

# High-performance gyroscope for rotational seismology.

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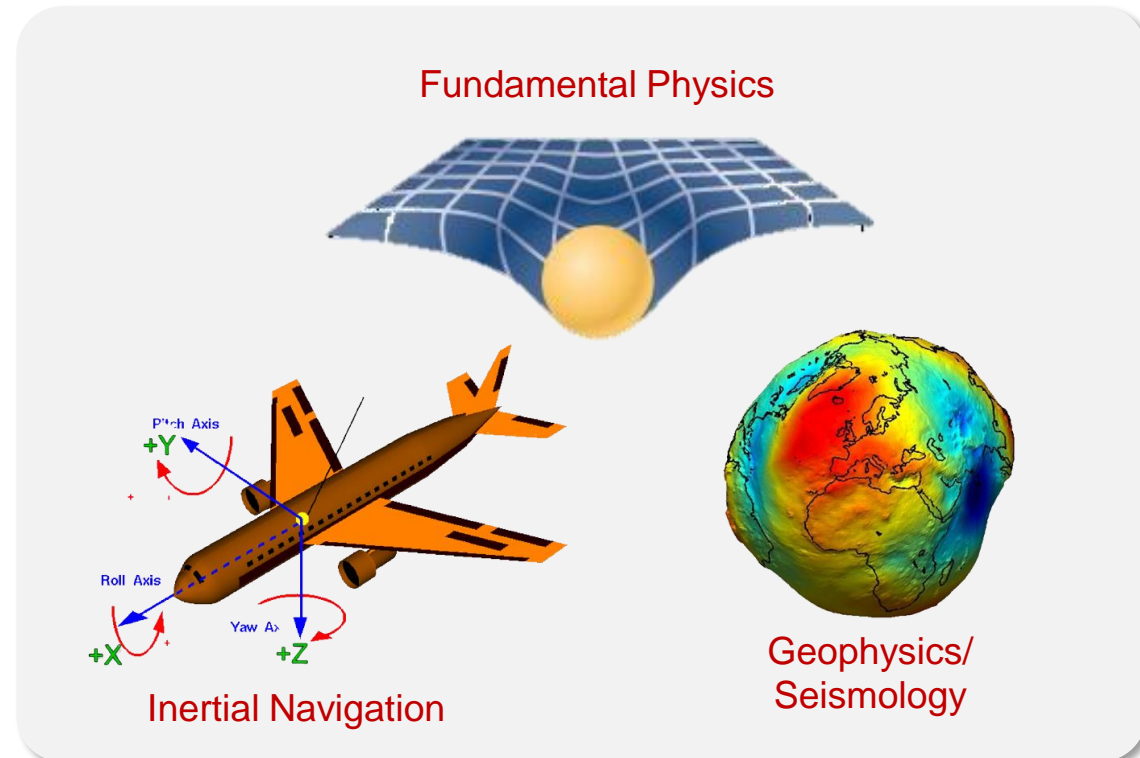
## Presentation of cold atom sensors

### IACI: Atomic interferometry and Inertial Sensors

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

Ex: Gravimeters, gradiometers, gyroscopes...

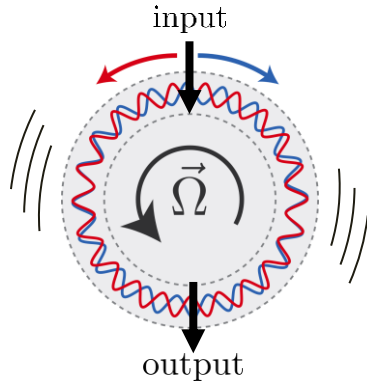
### Various fields of applications





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



## State of the art of Gyroscopes

### Fiber optics gyroscope



iXBlue FOG

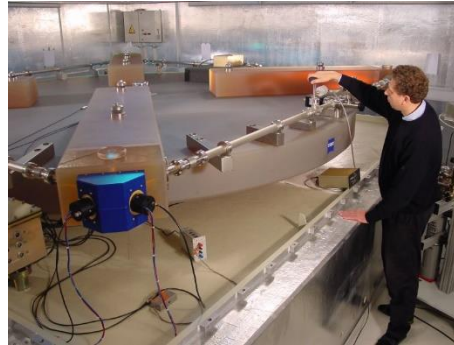
*Sensitivity:*

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

*Stability:*

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

### Gyrolaser G-Ring



G-Ring,  
16 m<sup>2</sup>

*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:*

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

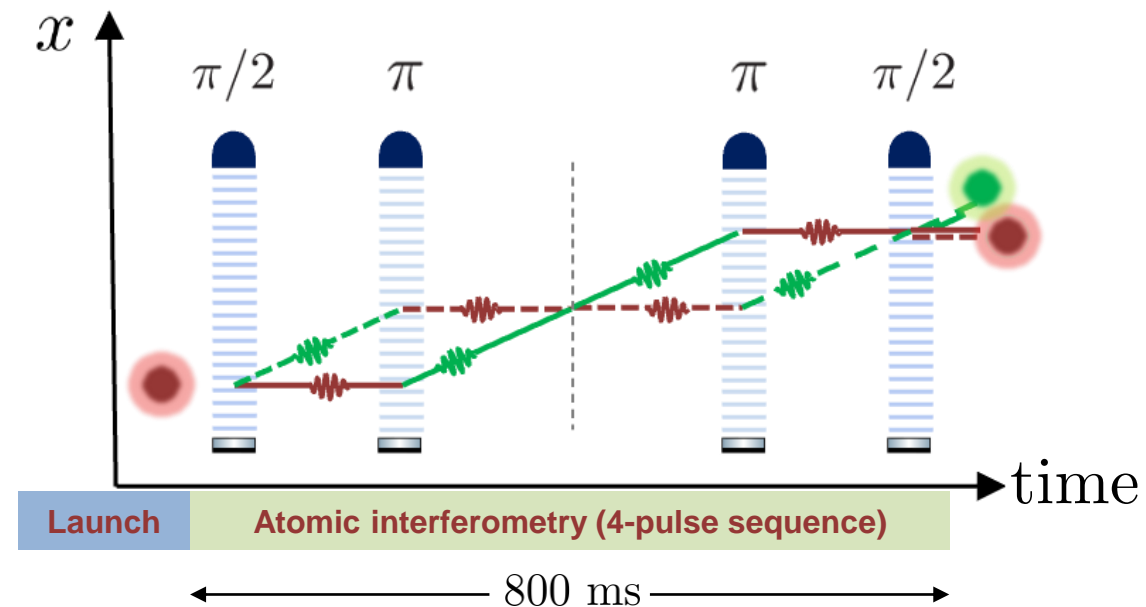
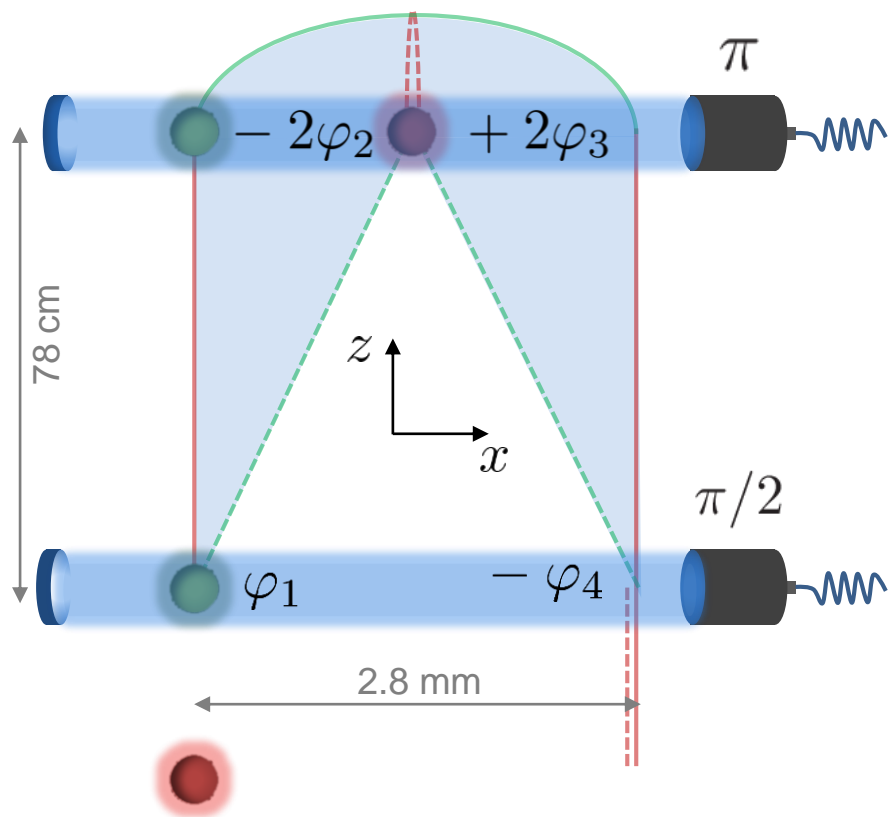
*Stability:*

