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High-performance gyroscope for rotational seismology.

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High-performance gyroscope for rotational seismology.

Nathan Marliere, Mohamed Guessoum,

Remi Geiger et Arnaud Landragin



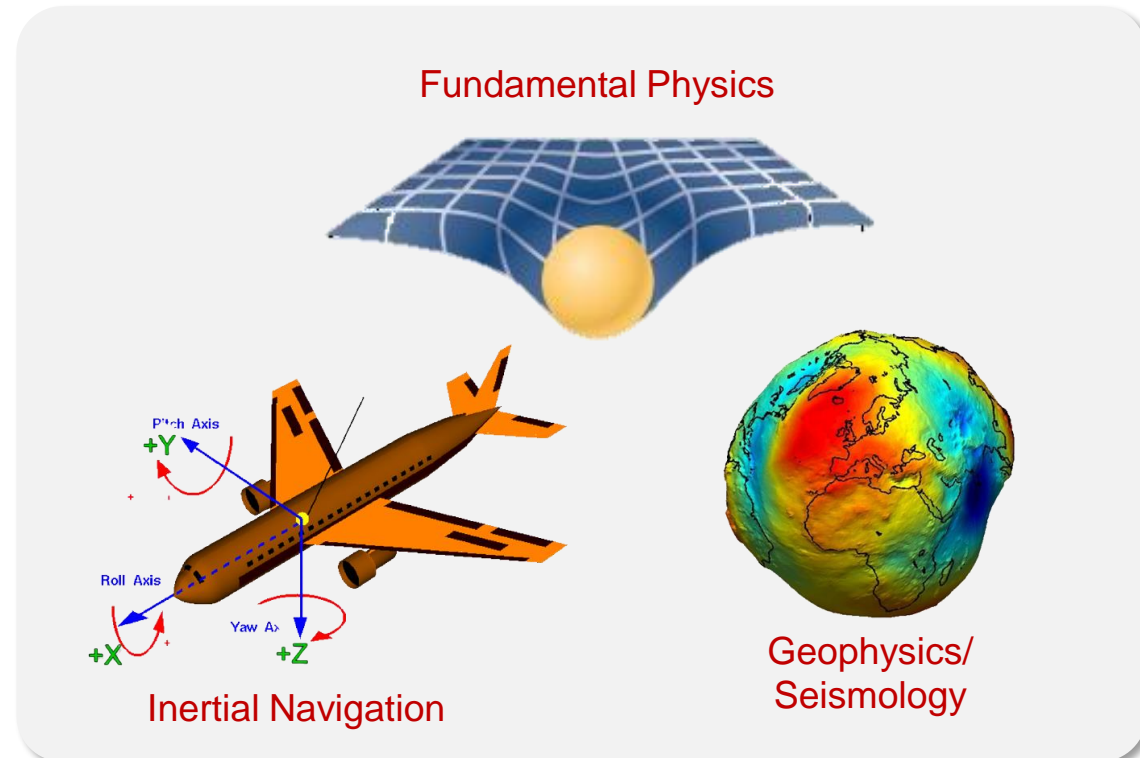
Presentation of cold atom sensors

IACI: Atomic interferometry and Inertial Sensors

An inertial sensor measures accelerations or rotations of an object in an inertial frame

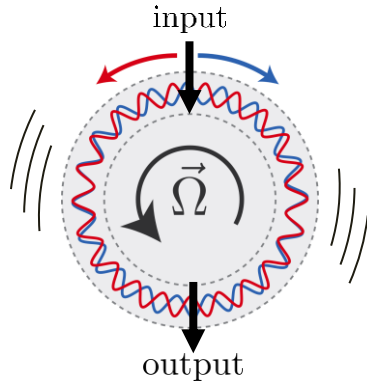
Ex: Gravimeters, gradiometers, gyroscopes...

Various fields of applications



Atomic gyroscopes Vs Optical gyroscopes

Sagnac effect: phase proportional to rotation at the output of an interferometer



$$\Delta\Phi_{\Omega} = \frac{4\pi E}{hc^2} \vec{A} \cdot \vec{\Omega}$$

E : Energy of the particle used

A : Area of the interferometer

Quick comparison Atoms/Optics :

	Energy	Area	Shot noise (sensitivity $\propto \sqrt{N}$)
Photons	$\sim 1 \text{ eV}$	In the order of m^2	$10^{15} \text{ Photons/s/mW}$
Atoms (Cs)	$\sim 10^{11} \text{ eV}$ 😊	$\text{mm}^2 \text{ to } \text{cm}^2$ (This work: 11cm^2) 😞	10^7 Atoms/s 😞



State of the art of Gyroscopes

Fiber optics gyroscope



iXBlue FOG

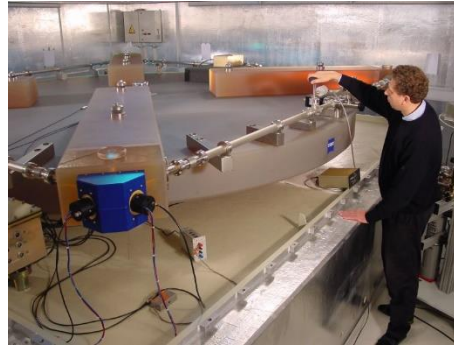
Sensitivity:

$6 \cdot 10^{-8} \text{ rad} \cdot \text{s}^{-1} \cdot \text{Hz}^{-1/2}$

Stability:

$4 \cdot 10^{-10} \text{ rad} \cdot \text{s}^{-1}$ (8 Days)

Gyrolaser G-Ring



G-Ring,
16 m²

Sensitivity:

$1.2 \times 10^{-11} \text{ rad} \cdot \text{s}^{-1} \cdot \text{Hz}^{-1/2}$

Stability:

$7 \times 10^{-13} \text{ rad} \cdot \text{s}^{-1}$ (2 h)

Cold atom gyroscope (This work)

Sensitivity:

$3 \times 10^{-8} \text{ rad} \cdot \text{s}^{-1} \cdot \text{Hz}^{-1/2}$

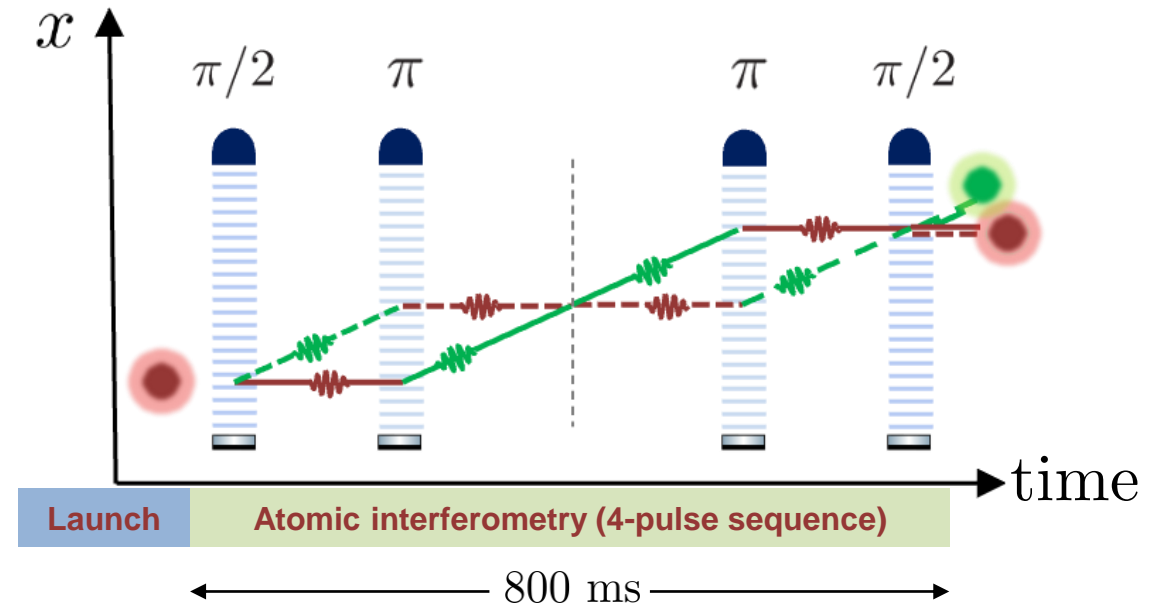
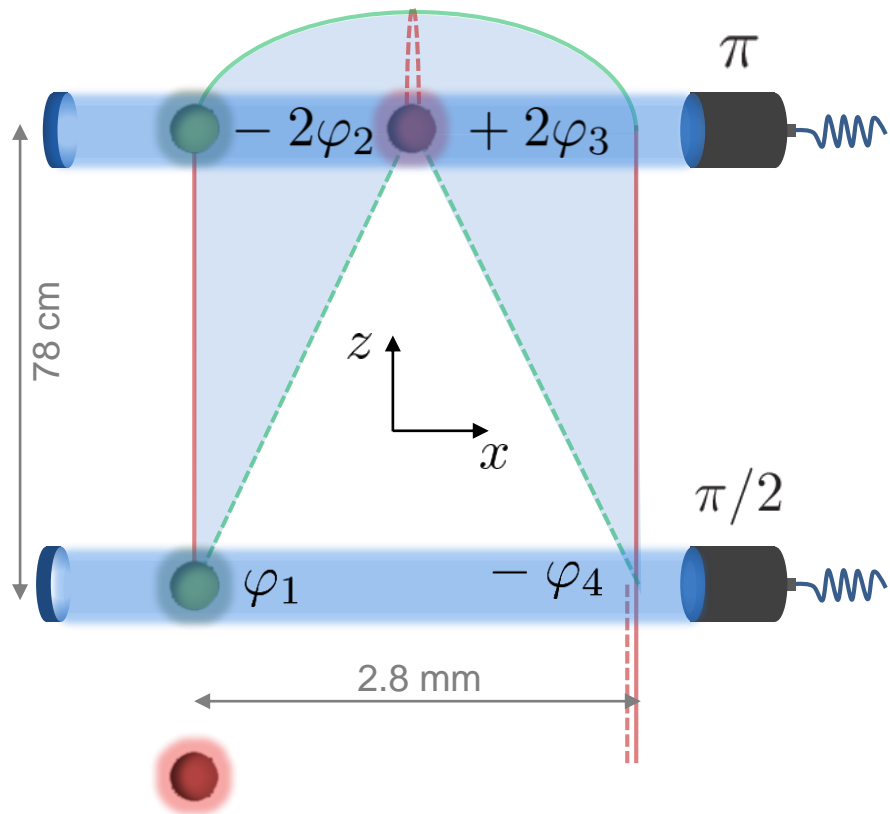
Stability:

