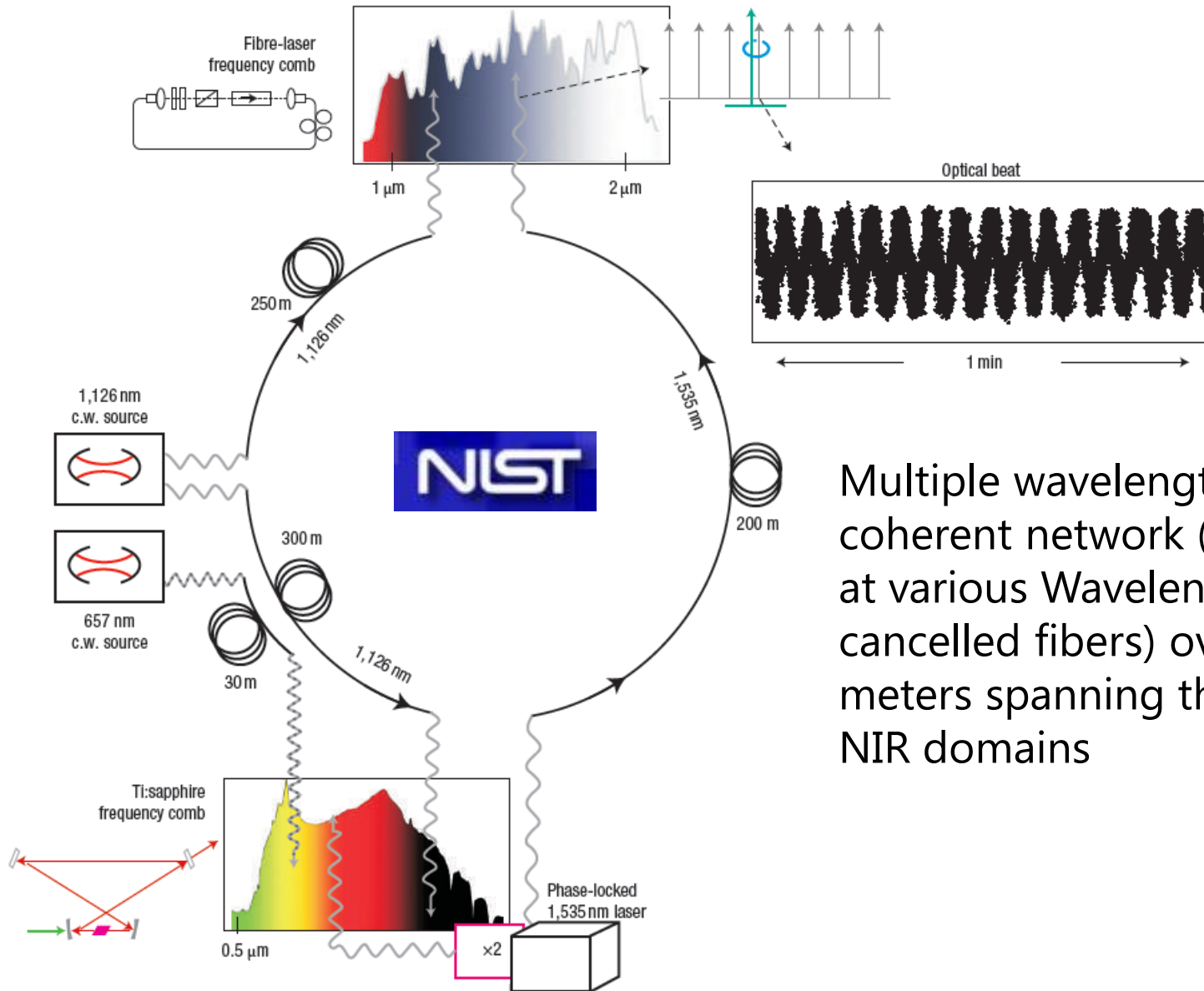
- Direct spectroscopy with 1 tooth of the comb
- Injection locking of a slave laser by a single tooth of the comb (experiment b)
- DFCS at the kHz level



PRL 97, 163905 (2006)

