Charlottesville, 13th Apr 2010

Test of the Equivalence Principle in the Laboratory

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Mass does not add up

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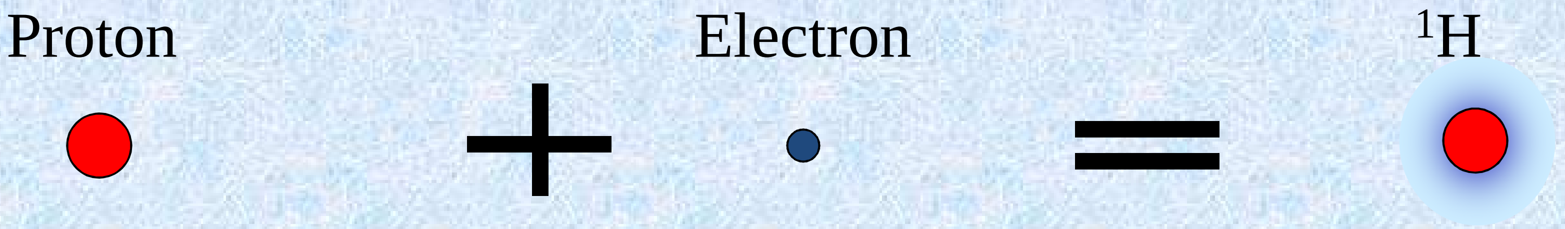
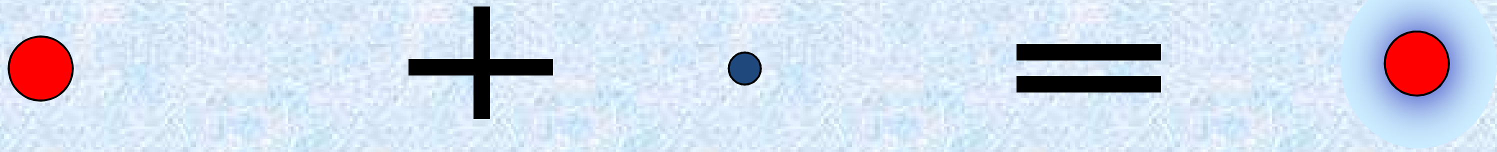


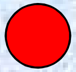
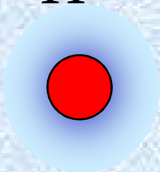
Mass does not add up

Proton + Electron = ^{1}H



$$938\,272\,013 \text{ eV}/c^2 + 510\,999 \text{ eV}/c^2 \neq 938\,782\,999 \text{ eV}/c^2$$

Mass does not add up

Proton		Electron		^{1}H
	+		=	
938 272 013 eV/c^2	+	510 999 eV/c^2	≠	938 782 999 eV/c^2
938 272 013 eV /c^2	+	510 999 eV/c^2	=	938 783 012 eV/c^2
				13.6 eV/c^2

Mass defect = binding Energy

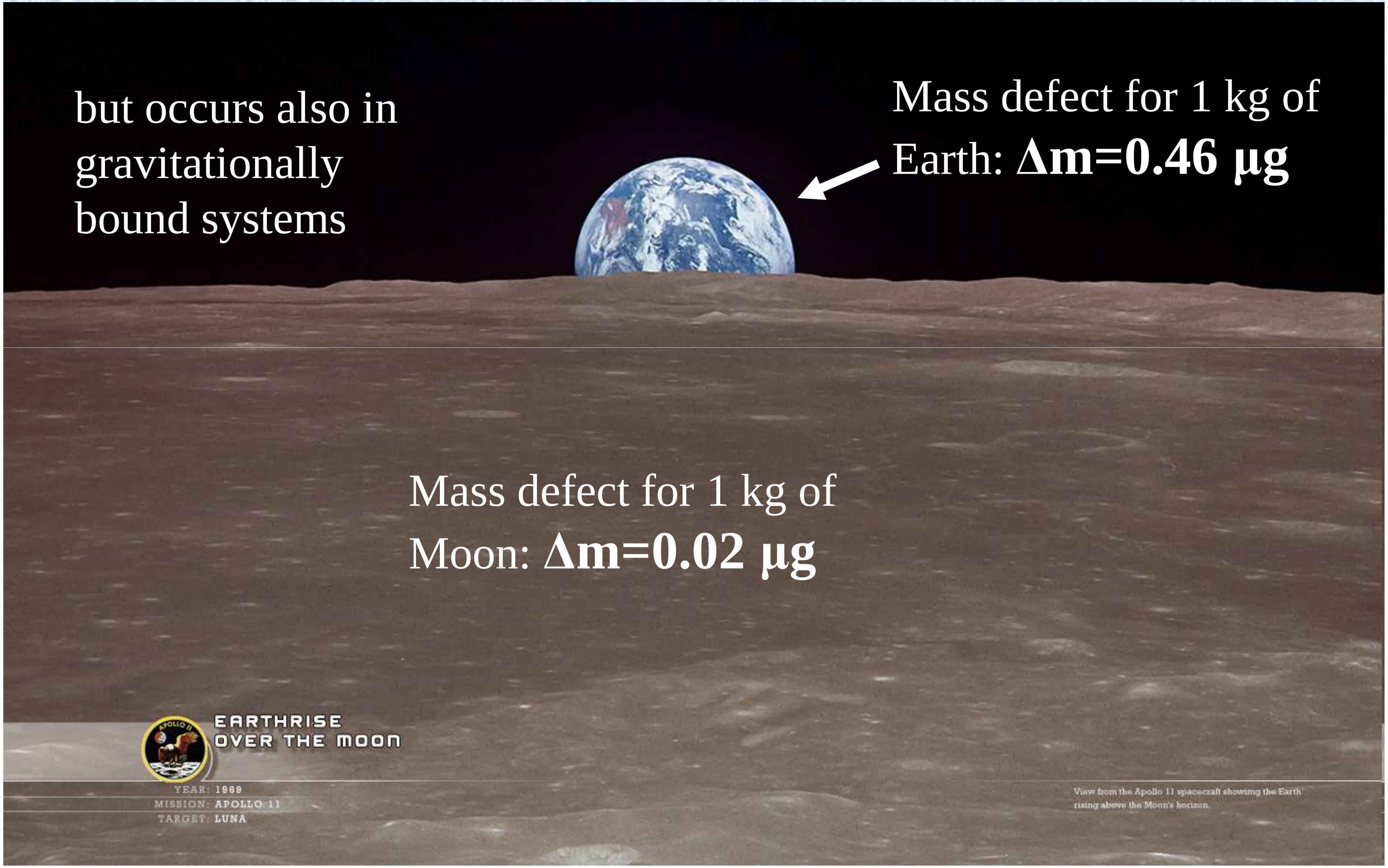
Binding Energy = $\Delta E_{pot} - \Delta E_{kin}$

The non-linearity is rather small

but occurs also in gravitationally bound systems

Mass defect for 1 kg of Earth: **Δm=0.46 µg**

Mass defect for 1 kg of Moon: **Δm=0.02 µg**



The mass of an object

$$m = \sum m_c + \sum Ekin - \sum Epot$$

Newton's Principia (1689)

Newton's 2nd Law

$$F_i = m_i\, a$$

Gravitational Law

$$F_G = G\, m_{g1}\, m_{g2} / r^2$$

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Equivalence Principle (EP): $m_i = m_g$

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Equivalence Principle (EP): $m_i = m_g$

Is the Equivalence Principle valid for all contributions to the mass?

Newton's Principia (1689)

Newton's 2nd Law

$$F_i = m_i\, a$$

Gravitational Law

$$F_G = G\, m_{g1}\, m_{g2} / r^2$$

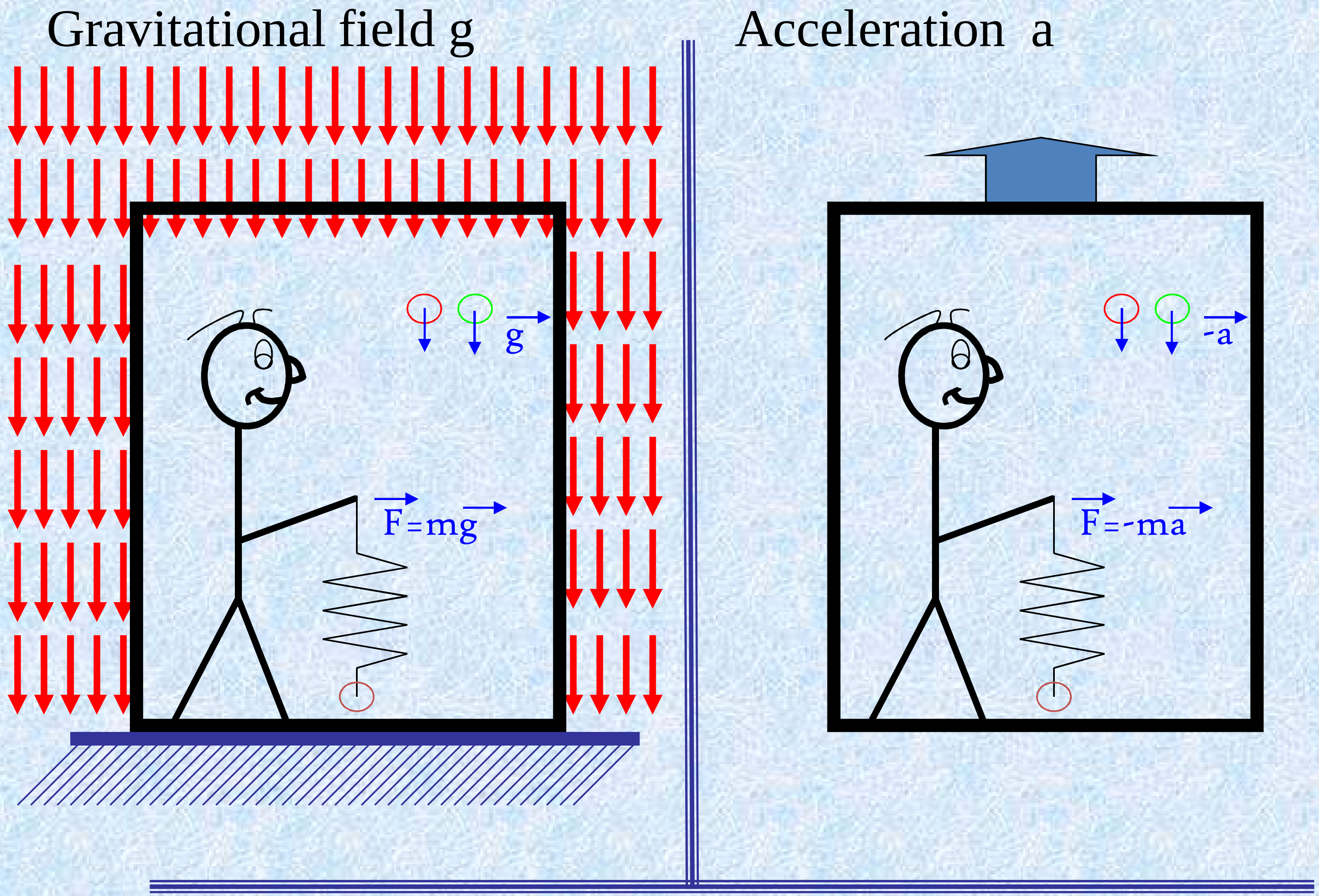
Equivalence Principle (EP): $m_i = m_g$

Is the Equivalence Principle valid for all contributions to the mass?

Weak Equivalence Principle: Gravitational binding energy is excluded.

Strong Equivalence Principle: Includes all 4 fundamental interactions.

In General Relativity



Inertial mass = gravitational mass, $m_I = m_G$ for all bodies

The known unknowns

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- GR is not a quantum theory.

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- Cosmological constant problem.

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- Is there another force (5^{th} force)?
- …

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The unknown unknowns

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- …

EP-Tests provide a big bang for the buck!

Searching for new interactions

$$V(r) = \alpha G \left(\frac{q_1}{\mu_1}\right)\left(\frac{q_2}{\mu_2}\right) \frac{m_1 m_2}{r_{12}} e^{-r_{12}/\lambda}$$

Strength relative to gravity

Source

Test mass

Interaction range

Searching for new interactions

$$V(r) = \alpha G \underbrace{\left(\frac{q_1}{\mu_1}\right)}_{\text{Source}} \underbrace{\left(\frac{q_2}{\mu_2}\right)}_{\text{Test mass}} \frac{m_1 m_2}{r_{12}} e^{-r_{12}/\lambda}$$

Strength relative to gravity (α)

Source

Test mass

Interaction range (λ)

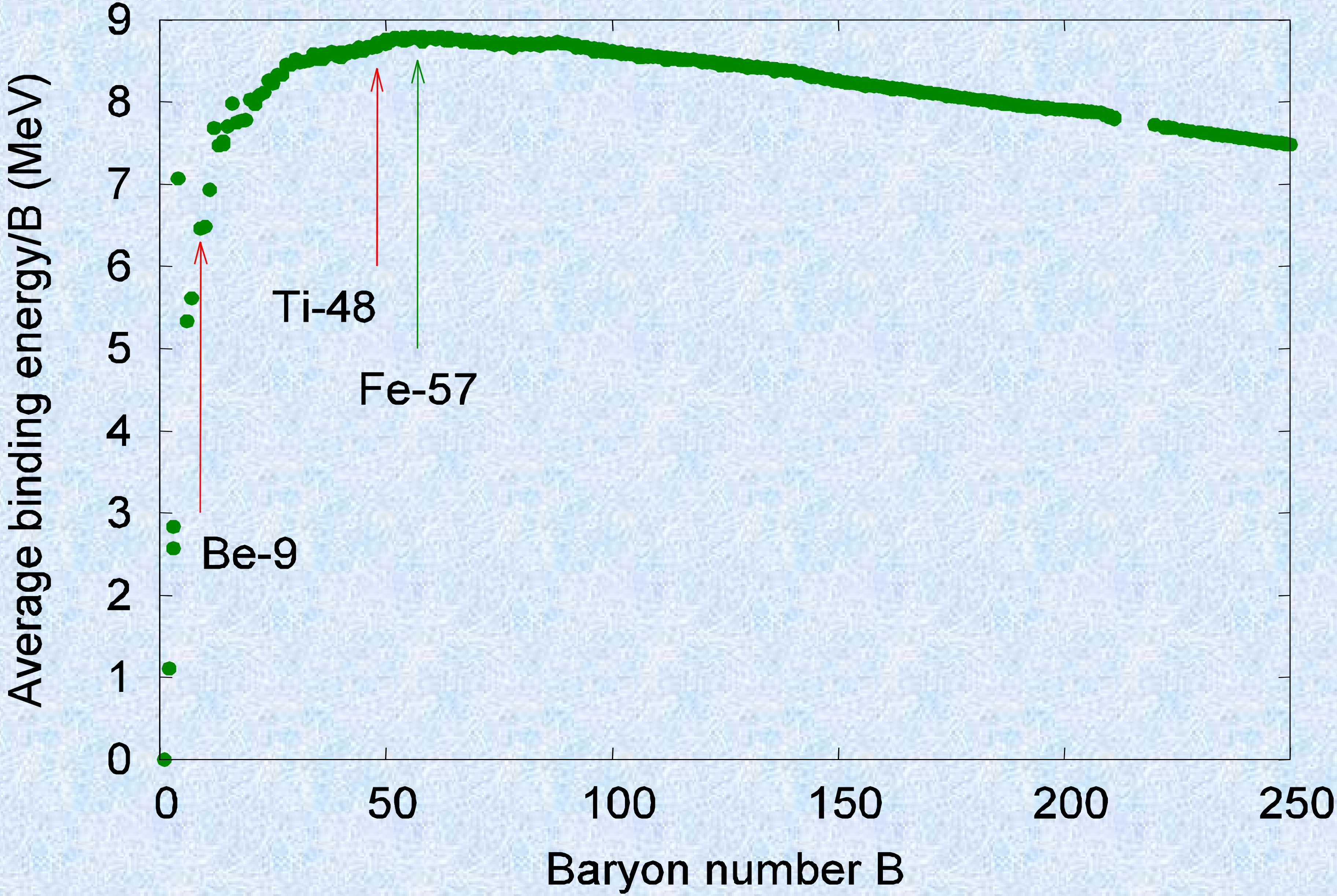
Assumed charge	**Be q/μ**	**Ti q/μ**	**Al q/μ**	**Be-Ti ($\times10^{-2}$)**	**Be-Al ($\times10^{-2}$)**
N	0.554 80	0.541 47	0.518 87	1.33	3.59
Z	0.443 84	0.459 61	0.481 81	-1.58	-3.80

and any linear combinations: $q(\Psi) = Z \cos\Psi + N \sin\Psi$

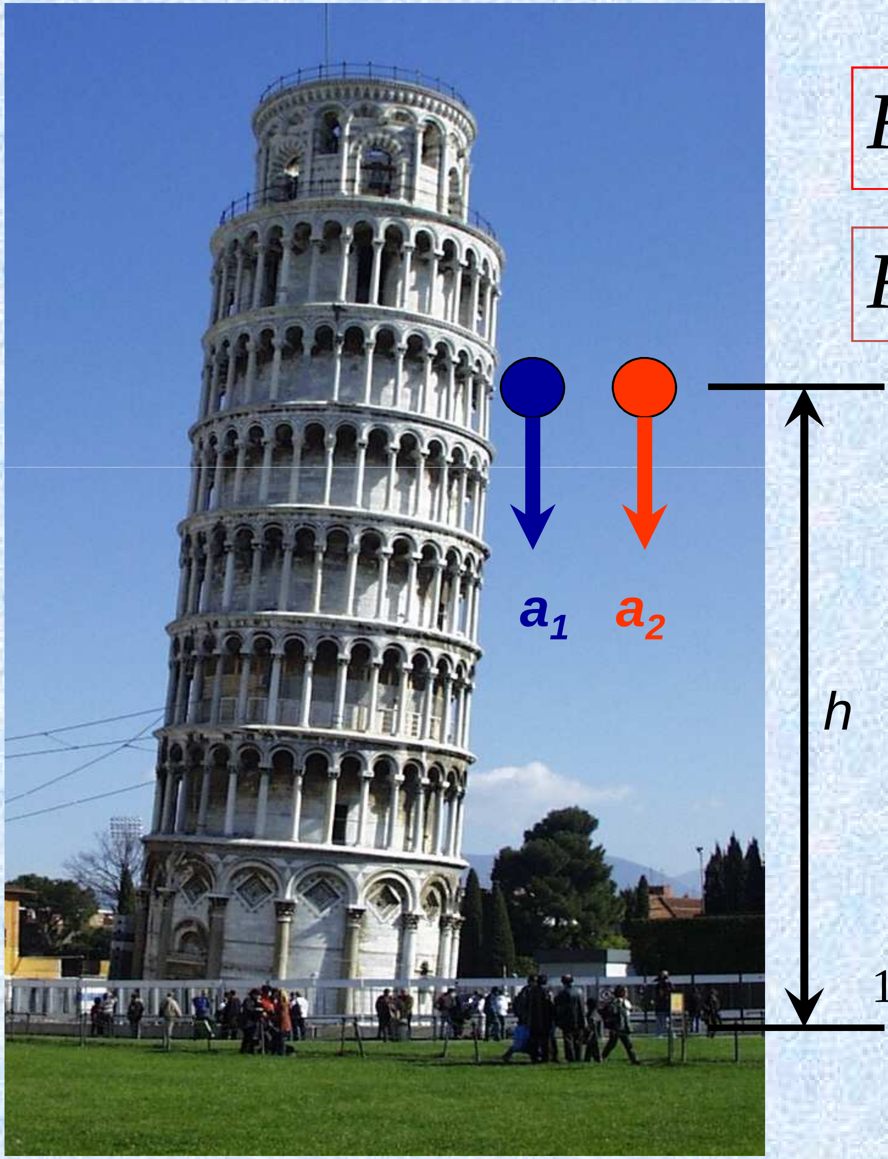
q/μ

	Mass (u)	q=B	q/μ
$^{1}_{1}p$	1.007 3	1	0.992 8
$^{1}_{0}n$	1.008 7	1	0.991 4
$^{9}_{4}Be$	9.101 2	9	0.998 7
$^{48}_{22}Ti$	47.947 9	48	1.001 1

