THE EQUIVALENCE PRINCIPLE

A Cryogenic Torsion Balance Test

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Outline

- What is the Equivalence Principle?
- How has it been tested?
- Why use a torsion balance?
- Why use a cryogenic torsion balance?
- Experiment features
- My work on experiment
- Future of experiment

Equivalence Principle:

A uniform gravitational field is locally indistinguishable from a uniformly accelerated reference frame

The Universality of Free Fall (UFF)

- In uniform gravitational field, particle trajectory independent of composition

$$F = m_i a$$

$$F_g = G\frac{m_E m_g}{r_E^2} = m_g g$$

$$\Big\} \; a = \frac{m_g}{m_i} g$$

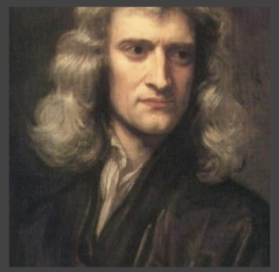
History of UFF Tests

- Tests characterized by Eötvös parameter

$$\eta = \frac{\Delta a}{\frac{1}{2}(a_1 + a_2)}$$

- Bounds on this parameter have been getting smaller and smaller
- But, several theories beyond the Standard Model predict it should not be zero!

~1600: Galileo (dropping balls)
$\eta <$ 1 part in 100

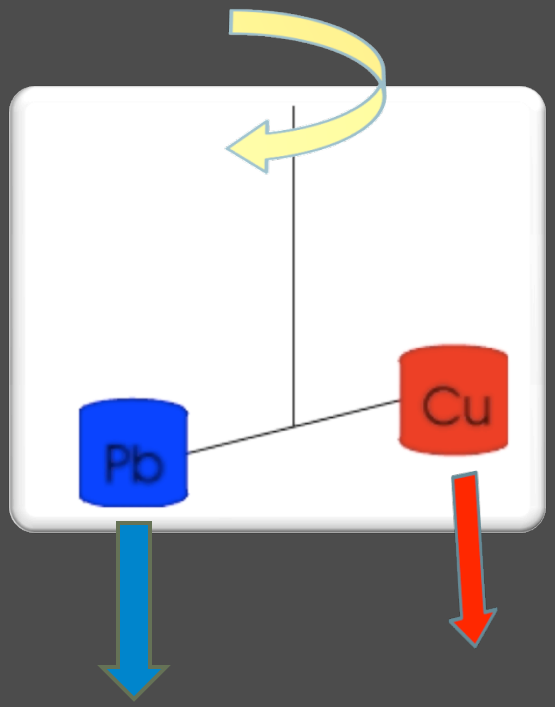


~1680: Newton (pendulum periods)
$\eta <$ 1 part in 1000

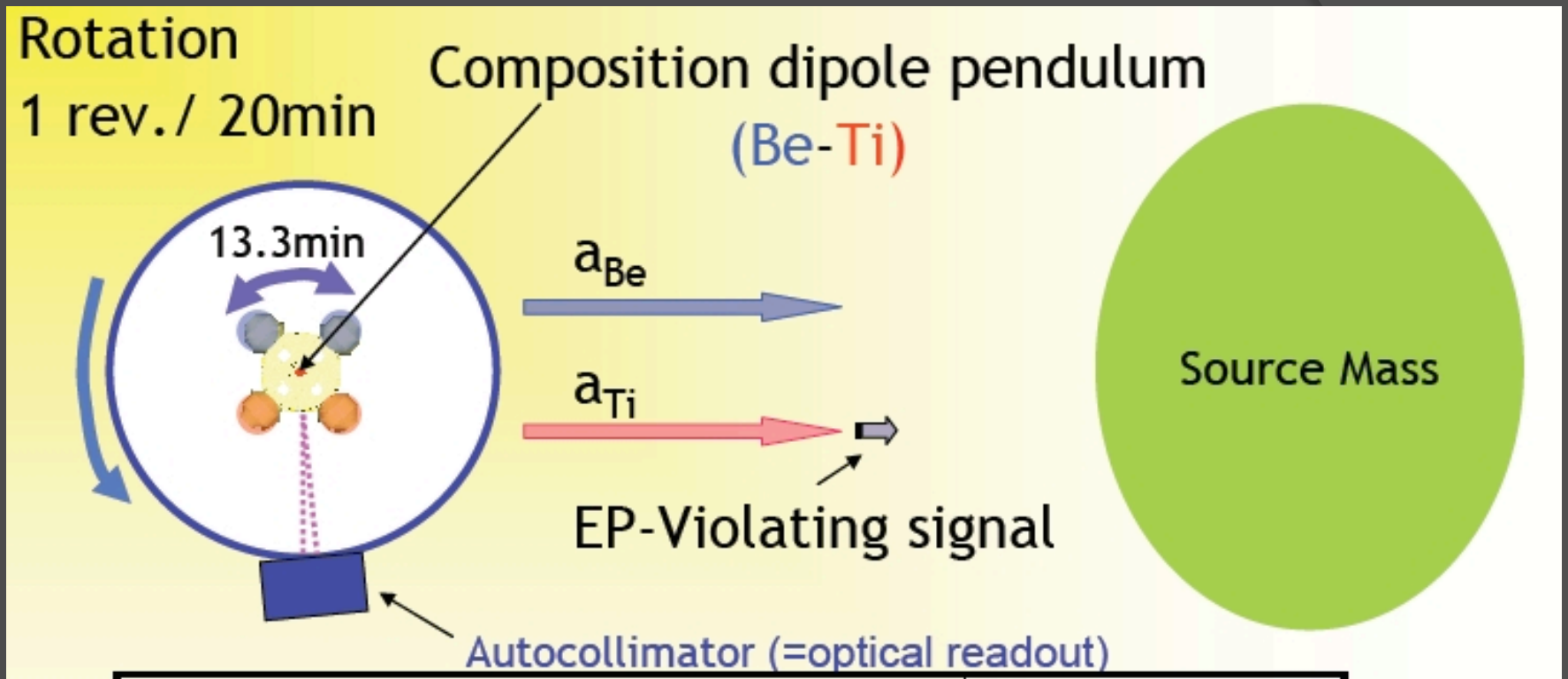
1922: Eötvös (torsion balance)
$\eta <$ 5 parts in 1 billion

2008: Schlamminger, Choi, Wagner, Gundlach, Adelberger (rotating torsion balance)
$\eta <$ 3 parts in 10 trillion

How does a torsion balance work?

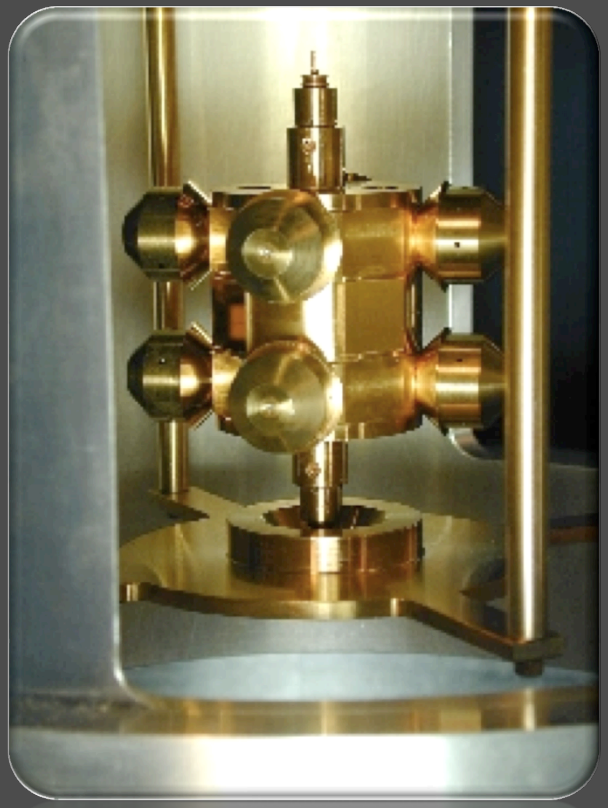


- Two bodies hang from very thin torsion fiber
- Sensitive to forces in horizontal plane
- Even a miniscule difference in horizontal forces on test bodies creates noticeable torque



source mass	λ (m)
local masses (hill)	$1 - 10^4$
entire earth	$10^6 - 10^7$
Sun	$10^{11} - \infty$
Milky Way (incl. DM)	$10^{20} - \infty$