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



## 4-pulse interferometer: Gyroscope

Large area: 11 cm<sup>2</sup>  
Macroscopic quantum effect



$$\Delta\Phi =$$

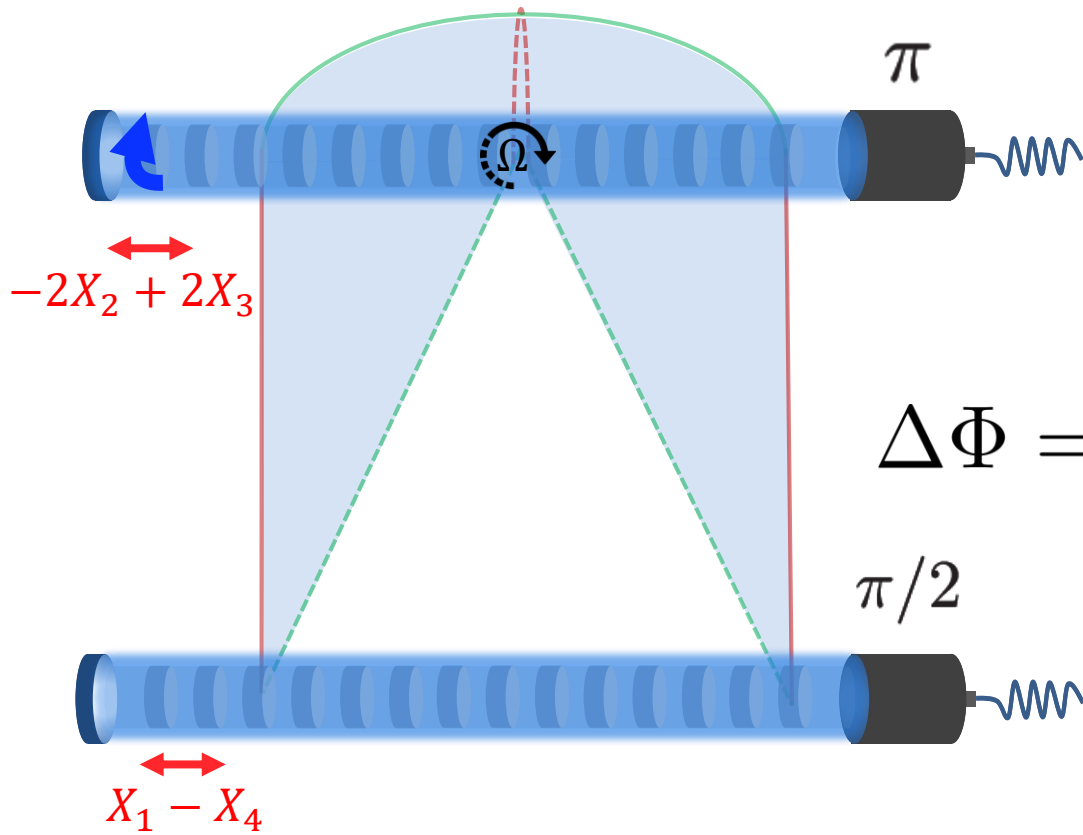
$$\varphi_i(t) = \vec{k}_{\text{eff}} \cdot \vec{r}(t) + \delta\Phi_{\text{laser}}$$

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

Symmetry → zero sensitivity to DC acceleration



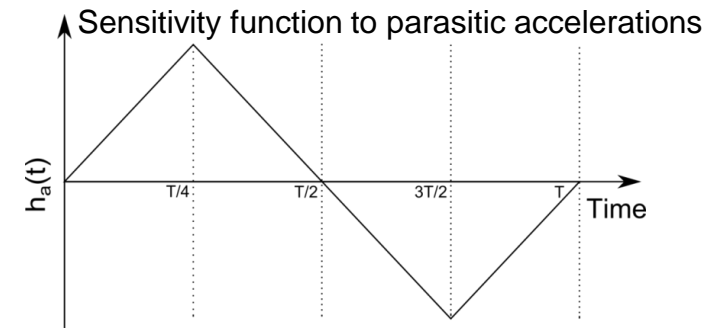
## Vibration noise sources



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

Variations of **acceleration**:

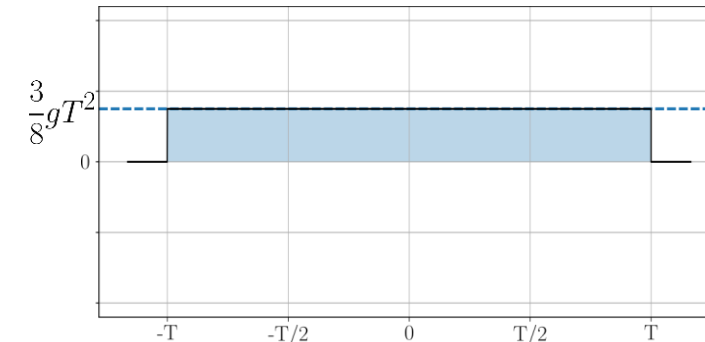
$$\phi_{vib/acc} \propto X_1 - 2X_2 + 2X_3 - X_4$$



Noise of **rotation**:

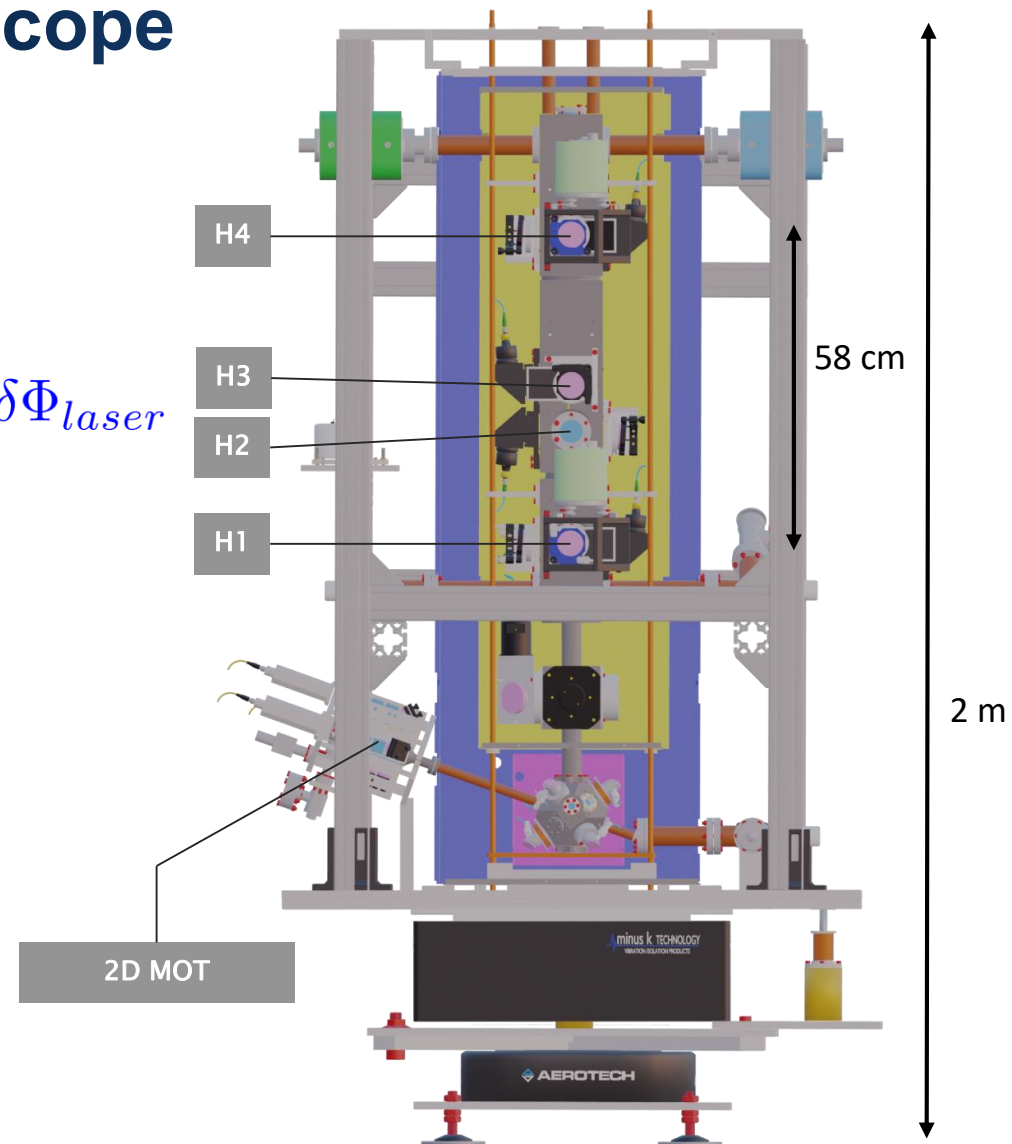
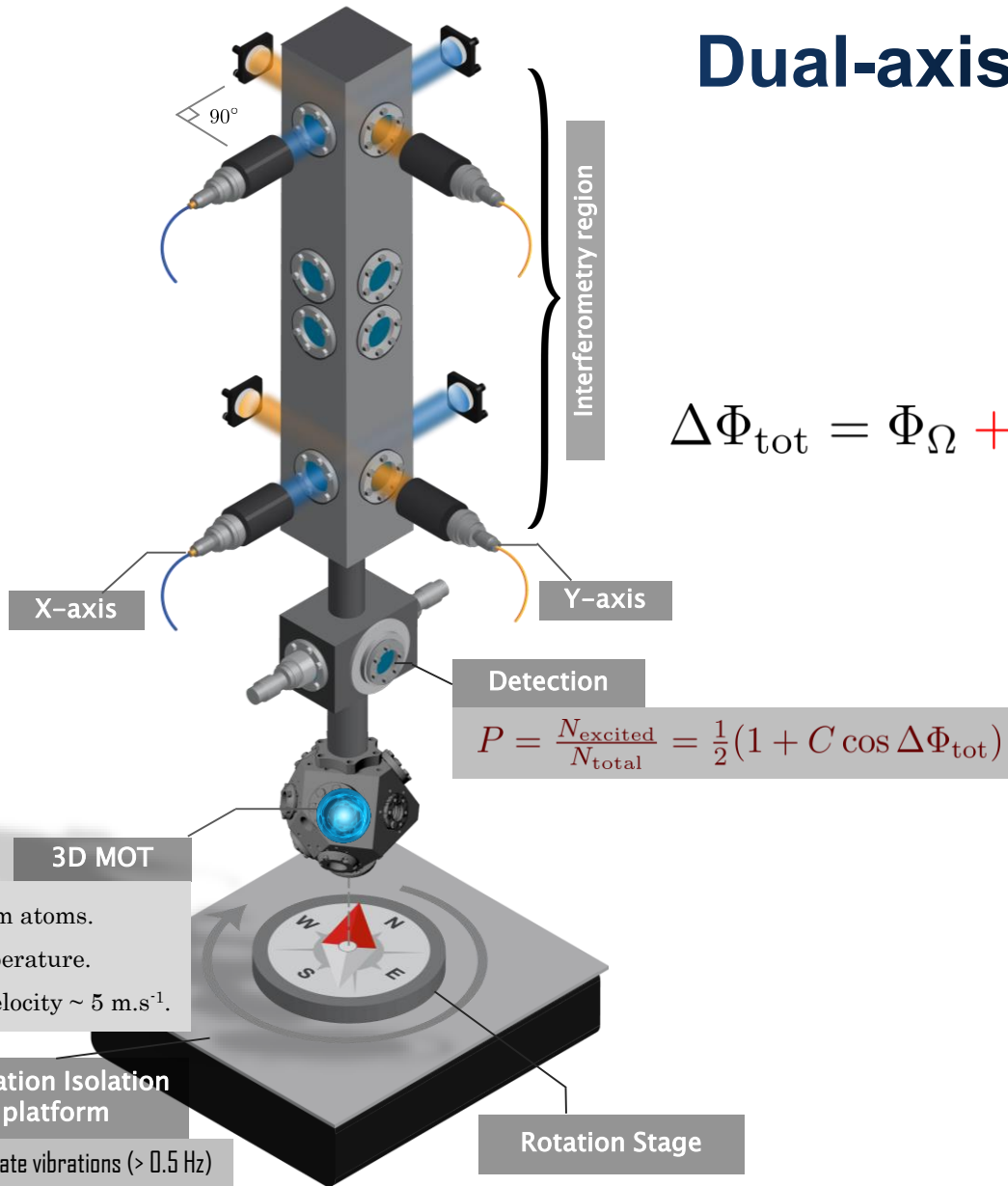
$$\phi_{rot} \propto \theta_1 - \theta_4 \propto \Omega g T^2$$