B/μ varies, because



1st Tests of the Equivalence Principle



$$F = m_G g$$

$$F = m_I a$$

$$a = \frac{m_G}{m_I} g$$

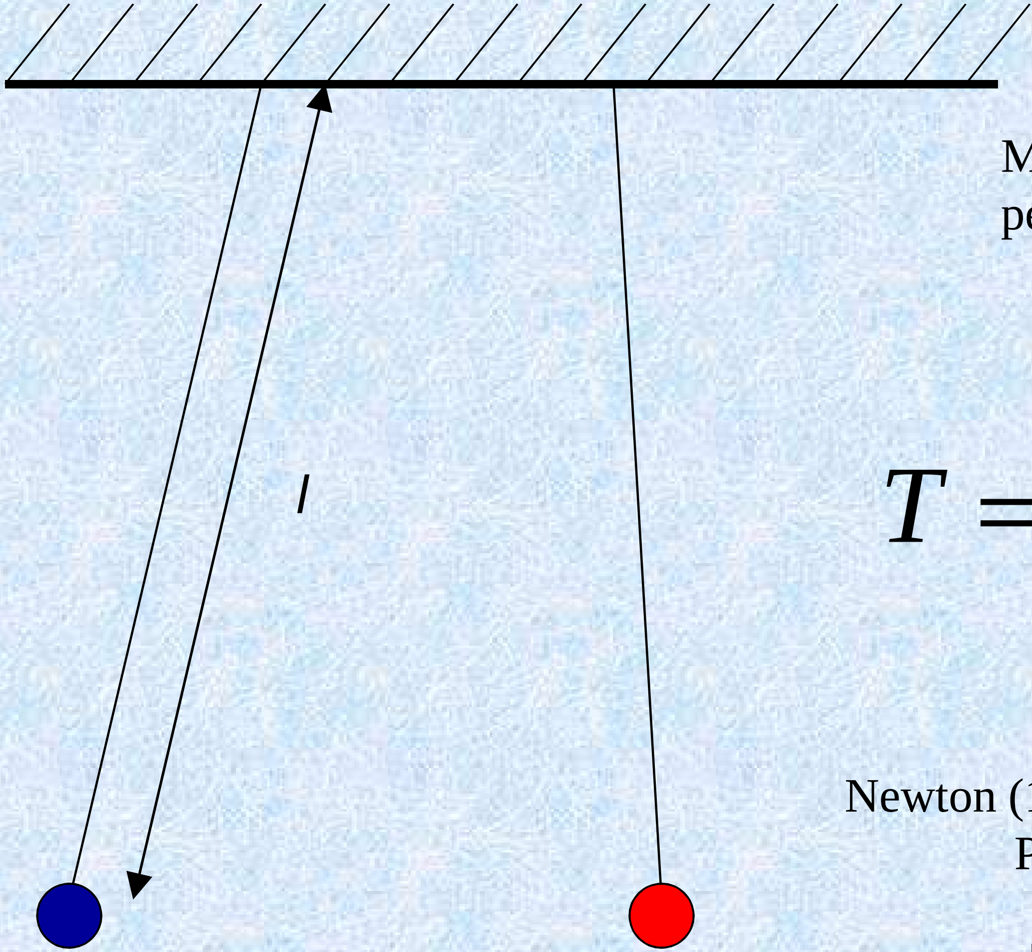
Time t to fall from h:

$$t = \sqrt{\frac{2h}{{m_G}/{m_I}\, g}}$$

1600 Galileo:

$$\eta = \frac{a_1 - a_2}{\tfrac{1}{2}(a_1 + a_2)} \approx 0.1$$

2nd Generation Tests



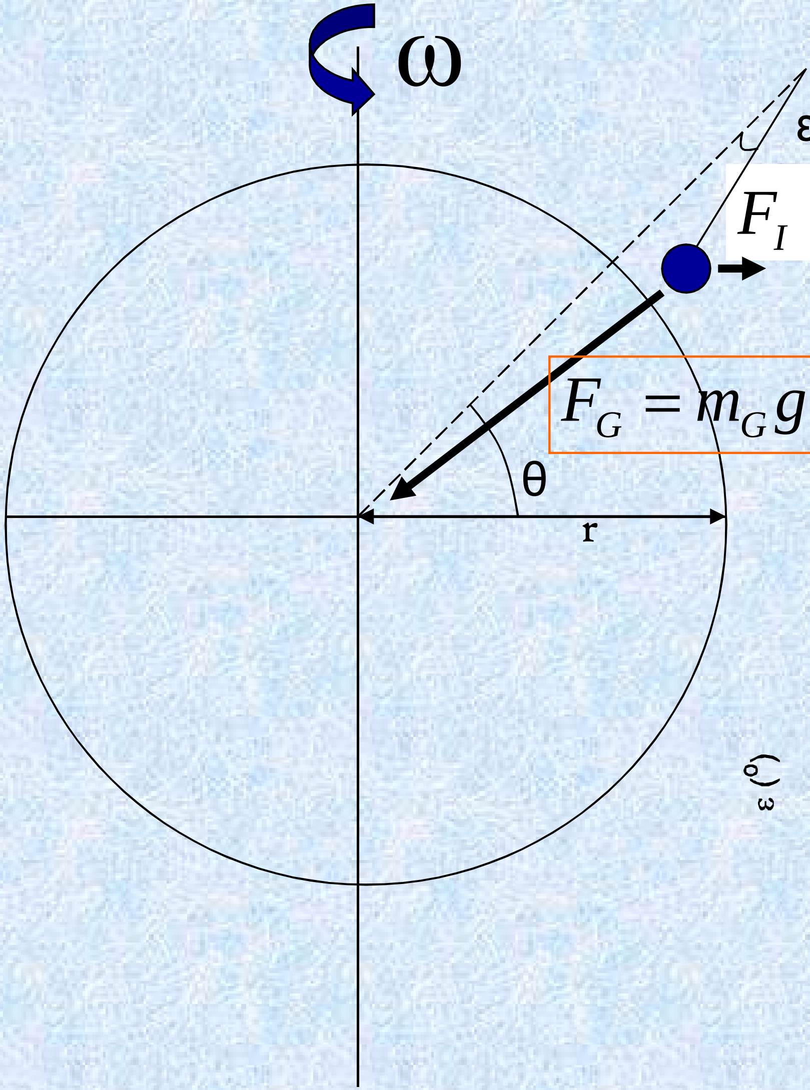
Measurement of the swing periods of pendula:

$$T = 2\pi \sqrt{\frac{L}{g} \frac{m_I}{m_G}}$$

Newton (1686), Bessel (1830), Potter (1923)

$$\eta \approx 2x10^{-5}$$

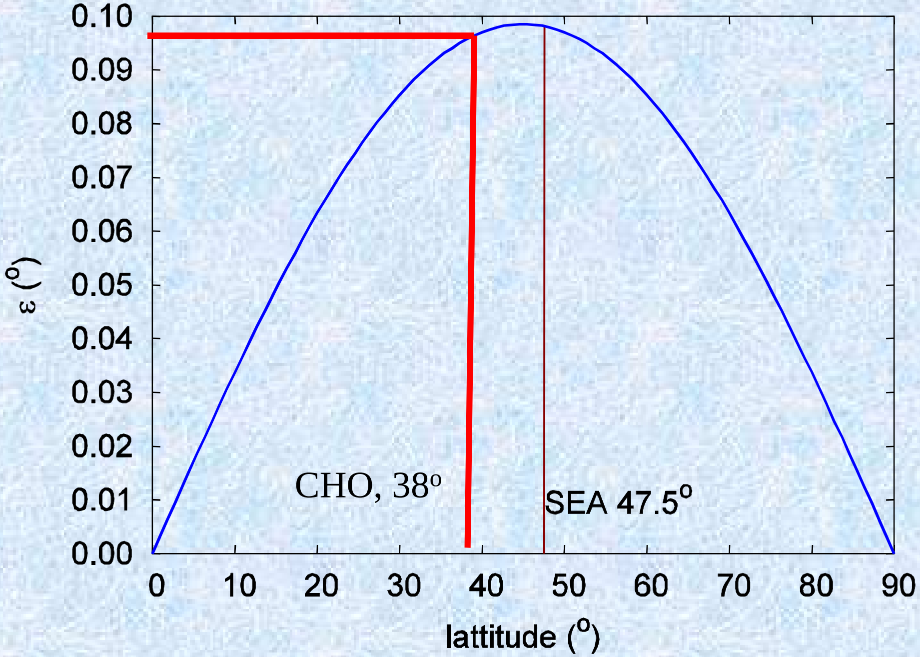
Eötvös Experiments



$$F_I = m_I \omega^2 r \cos\theta$$

$$F_G = m_G g$$

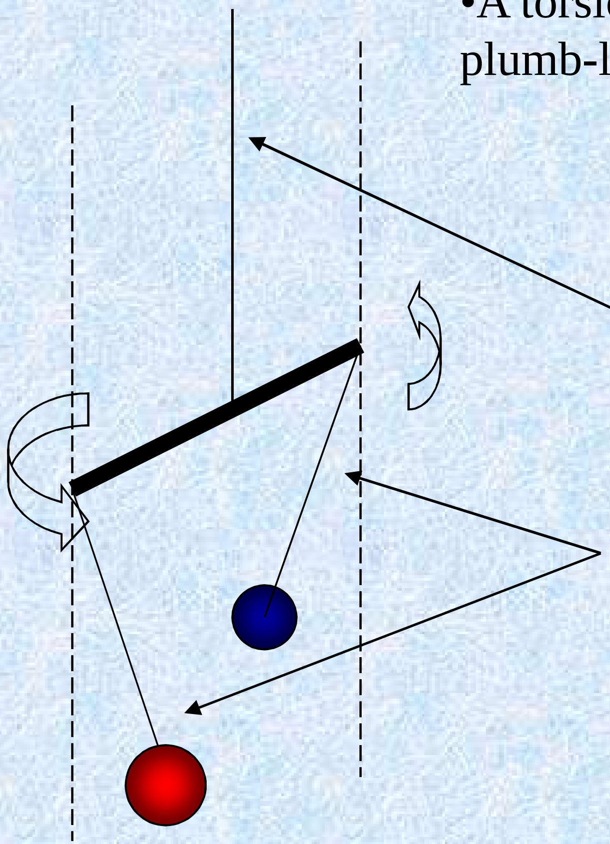
$$\varepsilon = \frac{m_I}{m_G}\frac{\omega^2 r}{2g}\sin(2\theta)$$



The torsion balance

• A violation of the EP would yield to different plumb-line for different materials.

•A torsion balance can be used to measure the difference in plumb-lines:



Torsion fiber hangs like the average plumb line.

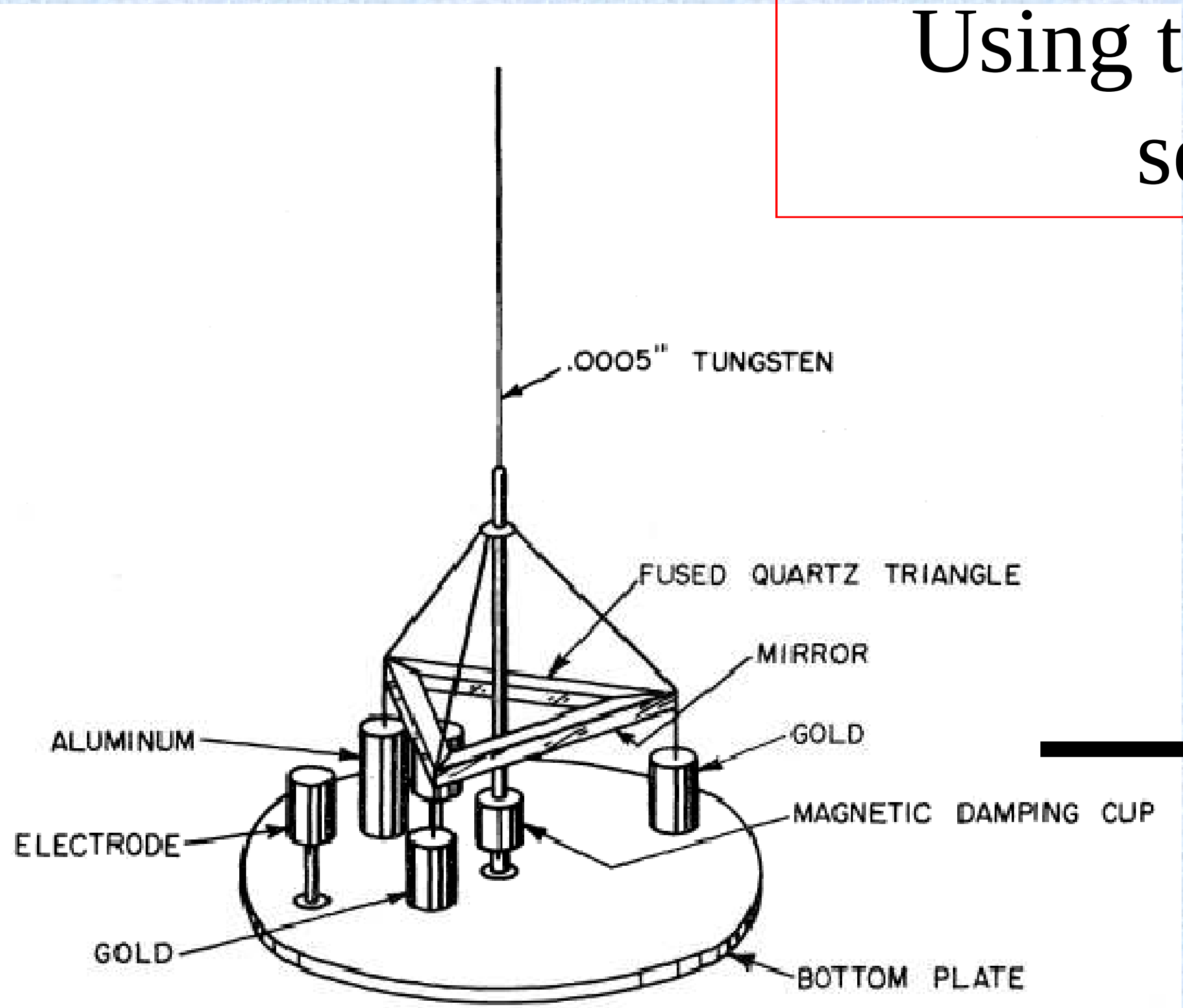
Difference in plumb lines produces a torque on the beam.