$2 \times 10^{-10} \text{ rad} \cdot \text{s}^{-1}$ (8h)



4-pulse interferometer: Gyroscope

Large area: 11 cm²
Macroscopic quantum effect



$$\Delta\Phi =$$

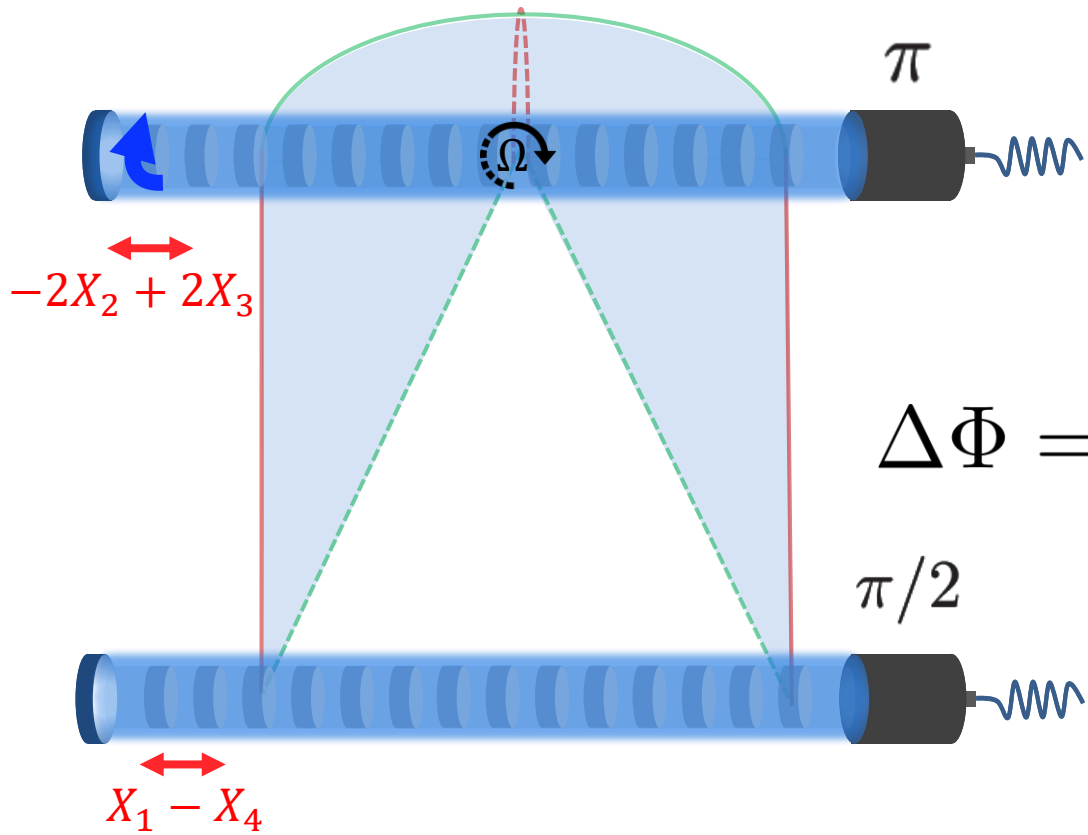
$$\varphi_i(t) = \vec{k}_{\text{eff}} \cdot \vec{r}(t) + \delta\Phi_{\text{laser}}$$

$$\Delta\Phi = \frac{1}{2} \vec{k}_{\text{eff}} \cdot (\vec{g} \times \vec{\Omega}) T^3 + \delta\Phi_{\text{vib}} + \delta\Phi_{\text{laser}}$$

Symmetry → zero sensitivity to DC acceleration



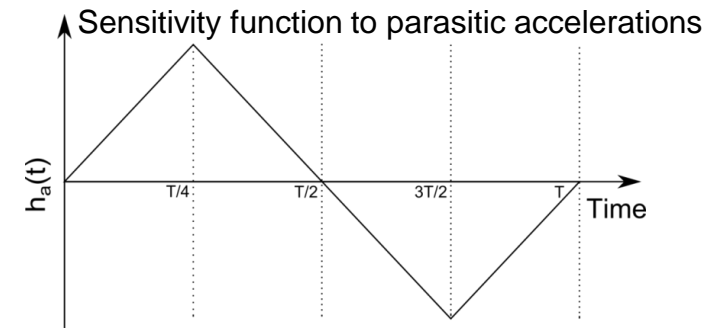
Vibration noise sources



$$\Delta\Phi = \phi_{rot} + \delta\phi_{vib}$$

Variations of **acceleration**:

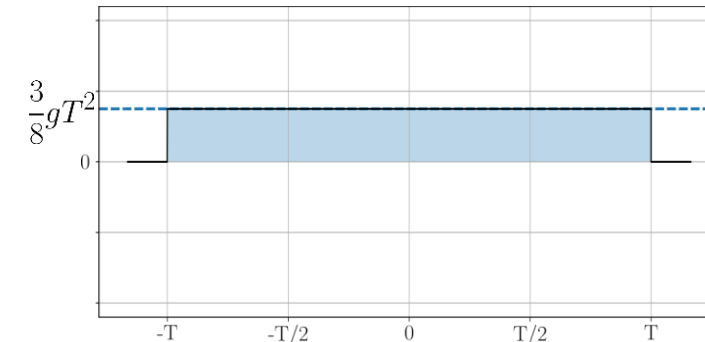
$$\phi_{vib/acc} \propto X_1 - 2X_2 + 2X_3 - X_4$$



Noise of **rotation**:

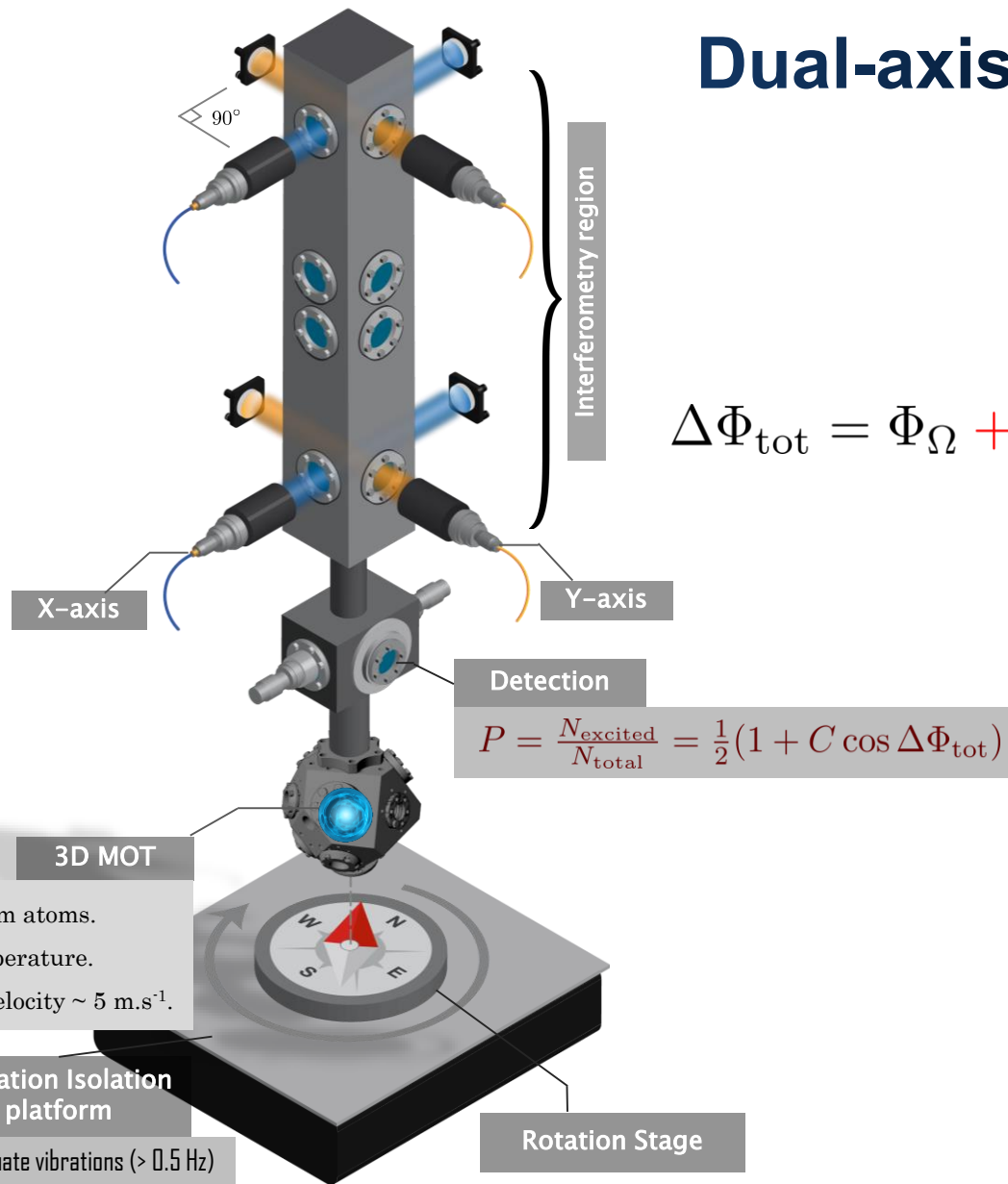
$$\phi_{rot} \propto \theta_1 - \theta_4 \propto \Omega g T^2$$

