Accelerometers as Probes for Dark Matter

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on behalf of the Eot-Wash group

Eot-Wash torsion balance techniques

- With NSF support, pioneered rotating torsion balances for 30 year and Performed a wide array of precision measurements:

- In the gravitational sector:
    - Best and broadest weak Equivalence Principle test
    - Shortest distance test of gravitational inverse square law at gravitational strength
- With spin-polarized pendulums:
    - Plank scale test of Lorentz violation
    - Best test of non-commutative space-time geometry
    - Searched for pseudo-goldstone bosons of hidden high energy symmetries

Eot-Wash torsion balance techniques

- Motivated by recent ideas in the field, and leveraging our torsion balance experience, we are investigating what we could do with dedicated torsion balance searches for ULDM

- We can look for two of the four general experimental observables identified by Surjeet:

    - Spin precession
    - Differential acceleration

- Over the lighter 30% of the relevant (logarithmic) mass range
- We will show a new analysis of our existing data looking for these effects
- And explain how a dedicated balance could be significantly more sensitive

    - Simpler systematics
    - Improved suspension, readout and turntable systems for lower noise

Light Dark Matter Possibilities

Type	Couples to
Axial/PS	Fermions
Vector/Scalar	Fields

Light Dark Matter Possibilities

Type	Couples to
Axial/PS	Fermions
Vector/Scalar	Fields

Light Dark Matter Observables

	Operator	Effect
pseudo-scalar/axial	$\mathcal{L} = g_{a\bar{\psi}\psi}(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	spin-torque
scalar/ vector	$\mathcal{L} = g_{\phi\bar{\psi}\psi}\phi\bar{\psi}\psi$	differential acceleration

Scalar/vector motivation

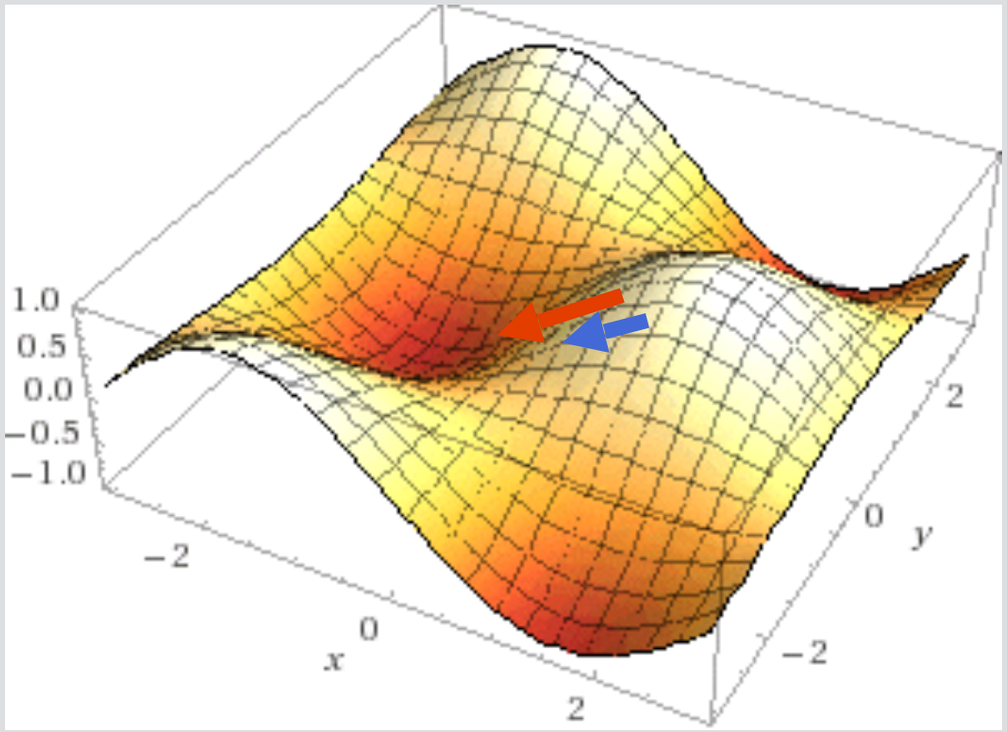
- Any motivation you have for a new light scalar or vector is instantly a well-motivated dark matter candidate:

They appear so often that theorists have to hide them…

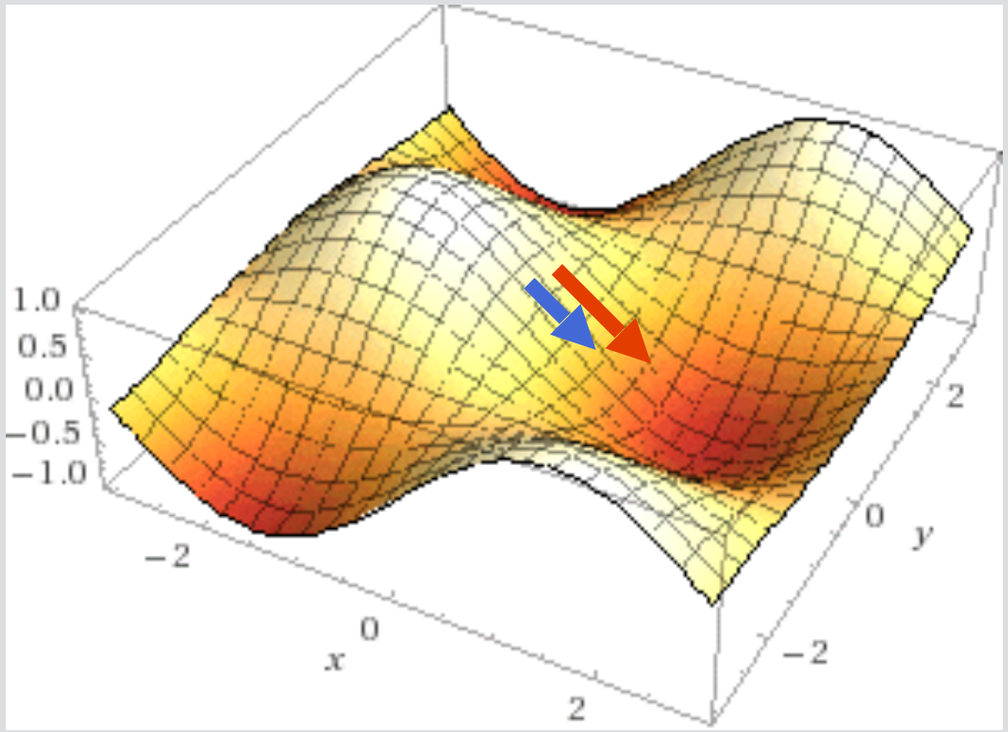
- relaxions to solve hierarchy problem
- light fields to unify GR and Quantum Mechanics

Torque Signal

ϕ-field at t = 0



ϕ-field at t = π/ω_c

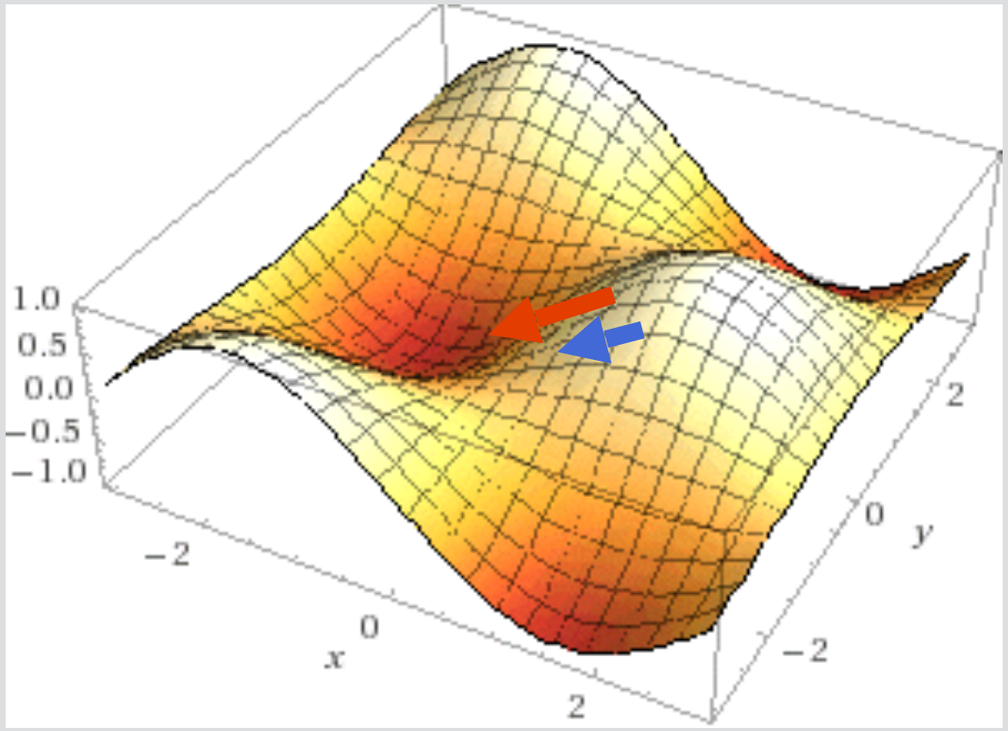


Pendulum observable

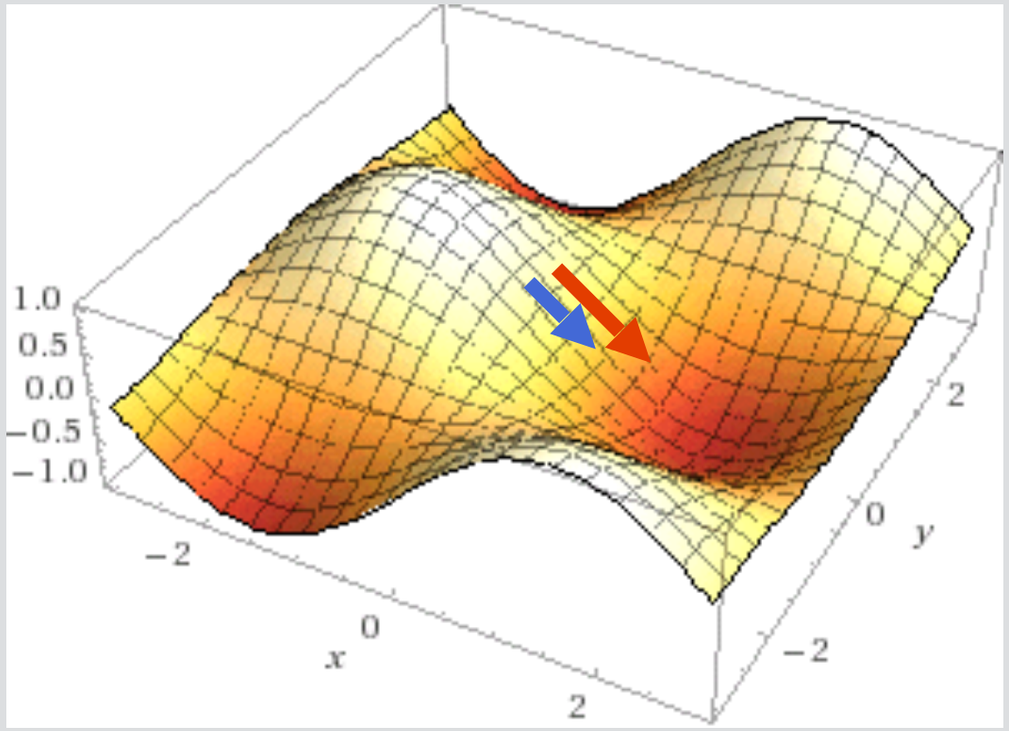
- Preferred pendulum orientation oscillates at DM compton frequency!!! (not turntable rotation frequency)

- Previous analysis technique would have averaged away the signal!