-> twist in the fiber

Eötvös (1922) $\eta \approx 5x10^{-9}$

Dicke's idea

Using the Sun as a source

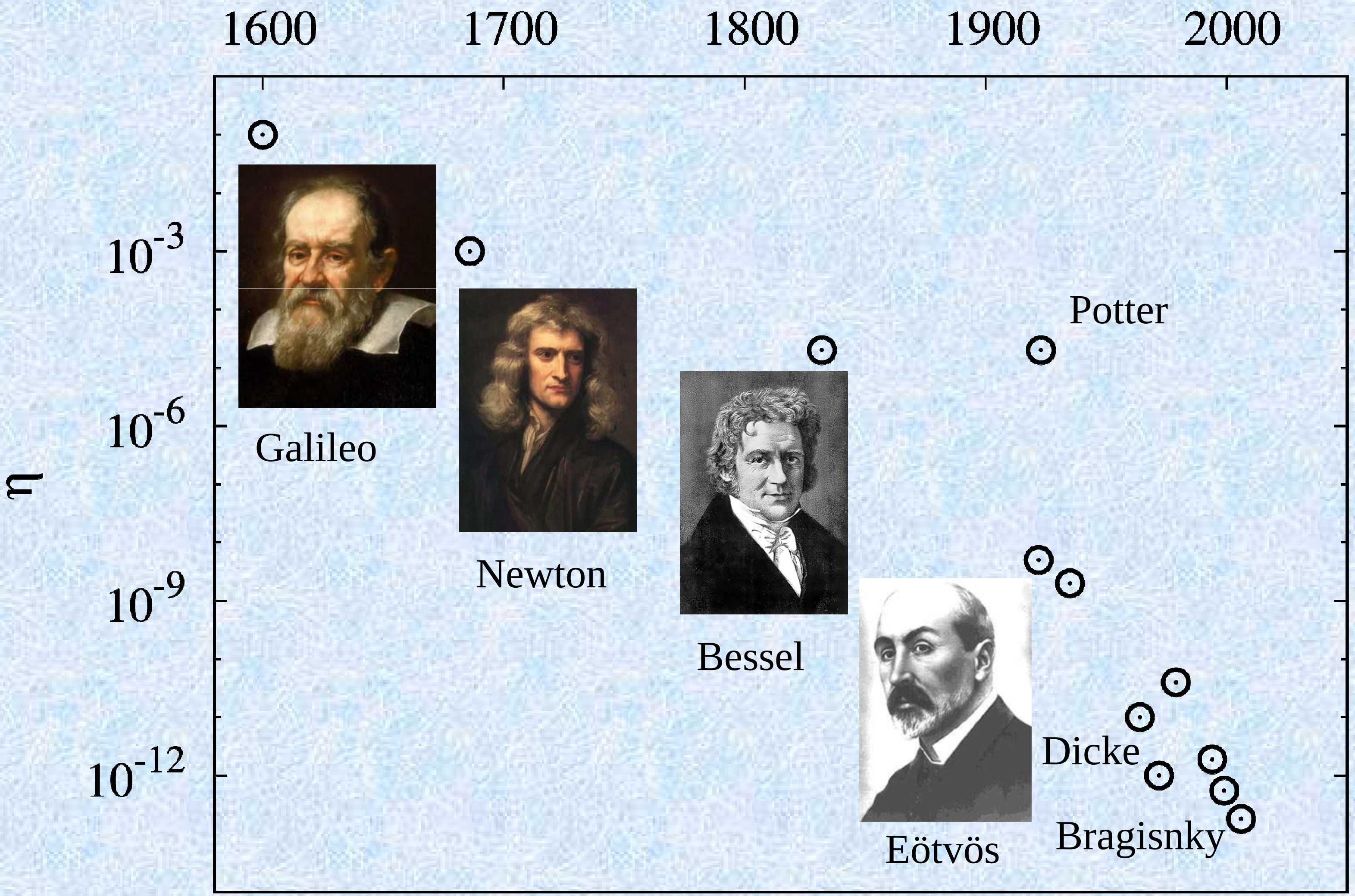


Sun

$$\eta \approx 1x10^{-11}$$

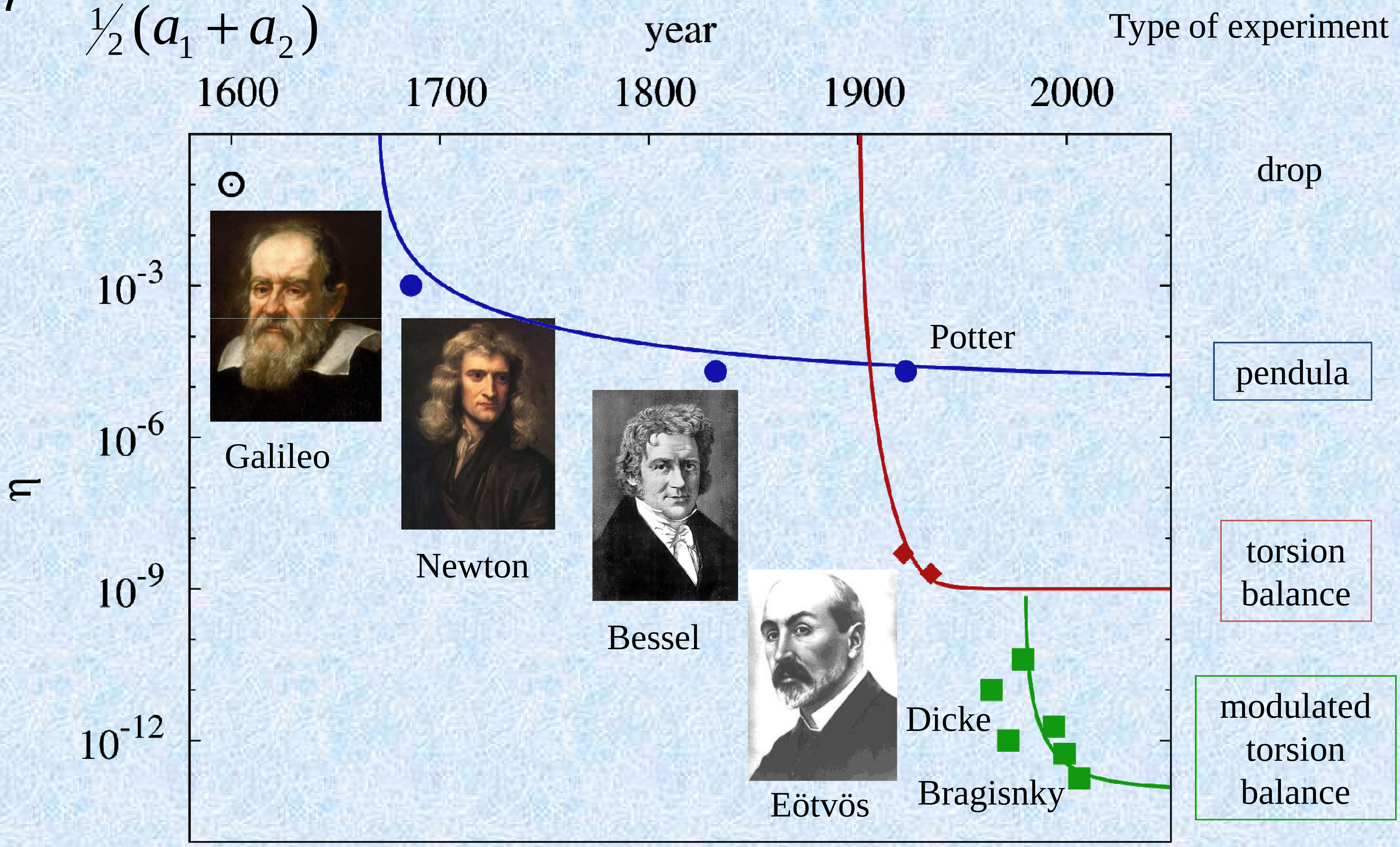
Historical overview

$$\eta = \frac{|a_1 - a_2|}{\frac{1}{2}(a_1 + a_2)}$$

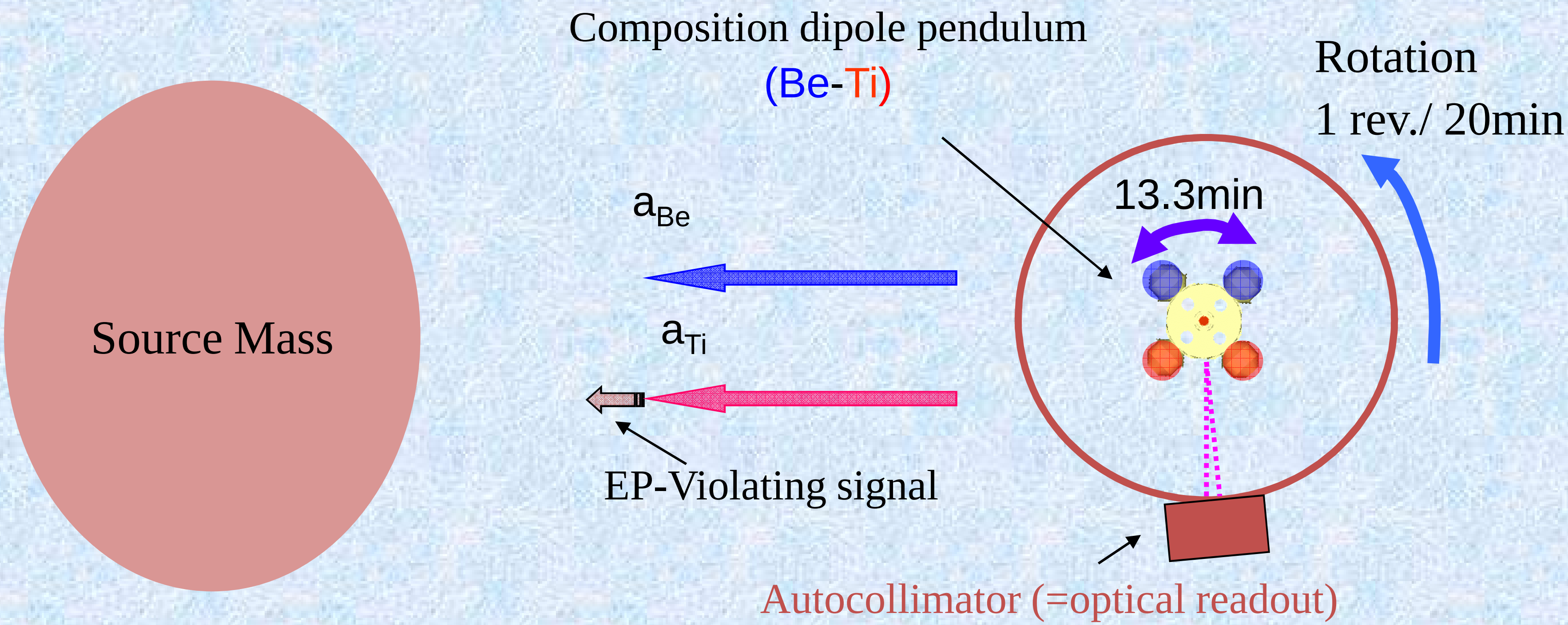


Historical overview

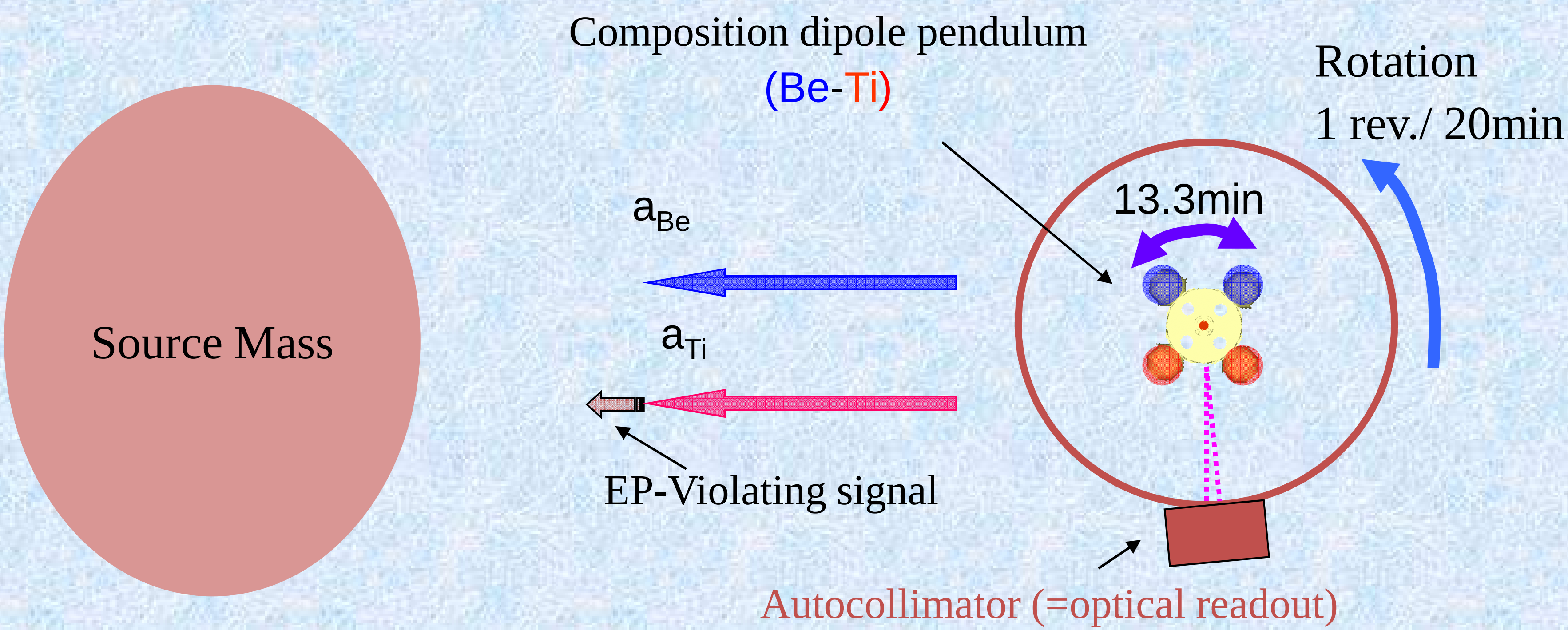
$$\eta = \frac{|a_1 - a_2|}{\frac{1}{2}(a_1 + a_2)}$$