Sensitivity function to rotation

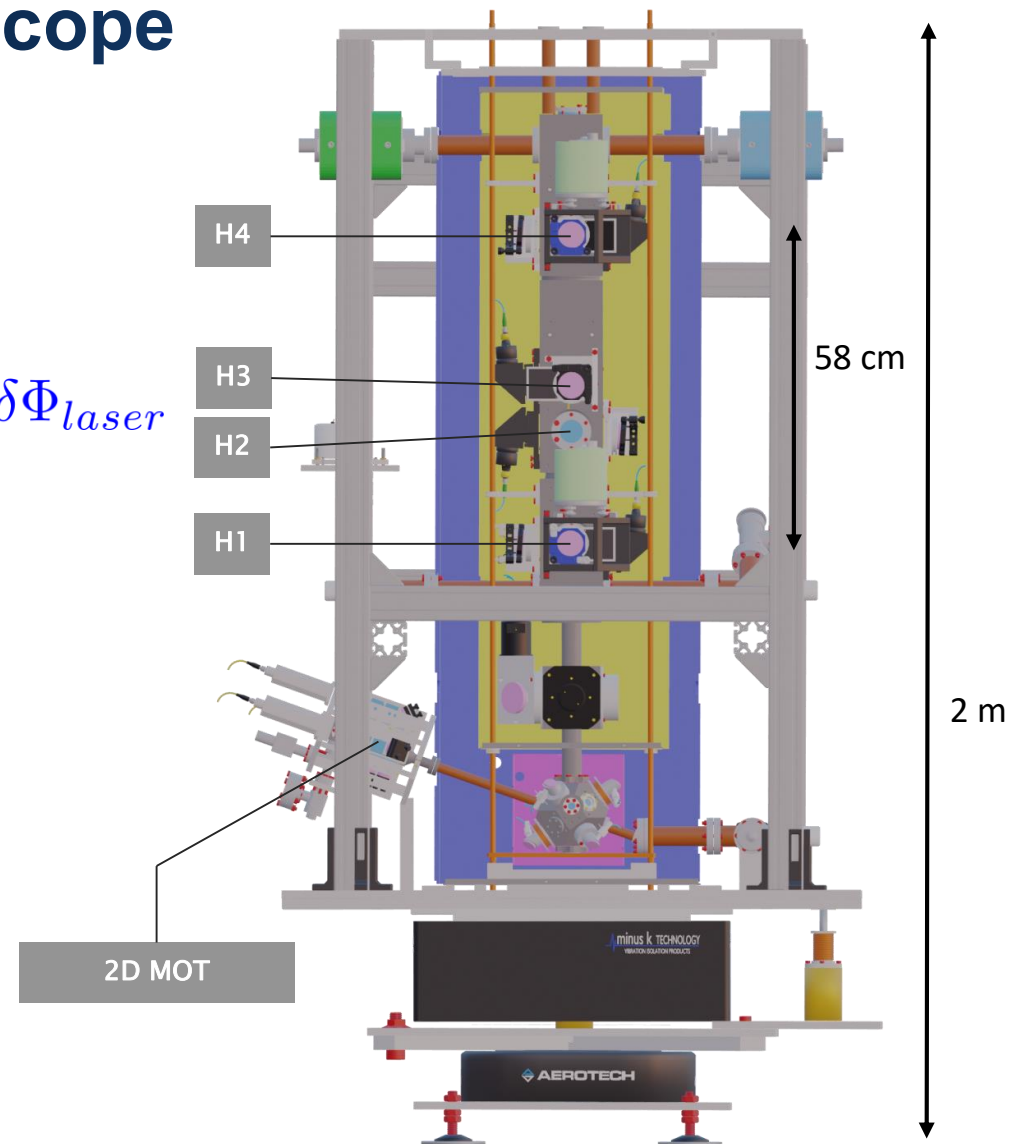




Dual-axis gyroscope



$$\Delta\Phi_{tot} = \Phi_{\Omega} + \delta\Phi_{vib} + \delta\Phi_{laser}$$

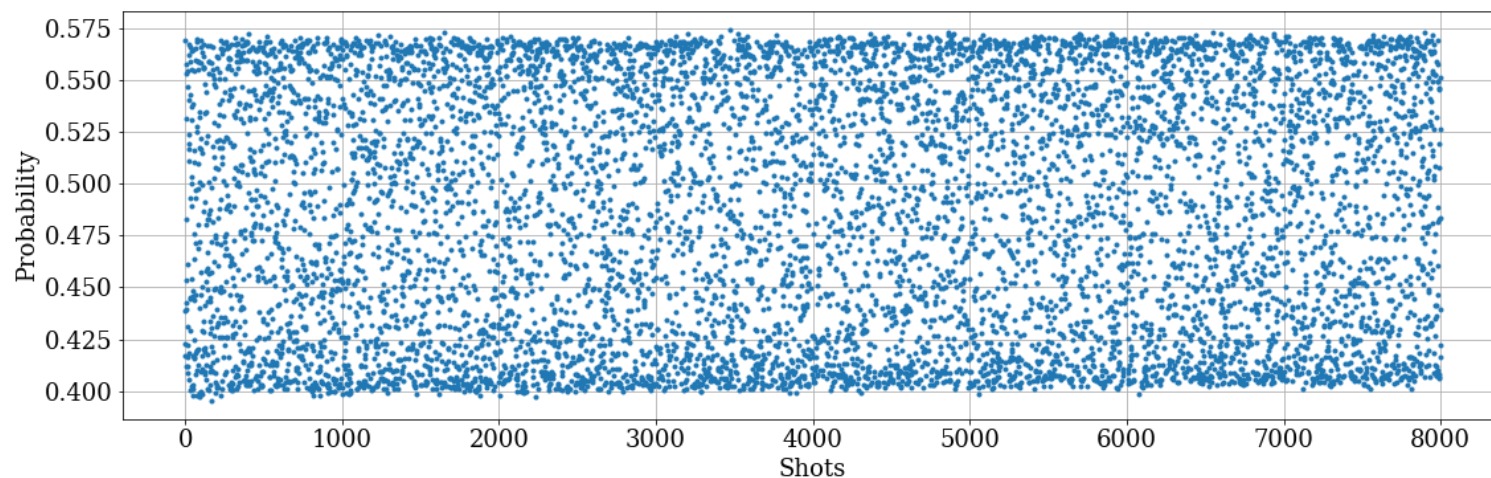
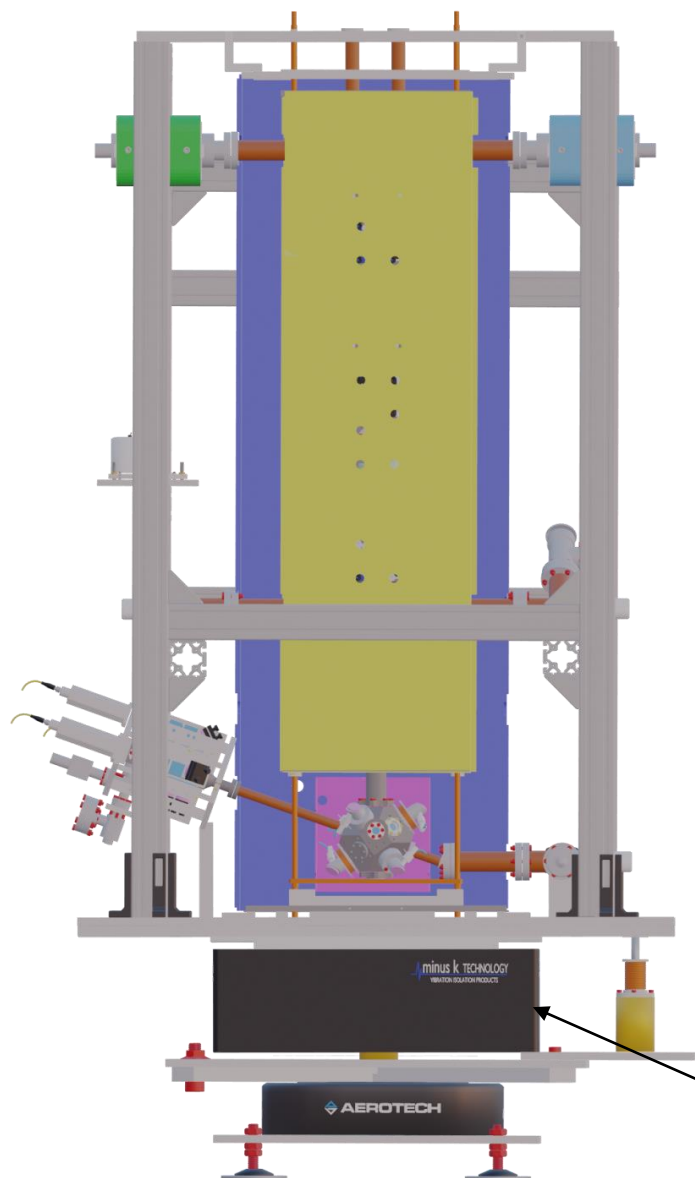




Vibration noise

$$\Delta\Phi_{\text{tot}} = \Phi_{\Omega} + \delta\Phi_{\text{vib}} + \delta\Phi_{\text{laser}}$$

Vibration noise covers several rad



Passive vibration isolation platform



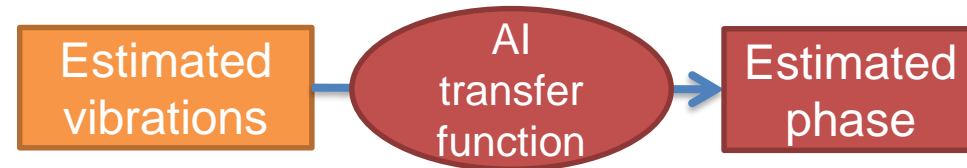
Attenuates high frequencies above 0.5 Hz