ϕ-field at t = 0

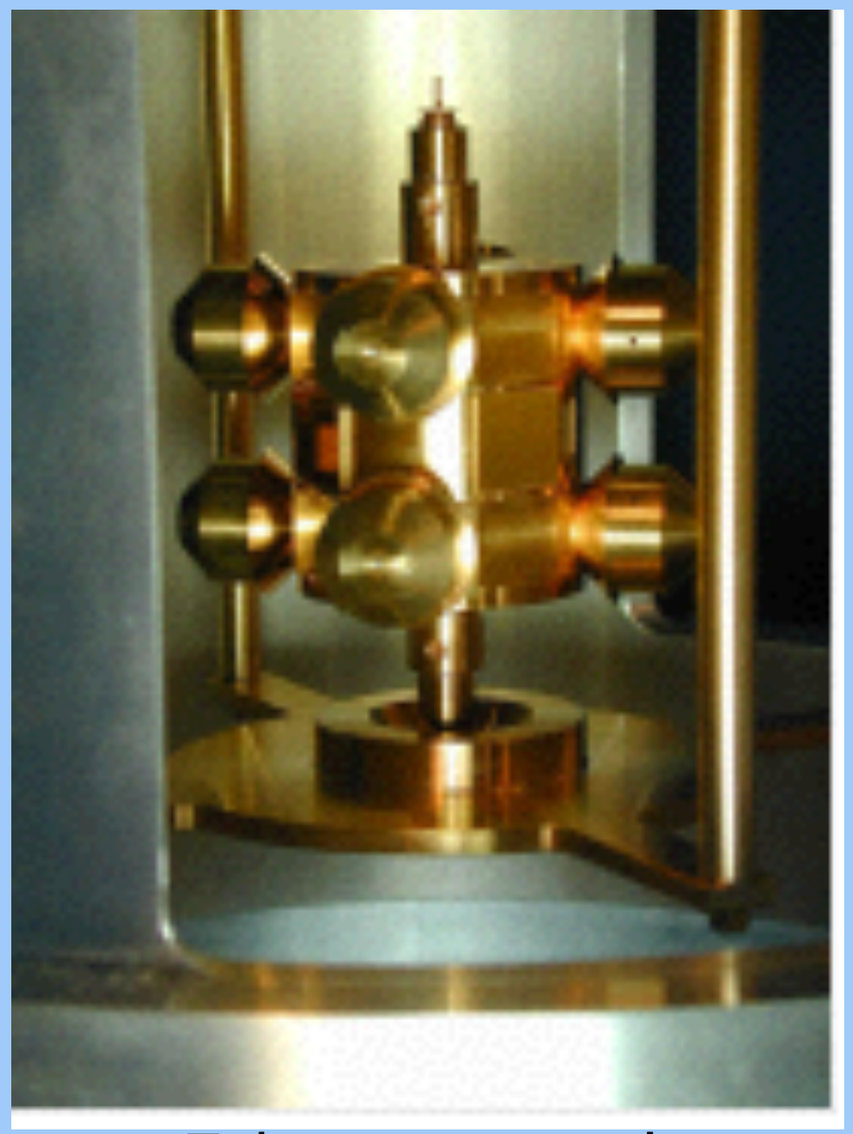


ϕ-field at t = π/ω_C



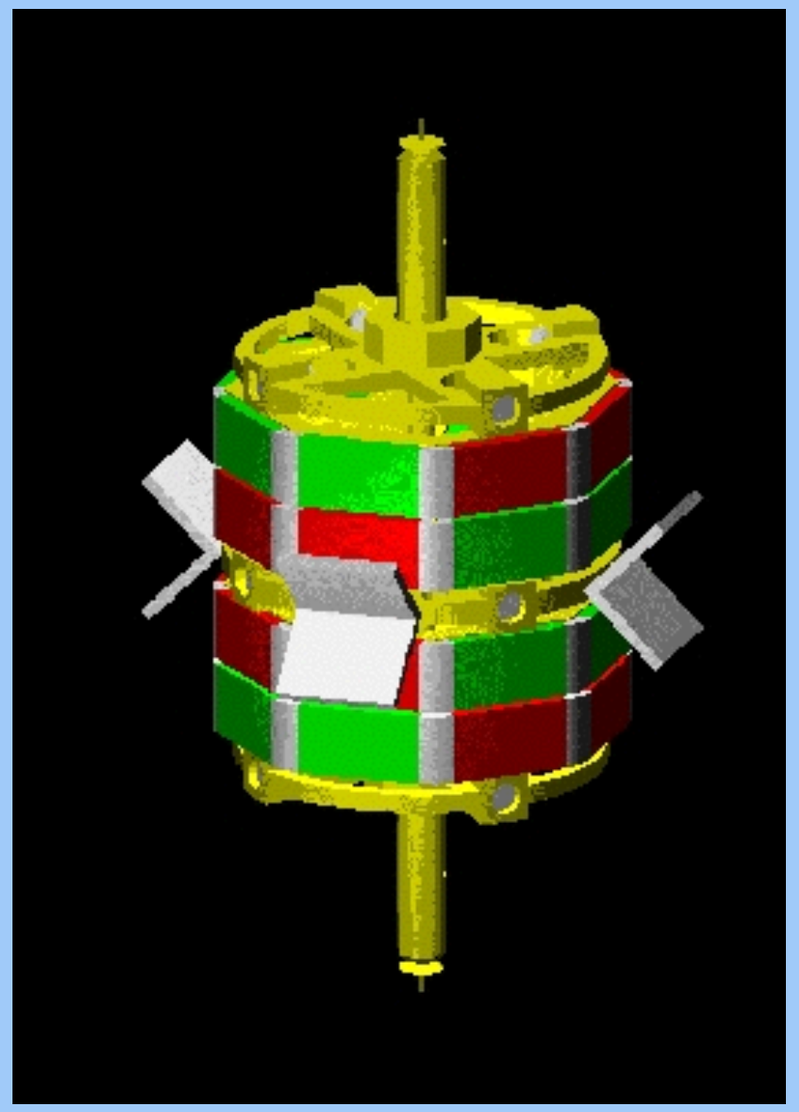
We Even Have the Right (Torsion) Pendulums for these Observables!

Scalar/Vector



> 5th generation

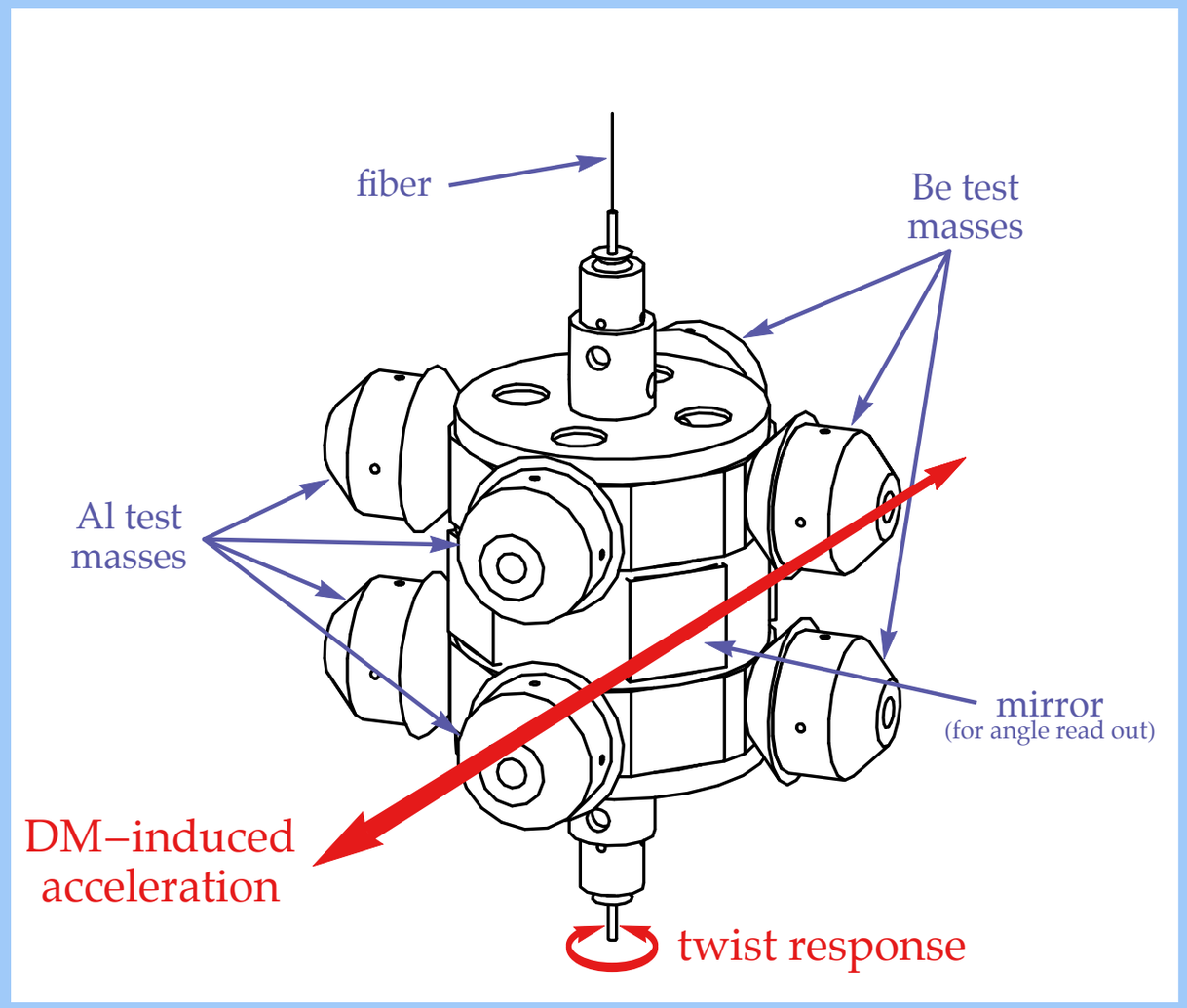
Axion



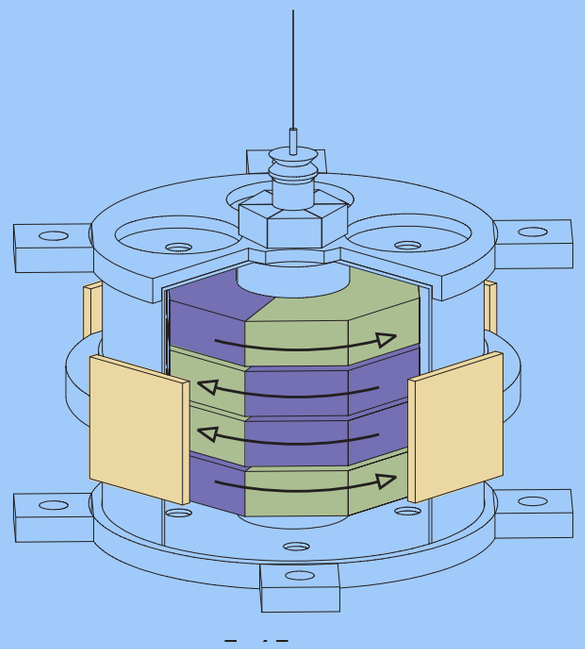
3rd generation

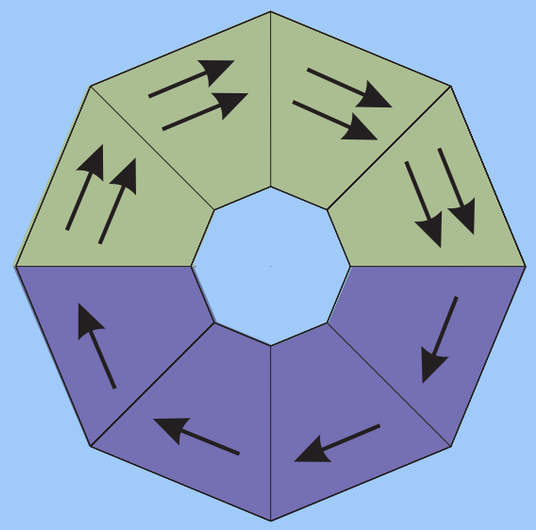
We Even Have the Right (Dipole) Pendulums for these Observables!