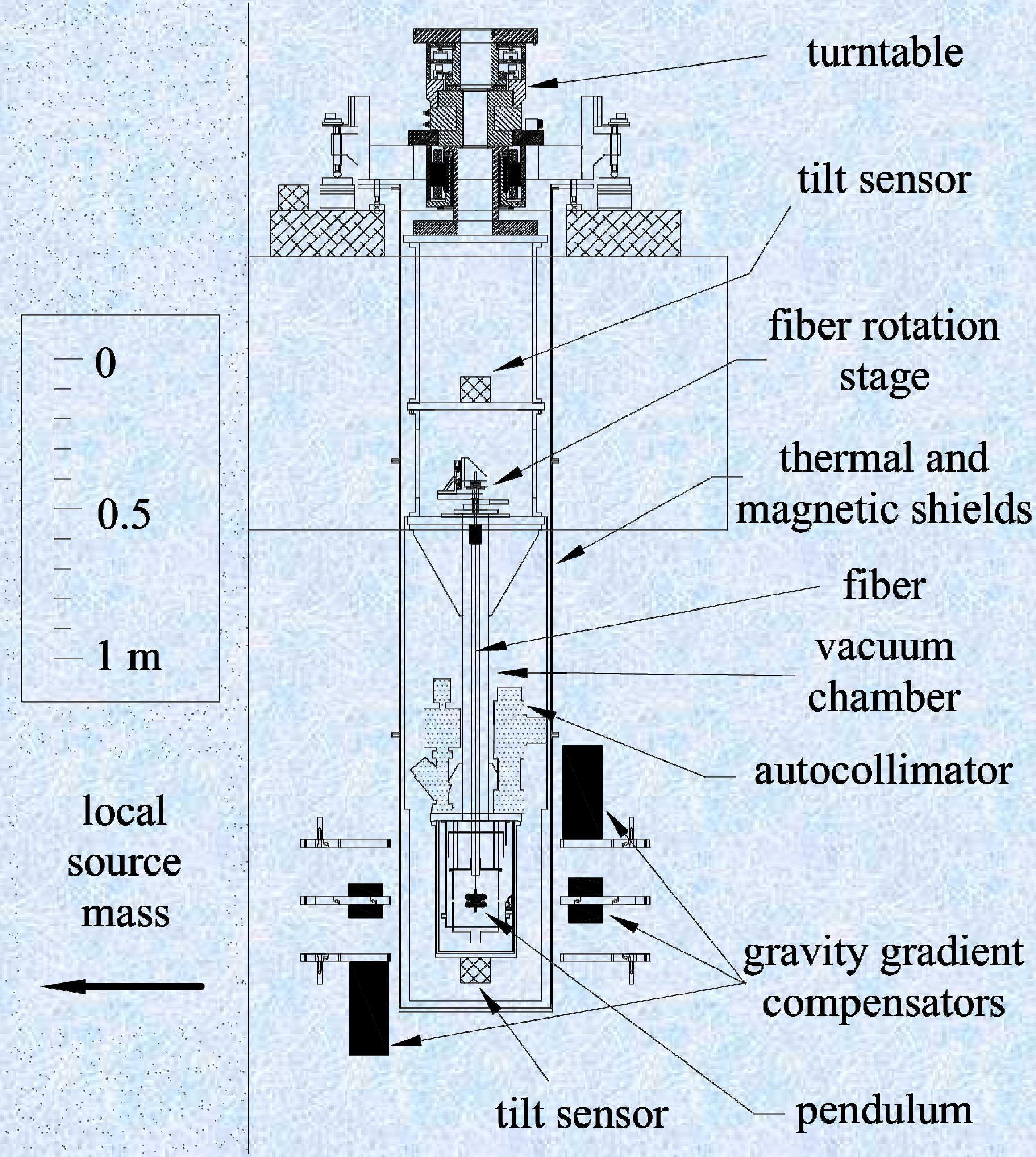
Principle of our experiment

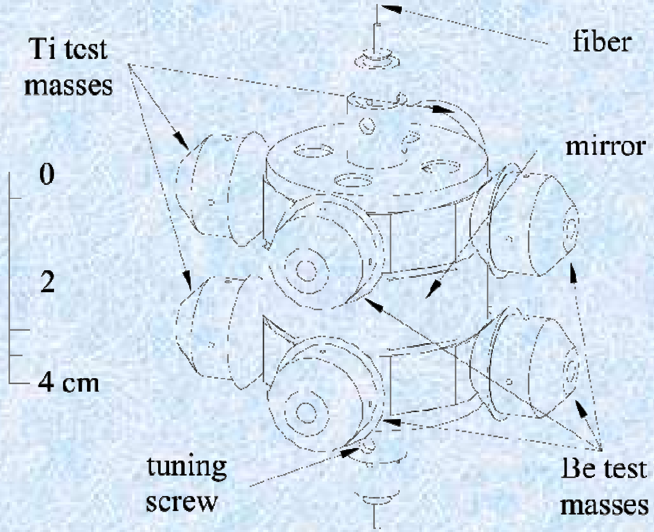


Principle of our experiment

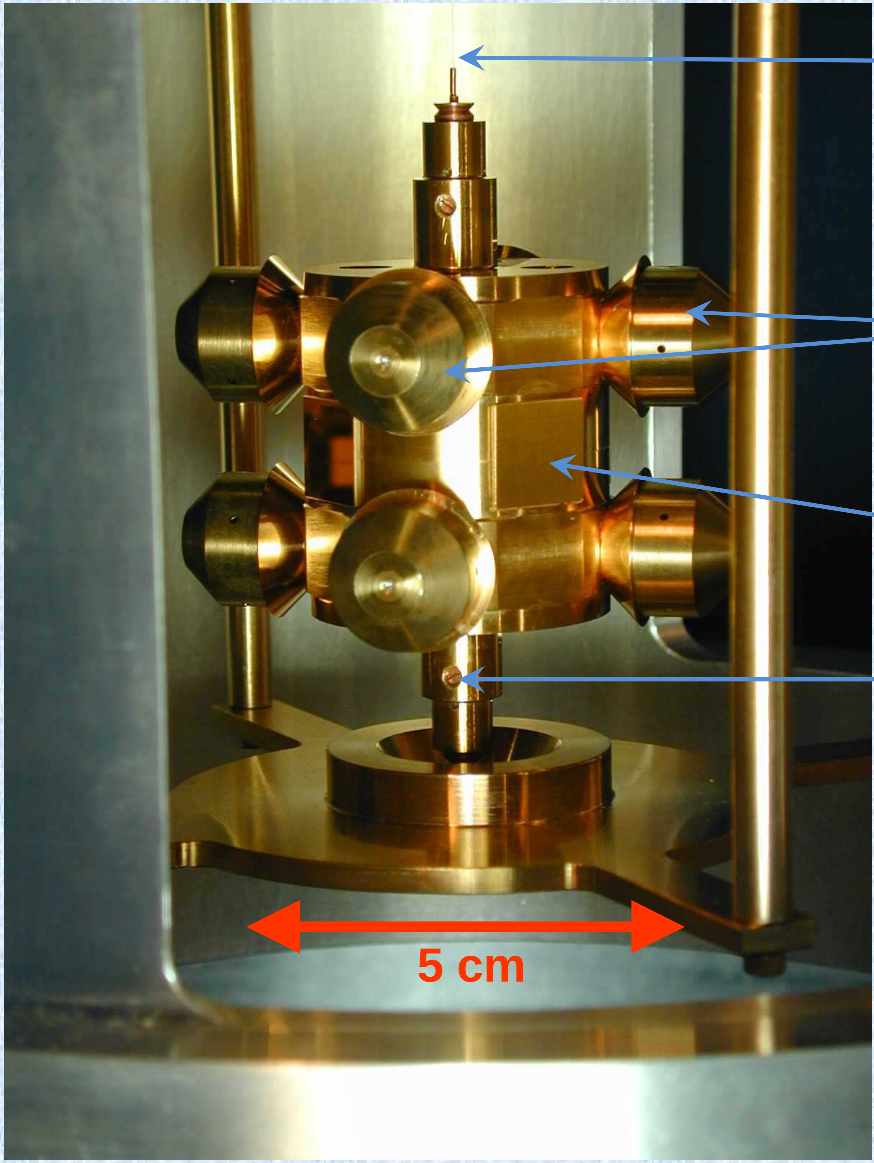


source mass	λ (m)	horizontal acc. (ms^{-2})	
local masses (hill)	1 - 10^4	< 7×10^{-5}	Northwest
entire earth	10^6 - 10^7	1.7×10^{-3}	North
Sun	10^{11} - ∞	5.9×10^{-3}	modulated
Milky Way (incl. DM)	10^{20} - ∞	1.9×10^{-10}	modulated


turntable
tilt sensor
fiber rotation stage
thermal and magnetic shields
fiber
vacuum chamber
autocollimator
gravity gradient compensators
tilt sensor
pendulum
0
0.5
1 m
local source mass


Ti test masses
fiber
mirror
0
2
4 cm
tuning screw
Be test masses

The torsion pendulum



20 μm diameter tungsten fiber
(length: 108 cm)
κ=2.36 nNm

8 test masses (4 Be & 4 Ti)
4.84 g each (within 0.1 mg)
(can be interchanged)

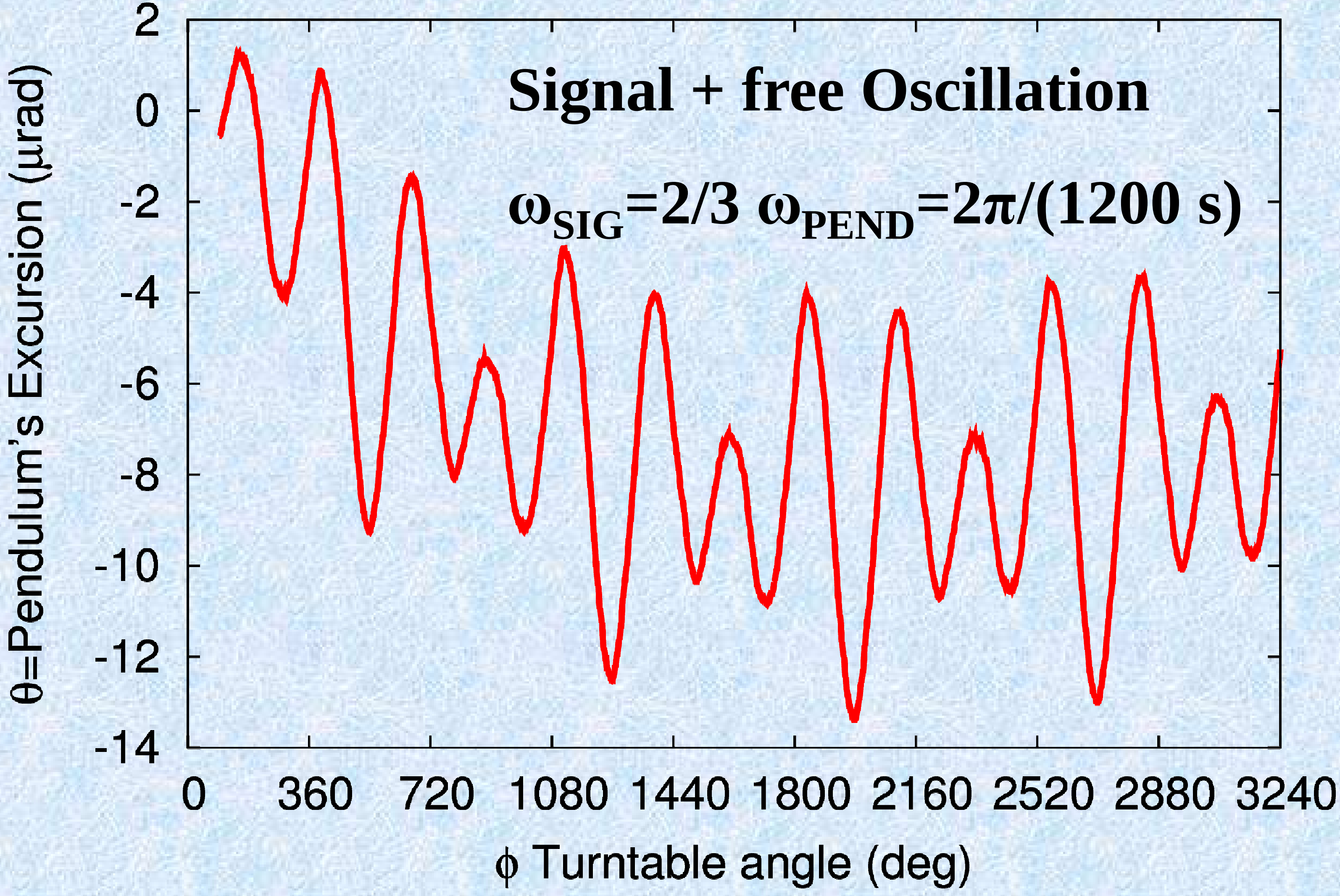
4 mirrors

tuning screws for adjusting tiny asymmetries

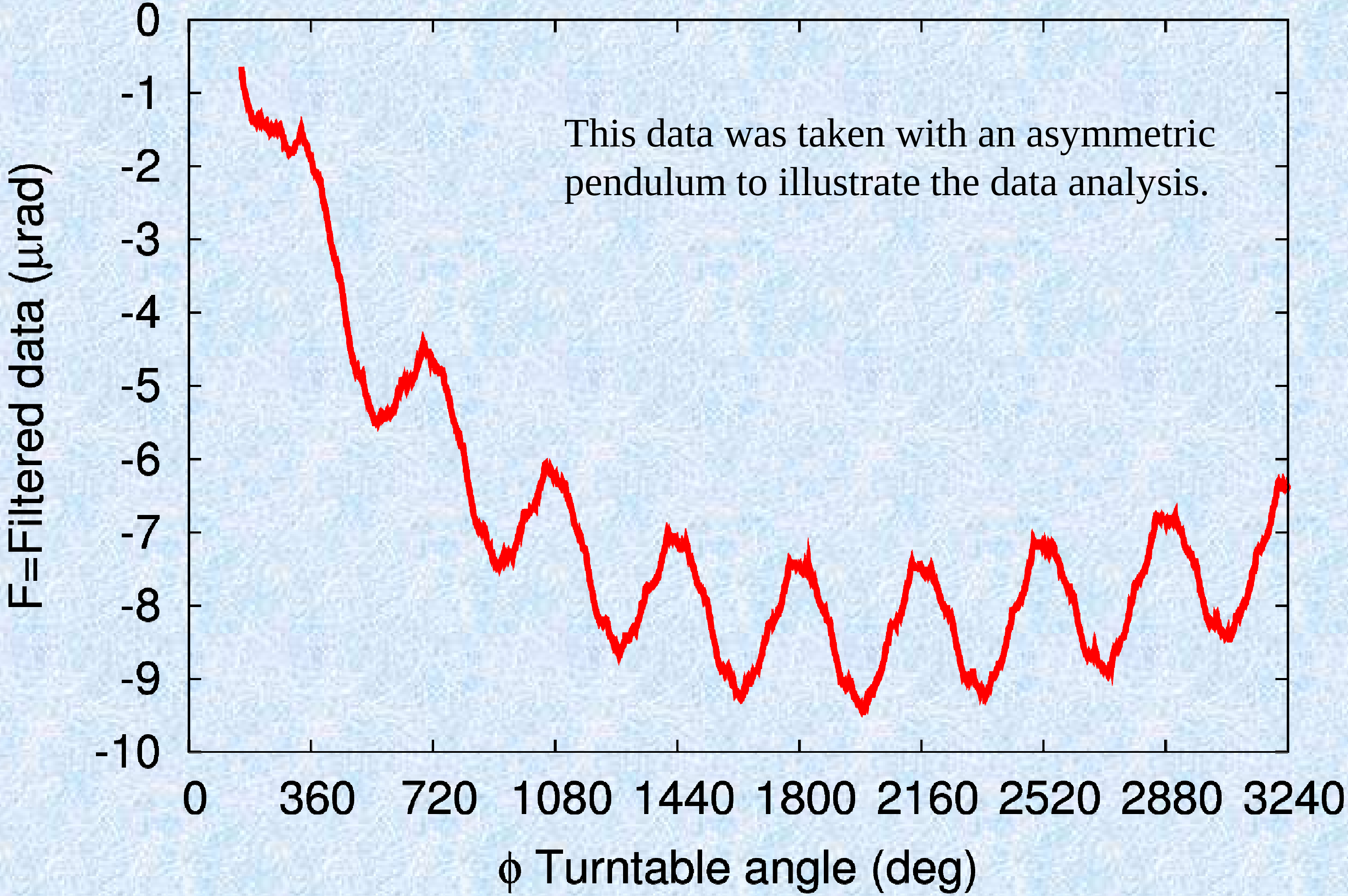
Data:

torsional period:	800 s
quality factor:	4000
decay time:	11d 19 hrs
machining tolerance:	5 μm
total mass :	70 g

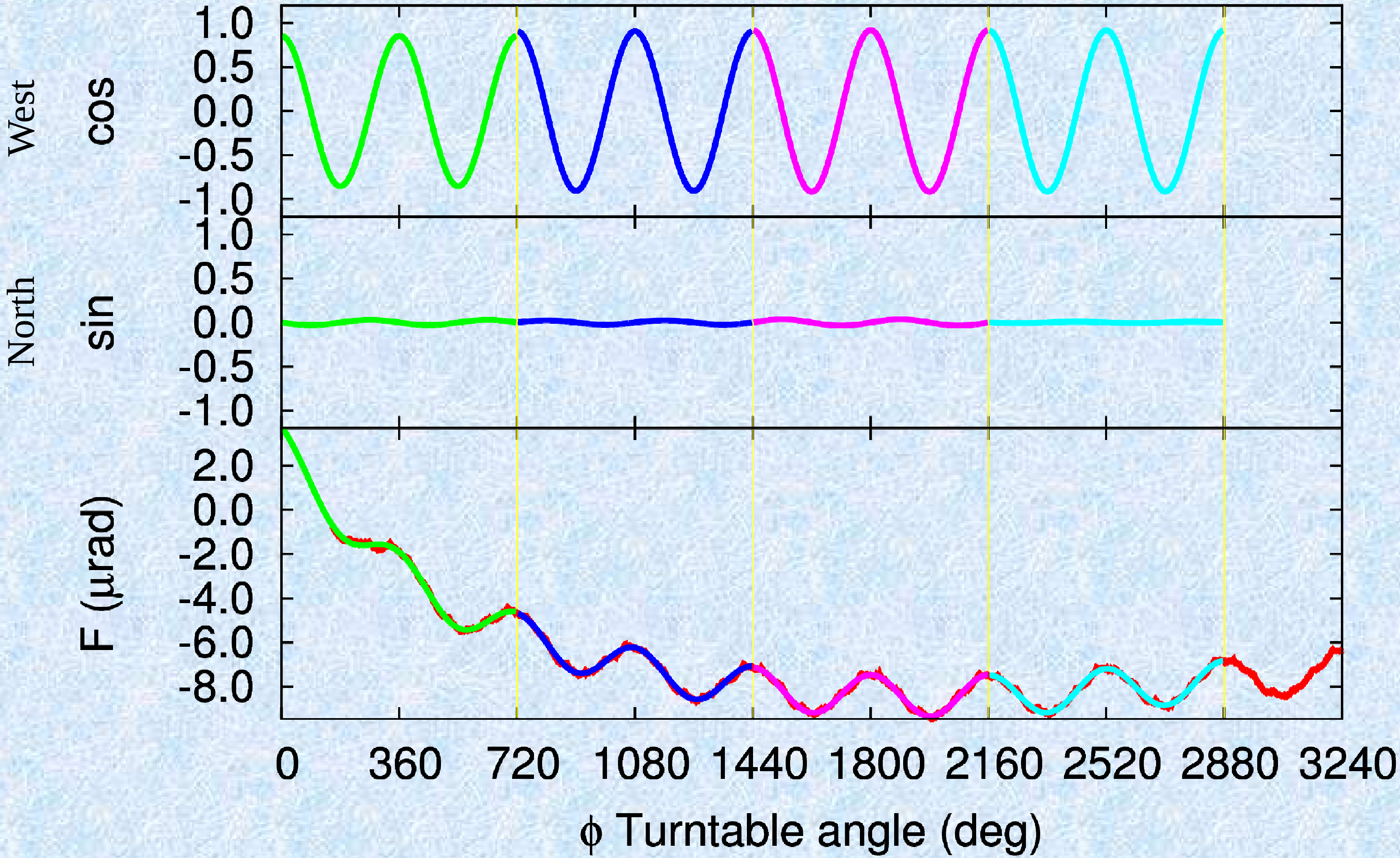
Raw data


Signal + free Oscillation
ωSIG=2/3 ωPEND=2π/(1200 s)
θ=Pendulum's Excursion (μrad)
2
0
-2
-4
-6
-8
-10
-12
-14
0
360
720
1080
1440
1800
2160
2520
2880
3240
φ Turntable angle (deg)