Sensitivity function to rotation





## Dual-axis gyroscope

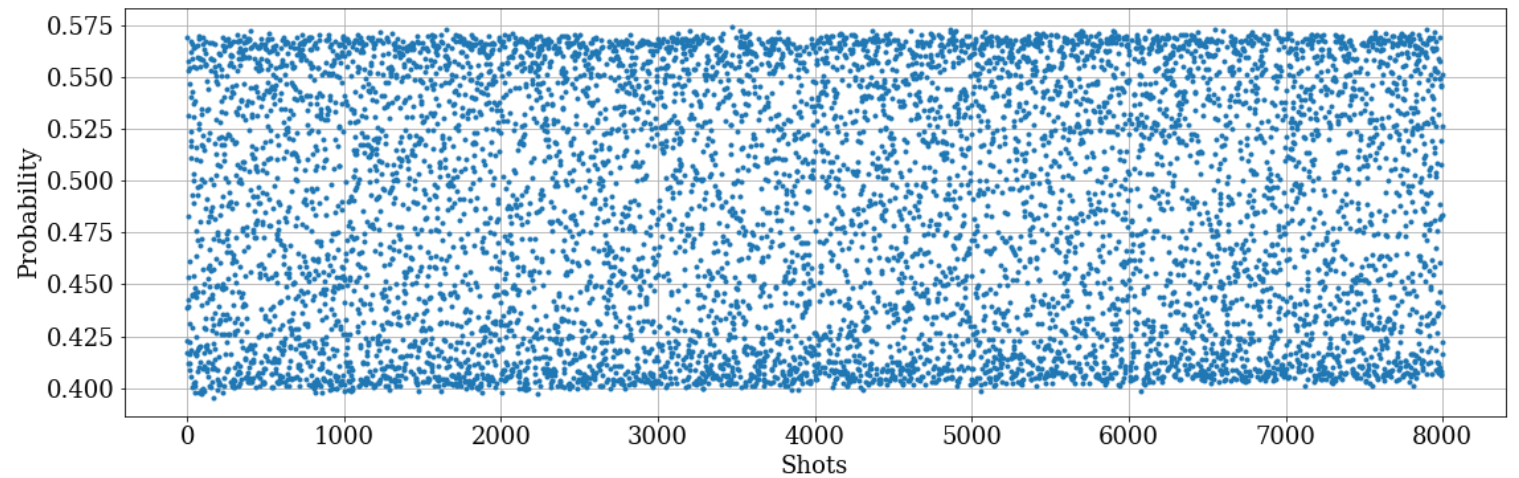
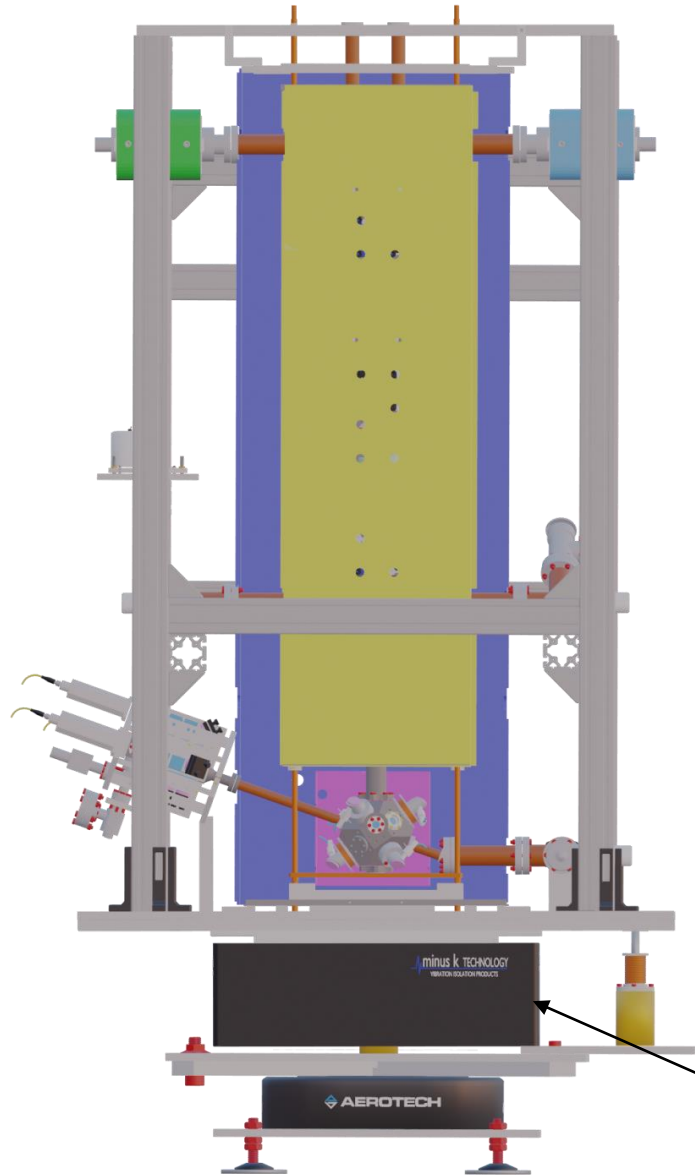