Also another detection technique for different lines in PRA 75, 040502 (2007)

Multi- λ and remote use comb/link networks



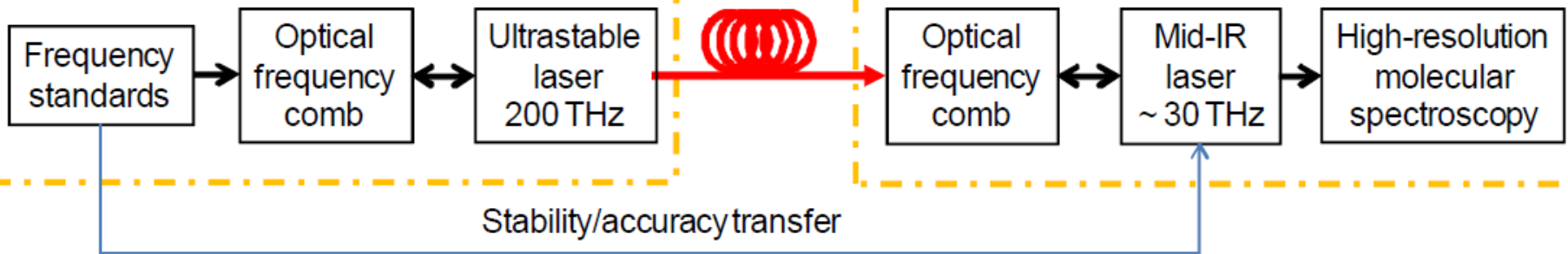
Multiple wavelength phase-coherent network (2 combs, 3 USL at various Wavelengths, noise cancelled fibers) over 100's of meters spanning the visible and NIR domains

Multi- λ and remote use comb/link networks

LNE-SYRTE

43-km
optical link

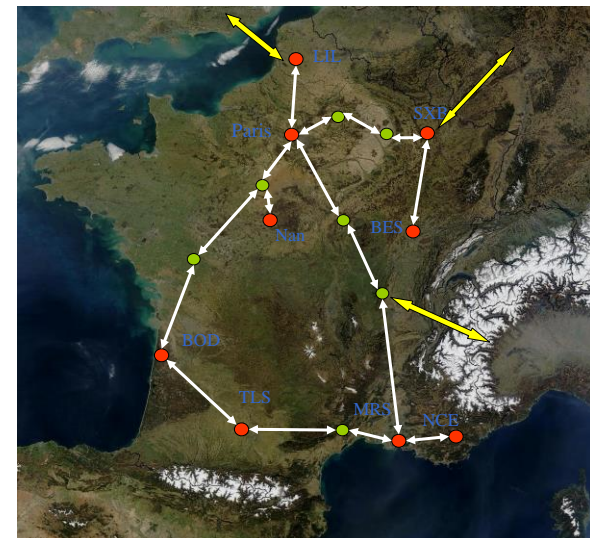
LPL



New J. of Physics 15, 073003 (2013)