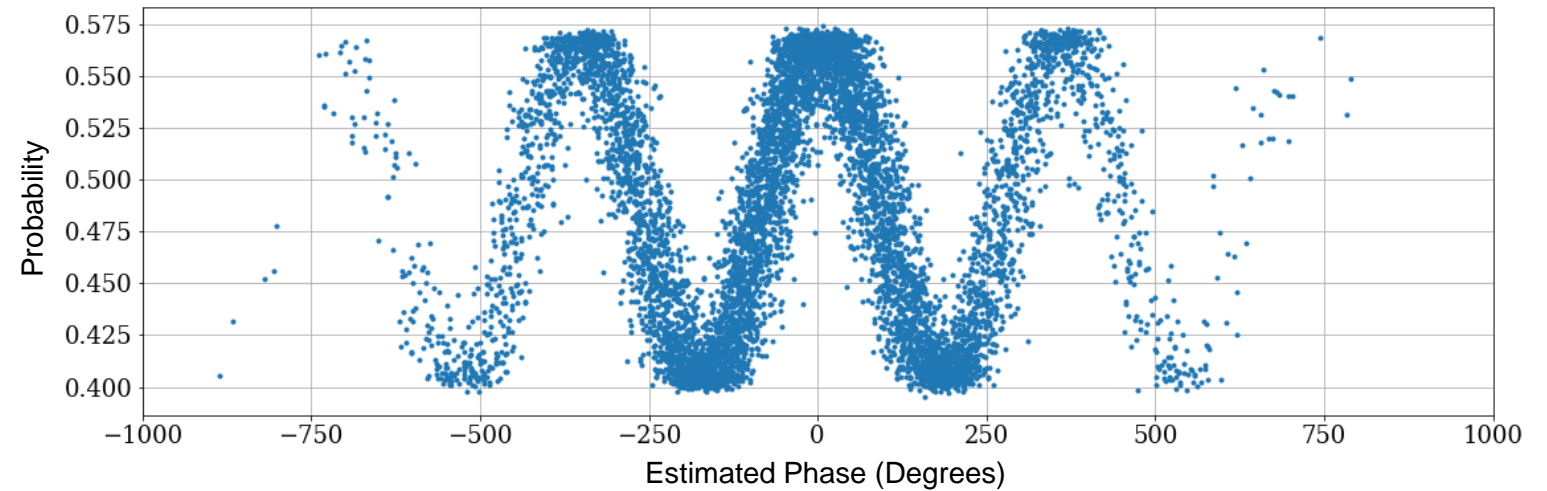
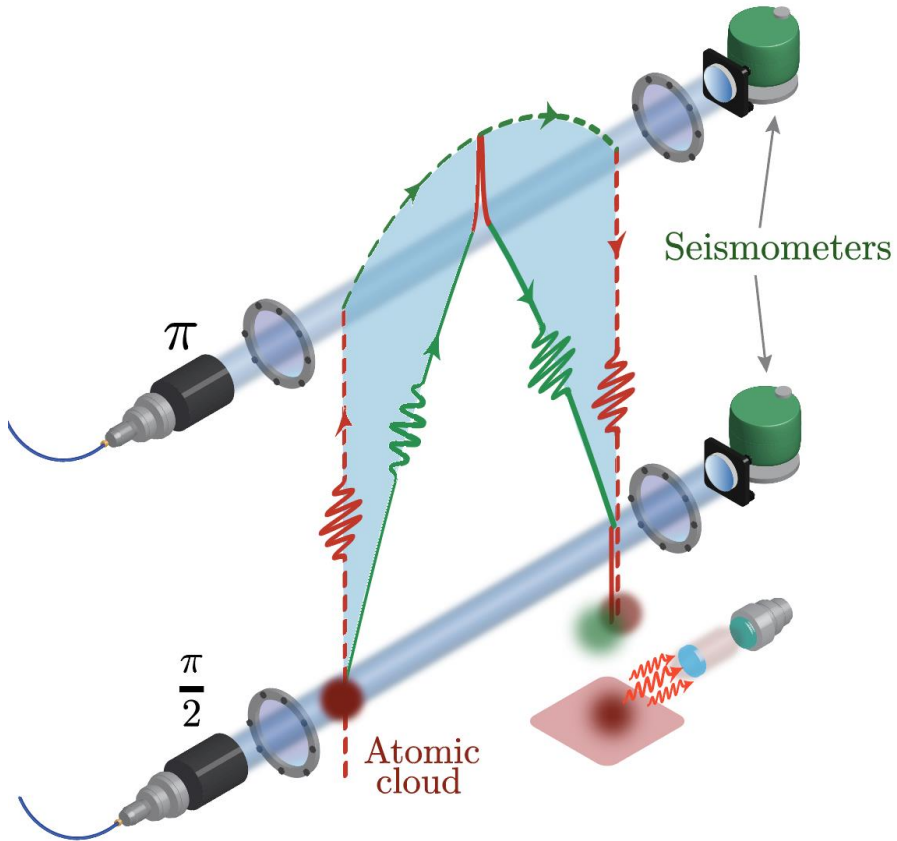
Vibration noise correlation

$$\Delta\Phi_{\text{tot}} = \Phi_{\Omega} + \delta\Phi_{\text{vib}} + \delta\Phi_{\text{laser}}$$

Vibration noise covers several rad



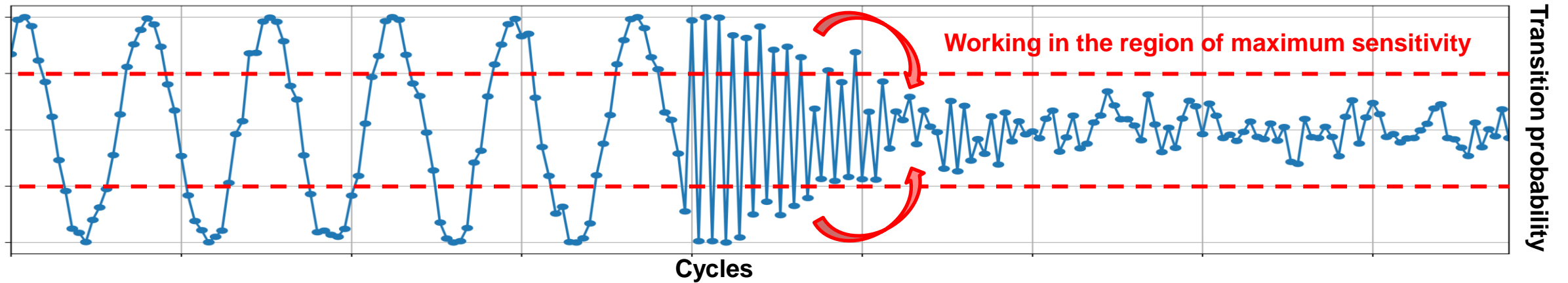
Correlation with classical sensors





Compensation of vibrations

Compensating vibrations using the laser phase

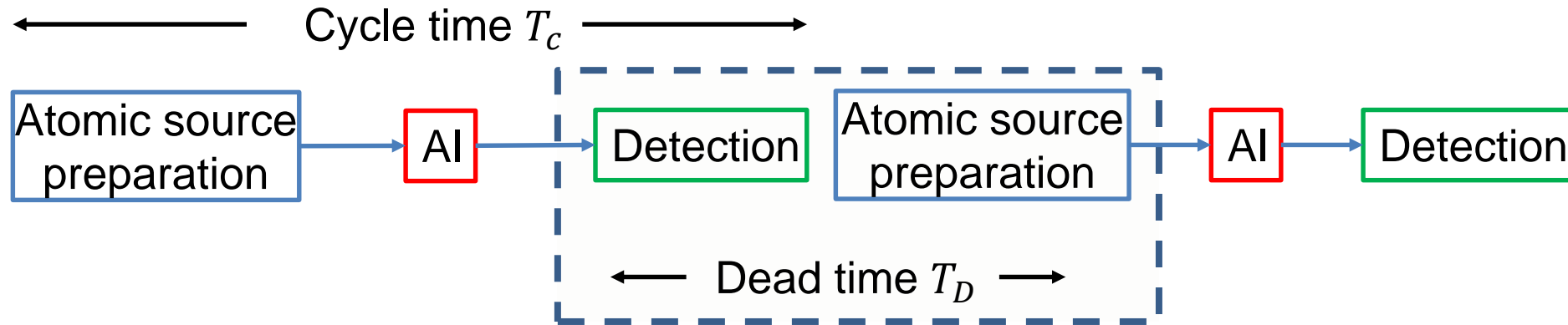


$$P = \frac{1}{2} (1 + C \sin(\Phi_{\Omega} + \underbrace{\Phi_{vib} + \Phi_{compensation}}_{\delta\phi_{residue} < 1} + \Phi_{laser}))$$



Gyroscope operation sequence

Sequential operation of cold atom interferometers:



Dead times → Prevents from reaching the quantum noise limit.