## Vibration noise

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

**Vibration noise covers several rad**



Passive vibration isolation platform

Attenuates high frequencies above 0.5 Hz

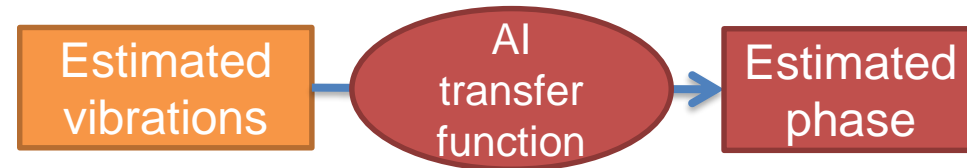




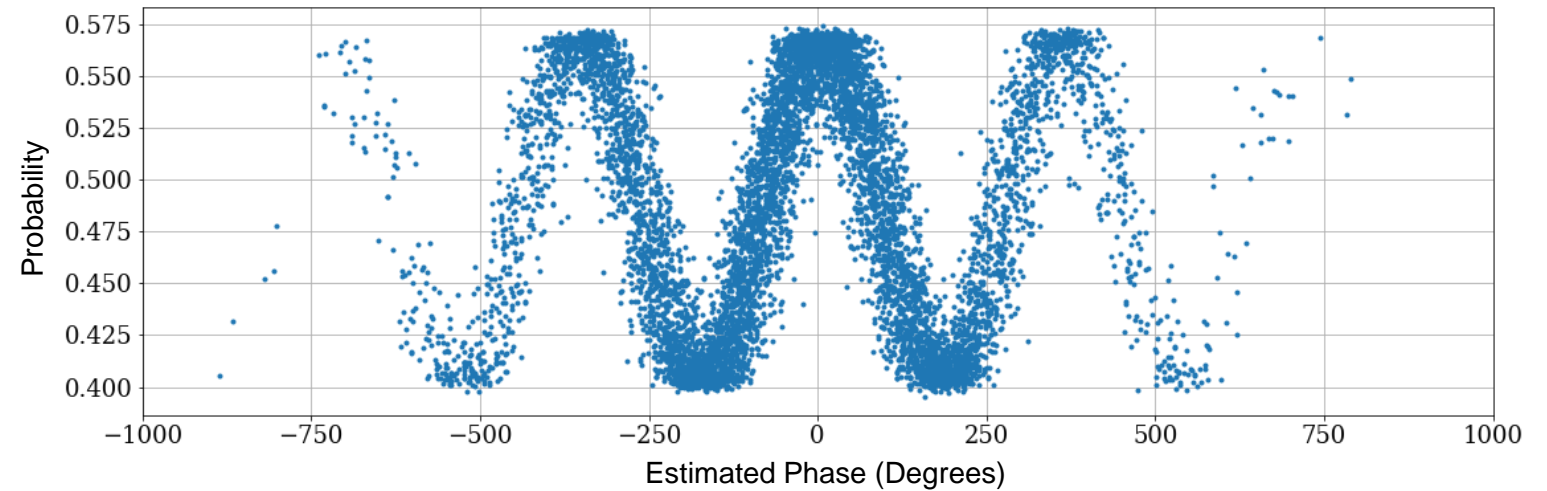
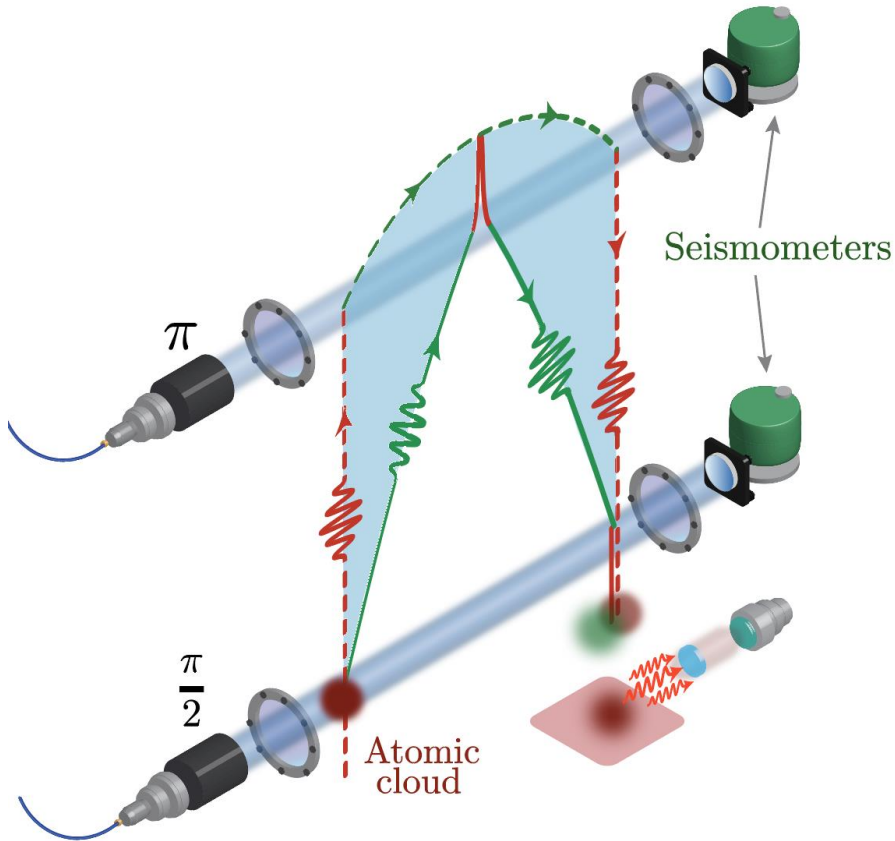
## Vibration noise correlation

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

**Vibration noise covers several rad**



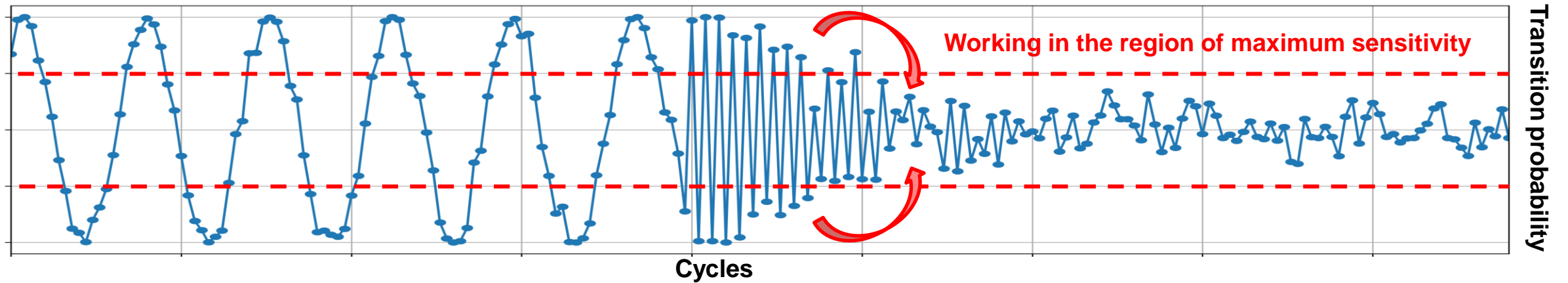
**Correlation with classical sensors**





## Compensation of vibrations

Compensating vibrations using the laser phase

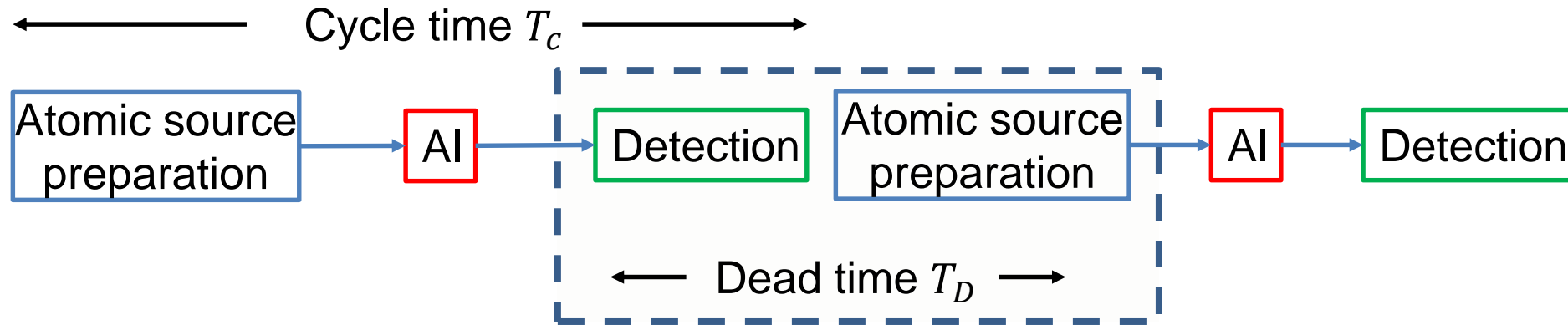


$$P = \frac{1}{2} (1 + C \sin(\Phi_{\Omega} + \underbrace{\Phi_{vib} + \Phi_{compensation}}_{\delta\phi_{residue} < 1} + \Phi_{laser}))$$



## Gyroscope operation sequence

Sequential operation of cold atom interferometers:



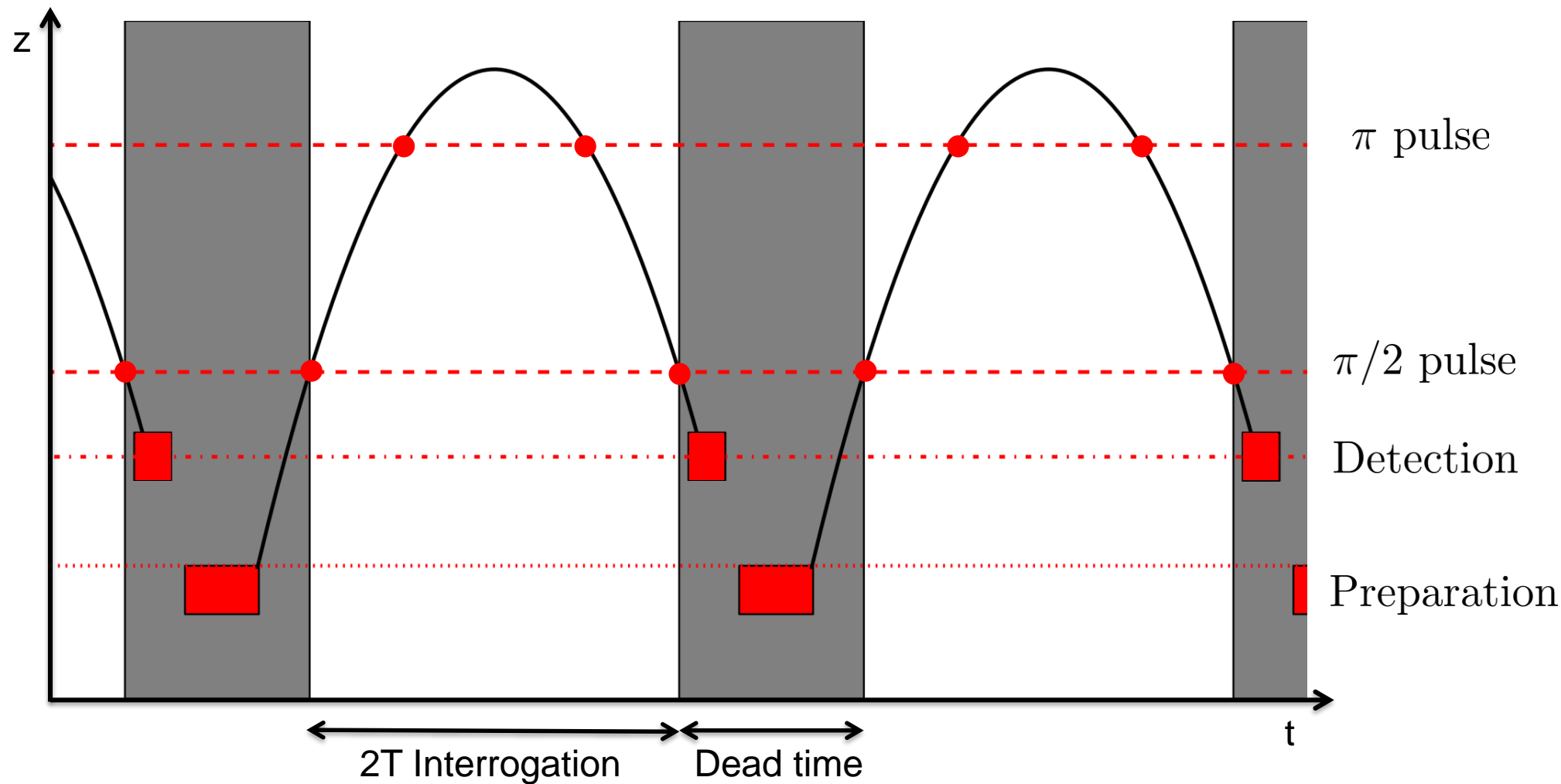
**Dead times** → Prevents from reaching the quantum noise limit.