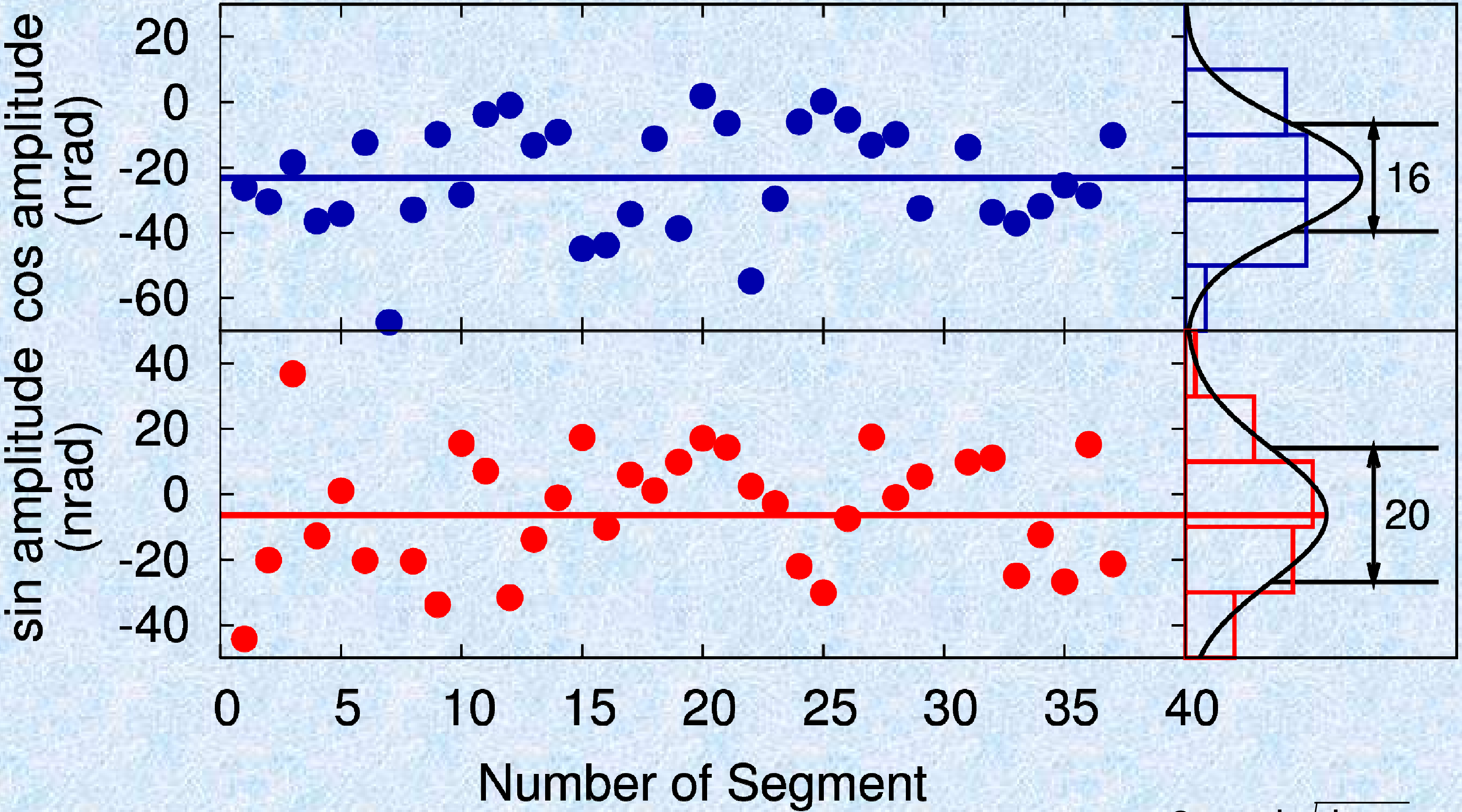
Filtered $F(t)=\Theta(t-T/4)+\Theta(t+T/4)$



Segmented & fitted

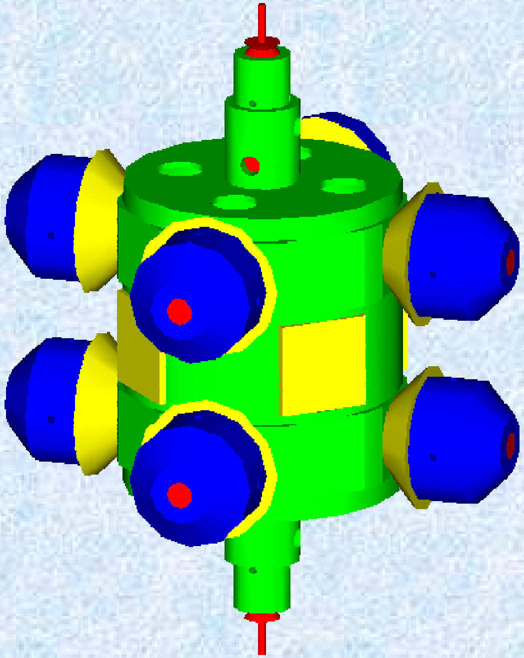


A day of data



σ≈ 3 nrad √day

Conversion of angle to differential acceleration



6.41×10^{-15} m/s^2 / nrad

$$\Delta a = \frac{\kappa}{4md}\varphi$$

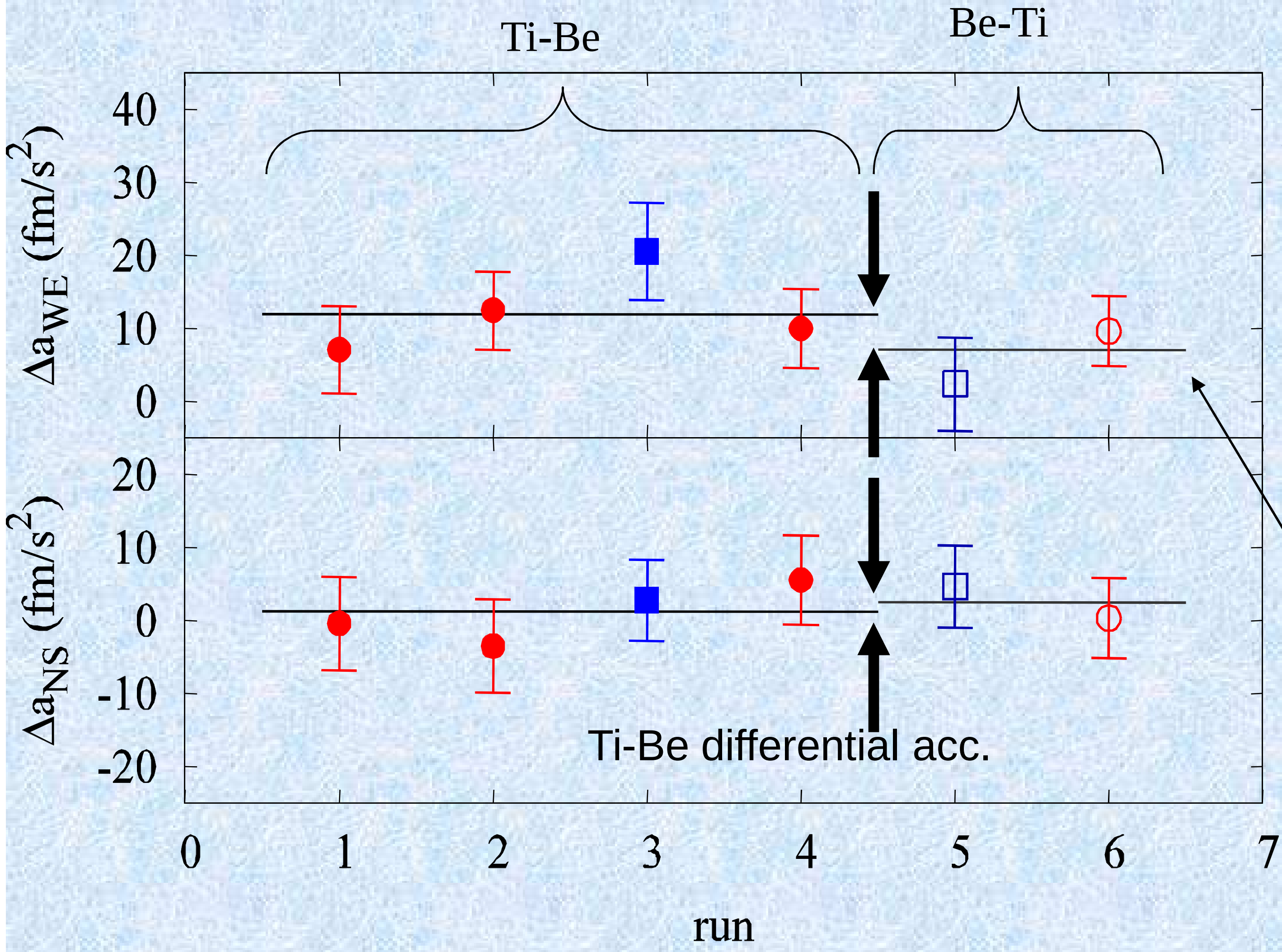
Can be measured with an uncertainty of 3 nrad per day

Δa can be measured to **20 fm/s²**

κ	2.36×10^{-9} Nm
m	4.84×10^{-3} kg
d	1.9×10^{-2} m

Data taking sequence

After a 2 months of data taking and systematic checks we physically invert the dipole on the pendulum and put it back into the apparatus.



These data points have been corrected for systematic effects.

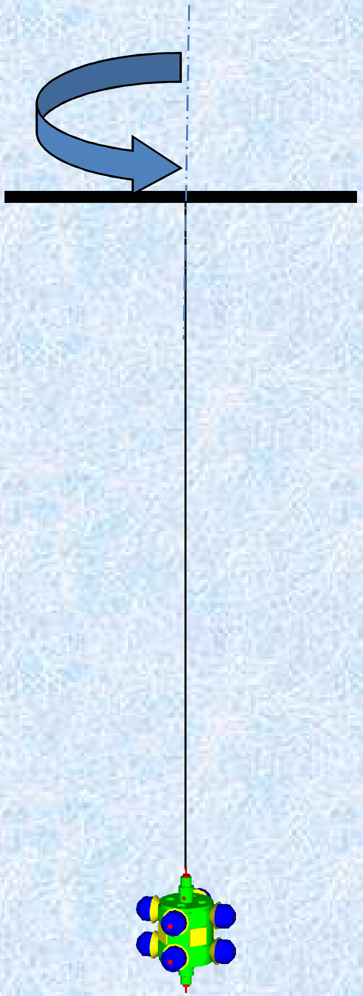
Only statistical uncertainties shown.

Offset is caused by the magnetic damper

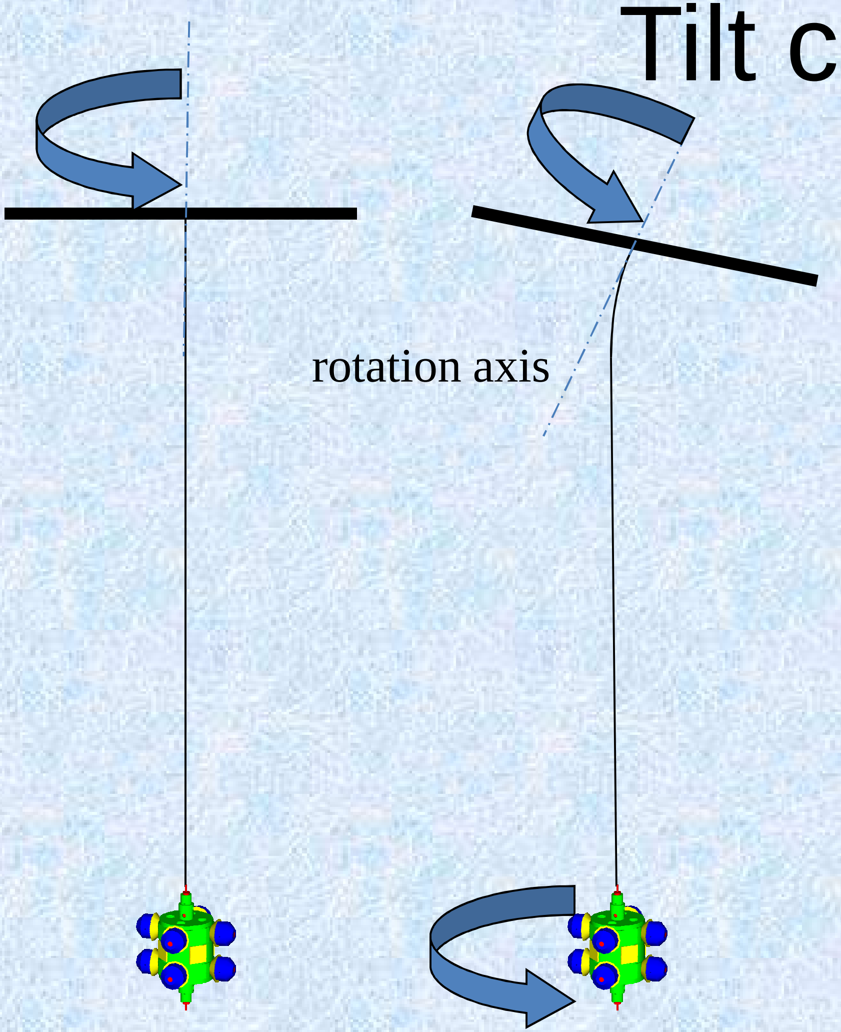
Corrected result

	$\Delta a_{N,Be\text{-}Ti}$ (10^{-15} ms^{-2})	$\Delta a_{W,Be\text{-}Ti}$ (10^{-15} ms^{-2})
measured	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
temperature gradients	0 ± 1.7	0 ± 1.7
magnetic coupling	0 ± 0.3	0 ± 0.3
corrected result	**0.6 ± 3.1**	**-2.5 ± 3.5**