Collaboration LNE-SYRTE/LPL

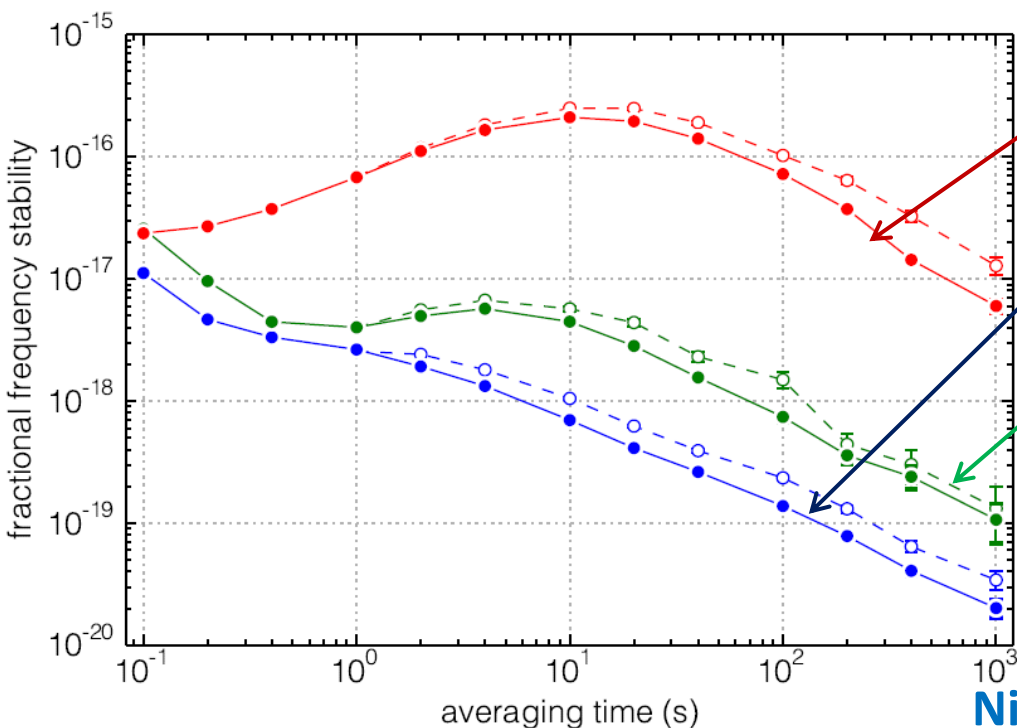
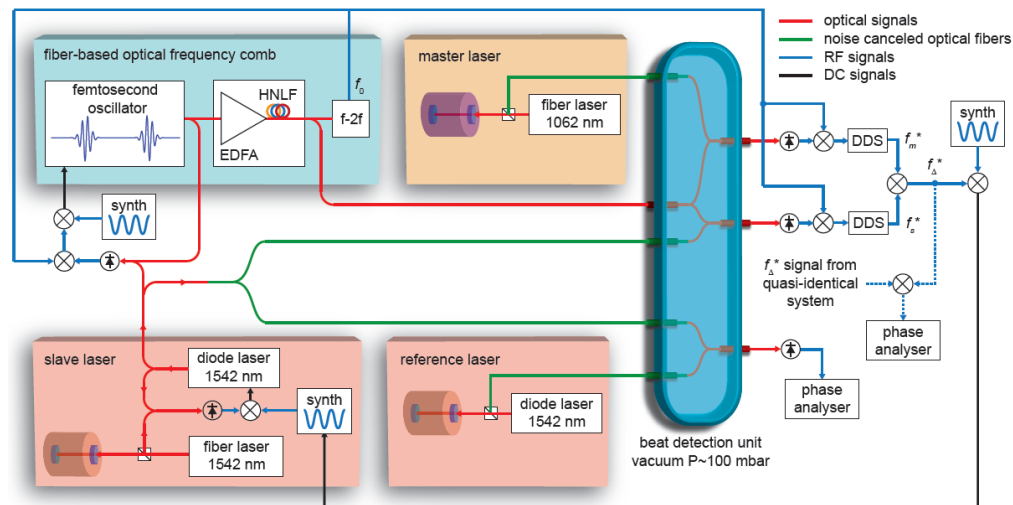
→ an embryo and test bench for the REFIMEVE+ network (G. Santarelli, P-E. Pottie) which will involve 10+ laboratories scattered over France (+ connection to Germany (PTB/MPQ), England (NPL), Italy (INRIM),...)



Transfer of spectral purity at the 10^{-18} (@1s) level

Fiber-comb locked to $1.5\mu\text{m}$
 USL for large SNR \rightarrow large
 feedback BW

problem: how to use a better
 USL at a wavelength $\neq 1.5\mu\text{m}$
 More generally :



Transfer from $1\mu\text{m}$ to $1.5\mu\text{m}$,
 little effort taken

Transfer from $1\mu\text{m}$ to $1.5\mu\text{m}$,
 (single branch, vacuum interf.,...)

With dual $1.5\mu\text{m}$ slaves and extra
 comparison between them

(— MVAR - - - AVAR, 0.5Hz BW)

\rightarrow Limitation at a few 10^{-18} at $\sim 1\text{s}$
 (>1 order of magnitude lower than
 current best demonstrated USL)

prospective

μ -wave generation

Higher linearity/power handling photodiodes

MUTC (cf work at NIST) ?