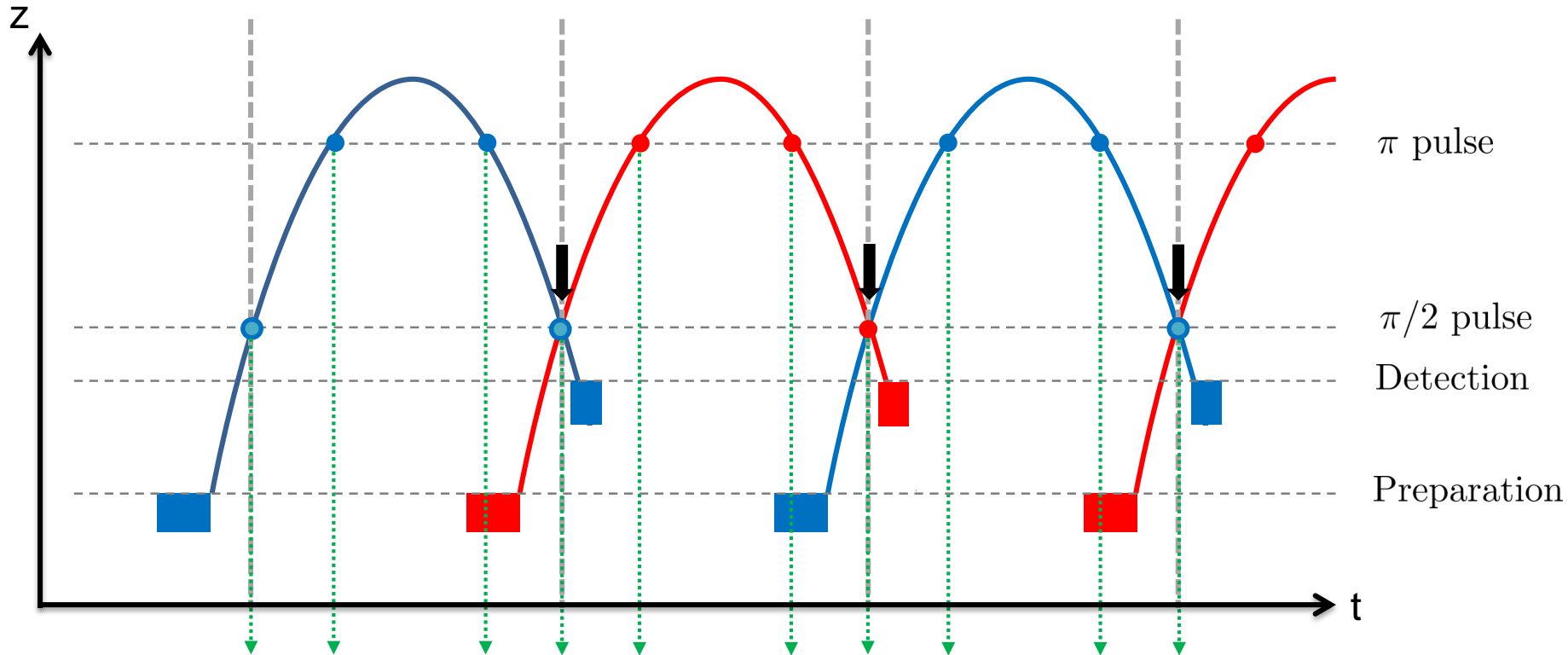
Cancelling dead times with other operating methods

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

## Dead Times with no-joint mode



## Simple-Joint Mode



Rotations

$\theta_1$  —  ~~$\theta_4$~~   ~~$\theta_4$~~  —  ~~$\theta_7$~~   ~~$\theta_7$~~  —  ~~$\theta_{10}$~~   ~~$\theta_{10}$~~  ...



Averaging in  $N^{-1}$

Accelerations

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



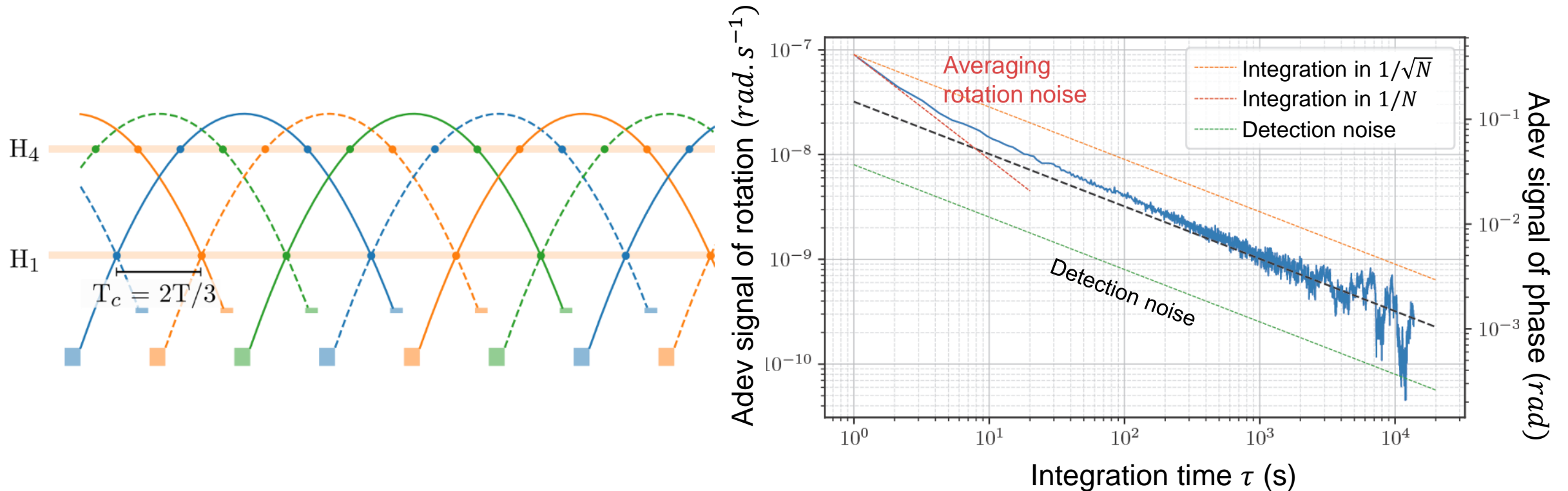
Averaging in  $N^{-1/2}$  and **dominant**



