Why High Precision w/ X-Ray FELO Comb ?

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- **Precise Frequency domain X-Ray** spectroscopy,
  - quantum state energy measurements, interactions and perturbations

AND

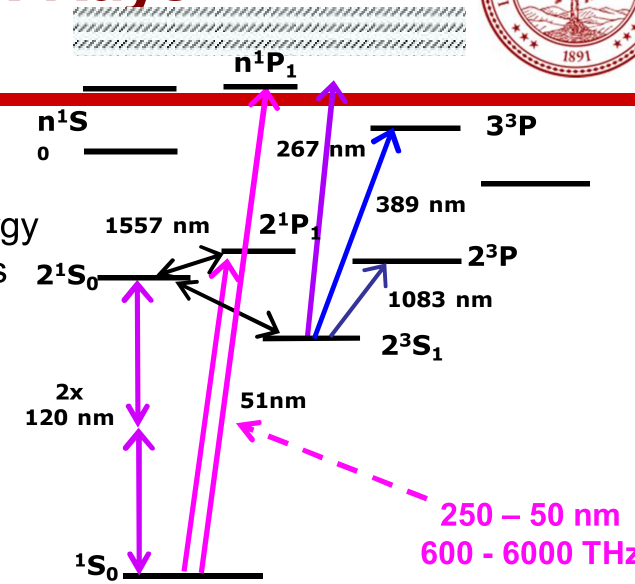
- **Time domain** including with X-ray phase control

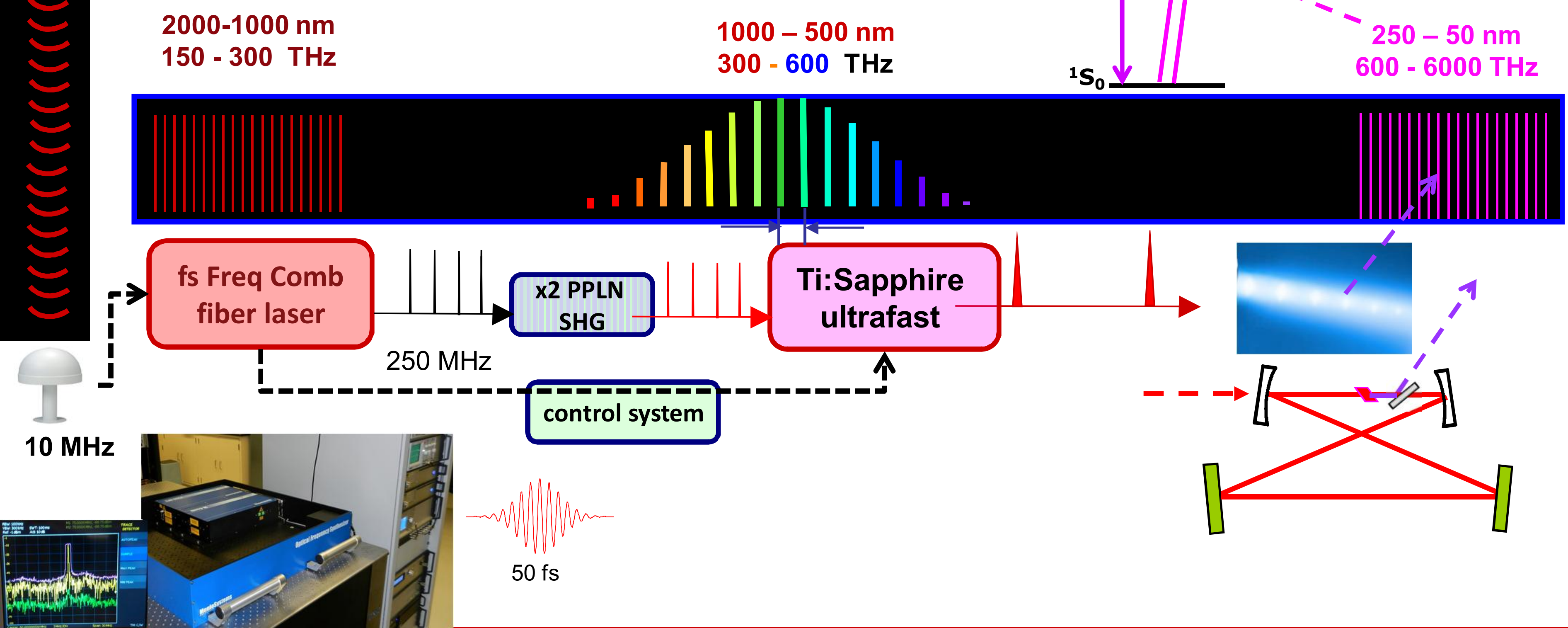
- X-Ray coherent pumping and probing of:
  - Ions
  - nuclear transitions
  - nonlinear spectroscopy multi-transitions in cascades
    - X-Ray + X-Ray and/or X-Ray + optical
  - Nuclear state dependent reactions
    - X-Ray induced nuclear association ?