Scalar/Vector

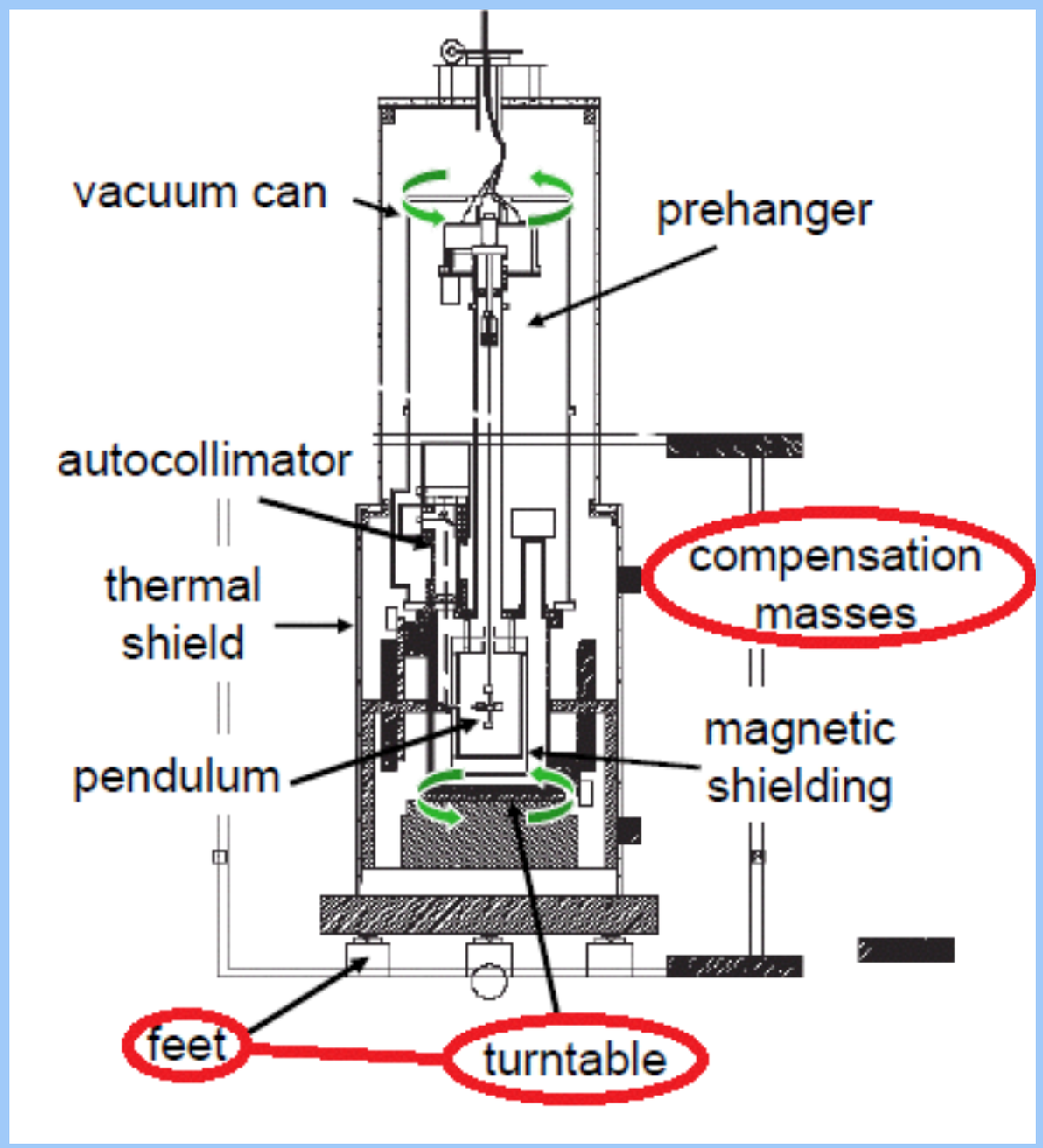


Axion





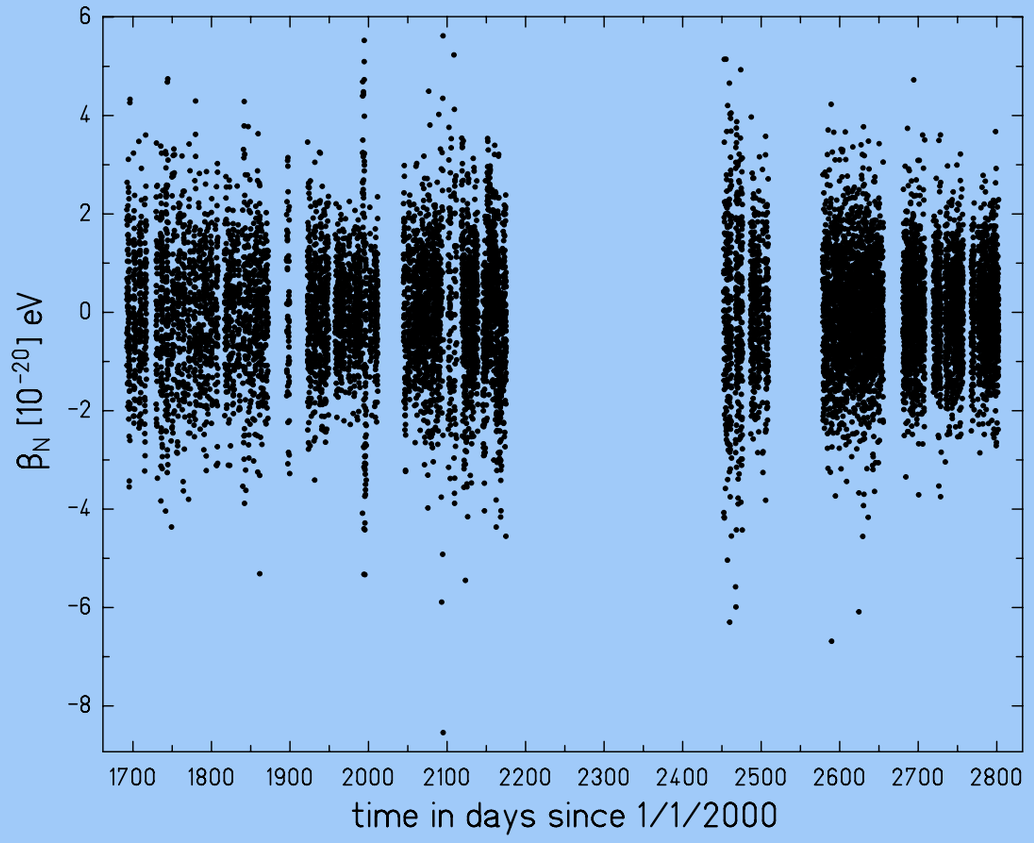
Rotating Balance

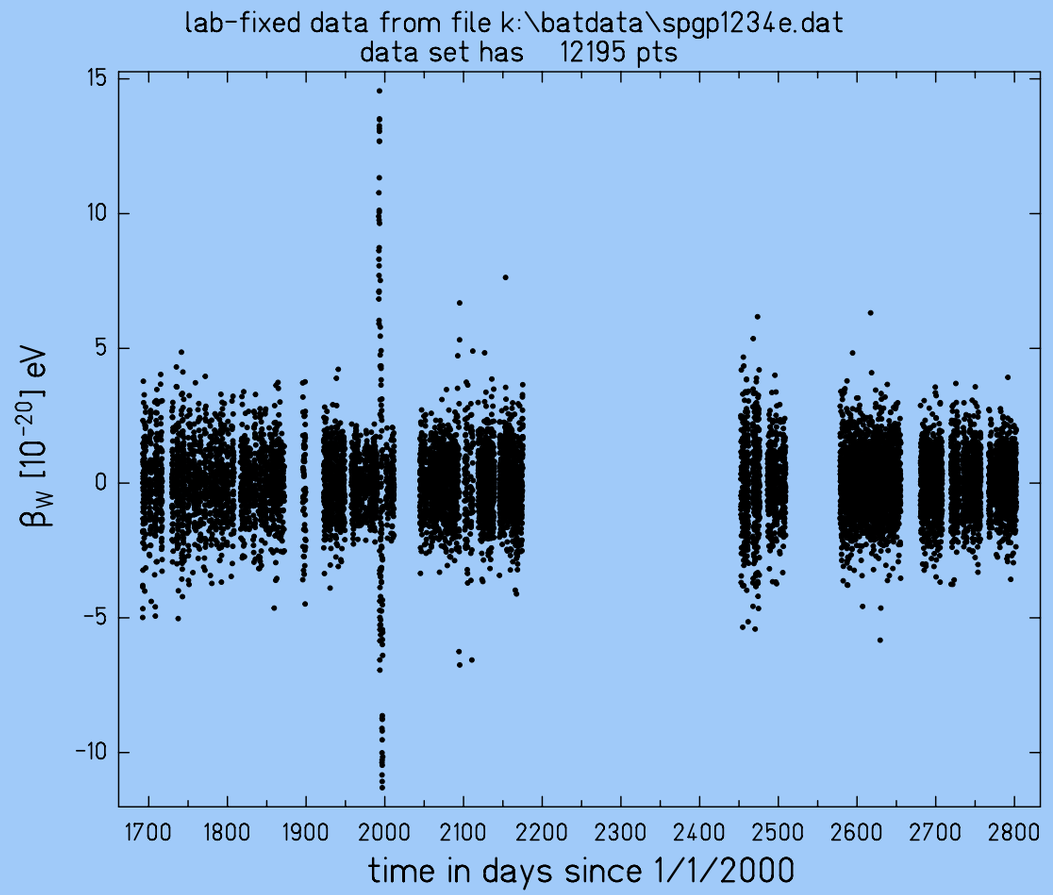


- Shifts science signal to turntable frequency
  - Allows study of lab-fixed signals
    - Better 1/f noise
- Rotation rate must be very uniform (36,000 stripe encoder)
- Tilt axis very stable (adaptive length feet)