## Stability record - triple-joint sequence

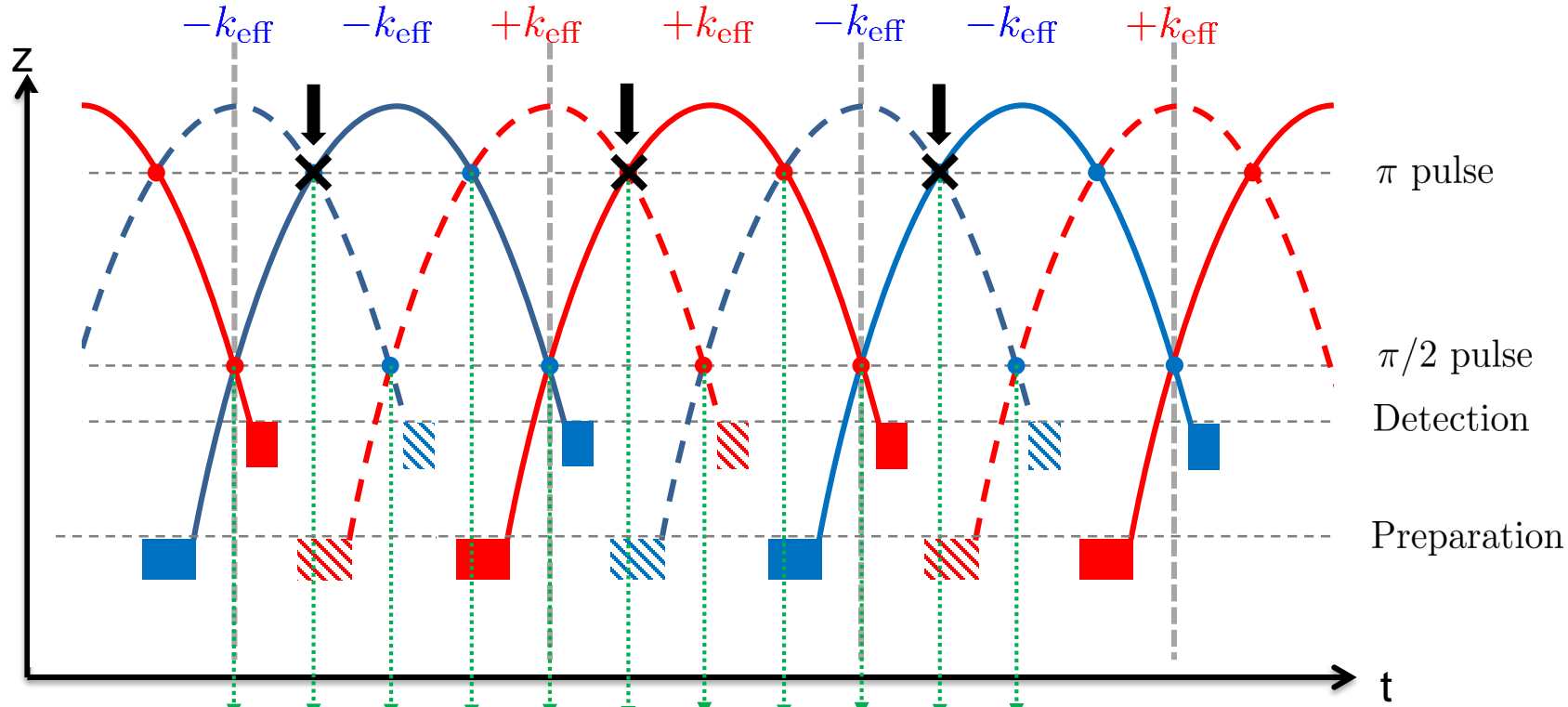
### Triple-Joint Interrogation:

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

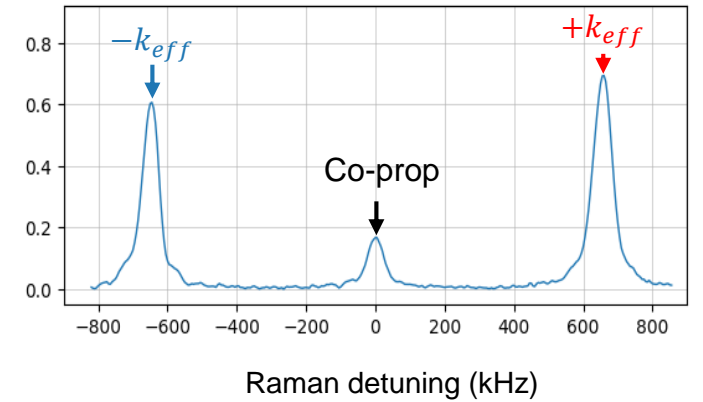


*Savoie et al., Sci. Adv 4.12 (2018)*

## Double-Joint Mode



### Resonance conditions:



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

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

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

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

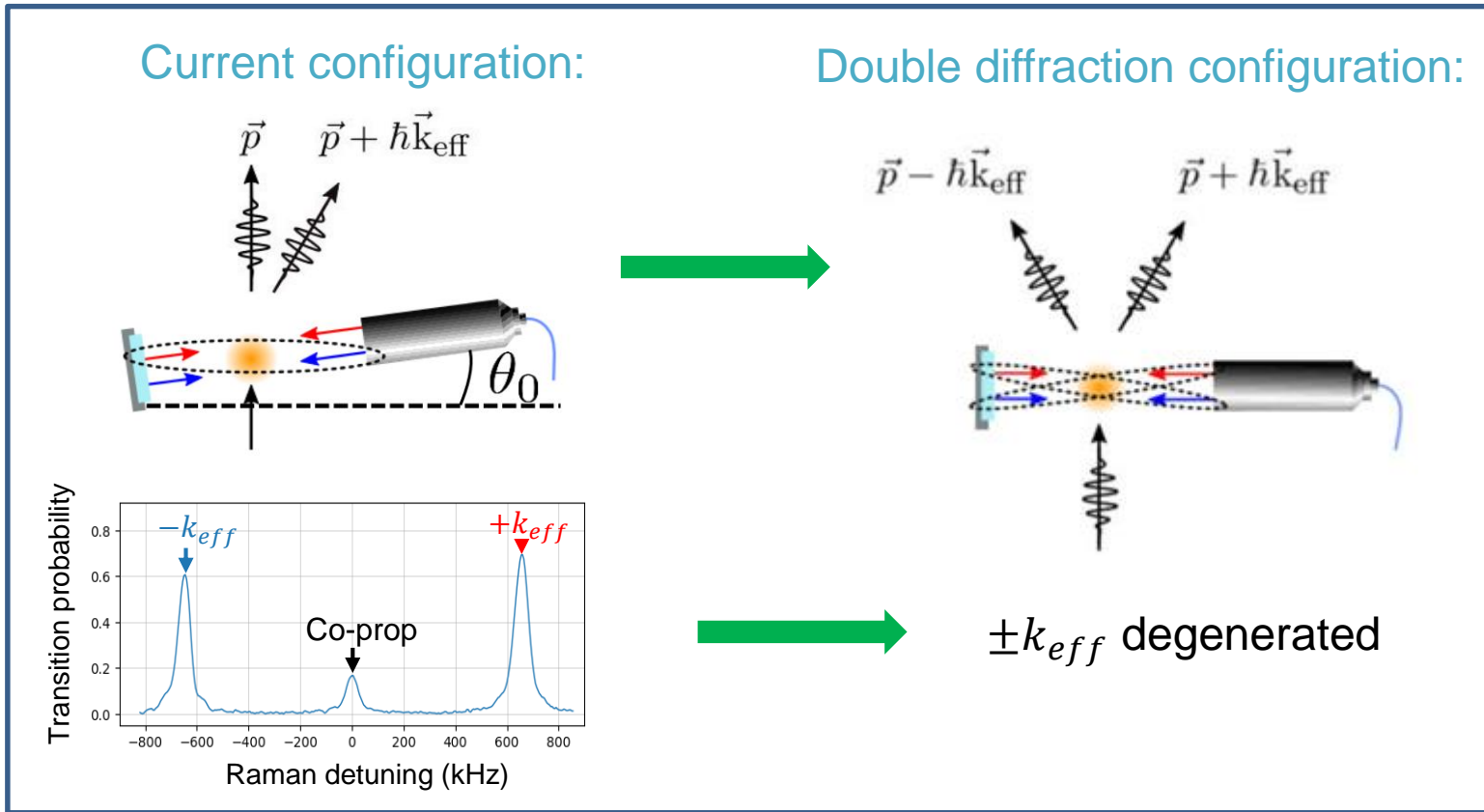


Averaging of rotations and accelerations ( $N^{-1}$ )

Accelerations



## The double-diffraction



### Main advantages:

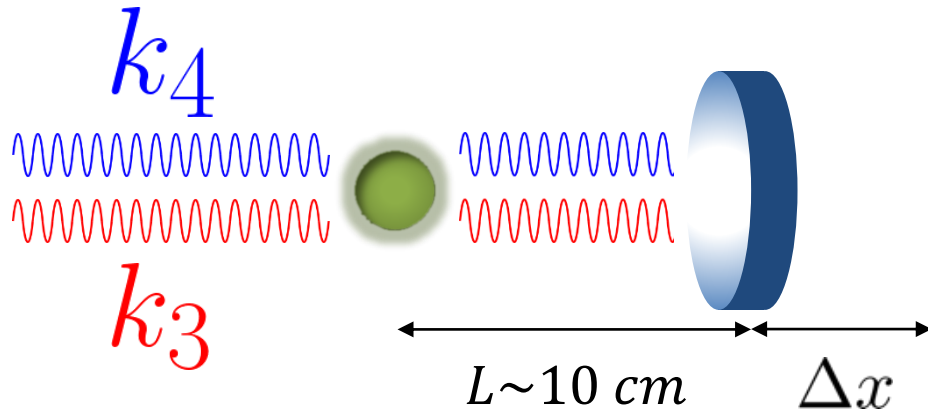
- ❖ Enable the Double-joint mode
- ❖ Enhance sensitivity by doubling interferometric area
- ❖ Rejection of systematic effects

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

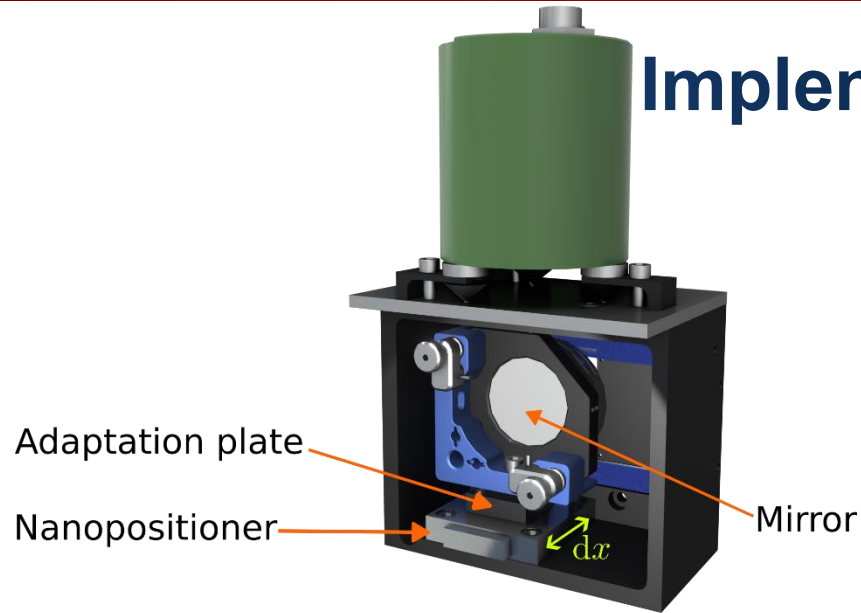
$$\Phi^{(\pm k)} \approx \phi_L \mp (k_{\text{eff}} + dk_{\text{eff}})L$$