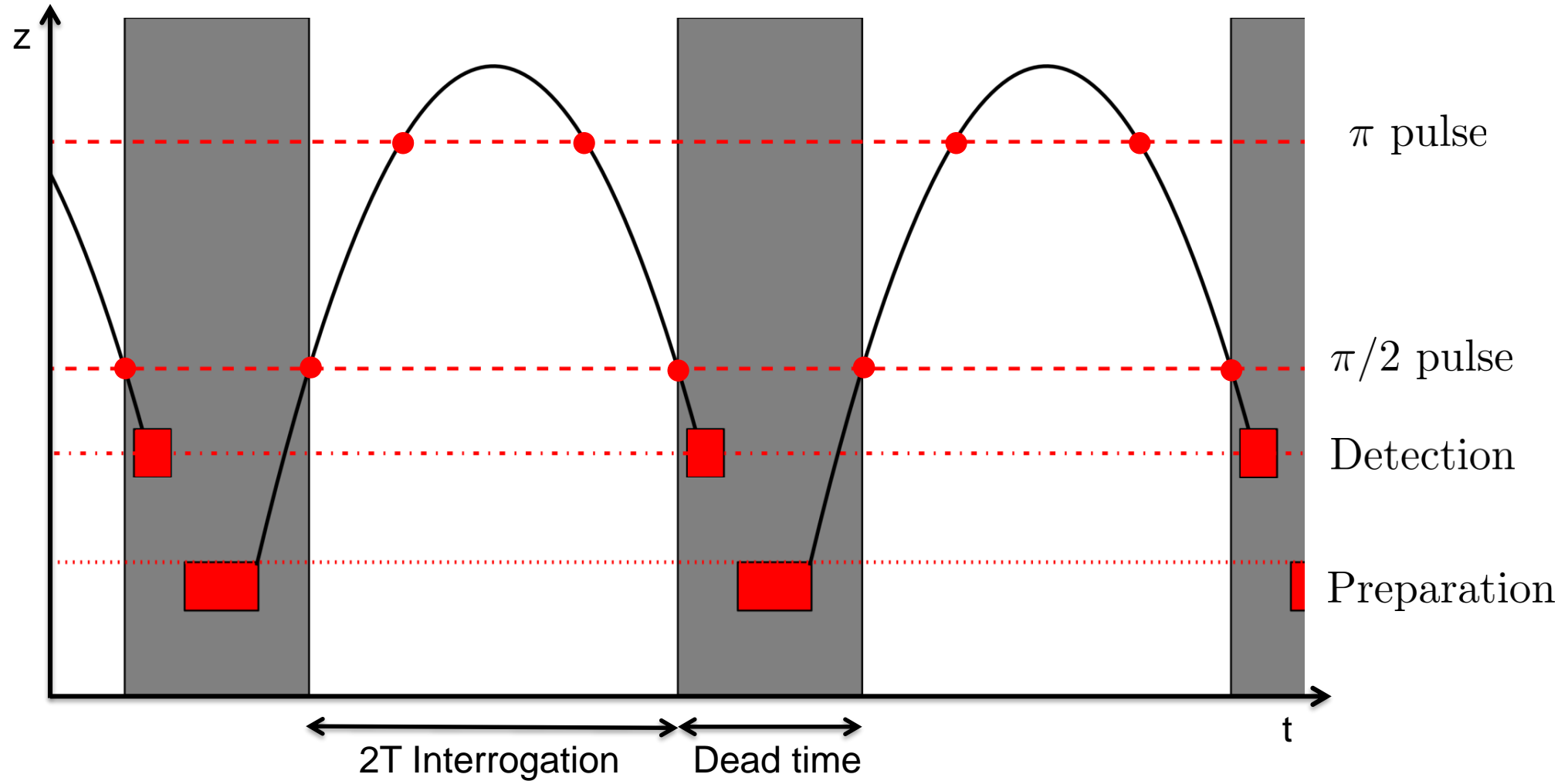


Cancelling dead times with other operating methods

Meunier, PRA (2014)
Jekeli, Navigation 52, 1 (2005)

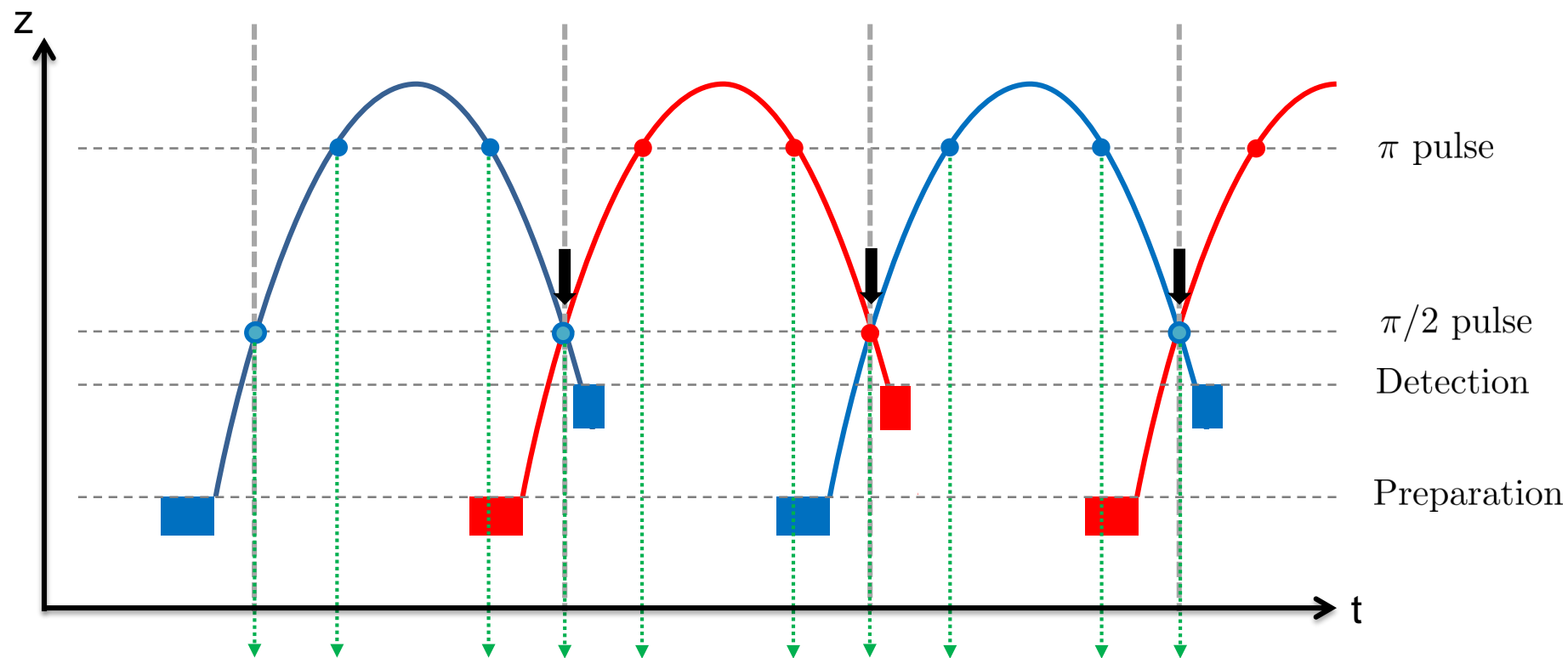


Dead Times with no-joint mode





Simple-Joint Mode



Rotations

θ_1 — ~~θ_4~~ ~~θ_4~~ — ~~θ_7~~ ~~θ_7~~ — ~~θ_{10}~~ ~~θ_{10}~~ ...



Averaging in N^{-1}

Accelerations

$X_1 - 2X_2 + 2X_3 - \cancel{X_4}$ $\cancel{X_4} - 2X_5 + 2X_6 - \cancel{X_7}$ $\cancel{X_7} - 2X_8 + 2X_9 - \cancel{X_{10}}$ $\cancel{X_{10}}$...



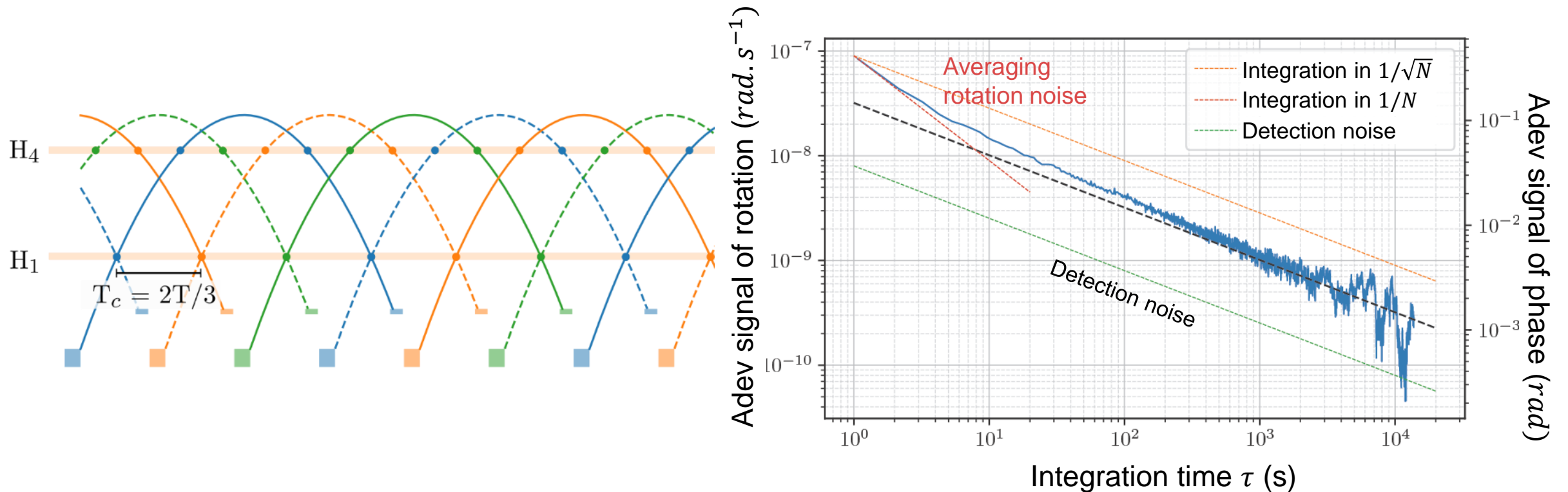
Averaging in $N^{-1/2}$ and **dominant**



Stability record - triple-joint sequence

Triple-Joint Interrogation:

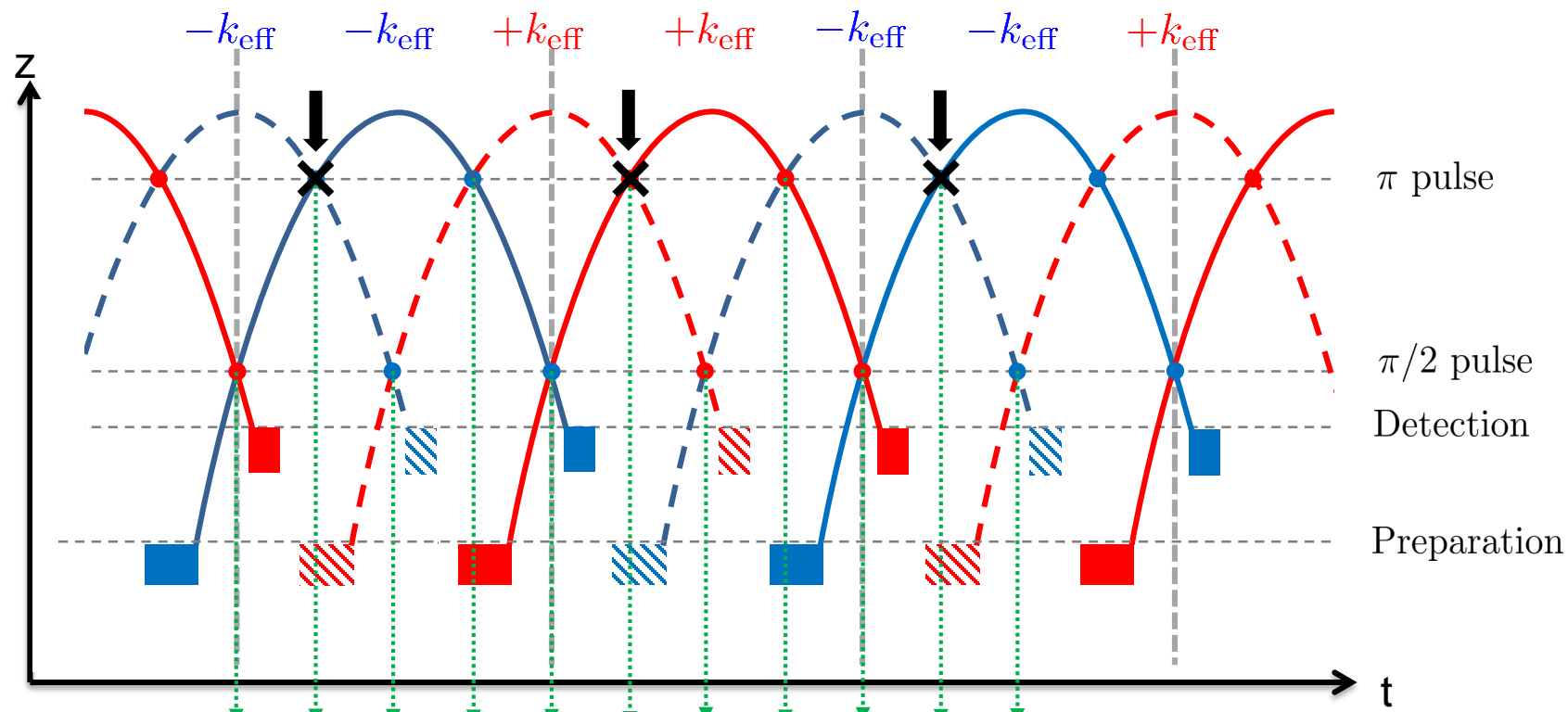
Faster averaging of rotations (N^{-1}) visible due to a better estimation of noise



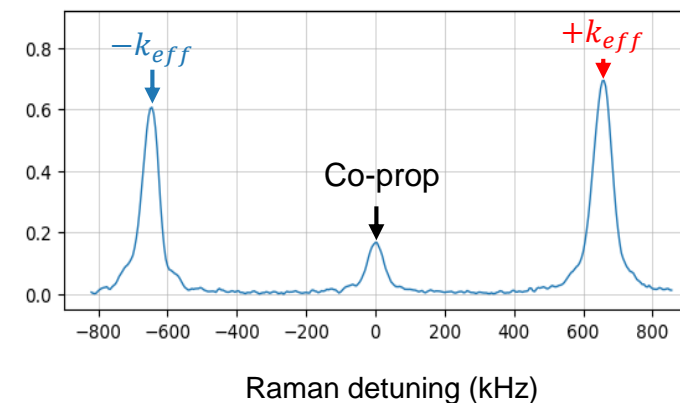
Savoie et al., Sci. Adv 4.12 (2018)



Double-Joint Mode



Resonance conditions:



Falling and Rising clouds + same k_{eff} configuration
Different resonant pics at same time

$$X_1 - 2X_2 + 2X_3 - X_4$$

$$X'_1 - 2X_3 + 2X_5 - X'_4 + 2X_6 - X_7$$

$$X'_4 - 2X_6 + 2X_8 - X'_8 \dots$$

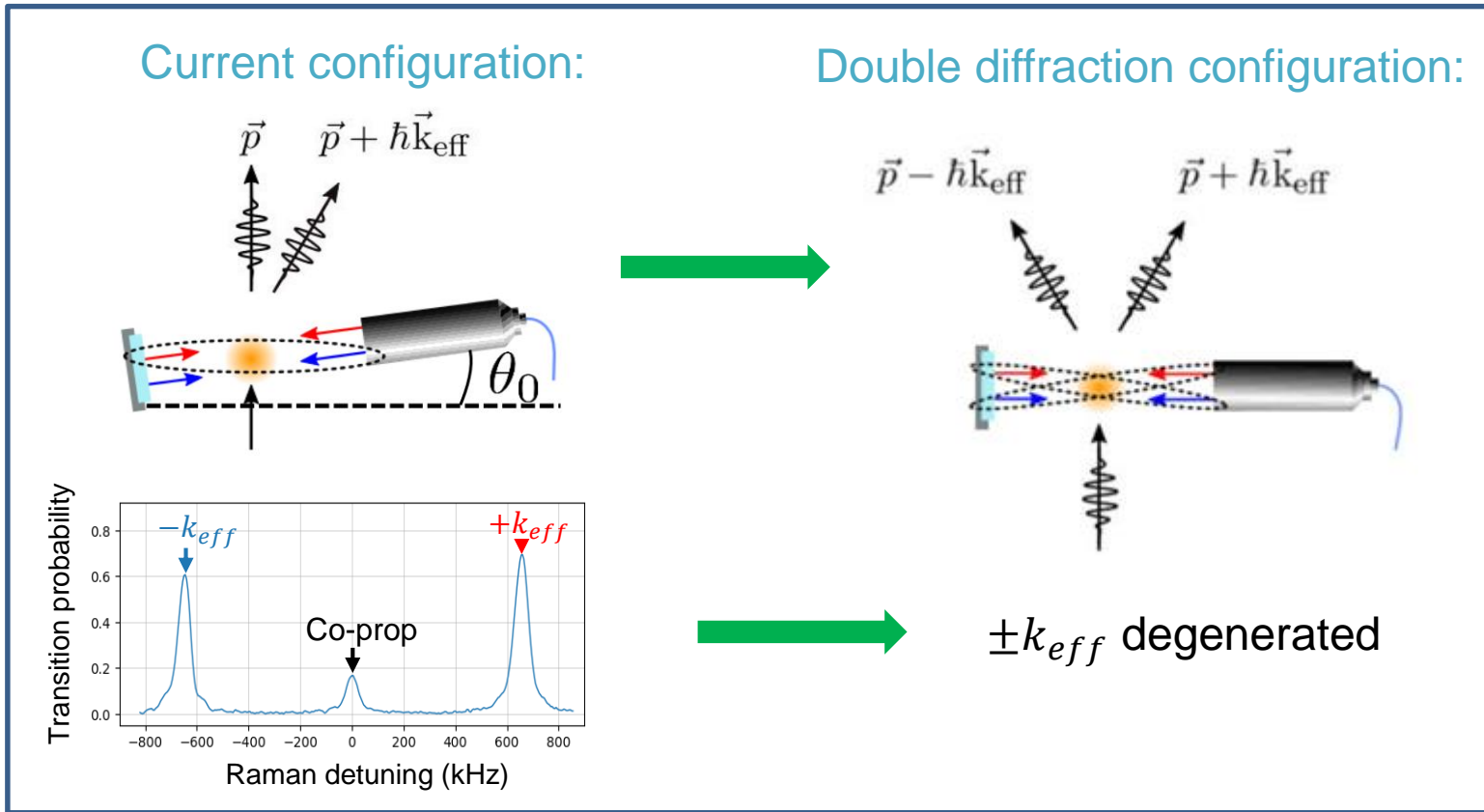
Accelerations



Averaging of rotations and accelerations (N^{-1})



The double-diffraction

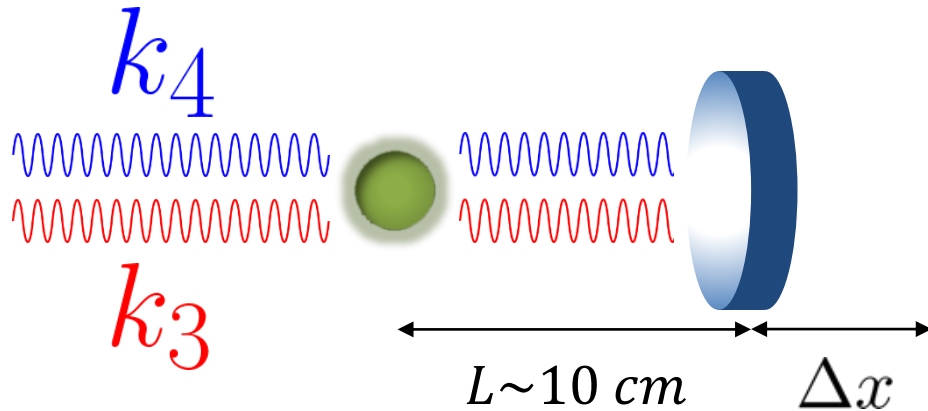


Main advantages:

- ❖ Enable the Double-joint mode
- ❖ Enhance sensitivity by doubling interferometric area
- ❖ Rejection of systematic effects

Double Diffraction → Laser phase not available to scan fringes → Develop new methods to scan the phase

New techniques to scan the interferometric phase



Mirror Jumps Method

Simple diffraction

$$\Phi^{(\pm k)} \approx \phi_L \mp k_{\text{eff}}(L + \Delta x)$$

Double diffraction

$$\Delta\Phi \approx 2|k_{\text{eff}}|(L + \Delta x)$$

Imprinted Phase by a Raman

Laser phase

$$\Phi = \vec{k}_{\text{eff}} \cdot \vec{r} + \phi_L$$

Frequency Jumps Method

Simple diffraction

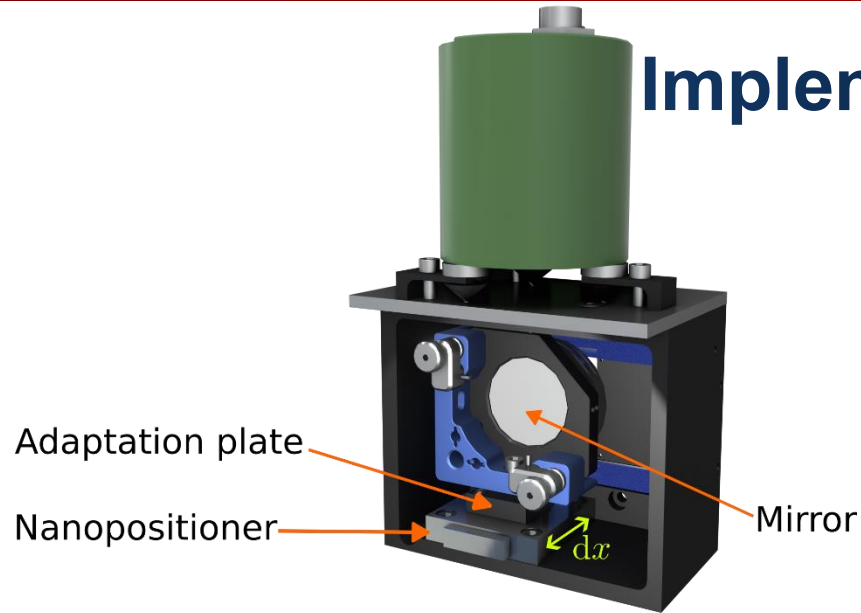
$$\Phi^{(\pm k)} \approx \phi_L \mp (k_{\text{eff}} + dk_{\text{eff}})L$$