Precision atomic structure -- testing QED w/ Phase-Coherent X-Rays

Precision spectroscopy of simple atoms

- Most stringent test of quantum theory & QED at low energy
- Energy levels and lifetimes calculable from first principles
- Simplest atoms H, He, and H-like and He-like ions
- Most important transitions in VUV to X-Ray

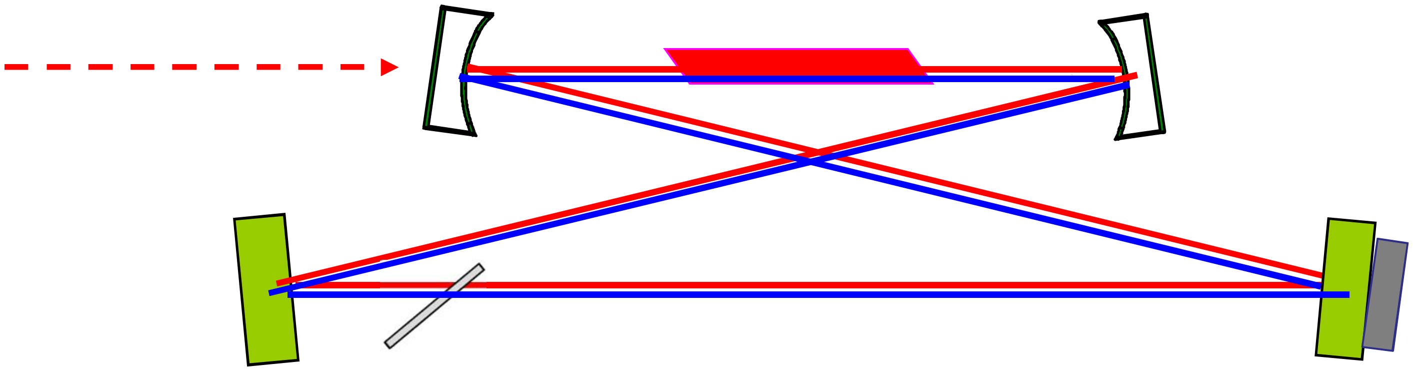




Optical stabilization of X-Ray Ring Laser

For laser resonator

$$\frac{\Delta l}{l} = \frac{\Delta \omega}{\omega} = \frac{\Delta E}{E} = \frac{\Delta t}{t}$$



Comb spacing f_{rep} = 25 MHz ?