Double diffraction

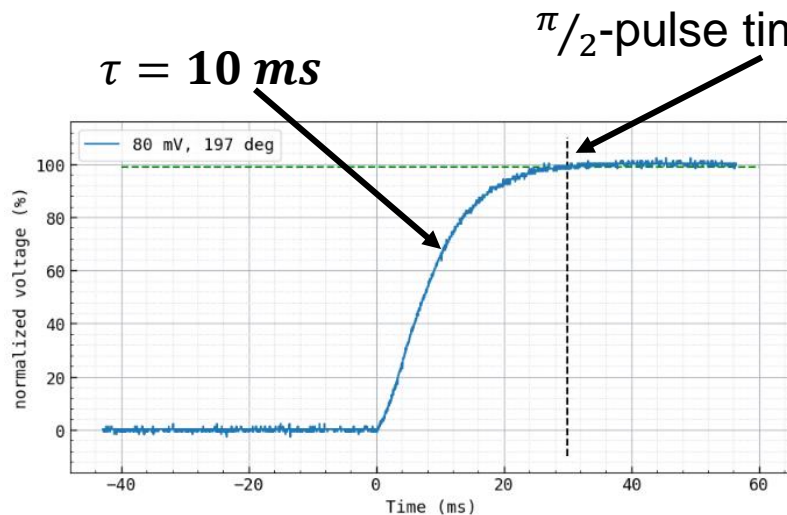
$$\Delta\Phi \approx 2(k_{\text{eff}} + dk_{\text{eff}})L$$



## Implementation of Mirror jumps

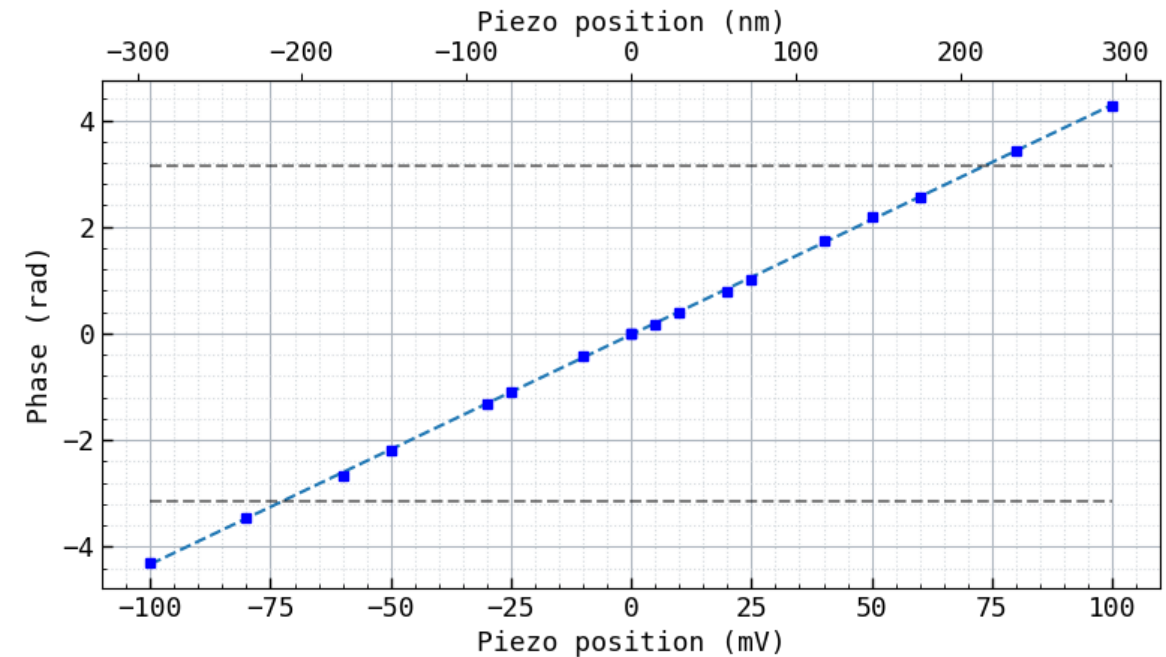


## Characterization of the step response



## Characterization of the Scale factor

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



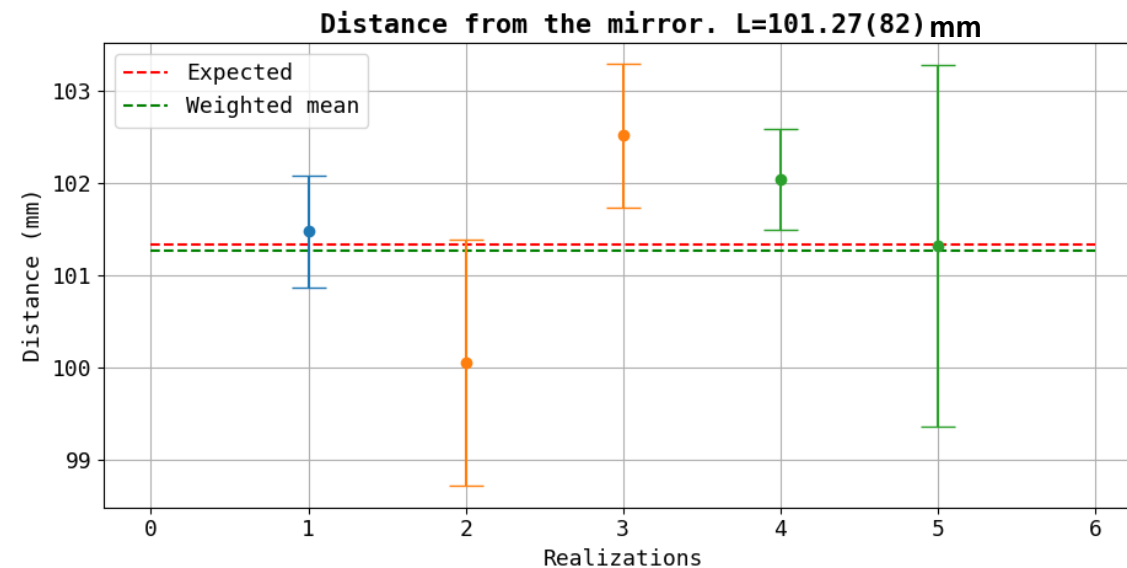
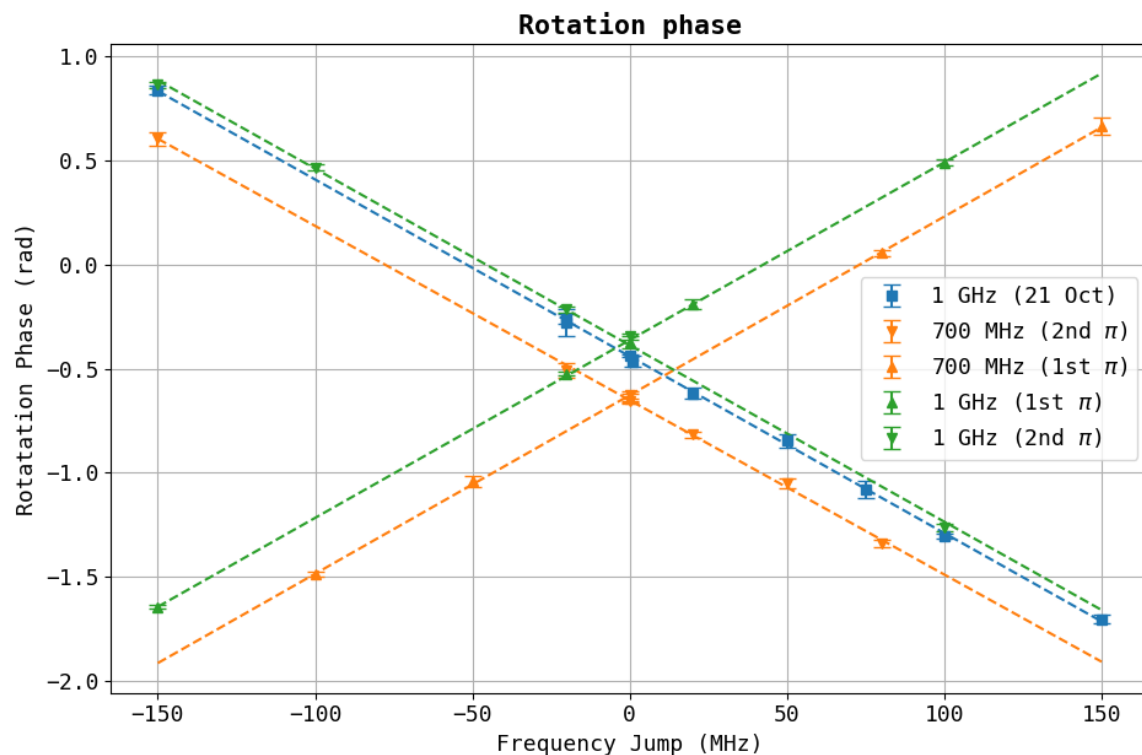
**$\sim 426 \text{ nm}/360^\circ$  on  $\pi/2$  pulse**  
**(Divided by 2 in double diffraction)**