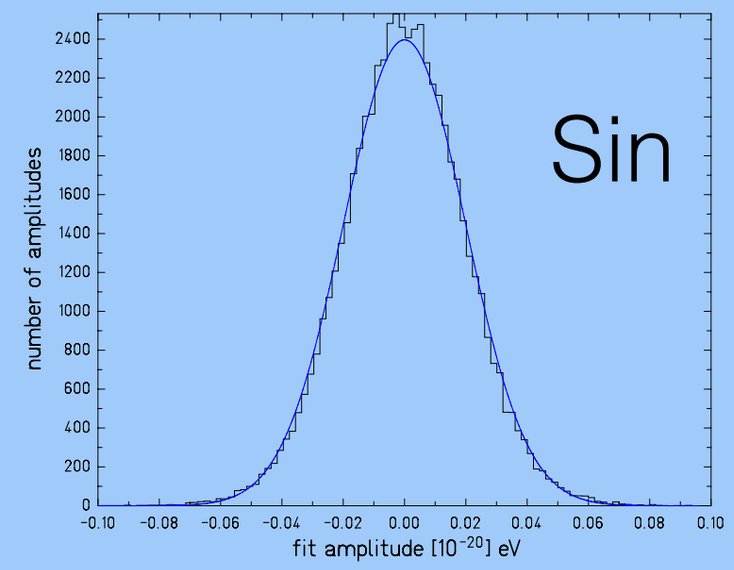
New Analysis of 4 years of spin pendulum data

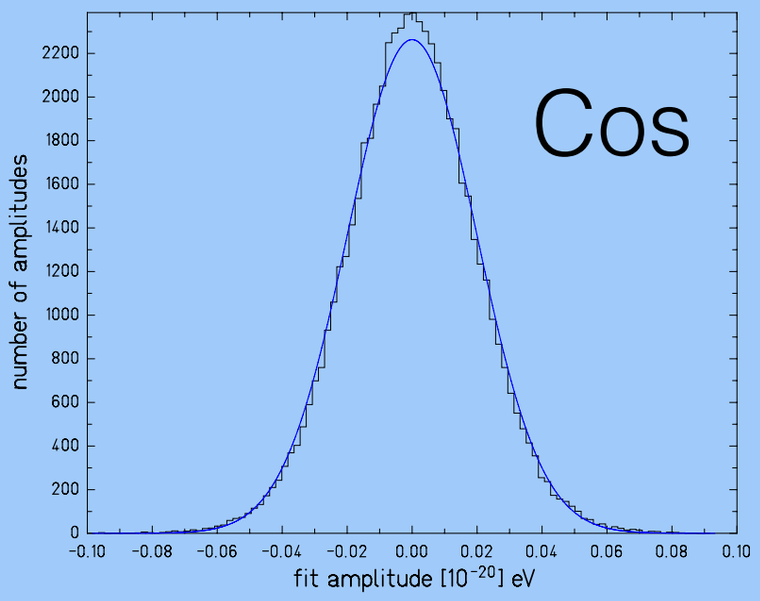
Torque per electron after demodulating the turntable rotation