Double diffraction

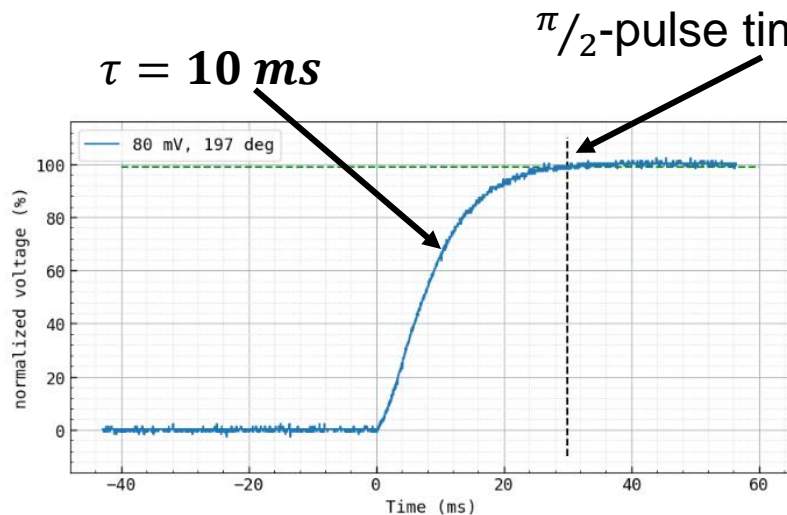
$$\Delta\Phi \approx 2(k_{\text{eff}} + dk_{\text{eff}})L$$



Implementation of Mirror jumps

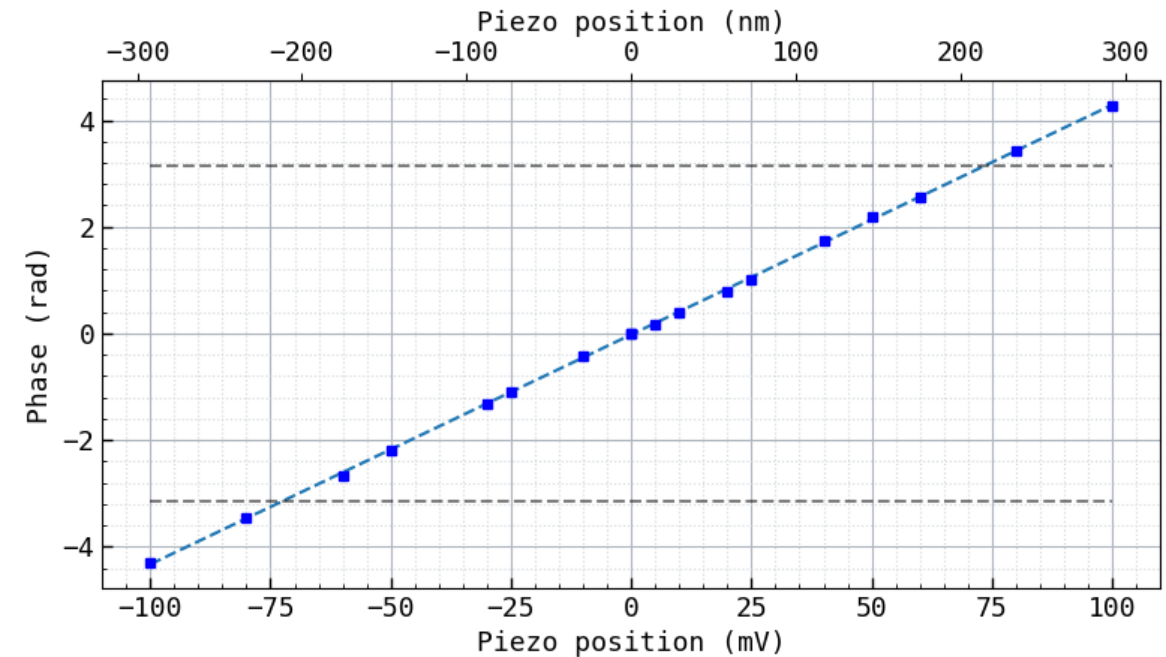


Characterization of the step response



Characterization of the Scale factor

$$\Delta\varphi = k_{eff} \alpha \Delta V$$



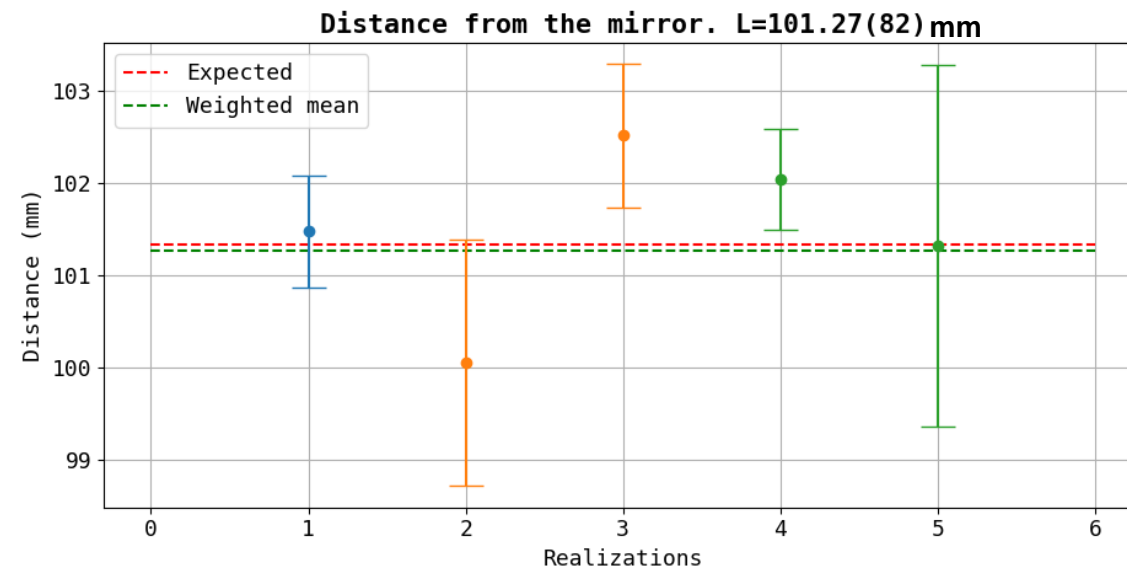
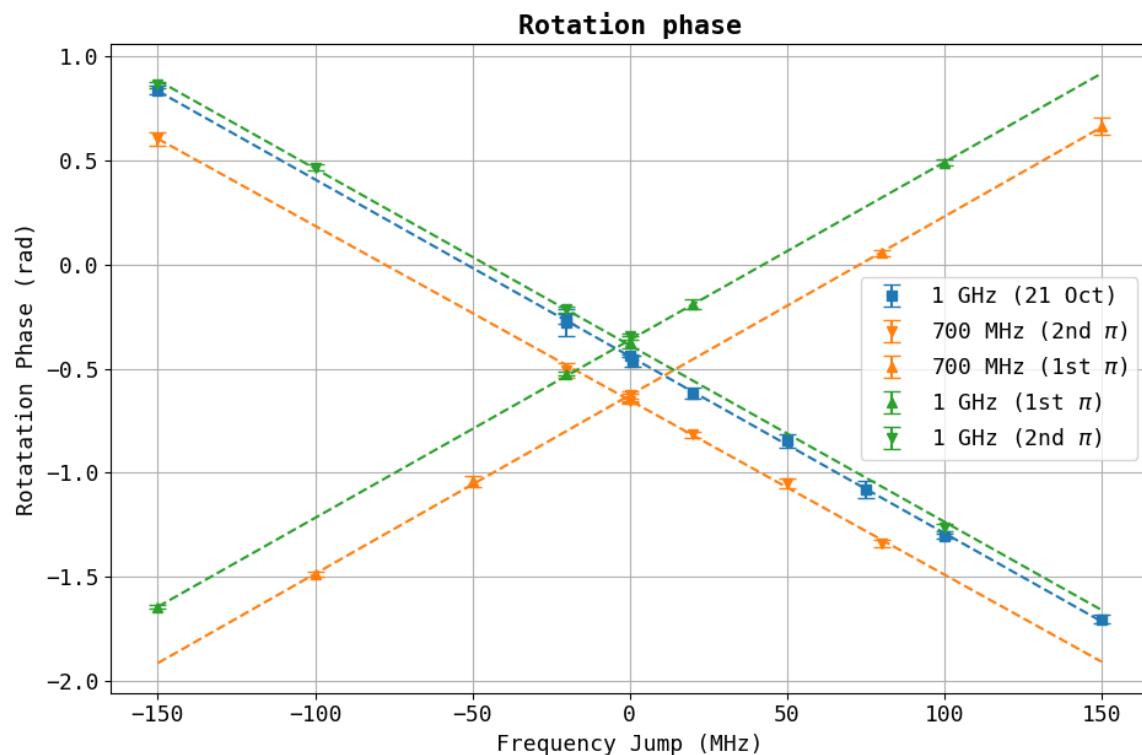
$\sim 426 \text{ nm}/360^\circ$ on $\pi/2$ pulse
(Divided by 2 in double diffraction)