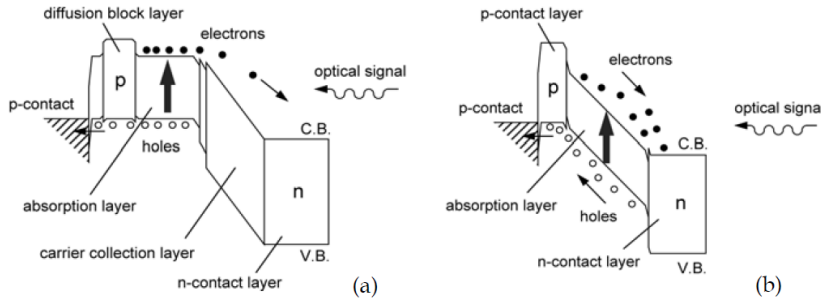
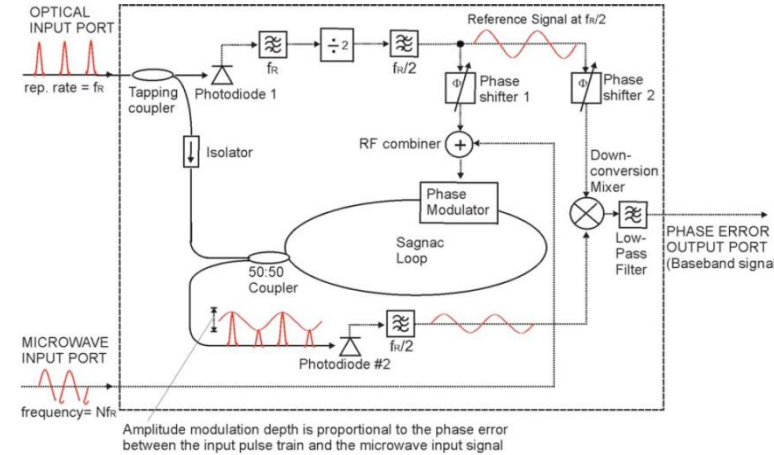


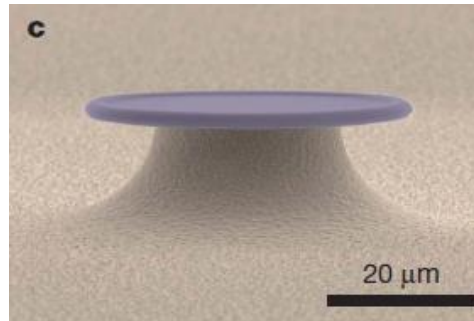
Fig. 1. Band diagram of a UTC-PD (a) and a pin-PD (b).

Use of BOM-PD for lower flicker limits ?
cf work from MIT, KAIST, NPL



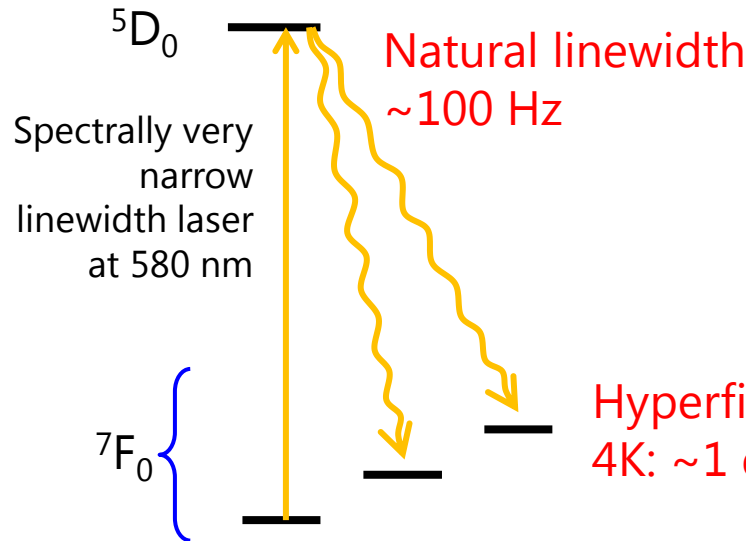
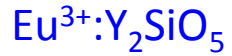
Different types of combs

- « figure 9 » combs (soliton vs. Stretched pulse)
- harmonically mode-locked lasers
- micro-combs



→ Emphasis towards industrial transfer...