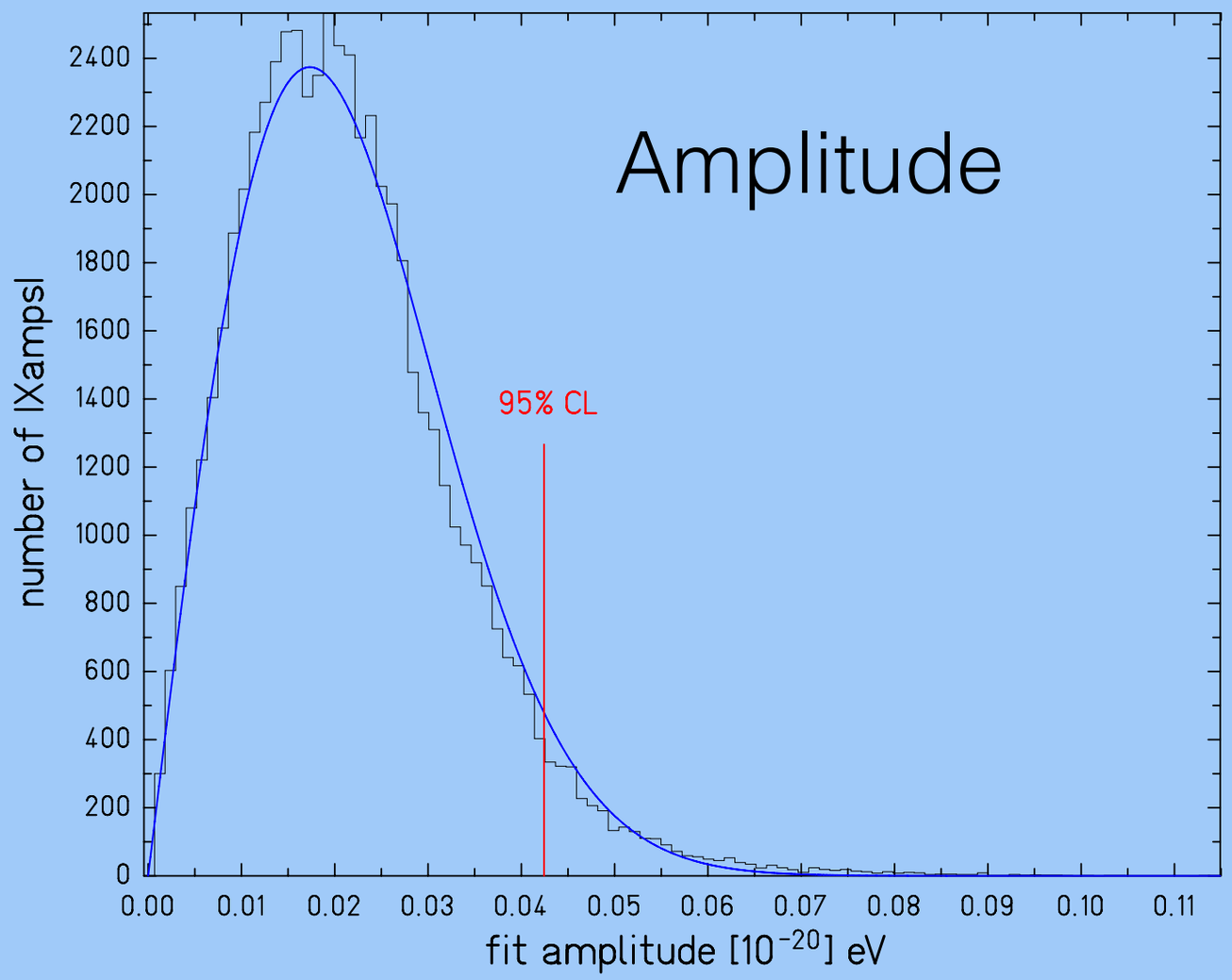


Fitting the torques to DM signal

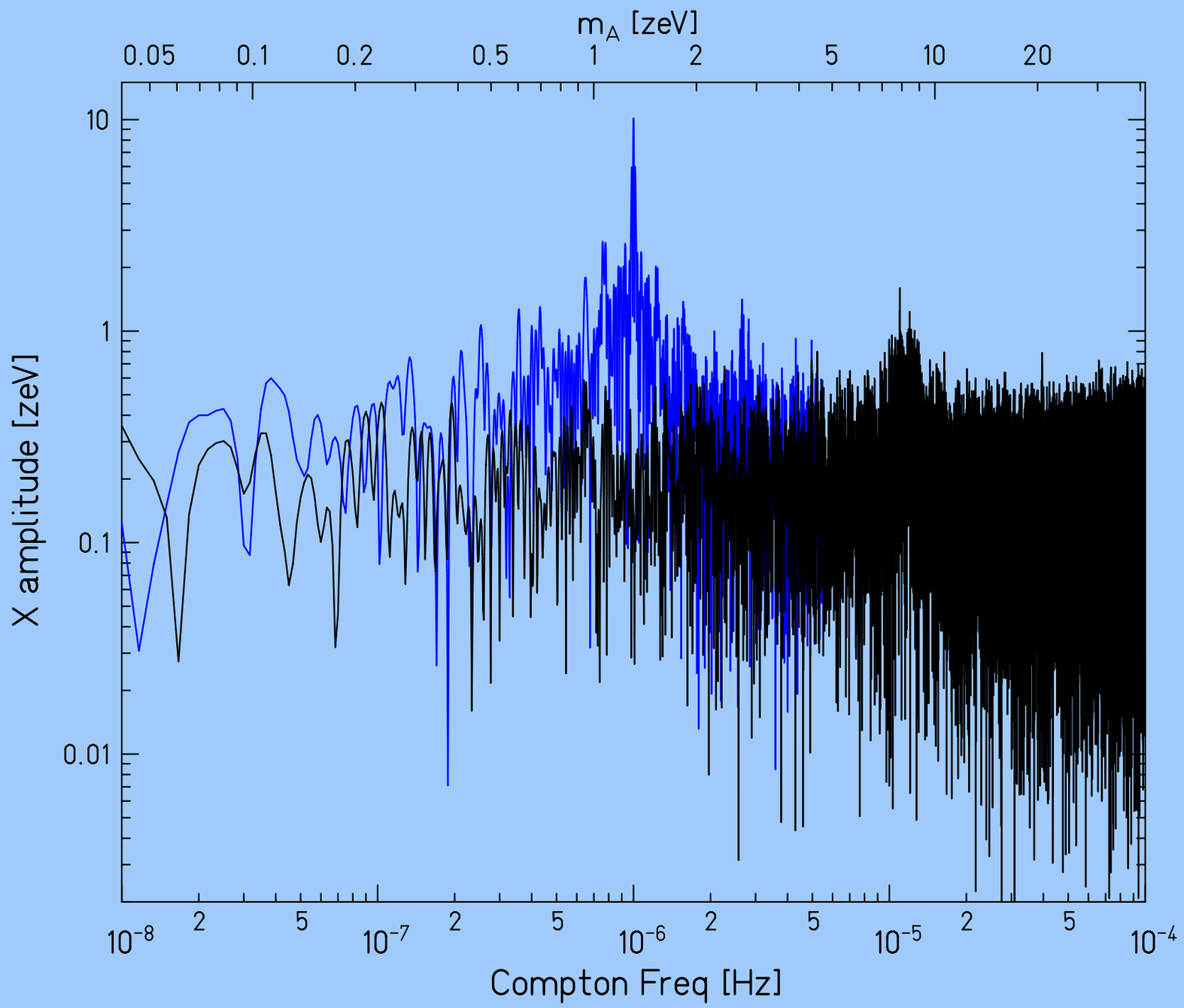




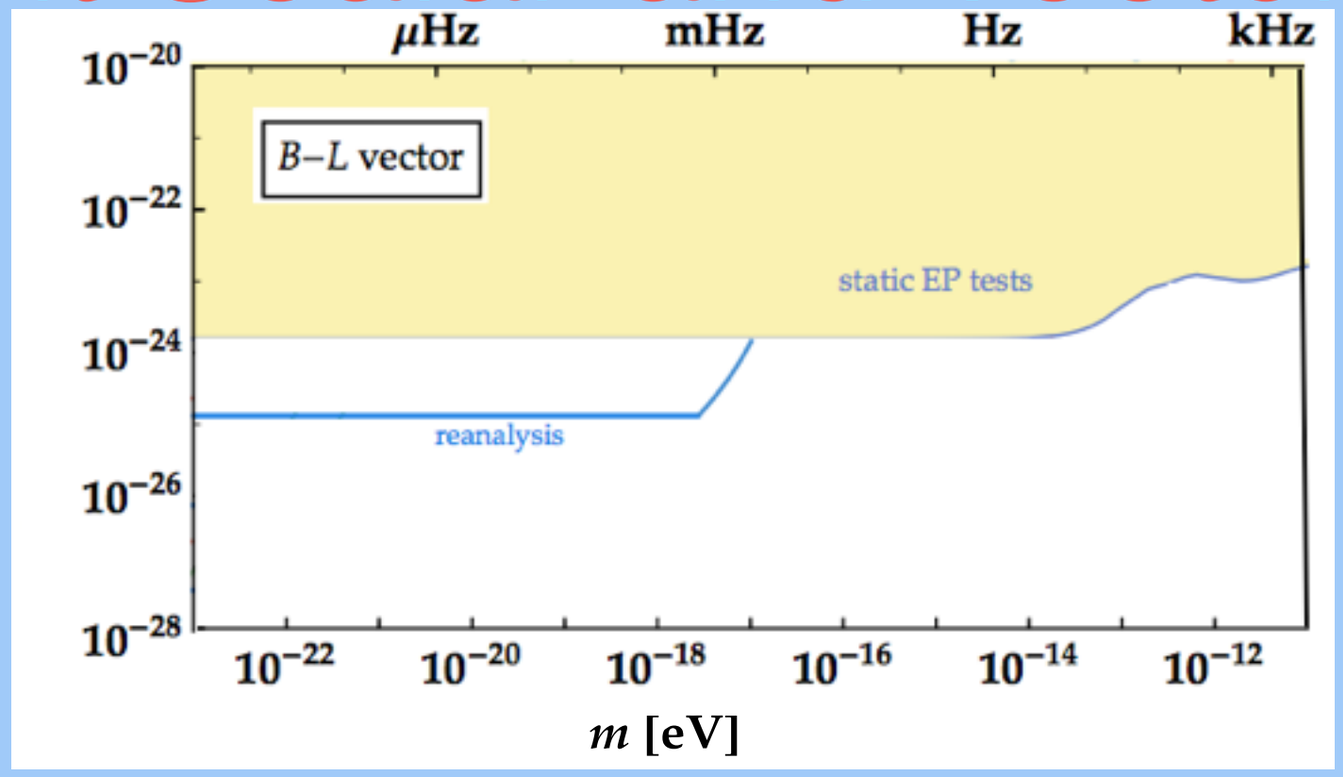
Product of sidereal frequency with 60k DM frequencies

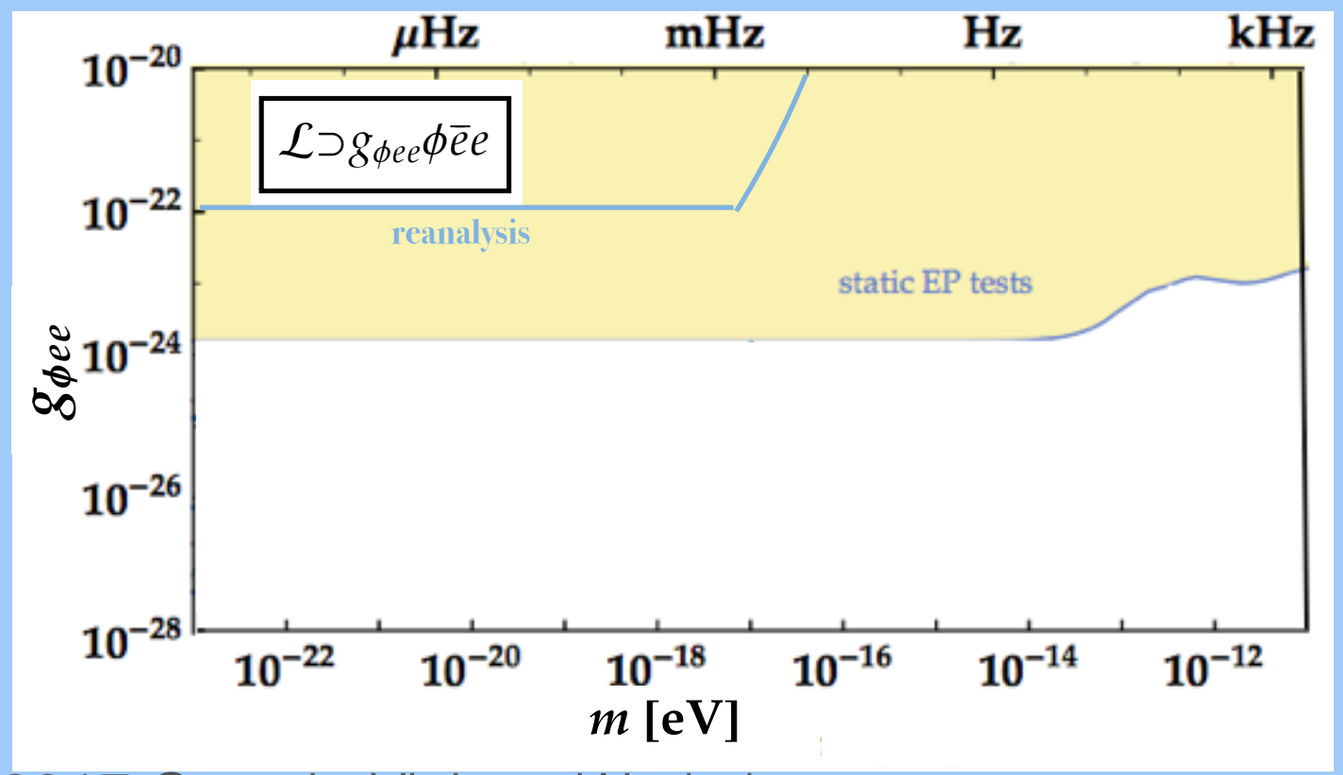


Results:


m_A [zeV]
0.05
0.1
0.2
0.5
1
2
5
10
20
X amplitude [zeV]
10
1
0.1
0.01
10^-8
2
5
10^-7
2
5
10^-6
2
5
10^-5
2
5
10^-4
Compton Freq [Hz]

Current Scalar and Vector limits





DM frequency means science is not at turntable frequency!

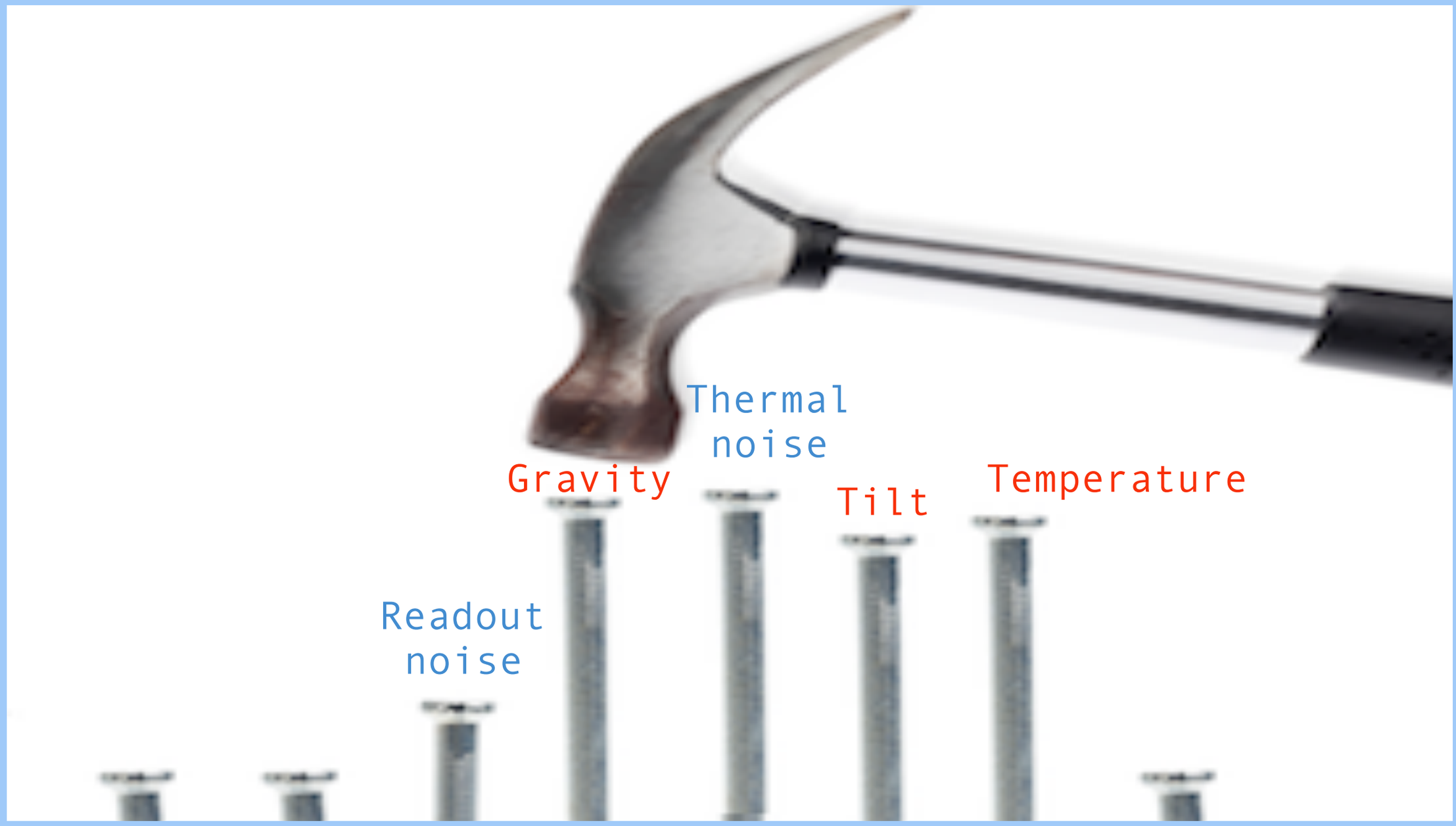
- Science signal triply modulated at TT, compton and sidereal
- Systematics are dominated by effects that come at the the turntable frequency

Table 2. Error budget for the lab-fixed Be-Ti differential accelerations. Corrections were applied for gravitational gradients and tilt, only upper limits were obtained on the magnetic and temperature effects. All uncertainties are $1\,\sigma$.

Uncertainty source	$\Delta a_{\mathrm{N,Be-Ti}}$ (10^{-15} m s^{-2})	$\Delta a_{\mathrm{W,Be-Ti}}$ (10^{-15} m s^{-2})
Statistical	3.3 ± 2.5	-2.4 ± 2.4
Gravity gradients	1.6 ± 0.2	0.3 ± 1.7
Tilt	1.2 ± 0.6	-0.2 ± 0.7
Magnetic	0 ± 0.3	0 ± 0.3
Temperature gradients	0 ± 1.7	0 ± 1.7

- Past experience proves sidereal signals have greatly reduced systematics

Japanese Proverb:
The nail that sticks out the farthest
gets hammered the hardest