Tilt coupling

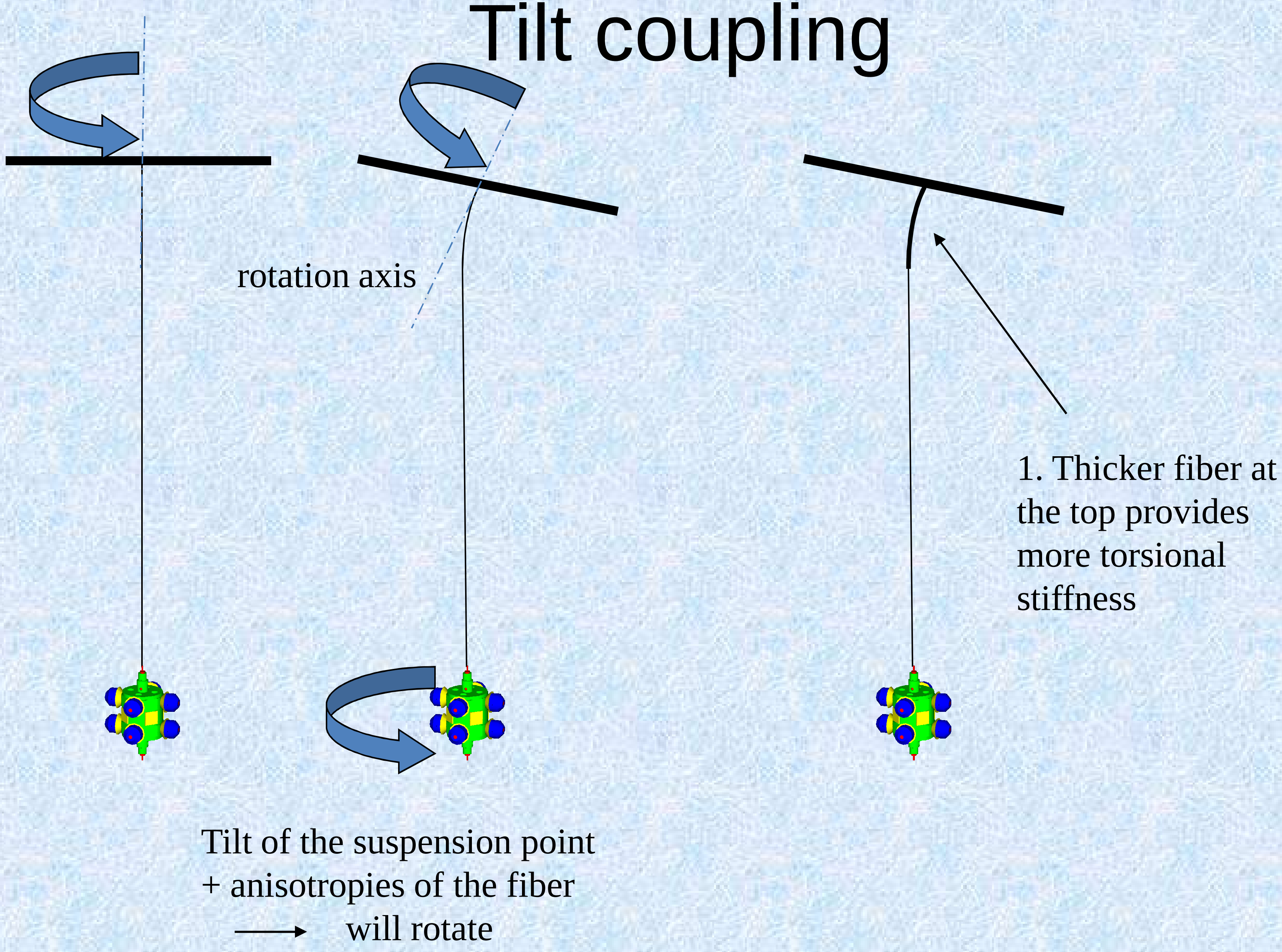


Tilt coupling

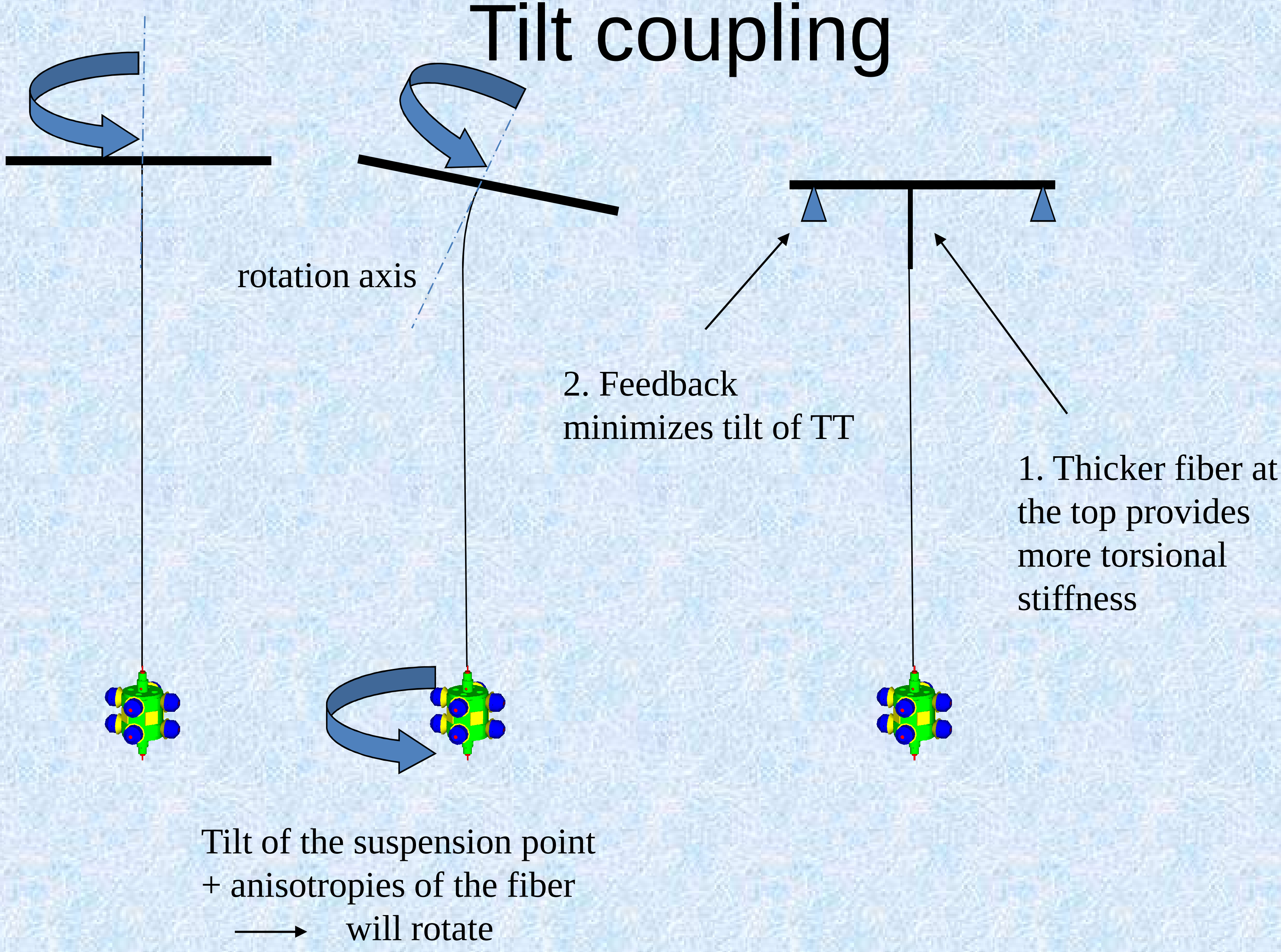


Tilt of the suspension point
+ anisotropies of the fiber
⟶ will rotate

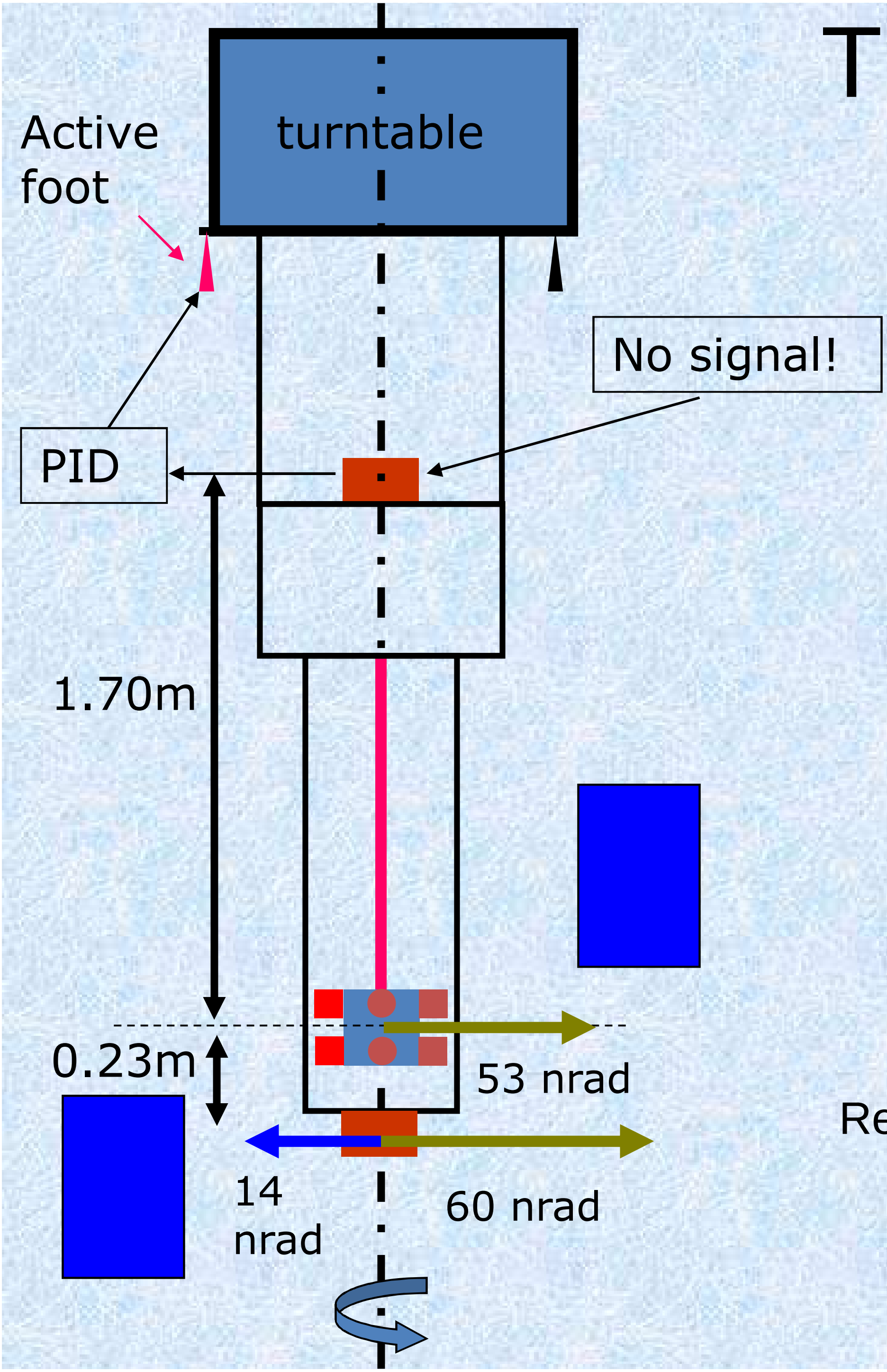
Tilt coupling

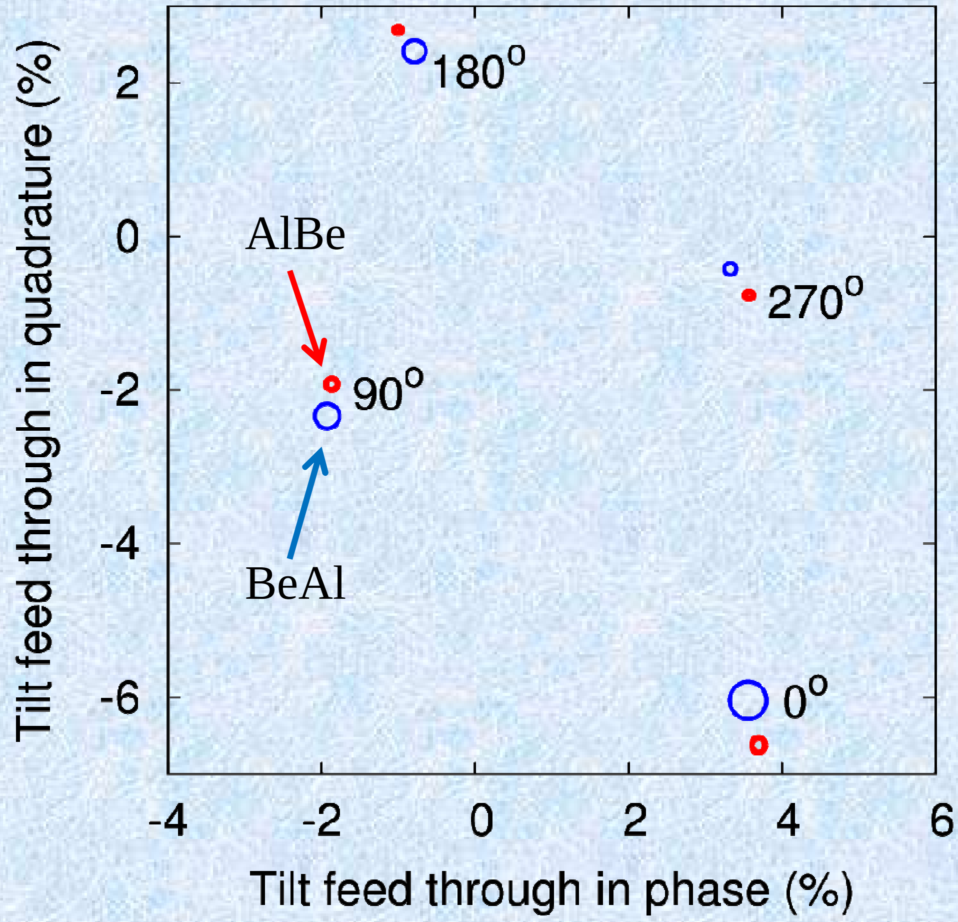


Tilt coupling



The tilt matrix



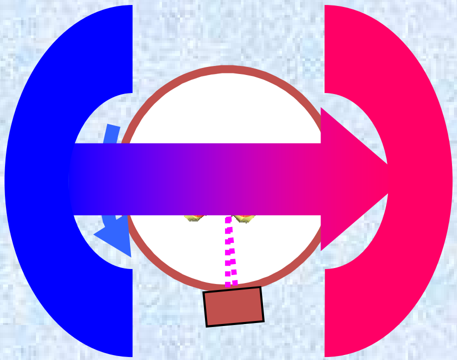


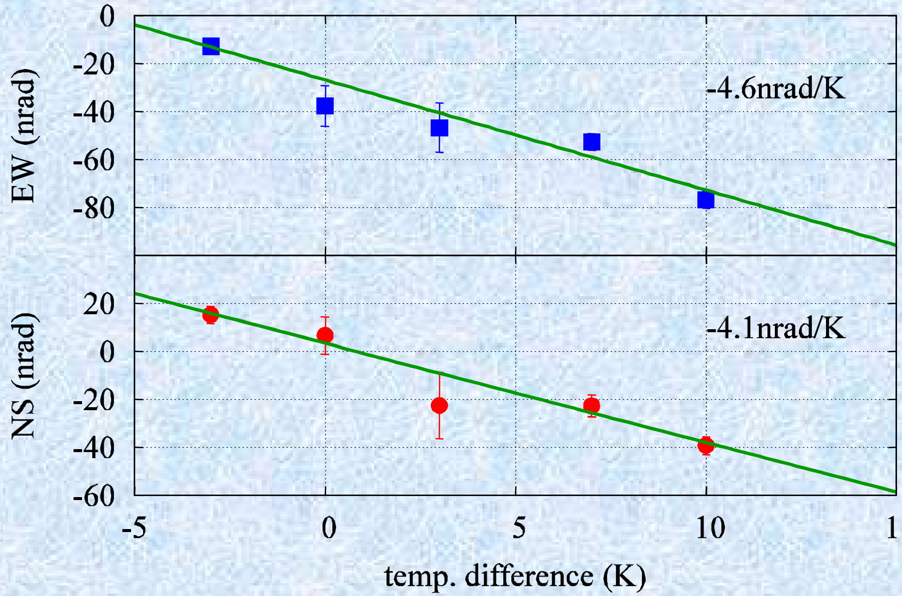
Remaining tilt uncertainty:

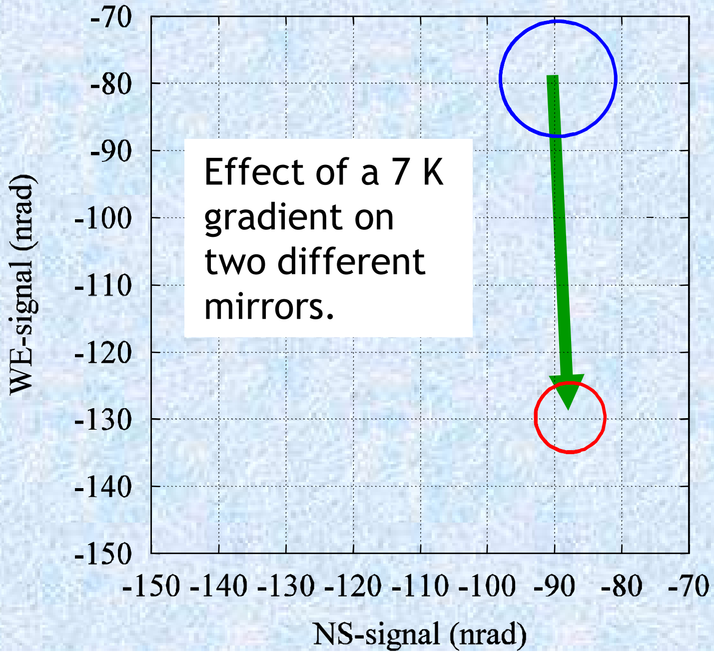
0.6 fm/s^2 N
0.7 fm/s^2 W

Thermal

Effect on the applied gradient on the signal (measurement was done on one mirror):







50 nrad Signal

ΔT =7K

During data taking ΔT≈0.053 K

⇒ 0.38 nrad

1.7 fm/s² N

1.7 fm/s² W

Results

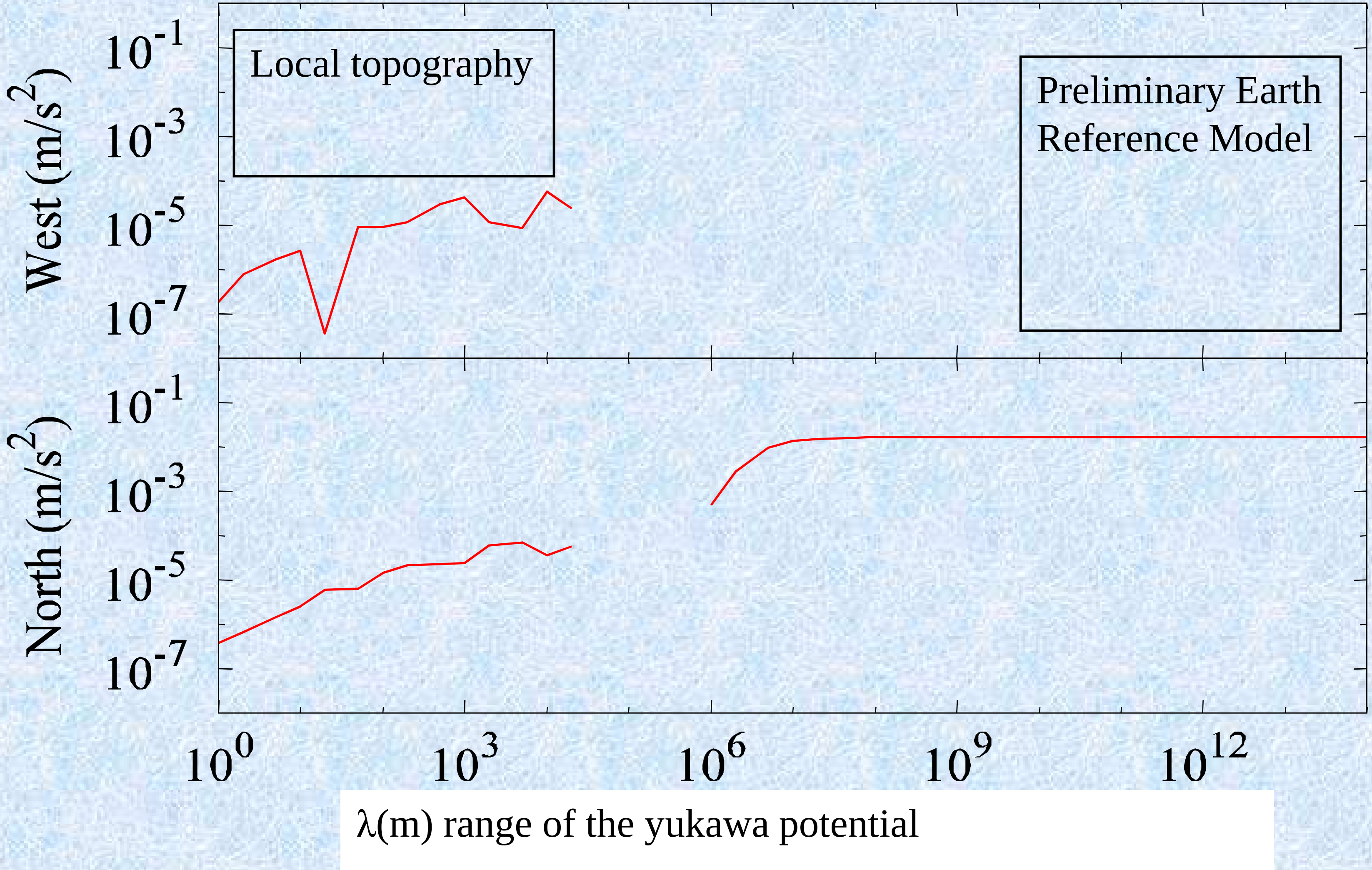
			Δa (10^{-15} ms^{-2})
$a_N(Be)$	-	$a_N(Ti)$	0.6 ± 3.1
$a_W(Be)$	-	$a_W(Ti)$	-2.5 ± 3.5
$a_N(Be)$	-	$a_N(Al)$	-2.6 ± 2.5
$a_W(Be)$	-	$a_W(Al)$	0.7 ± 2.5
$a_{Sun}(Be)$	-	$a_{Sun}(Ti)$	-1.8 ± 2.8
$a_{Sun}(Be)$	-	$a_{Sun}(Al)$	0.0 ± 2.5
$a_{Gal}(Be)$	-	$a_{Gal}(Ti)$	-2.1 ± 3.1
$a_{Gal}(Be)$	-	$a_{Gal}(Al)$	1.6 ± 2.8