Ultra-stable laser with Rare-earth-doped crystals

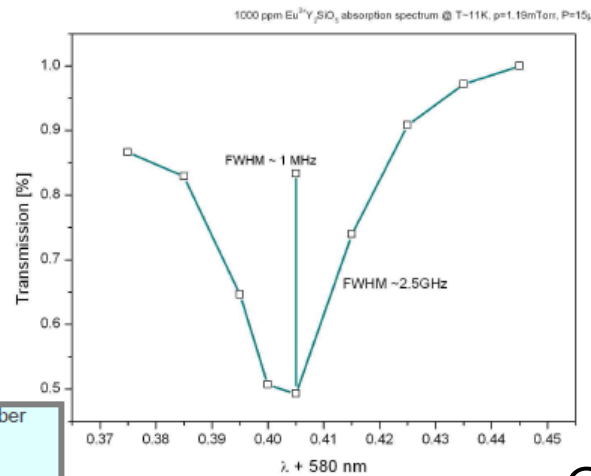
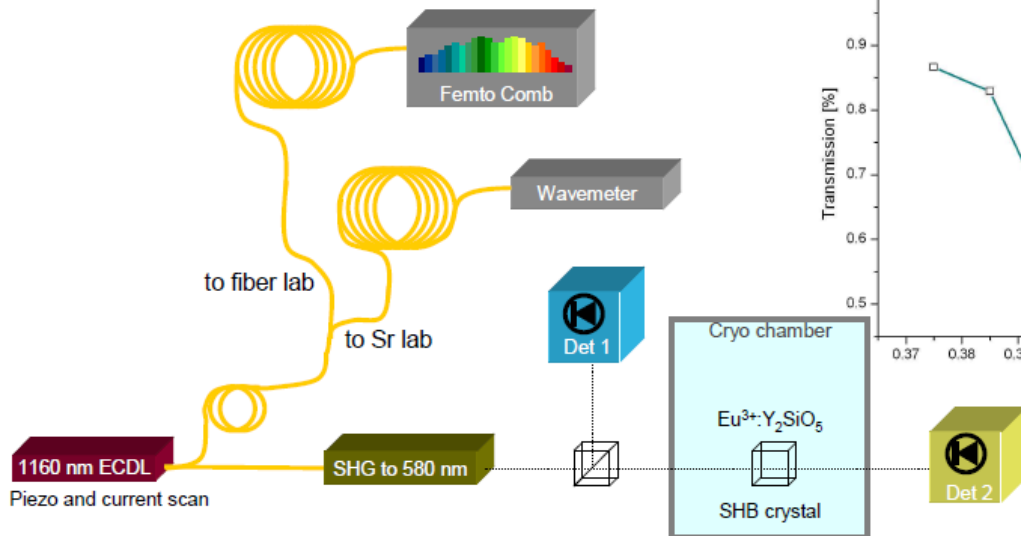


Result from NIST on $\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$:
 6×10^{-16} stability at 2s-8s

(see NIST-Rosenband, Nature Photonics 10, 1, 2011)
(see also U. Dusseldorf-Schiller, PRL 107, 223202, 2011)

Hyperfine population lifetime at
4K: ~1 day !!!