Japanese Proverb:
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Key Improvements

$$\mathcal{P}_{\tau,\mathrm{th}}(f) = 4T\kappa/(2\pi f Q)$$

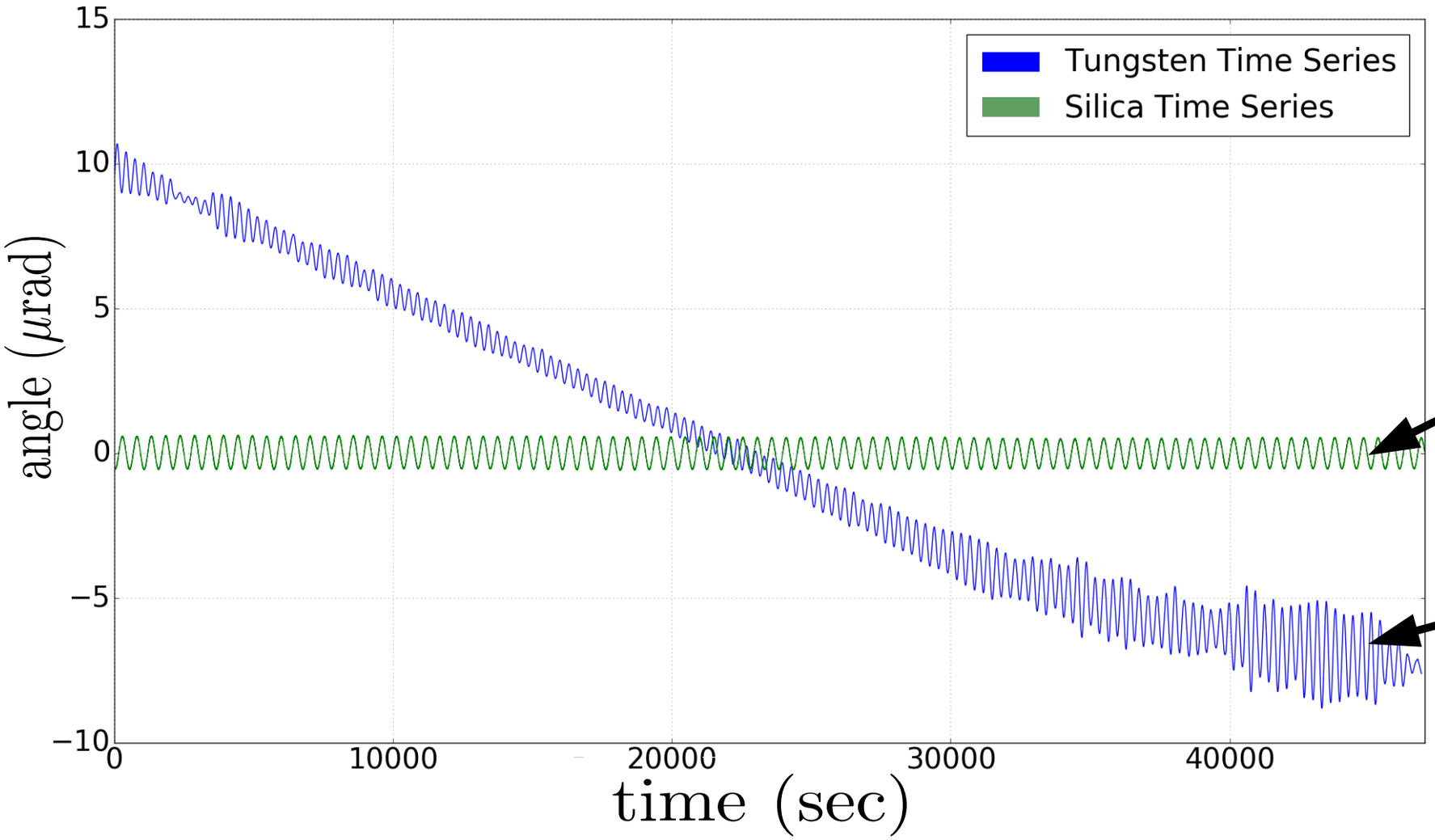
1. Ultra-low-noise suspension fibers

2. More sensitive twist-angle measurement

3. Higher performance turntables

4. Larger B-L composition dipole

1. Comparison of Fused Silica and Tungsten Fibers



~ 1 nrad/day drift!

~ 10,000 nrad/day

- Drifts are up to factor 10,000 better!
- Improves duty cycle and drift associated noise
- Less sensitive to temperature gradients

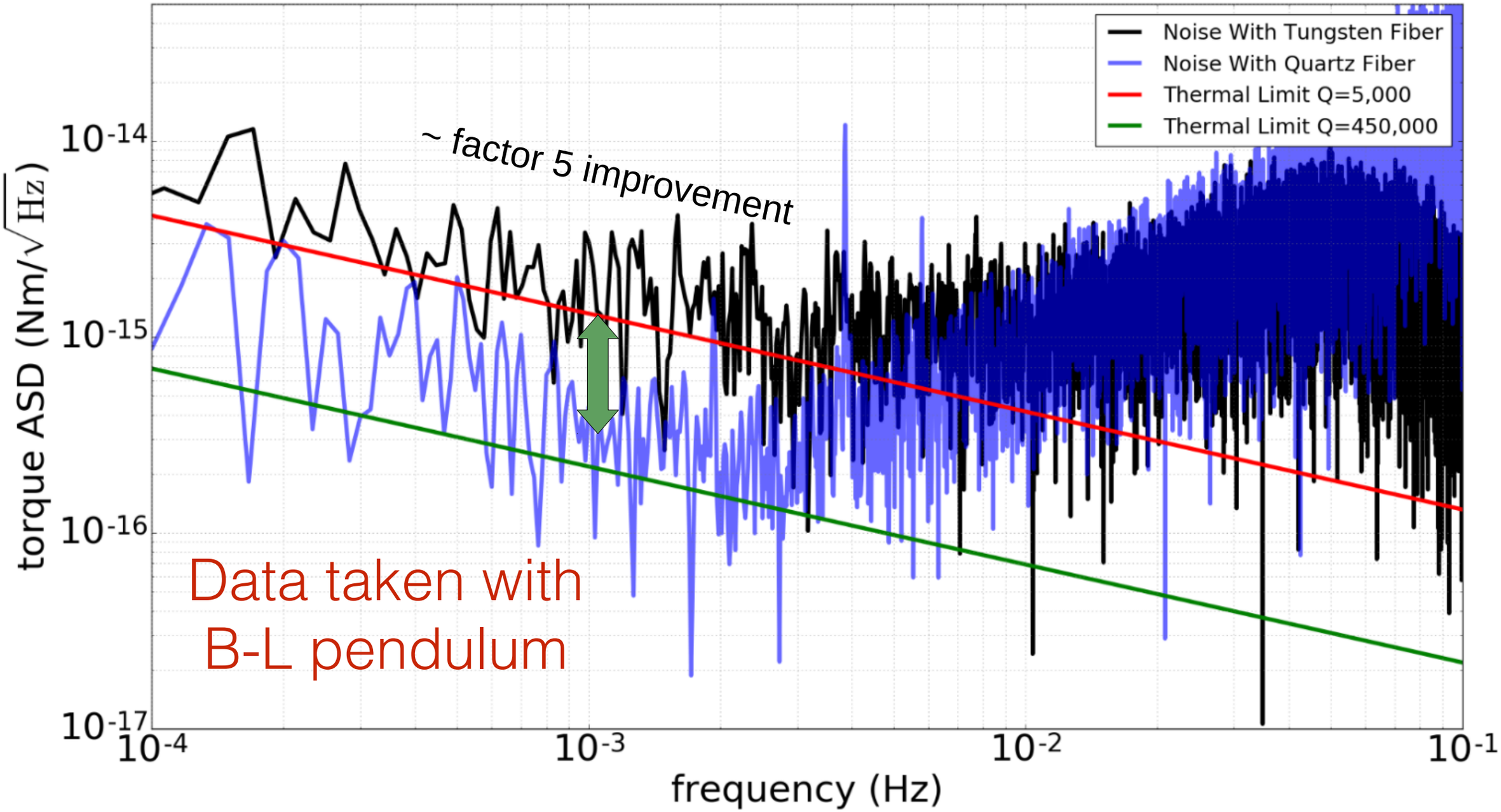
But fused silica is not conducting!

· Possibility of sacrificing dynamic range for angular readout sensitivity

Slide courtesy of Erik Shaw

Typical Noise Performance

$$\text{Tungsten } \sqrt{\kappa/Q} = 7 \times 10^{-7} \sqrt{\text{Nm}} \text{ and Silica} = 1.4 \times 10^{-7} \sqrt{\text{Nm}}$$