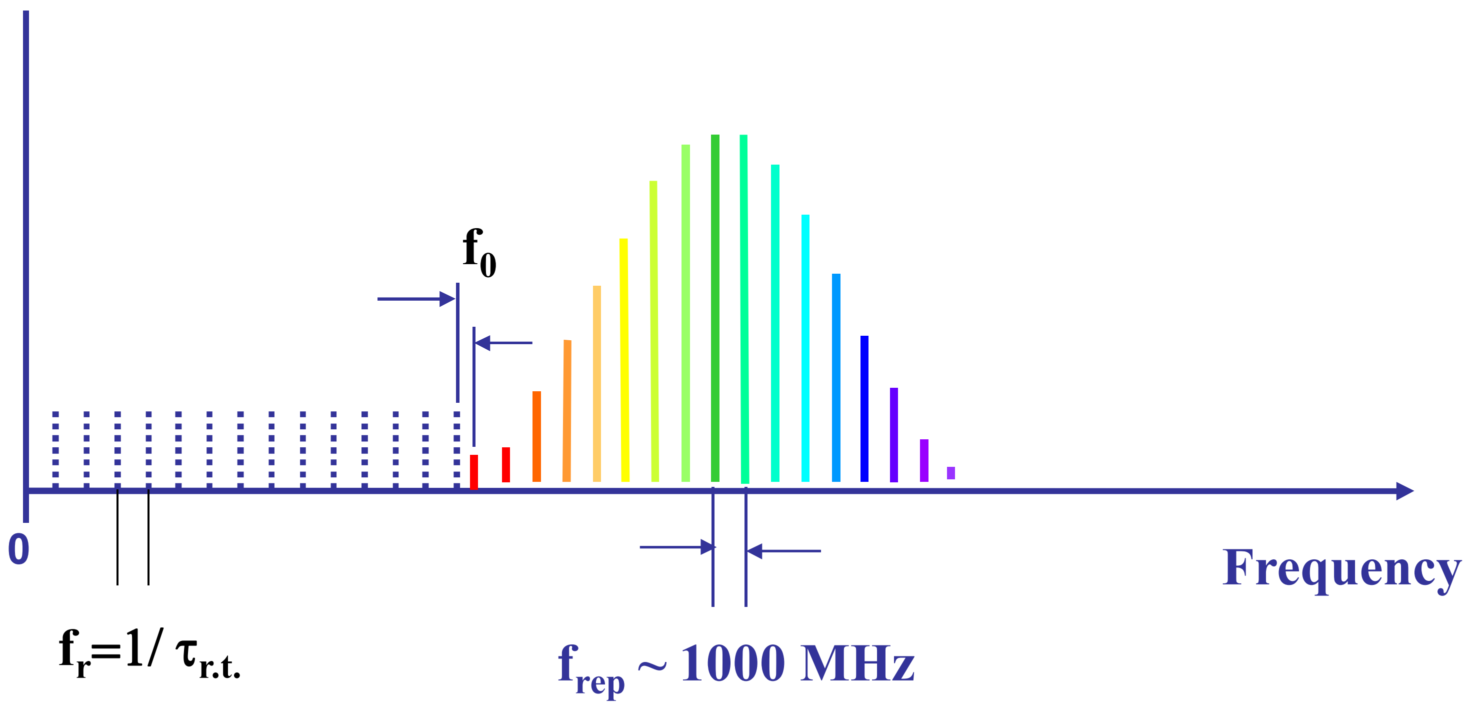
X-Ray at 10 keV = 2.4×10^{18} Hz

fractionally = 10^{-11} , corresponds to 100 neV

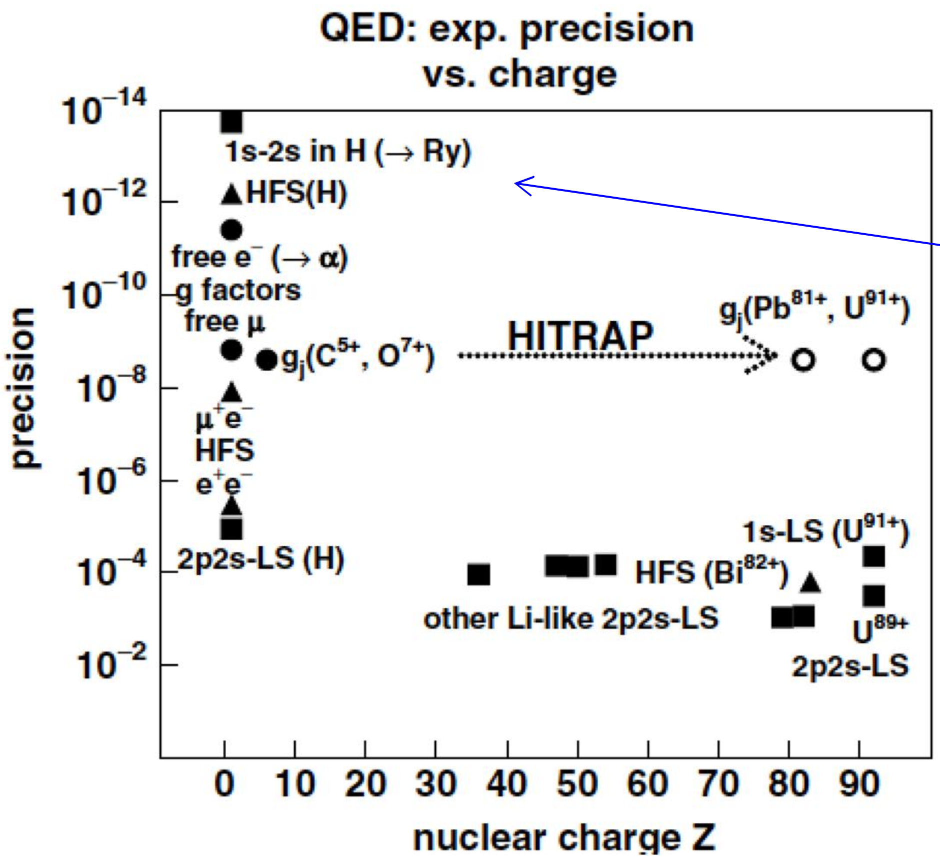
0

The frequency of a mode is simply $F_N = N * f_{rep} - f_0$

Where N is and integer ~ 10^6



Hydrogen-like Ion Spectroscopy



Enabled by:

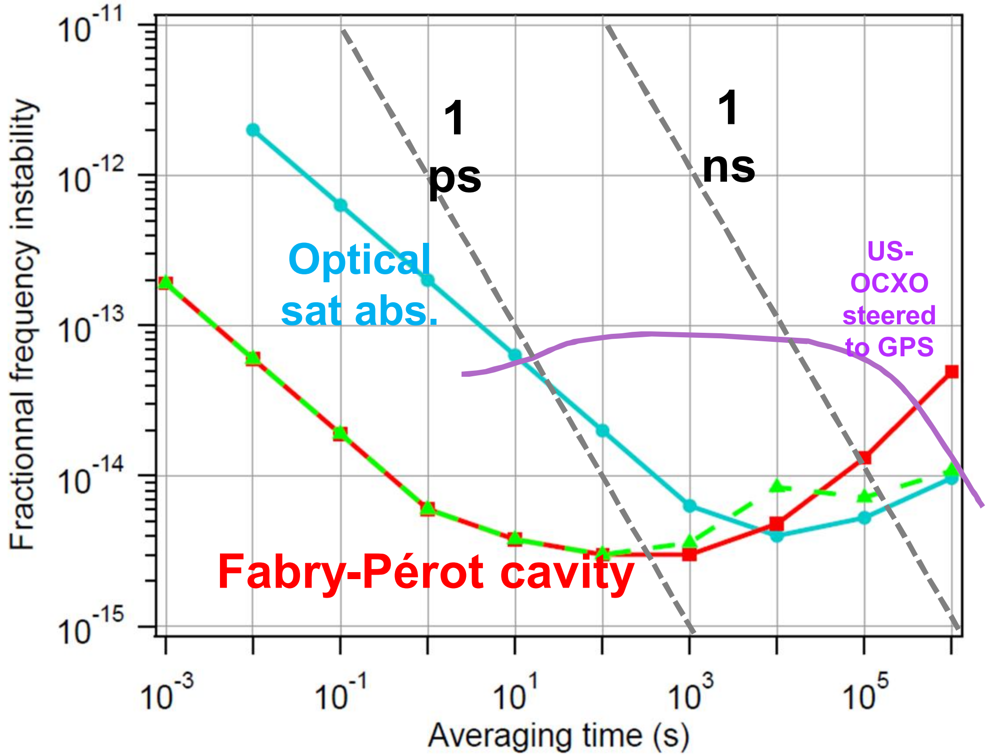
- -- frequency stable lasers
- -- fs optical combs
- -- laser cooled atoms