SHB laser stabilisation at SYRTE: Setup Sept 2013

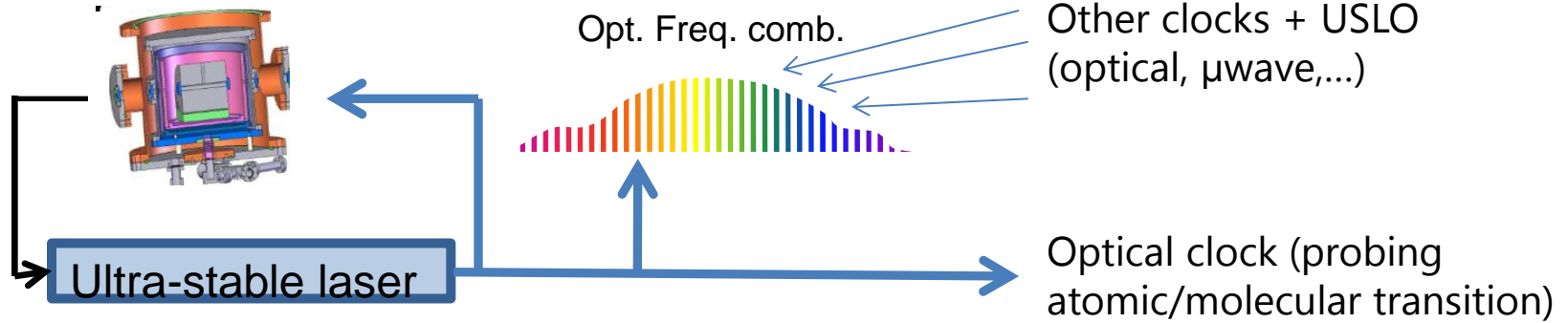


Collaboration with :

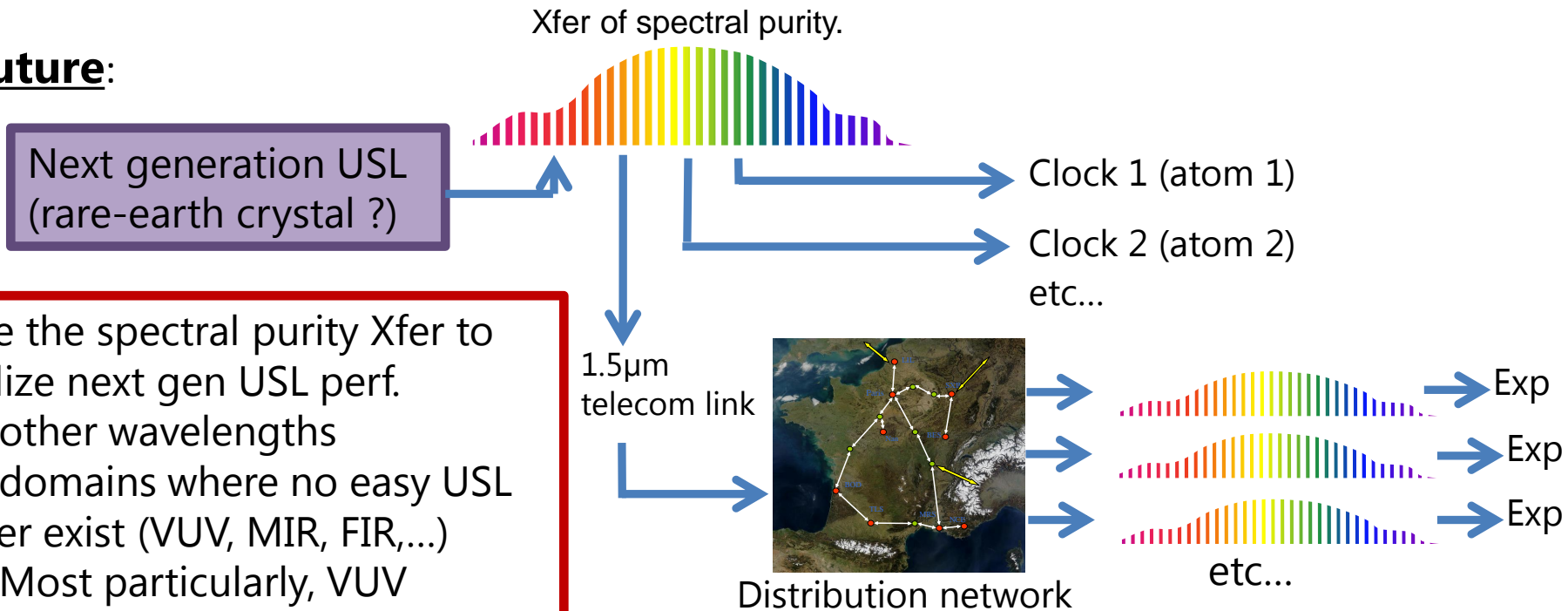


Toward a paradigm shift in optical clocks

Now:



Future:



Use the spectral purity Xfer to utilize next gen USL perf.
→ other wavelengths
→ domains where no easy USL laser exist (VUV, MIR, FIR,...)
→ Most particularly, VUV exploration (ex.: Thorium) with combs HHG and DFCS (for exemple)

→ Necessity of extremely reliable continuous operation combs !!!

The many people involved (thanks...)



P. Bouyer, A. Aspect, M. Fauquemberg, J.F. Riou, W. Guerin, S. Rangwalla, F. Moron, A. Villing, M. Lécivain, R. Nyman, G. Varoquaux, B. Villier, D. Sacchet, ...



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MenloSystems

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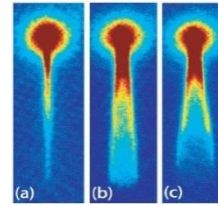
T. Chaneliere, p. Goldner,
JL. Legouet, A. Ferrier
A. Chauvet



A. Luiten,
M. Tobar

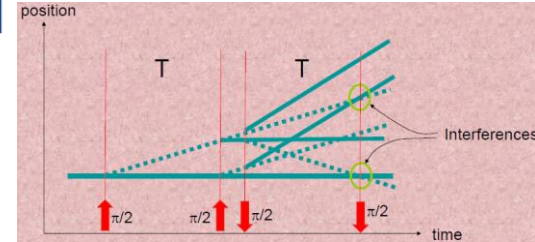
Summary

Initial training and background in BEC and atom lasers.



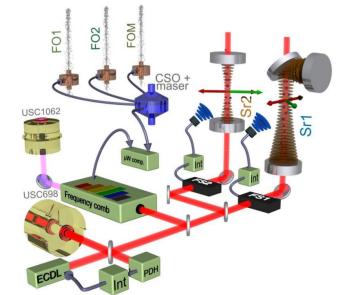
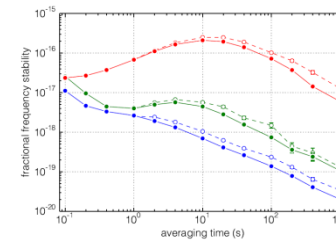
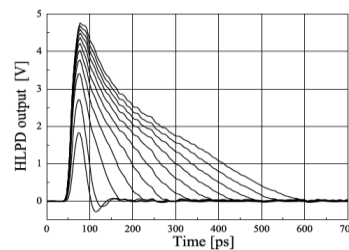
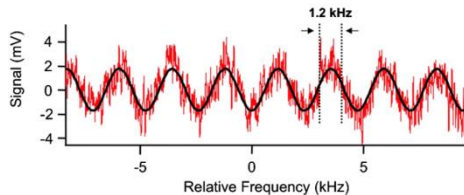
Work with a Ca optical clock :

- A **robust** optical frequency standard with $\sim 2 \cdot 10^{-16}$ stability at 200s



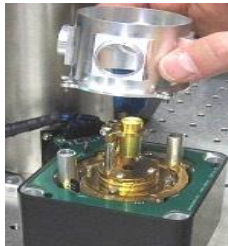
Work with optical frequency combs :

- **Optical frequency standards measurements** (Sr, Ca, Hg) and comparisons (measurement campaigns for accuracy assessments and improvements)
- **Low phase noise μ wave** signal generation (and application to fountain clocks)
- **Proof of principle experiments** using a comb (+ an optical fiber link) to probe atoms/molecules at a place and a wavelength different from that of the high quality local oscillator USL (DFCS, phase coherent networks, transfer of spectral purity)