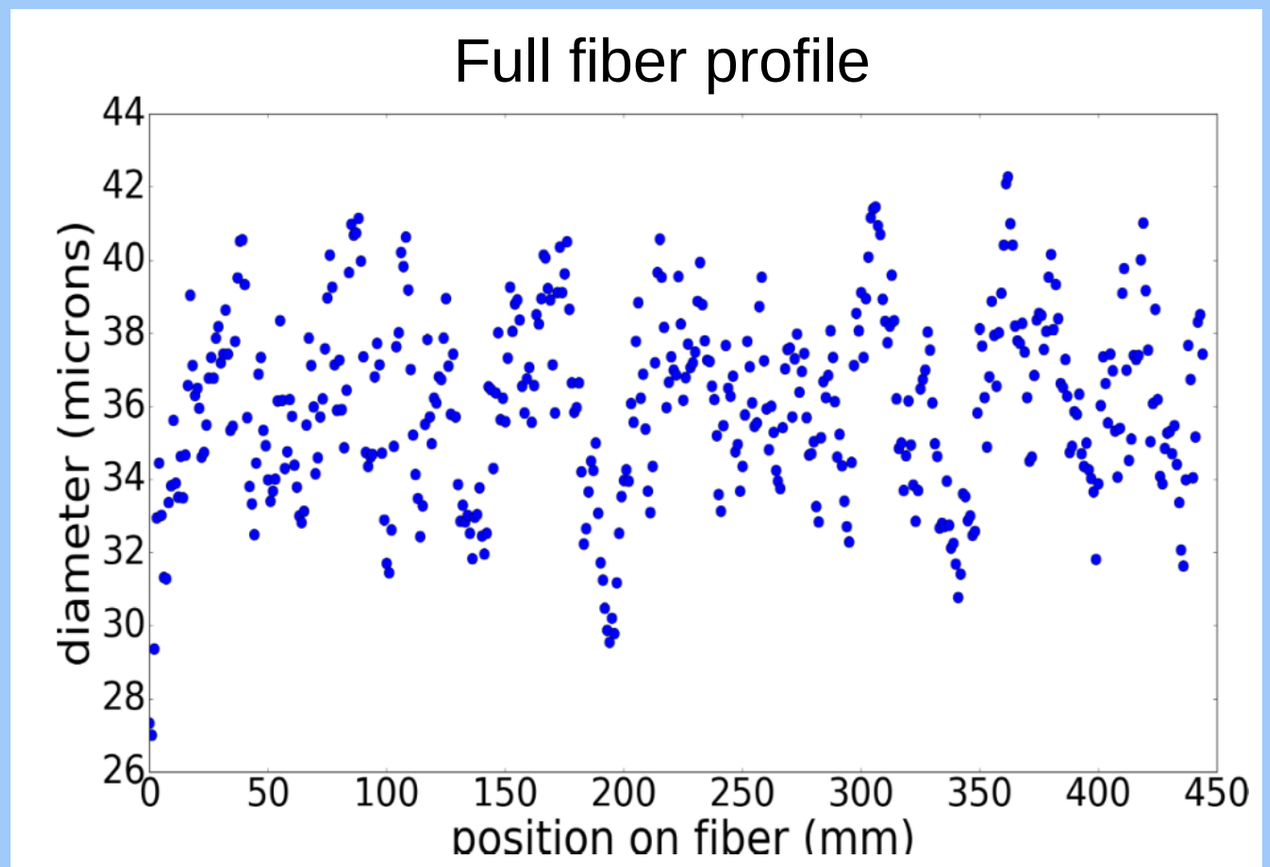


Now 1 day of clean data ~ 1 month of clean data with tungsten

$\Longrightarrow$ substantial statistical noise improvement

Slide courtesy of Erik Shaw

Lots of room for improvement remaining



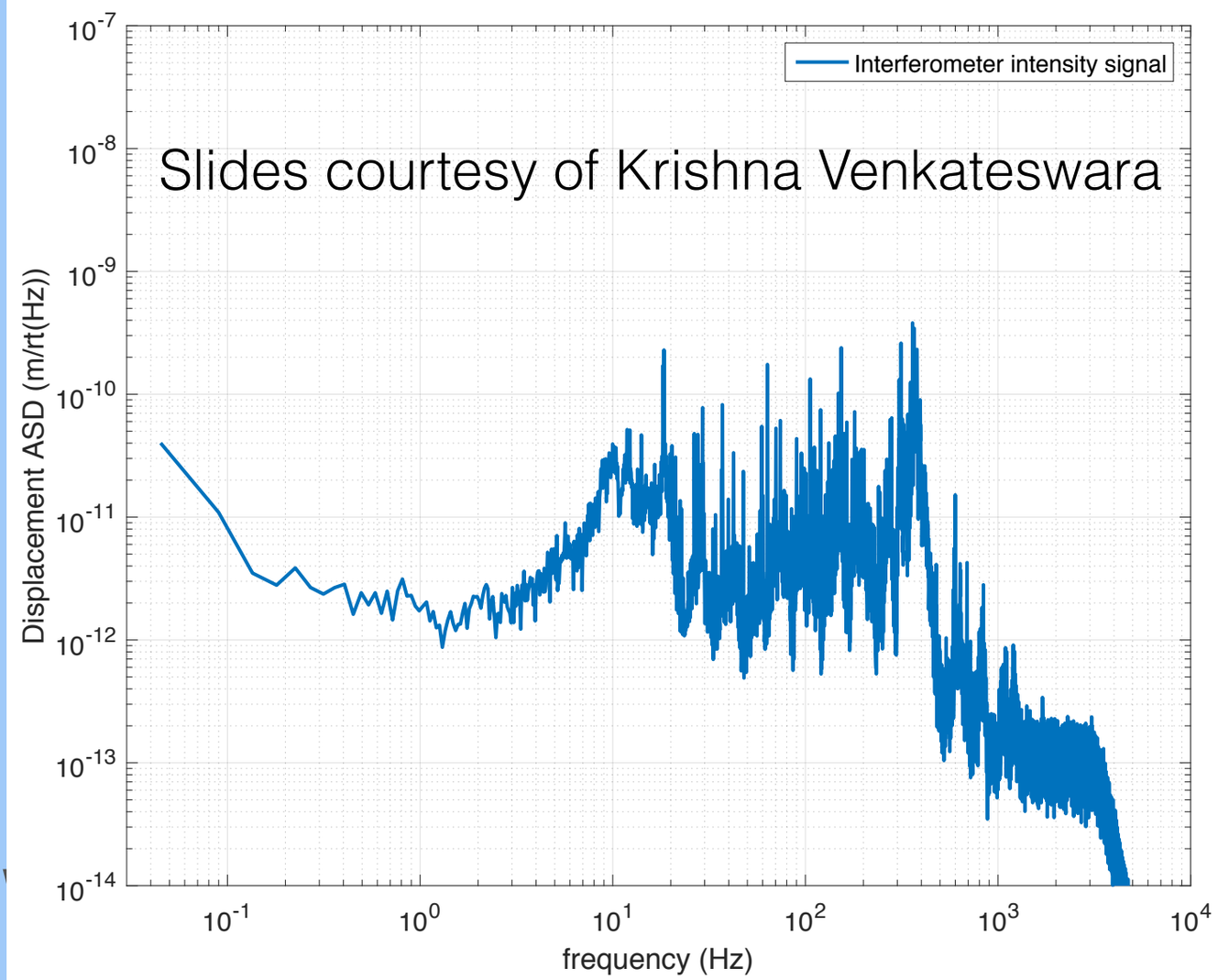
- thinner, more uniform fibers would greatly reduce kappa with same Q
- LIGO fibers have %-level uniformity
- kappa/Q improvement of 4 - 16 possible

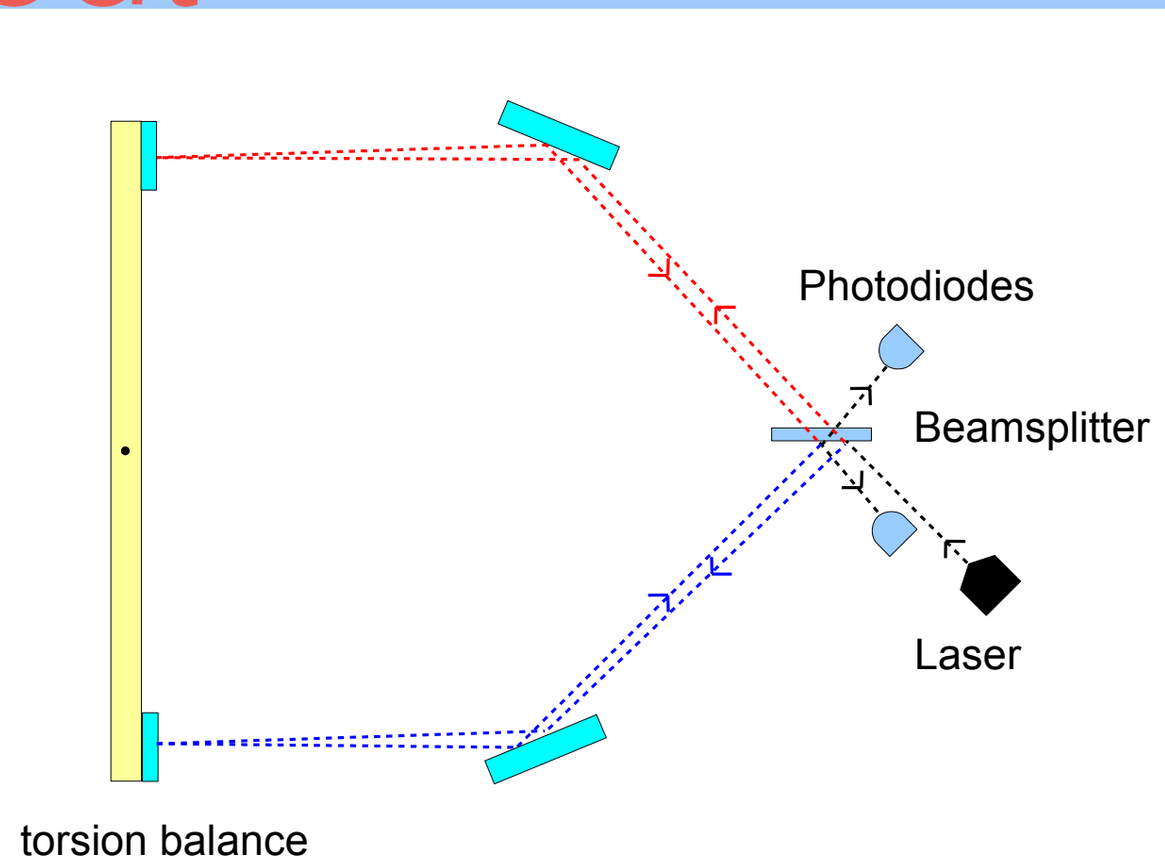
2. Angle readout improvements

- 10,000x smaller dynamic range required
- Potential for huge lever arm
  -> great angle resolution
- Testing interferometric readout systems