Results

		Δa (10^{-15} ms^{-2})	η
a_N(Be)	- a_N(Ti)	0.6 ± 3.1	(0.3 ± 1.8) x 10^{-13}
a_W(Be)	- a_W(Ti)	-2.5 ± 3.5	
a_N(Be)	- a_N(Al)	-2.6 ± 2.5	(-1.5 ± 1.5) x 10^{-13}
a_W(Be)	- a_W(Al)	0.7 ± 2.5	
a_{Sun}(Be)	- a_{Sun}(Ti)	-1.8 ± 2.8	(-3.1 ± 4.7) x 10^{-13}
a_{Sun}(Be)	- a_{Sun}(Al)	0.0 ± 2.5	(0.0 ± 4.2) x 10^{-13}
a_{Gal}(Be)	- a_{Gal}(Ti)	-2.1 ± 3.1	(-4.4 ± 6.5) x 10^{-5}
a_{Gal}(Be)	- a_{Gal}(Al)	1.6 ± 2.8	(3.4 ± 5.8) x 10^{-5}

Source integration

$$\Delta\vec{a} = \alpha\Delta\left(\frac{q}{\mu}\right)_p \vec{I} \qquad \vec{I} = G\int d^3 r' \rho(r') \left(\frac{q}{\mu}\right)_S \left(\frac{1}{r'} + \frac{1}{\lambda}\right) \frac{e^{-r'/\lambda}}{r'} \hat{r}'$$



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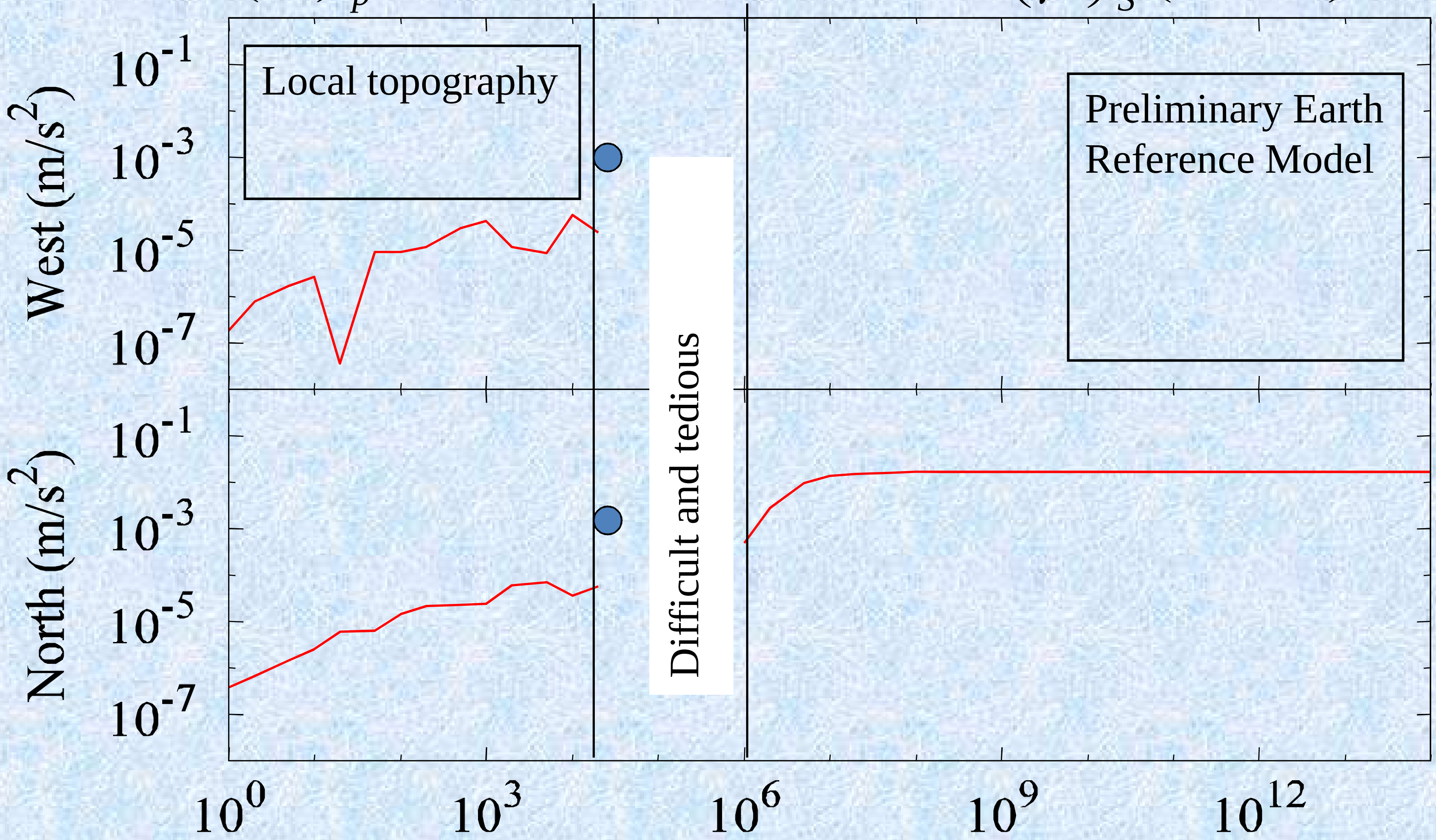
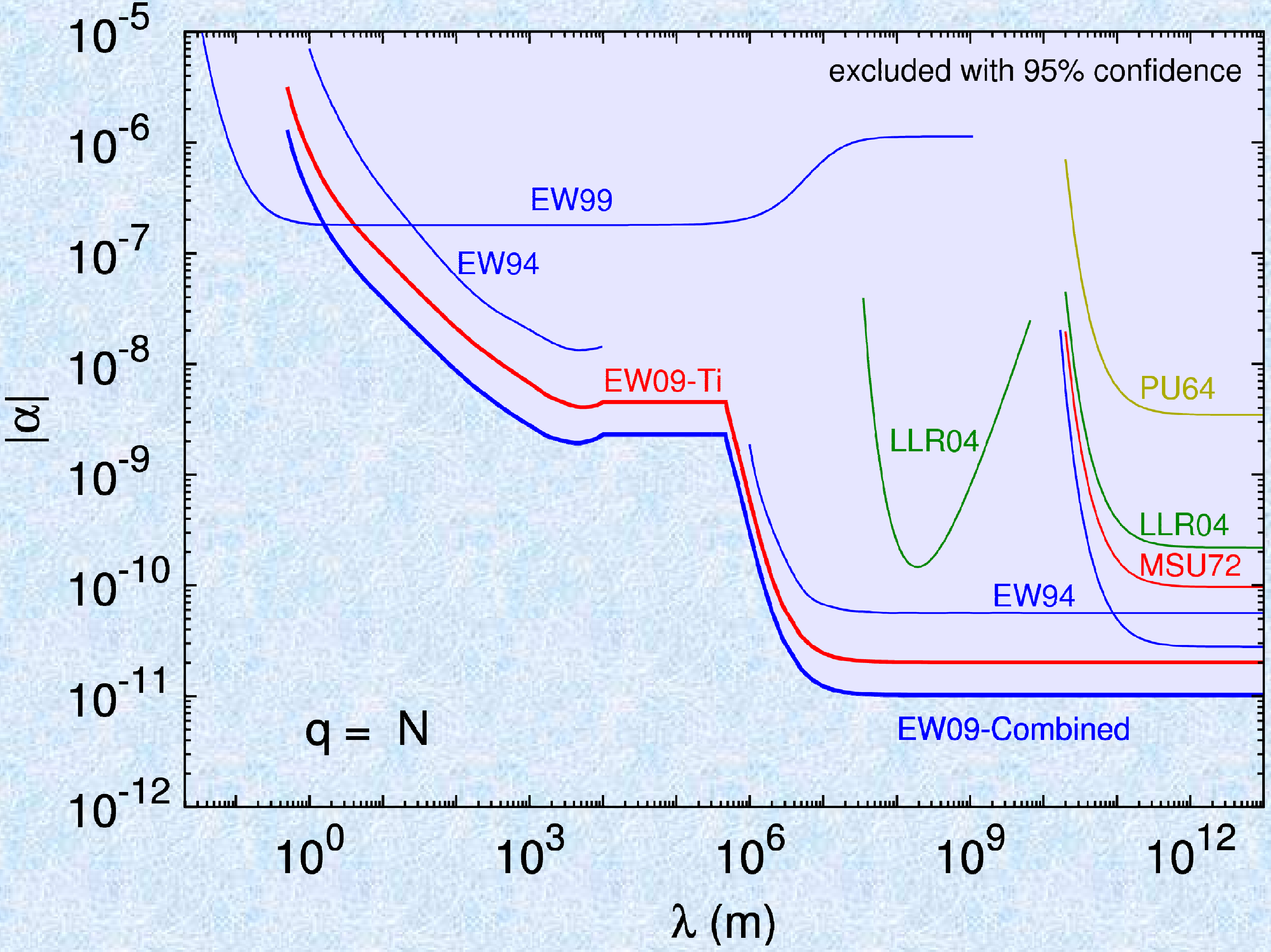
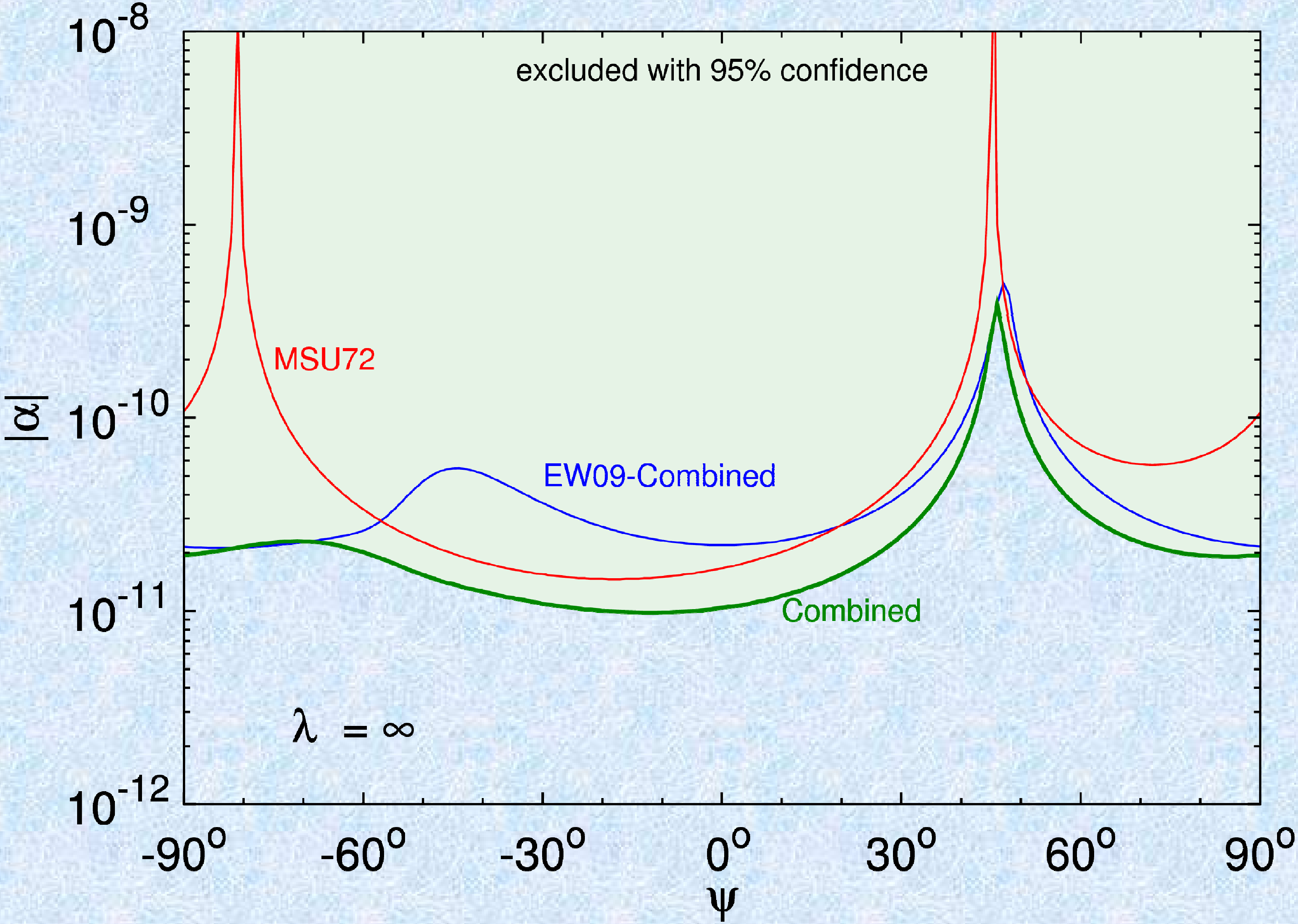


λ(m) range of the yukawa potential

α-λ plot for q=N ($\psi=\pi/2$)

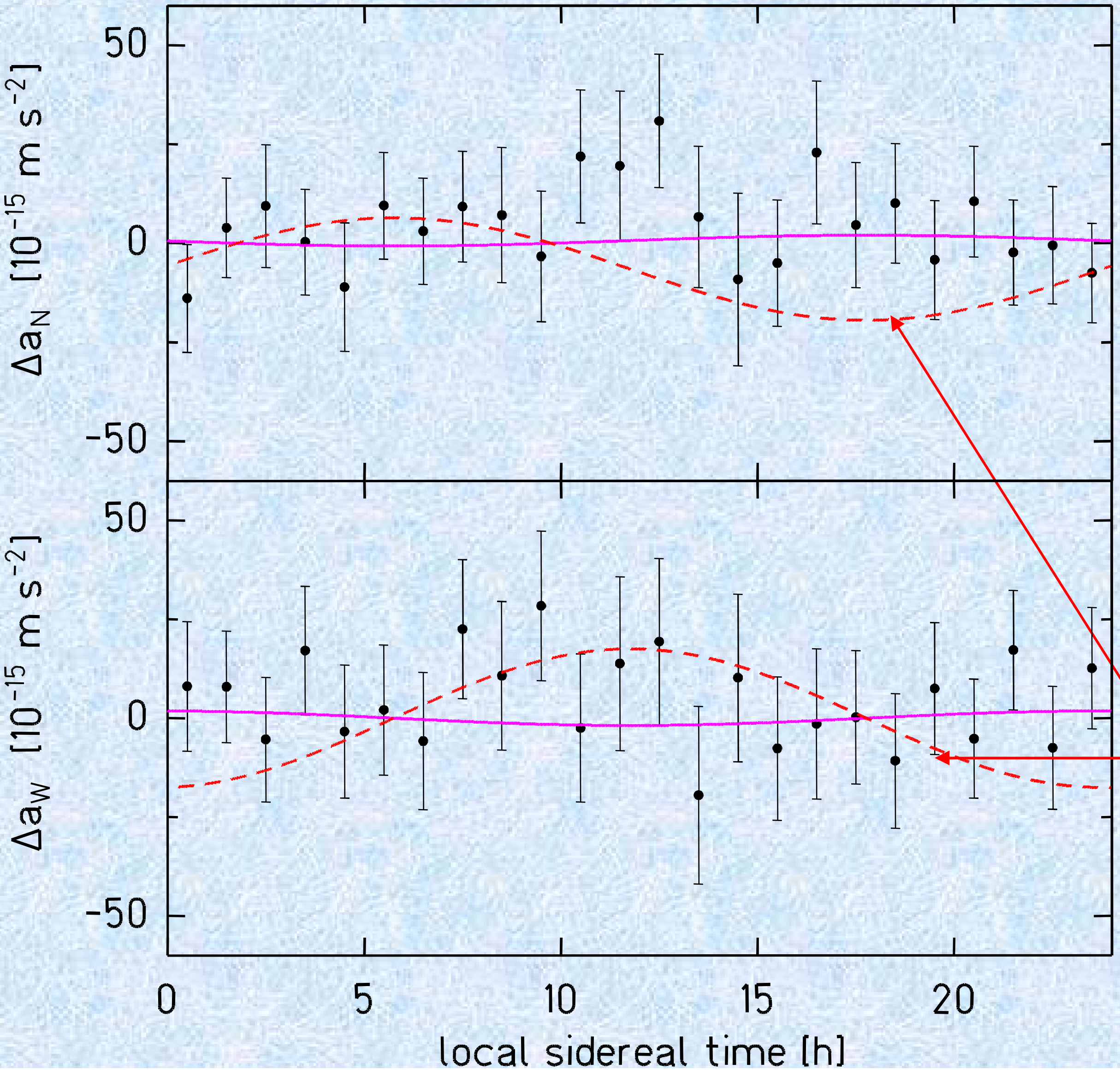


ψ-α plot for q=N (acc. towards the Sun)



Acceleration to the center of our galaxy

1825 h of data taken over 220 days



Differential acceleration to the center of the galaxy:

$(-2.1 \pm 3.1) \times 10^{-15}$ m/s^2

In quadrature:

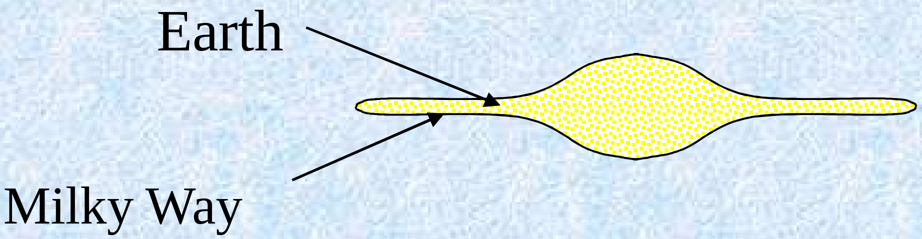
$(2.7 \pm 3.1) \times 10^{-15}$ m/s^2

Hypothetical signal:

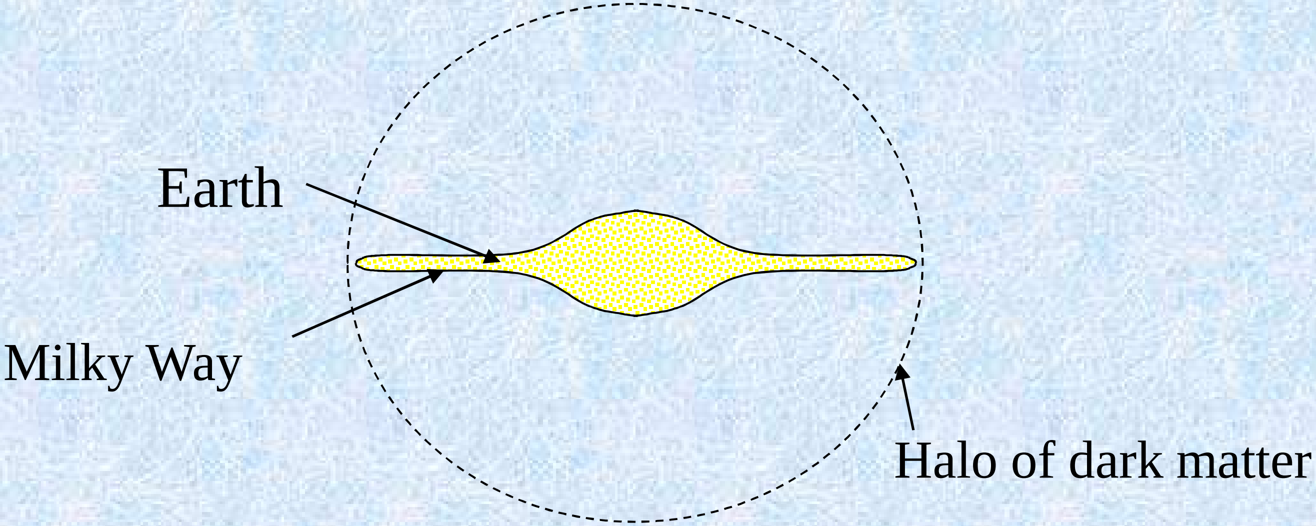
(7 times larger)

20×10^{-15} m/s^2

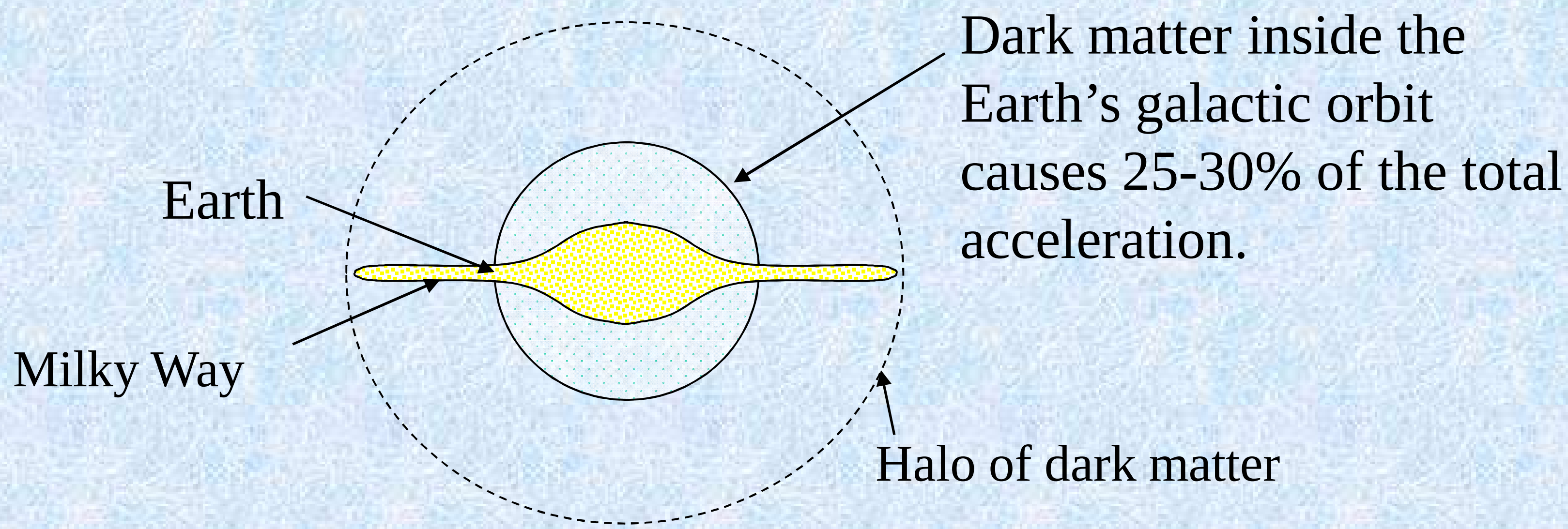
Galactic dark matter



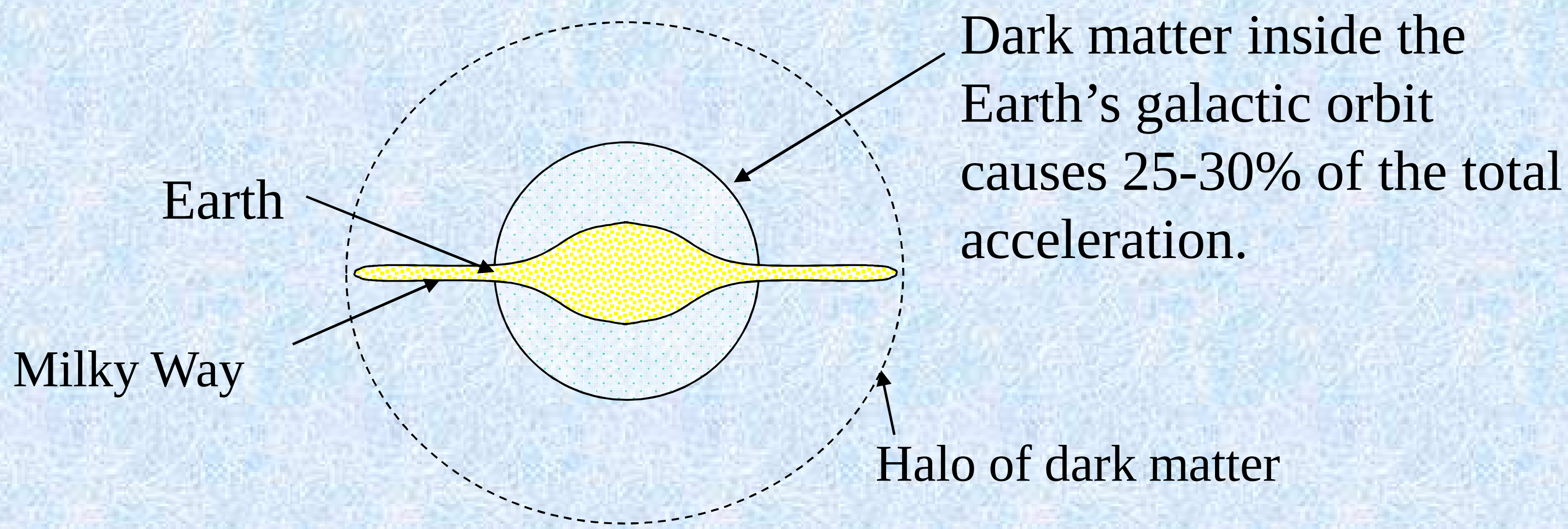
Galactic dark matter



Galactic dark matter



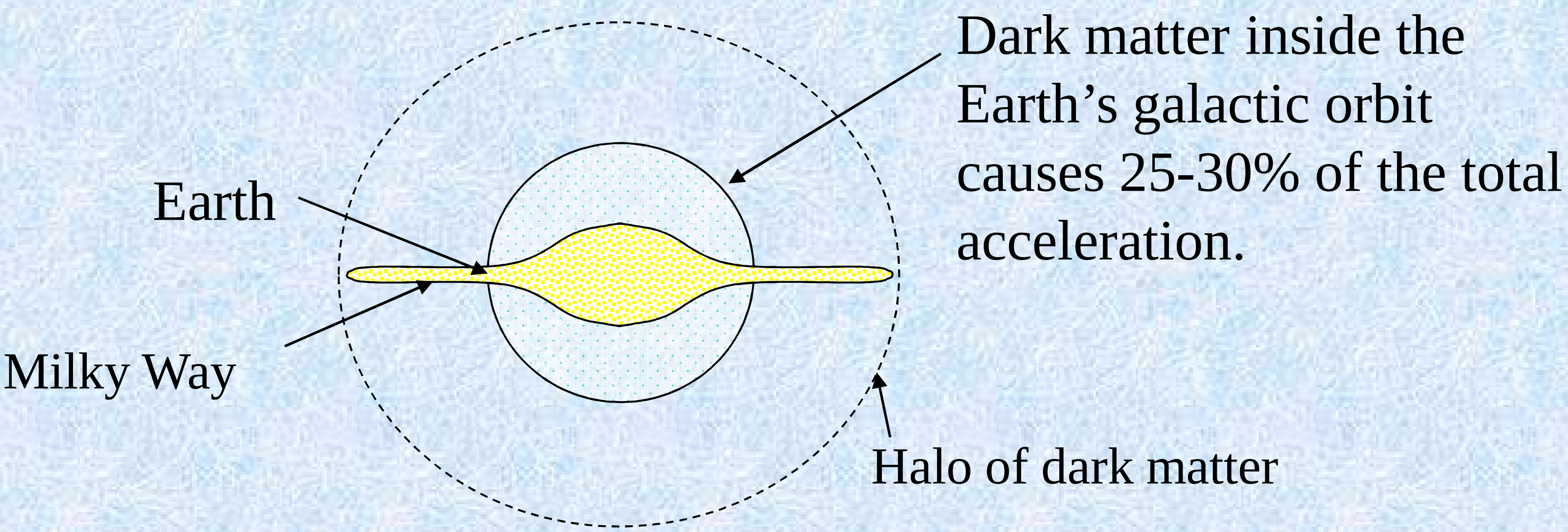
Galactic dark matter



Our acceleration toward the galactic center is:

$a_{gal} = a_{dark} + a_{ordinary} = 1.9 \times 10^{-10}$ m/s^2 => $a_{dark} = 5 \times 10^{-11}$ m/s^2

Galactic dark matter



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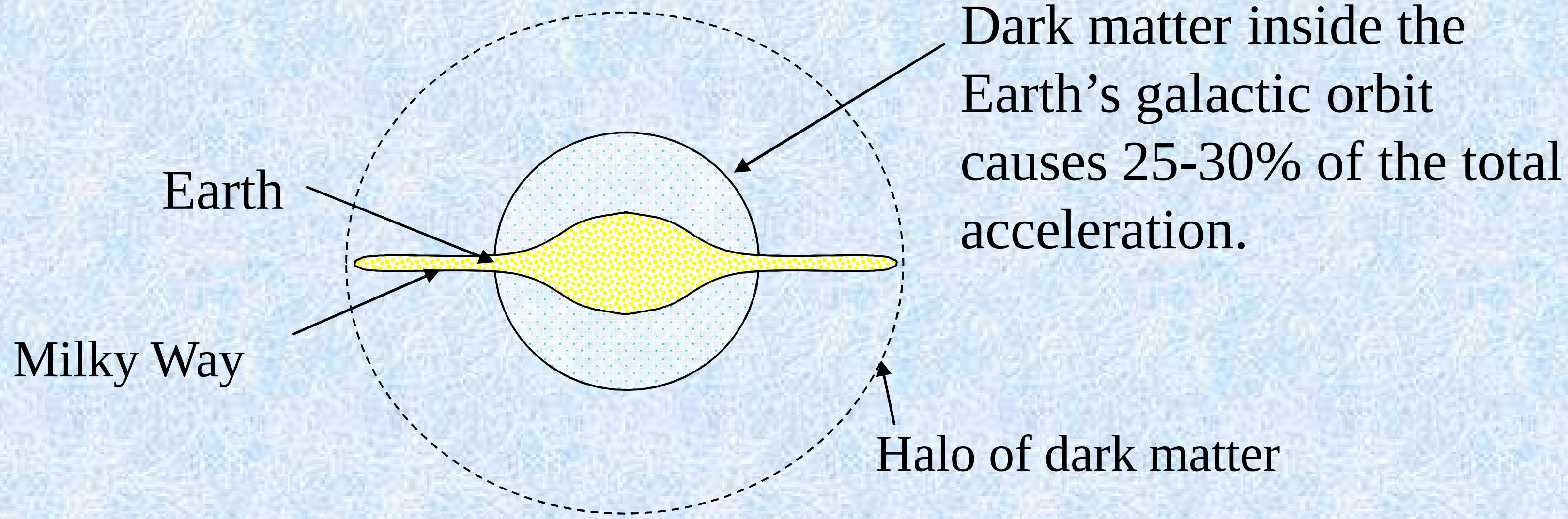
Measured differential acceleration toward the galactic center:

$\Delta a_{gal} = (-2.1 \pm 3.1) \times 10^{-15}$ m/s^2 => $\eta_{dark} = |\Delta a_{gal}|/a_{dark} = (-4 \pm 7) \times 10^{-5}$

Galactic dark matter



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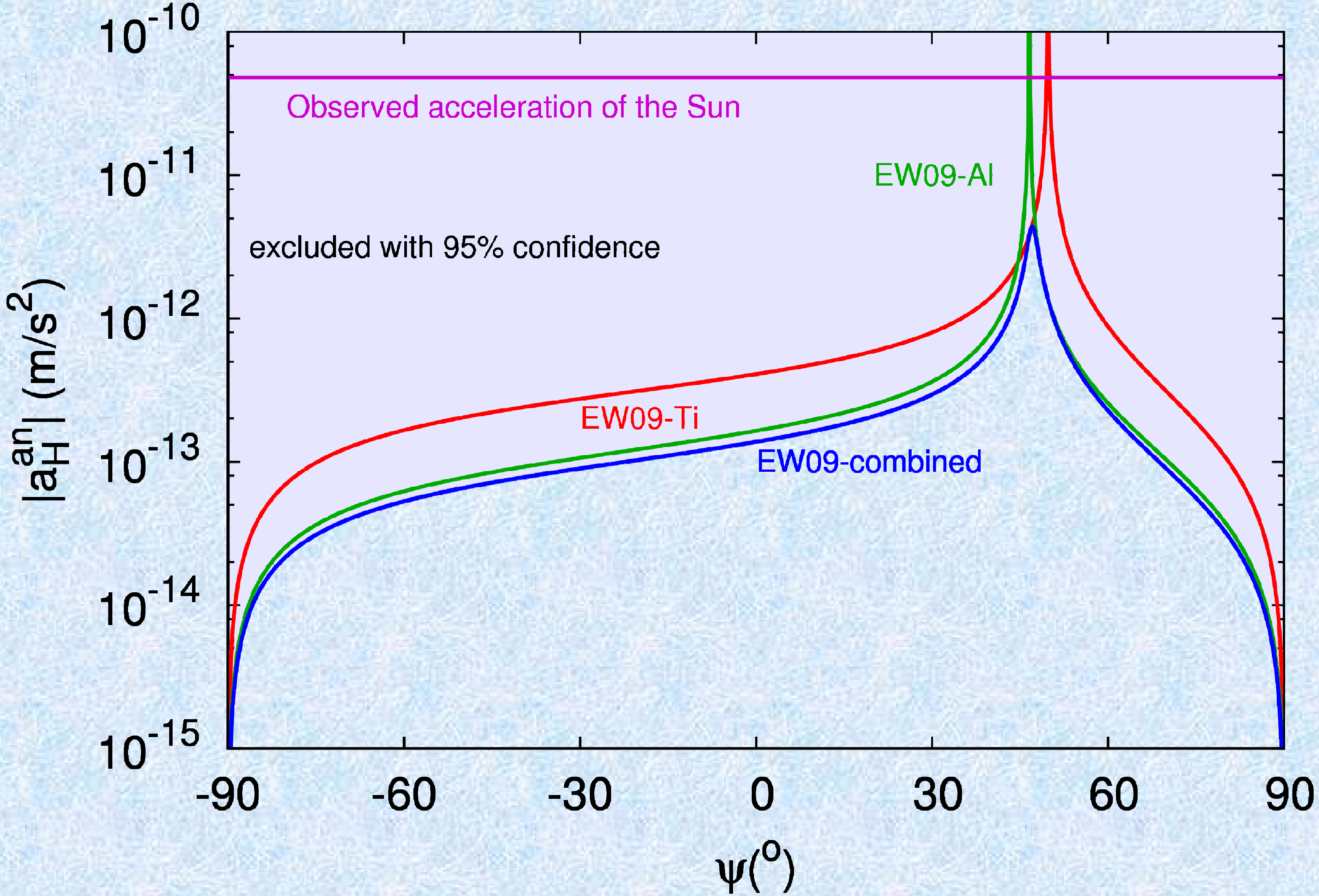
The acceleration of Be and Ti towards dark matter does not differ by more than 150 ppm (with 95 % confidence).

Limits on the acceleration of neutral H towards dark matter



Summary

- The test of the equivalence principle is a sensitive probe for fundamental physics.
- Principle of the measurement.
- Main systematic effects.
- Results
  - Earth (North): $\mathbf{a_{Be}-a_{Ti}=(0.6 \pm 3.1) \times 10^{-15}\ m/s^2}$.
  - $\boldsymbol{\eta}\mathbf{=(0.3 \pm 1.8) \times 10^{-13}}$.
  - Towards Galaxy: $\mathbf{a_{Be}-a_{Ti}=(-2.1 \pm 3.1) \times 10^{-15}\ m/s^2}$.
  - $\boldsymbol{\eta}_{\mathbf{DM}}\mathbf{=(-4 \pm 7) \times 10^{-5}}$.

  - 10x improved limits on a long range interaction.

Thank you

J.H. Gundlach
E.G. Adelberger
B.R. Heckel
K.-Y. Choi
T.A. Wagner
C.A. Hagedorn