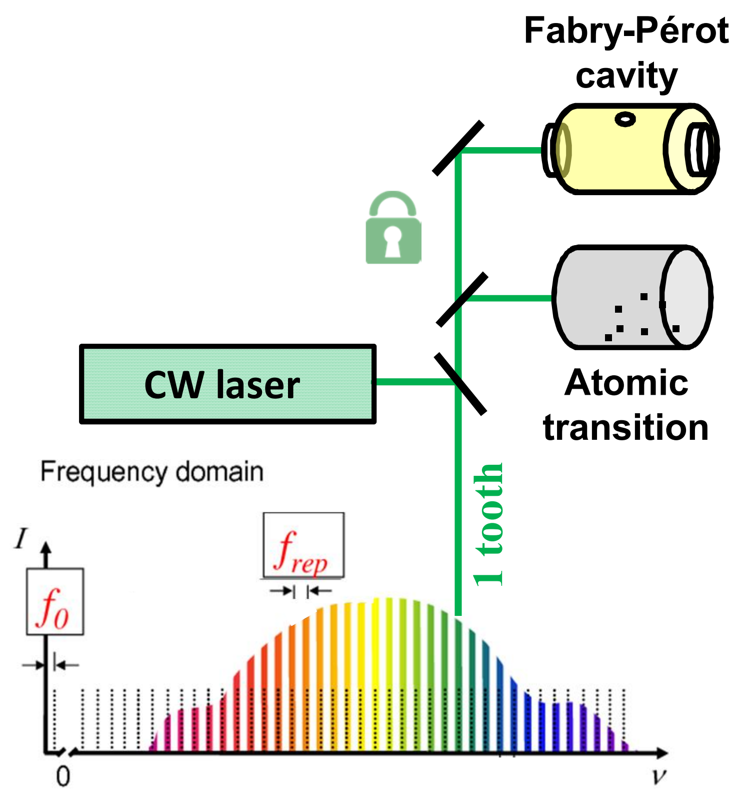
HTRAP at GSI Darmstadt , NIM B 2005

Laser Stabilization at Stanford

STANFORD UNIVERSITY

- Short time scales: Fabry-Pérot cavity
- Intermediate time scales: optical transitions in vapor cells (Rb, I_2 soon Yb)
- Long time scales: GPS steered quartz (10 MHz) locks fs comb at 200 THz





High resolution opportunities:

- Atomic physics : the best tests of QED at low energy
- nuclear structure (at least average charge radius, perhaps more ... e.g. spin structure?) probed by electronic wavefunction at nucleus.
- 1 and 2 electron atoms calculable from QED
  - highly striped ions
- Ion Traps: EBIT (UC Berkeley, NIST, ...)

- Present discrepancies in H vs muonic H, magnetic moments...

- Nuclear spectroscopy comments:
  - Often don't require absolute calculation of energy to gain structural information
  - Measure multiple levels in same nucleus constrains nuclear structure, measure ratios of frequencies
- Direct X-Ray comb spectroscopy
  - Pulse shaper methods

X-Ray Comb Precision Control of Frequency

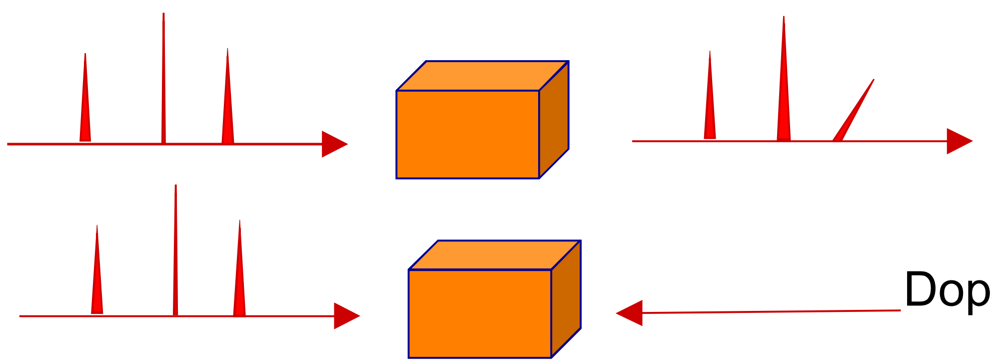
- At first glance my view is that f_{ceo} locking most interesting for time domain measurements.

- Without control of f_{ceo} with knowledge of a spectral reference (e.g. atomic transition or Mössbauer line) and f_{rep} control can do high precision spectroscopy.
    - Don’t necessarily need reference to Cs definition of the S.I. second

- Can do very high precision spectroscopy and frequency metrology with interferometric and heterodyne methods

X-Ray Phase Coherence for long times open new opportunities

- X-Ray heterodyne methods
  - spectroscopy
  - X-Ray phase sensitive methods
- X-Ray heterodyne spectroscopy