One Possible Interferometric Readout

- Preliminary test running in air

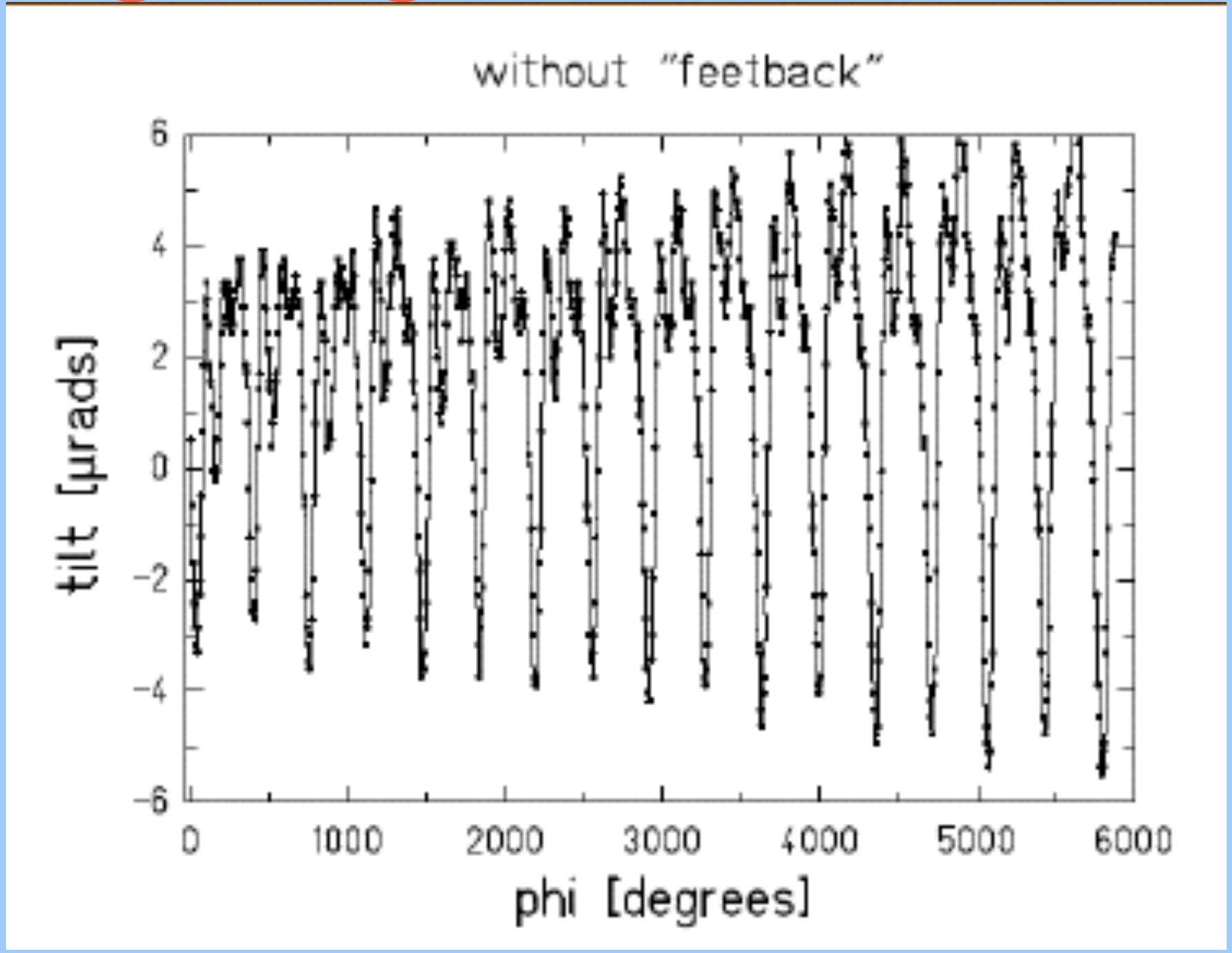




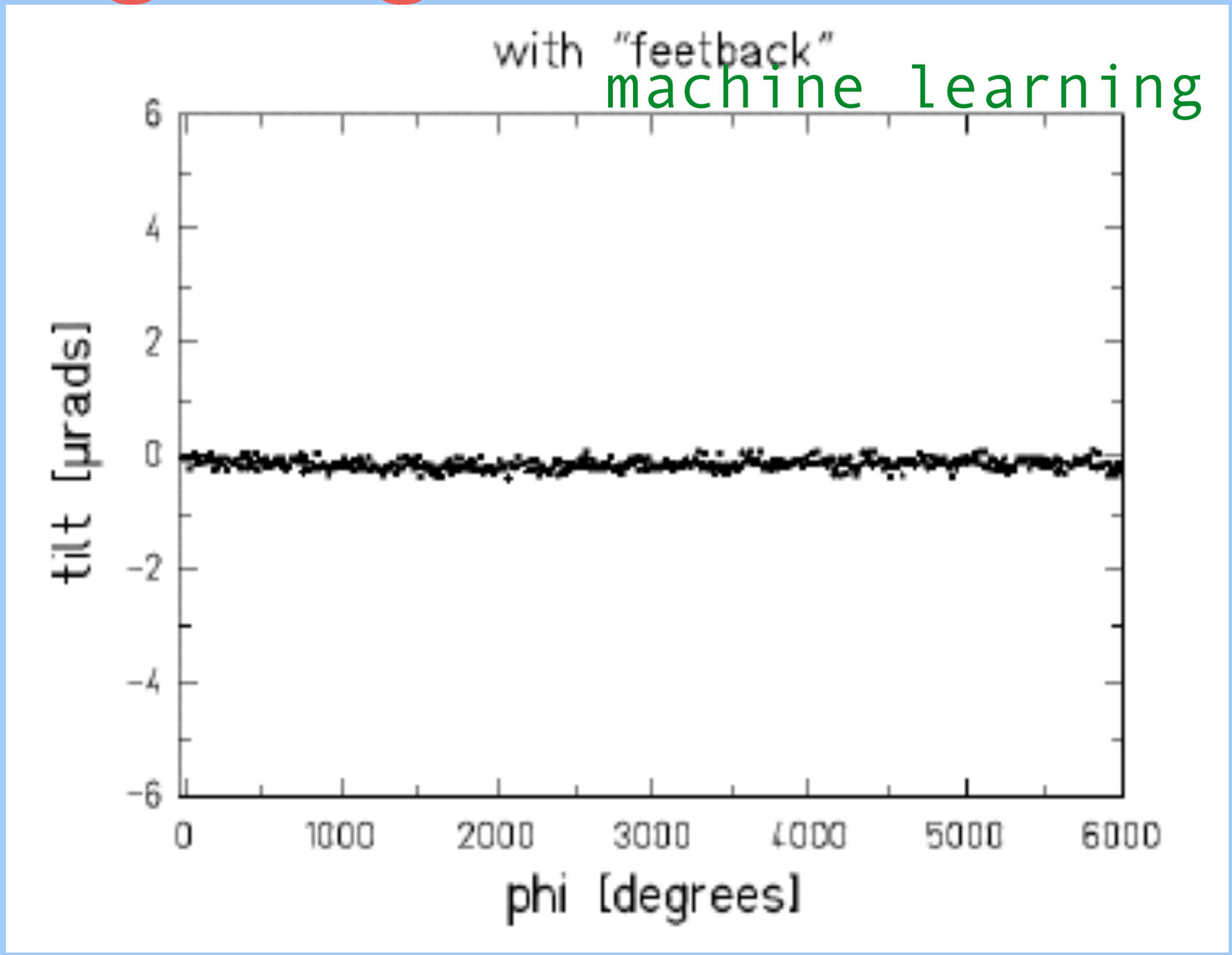
3. Turntable Improvements

- Necessary to take full advantage of lower noise
- Key requirements:
  - stability of rotation rate
  - alignment of rotation axis with local vertical
- May allow higher turntable frequencies (less 1/f noise)

Aligning Rotation Axis



Aligning Rotation Axis



Increase in B-L charge

- Be - Al charge difference: 0.036
- Be - PP charge difference: .127
- Main challenges
  - Gold Coatings
  - Thermal stability
  - Outgassing

Material	B-L
Beryllium	0.5548
Aluminum	0.5189
Polypropylene	0.4285

Estimated potential improvements

- B-L test can be improved by as much as 40x with better fibers and a potential 4x with Polypropylene test bodies

- Axion limit improved by as much as 80x with new fibers

Proposal for dedicated Axion and B-L DM experiments

Stage 1)

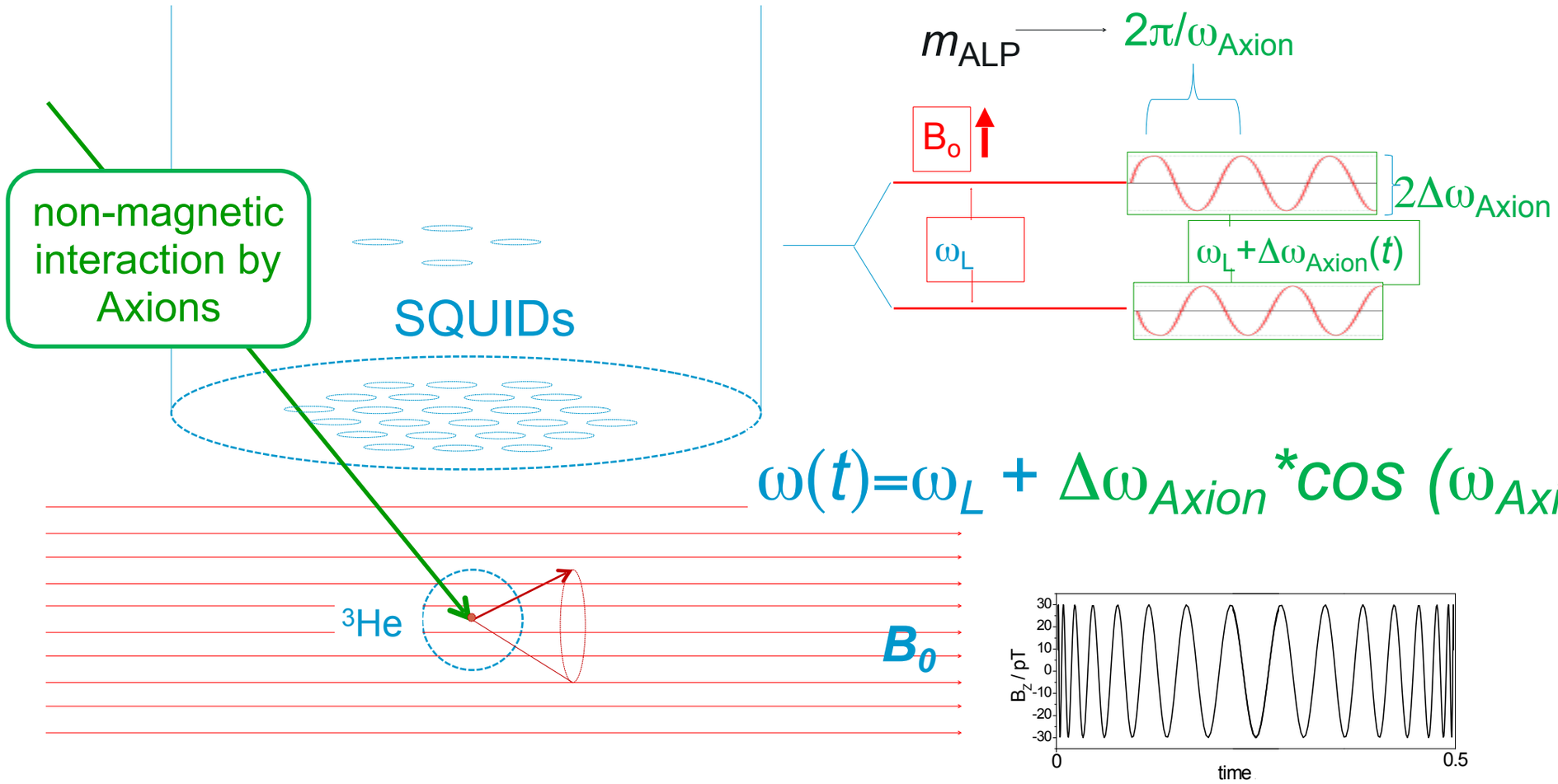
- Build dedicated fiber pulling set-up to optimize fused silica fibers
- Design, build and commission ultra-high sensitivity rotating balances at CENPA with B-L and spin pendulums
- 1 year of data taking

Stage 2)

- Move to shallow site at DUSEL site for 3 years of data taking

Side bands in Larmor Frequency Induced by Axions

non-magnetic interaction acts like an oscillating magnetic field $B_{\text{"Axion"}} = \frac{\Delta\omega_{\text{Axion}}}{\gamma_{\text{He}}}$



$$\omega(t)=\omega_L + \Delta\omega_{Axion} * cos\ (\omega_{Axion} * t)$$

P. Graham and S. Rajendran, PRD 2011, 2013

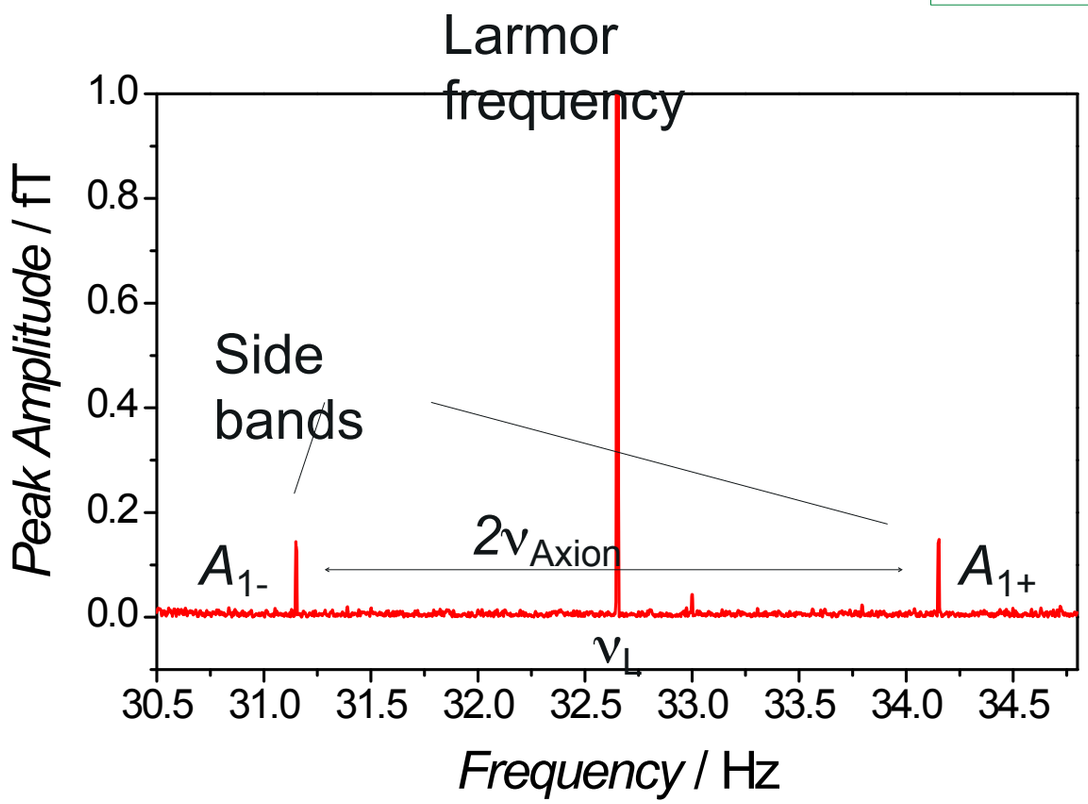
Experimental simulation at B_0 = 1 μT

Mimicking the axion by an oscillating magnetic field

$B_{\text{“Axion“}}$ = 1 nT ± 0.1 nT
$\nu_{\text{“Axion“}}$ = 1.5 Hz
A_0 = 12.6 fT

Averaging over 3h:

A_1 = 145 aT± 10 aT
ν_{Axion} = 1.5 Hz



The side bands are at well defined relative frequencies !

Food for thought: EP interferometer