Source: “Tests of the Equivalence Principle”, Stephan Schlamminger

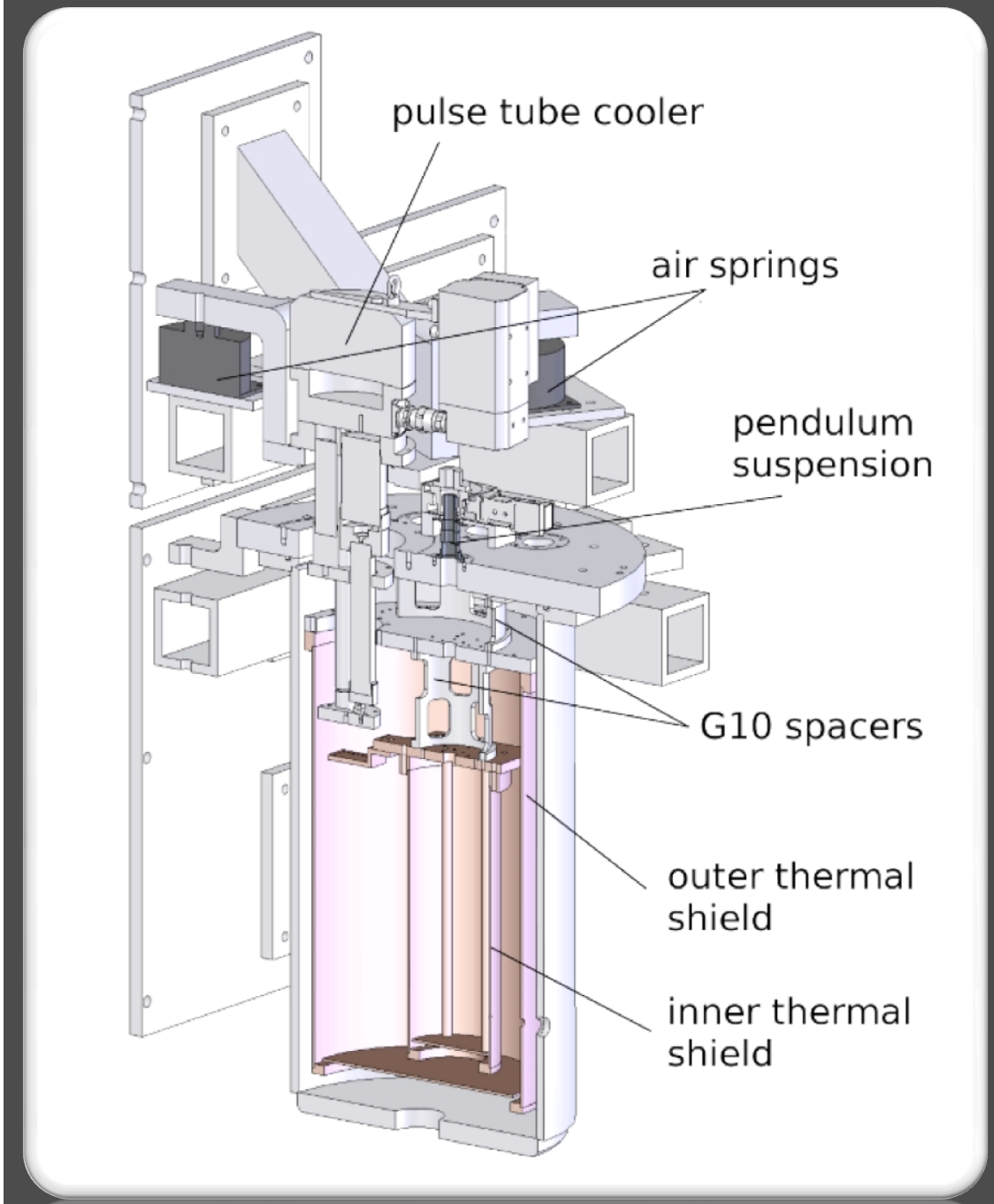


Common Features of Eöt-Wash Balances

- Autocollimator used to measure deflection angle
- Source mass rotates relative to torsion pendulum
- Since gravitational field on Earth not actually uniform, pendulum must be designed so as not to couple strongly to gravity gradients (more on this later)