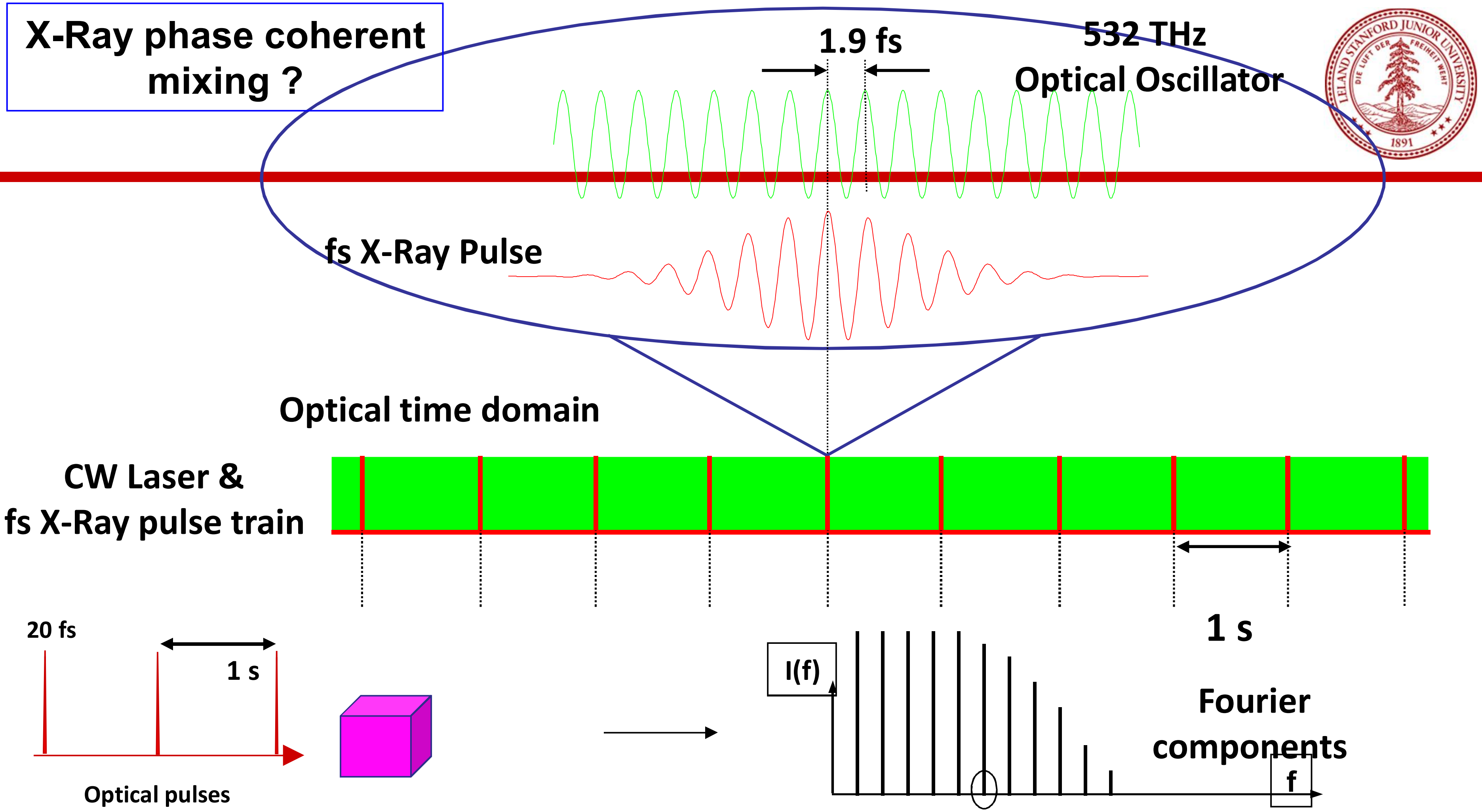
Doppler Free X-Ray spectroscopy
in gases and liquids

Gas phase, room temperature

$$\frac{\Delta\omega_{Doppler}}{\omega} \approx 1x10^{-5}$$

Tools to Enable Precision X-Ray Spectroscopy

- X-Ray modulators
  - $\Delta\varphi$ phase modulators
    - mechanical PZT
    - electrical EOM
    - Laser driven X-Ray phase modulator
  - Amplitude e.g. (AOM) → AXM
    - coherent RF driven acoustic
    - phase coherent with X-Ray comb
- X-ray interferometers with phase sensitive readout


X-Ray phase coherent mixing ?
1.9 fs
532 THz
Optical Oscillator
fs X-Ray Pulse
Optical time domain
CW Laser &
fs X-Ray pulse train
1 s
20 fs
1 s
Optical pulses
I(f)
Fourier
components
f

Questions

- Question: How much does f_{ceo} change due to normal fluctuations of an XFELO ??

  - Can estimate some factors that determine fceo.
  - Most cases would not need to know or control fceo.
  - Many factors affect cavity dispersion: thermal, gain, power, angles,
  - should be many approaches to control f_{ceo} in XFELO
    - power (pump, cavity loss, inserted thin dispersive wedge, optical heating of diamond, small angle changes, ...). Some calculable.