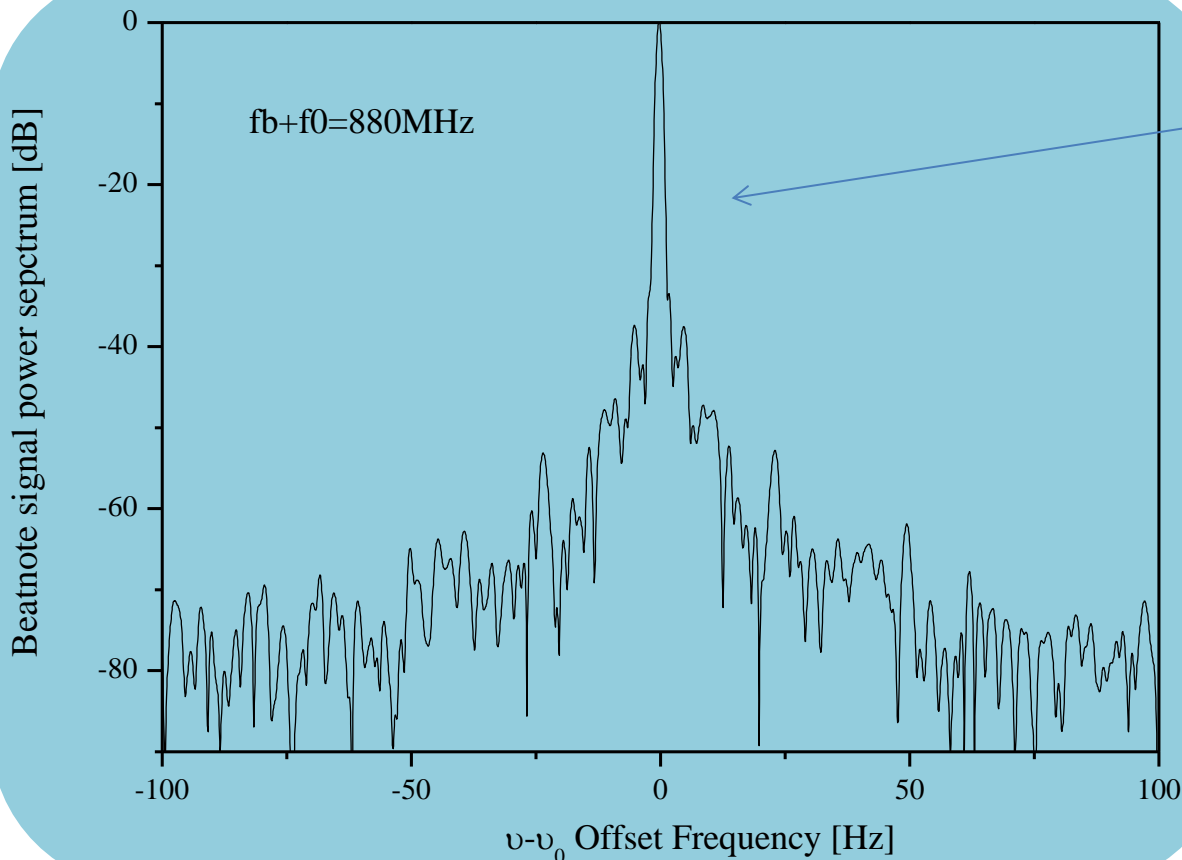
Future work :

- Towards a **low maintenance, multi purpose** (μ wave for the fountains, measurements of optical clocks), **continuously operated** fiber-based frequency comb \rightarrow optical secondary frequency standards participation to TAI
- **Furthering low-noise μ wave performance**, transfer to industry
- **Rare-earth doped cryogenic crystal based USL**, transfer to optical clocks probing wavelengths, toward QPN limited lattice clocks...



The importance of narrow linewidth regime

IF comb phase-locked to USL with ~ 1 Hz linewidth (divider scheme)
AND free-running comb noise low enough
+ f-locking BW and gain large enough
THEN narrow linewidth regime (residual lock phase noise \ll USL)
= each tooth of the comb is as narrow as the master USL
= other optical beatnotes with other USL will have ~ 1 Hz linewidth



A typical out-of-loop beatnote for a comb in the narrow linewidth regime

Although SNR is very low in large measurement BW,
One can filter out noise with narrow BW filter \rightarrow large SNR