Implementation of Frequency jumps

Precise measurement on L

$$d\phi = df \times \left(\frac{4\pi L}{c} \right) \leftarrow \text{Scale factor}$$

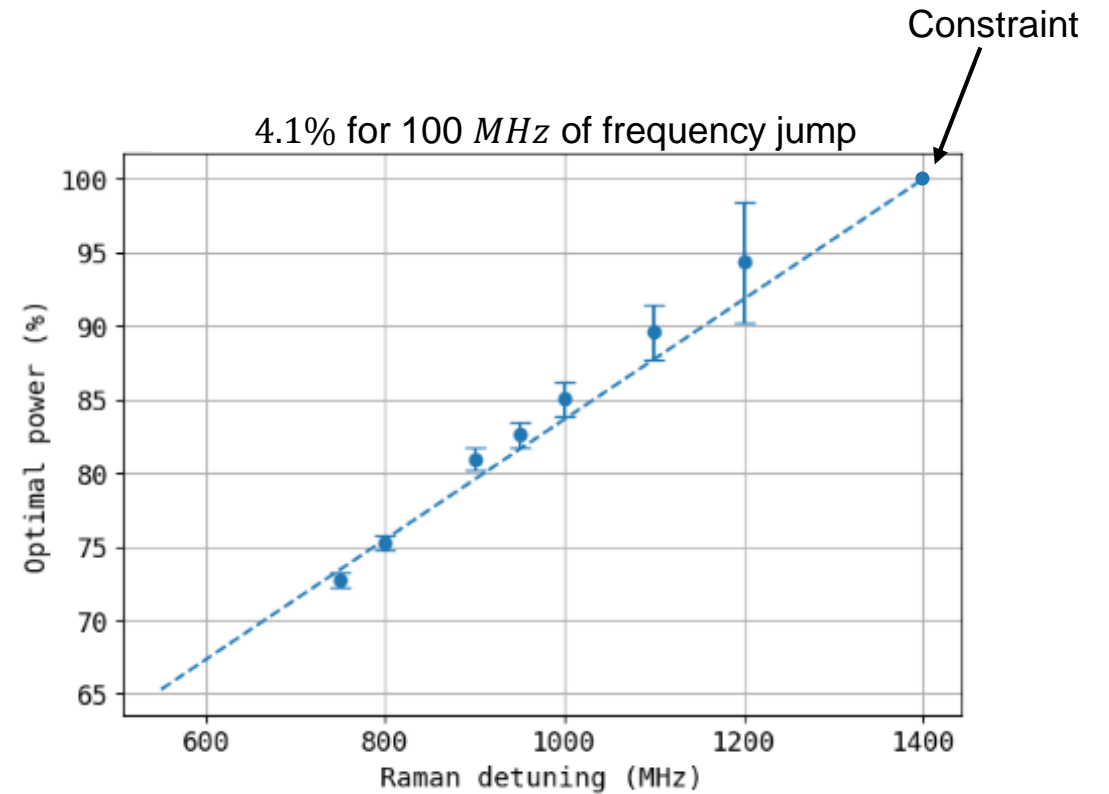
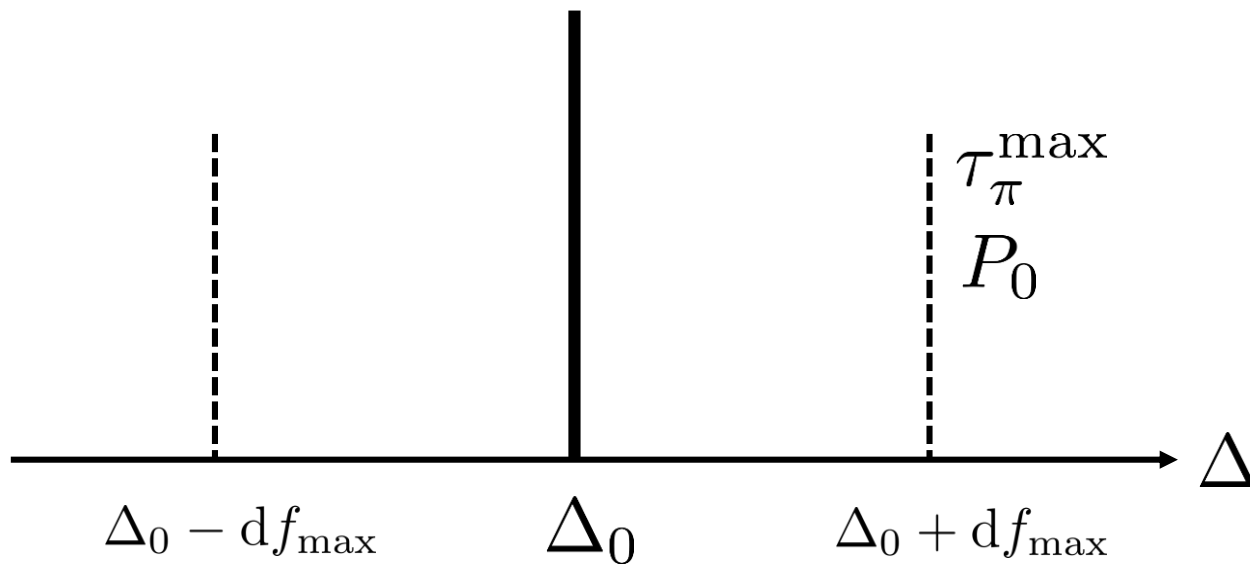


~ 370 MHz/180° on $\pi/2$ pulse
(Divided by 2 in double diffraction)

Compensate Ω_{eff}

$$\Omega_{eff} \propto \frac{1}{\Delta_0 + \delta f}$$

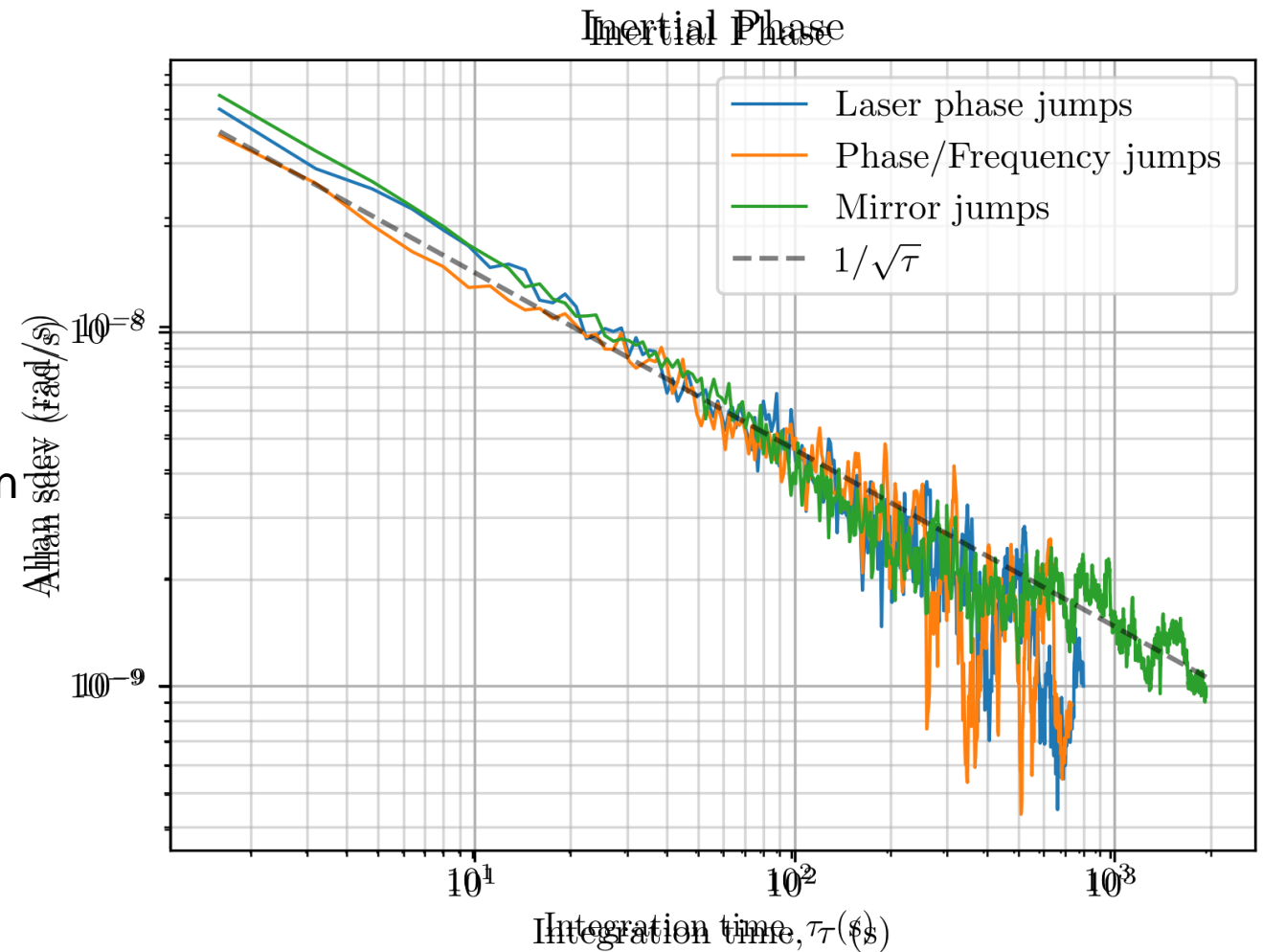
τ_π or P_0





Comparison of results obtained for each methods

Allan Variance for the methods in simple diffraction



Conclusion

- ▶ New methods for RTC **demonstrated** in simple diffraction to enable **Double-Diffraction**
- ▶ Implementation of **Double-Diffraction**:
 - **Cancelling** systematic effects
 - **Double** interferometer area
 - **Enable** Double-Joint sequence
 - **Space applications**
- ▶ Implementation and test of **Double-Joint**:
 - **Faster averaging** of vibrations
 - **Rotational seismology Applications**

Thanks for your attention