## Implementation of Frequency jumps

### Precise measurement on L

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

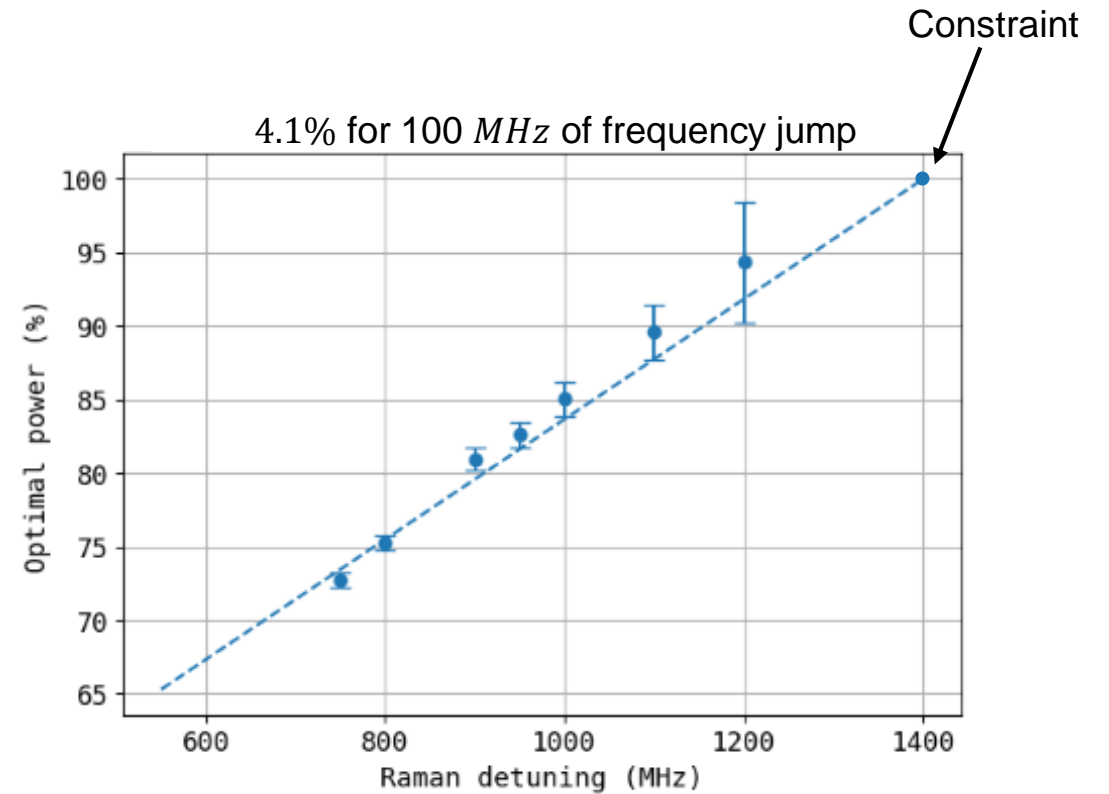
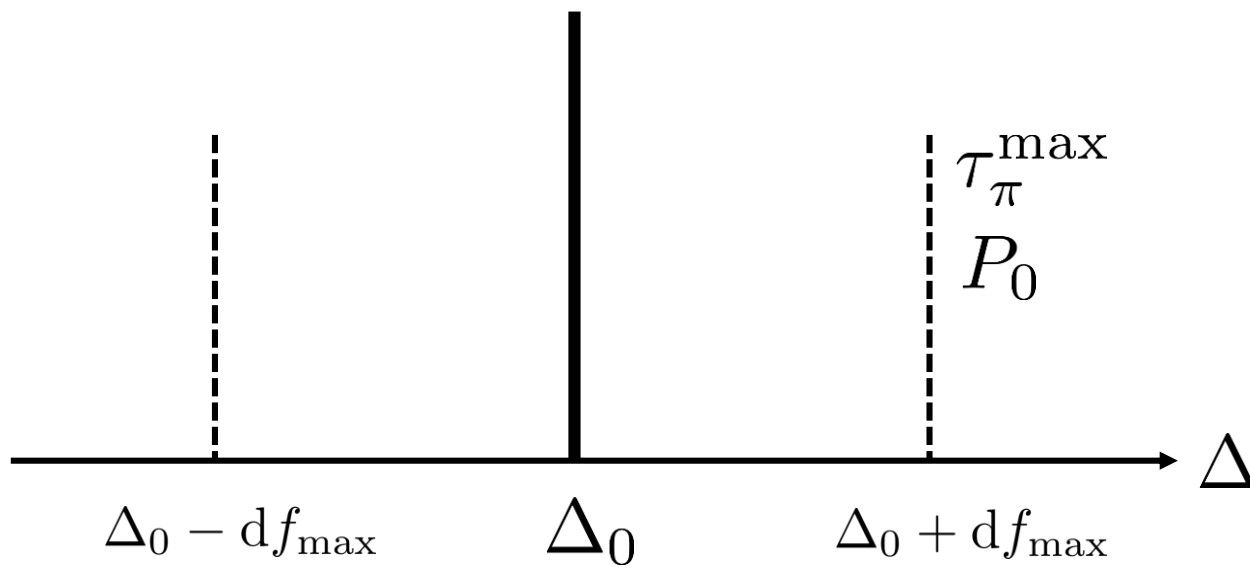


**~ 370 MHz/180° on  $\pi/2$  pulse**  
**(Divided by 2 in double diffraction)**

## Compensate $\Omega_{eff}$

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

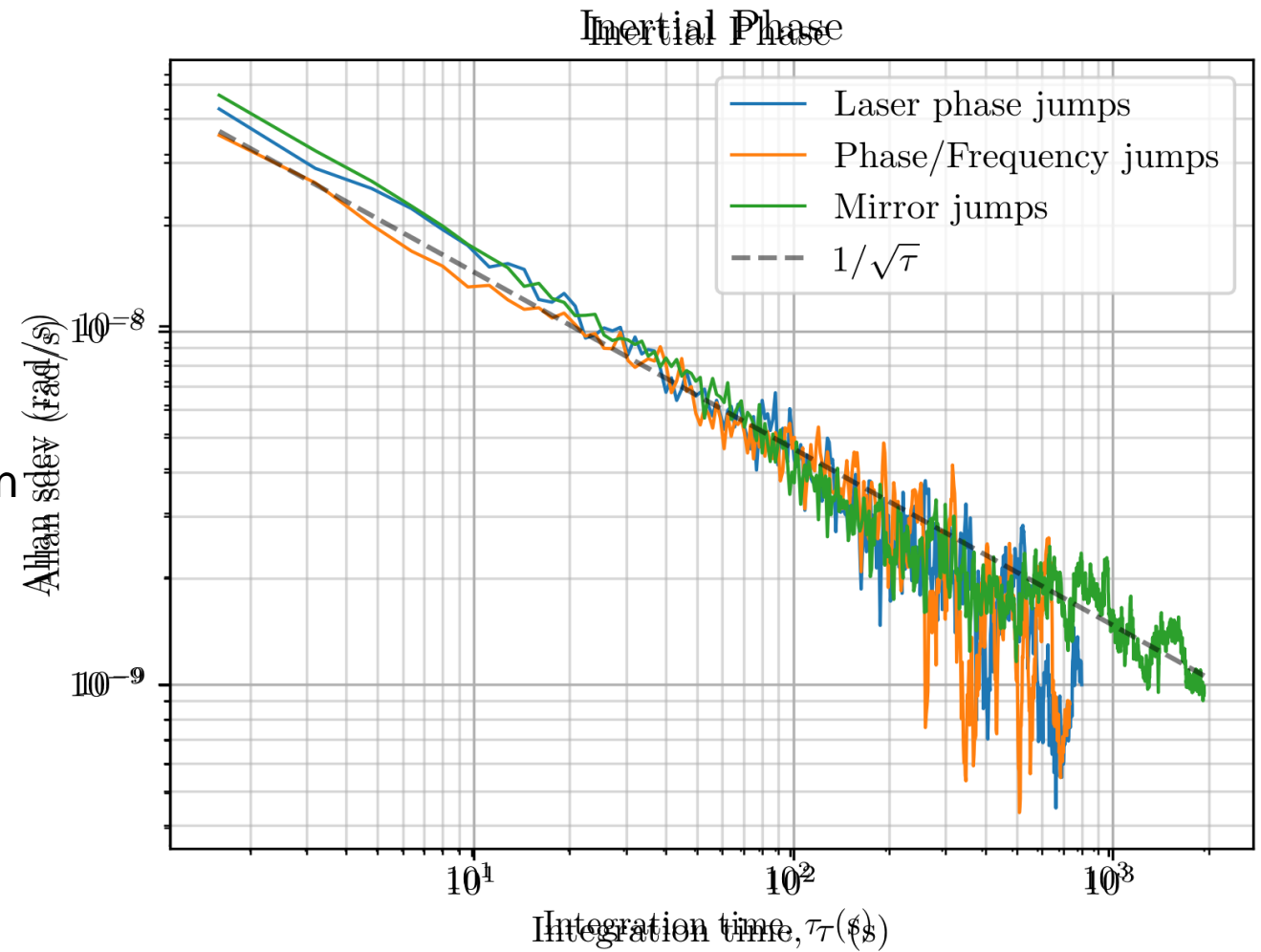
$\tau_\pi$  or  $P_0$





## 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