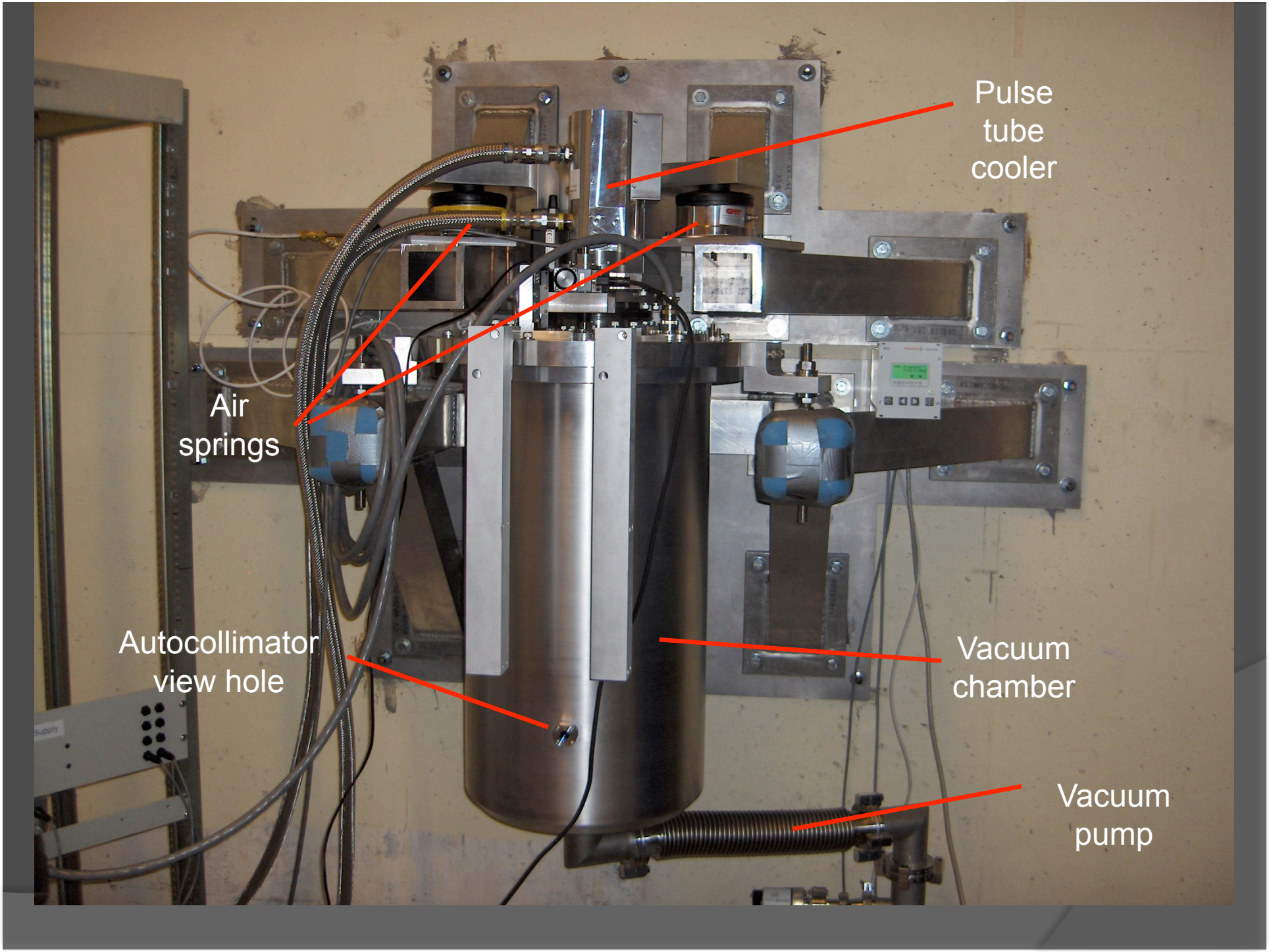
Advantage of Cryogenic Torsion Balance

- Thermal noise is reduced with lower temperatures and higher quality factor Q of torsion fiber
- Reducing temperature has been shown to increase Q in some fiber materials
- Could reduce uncertainty in Eötvös parameter η by order of magnitude

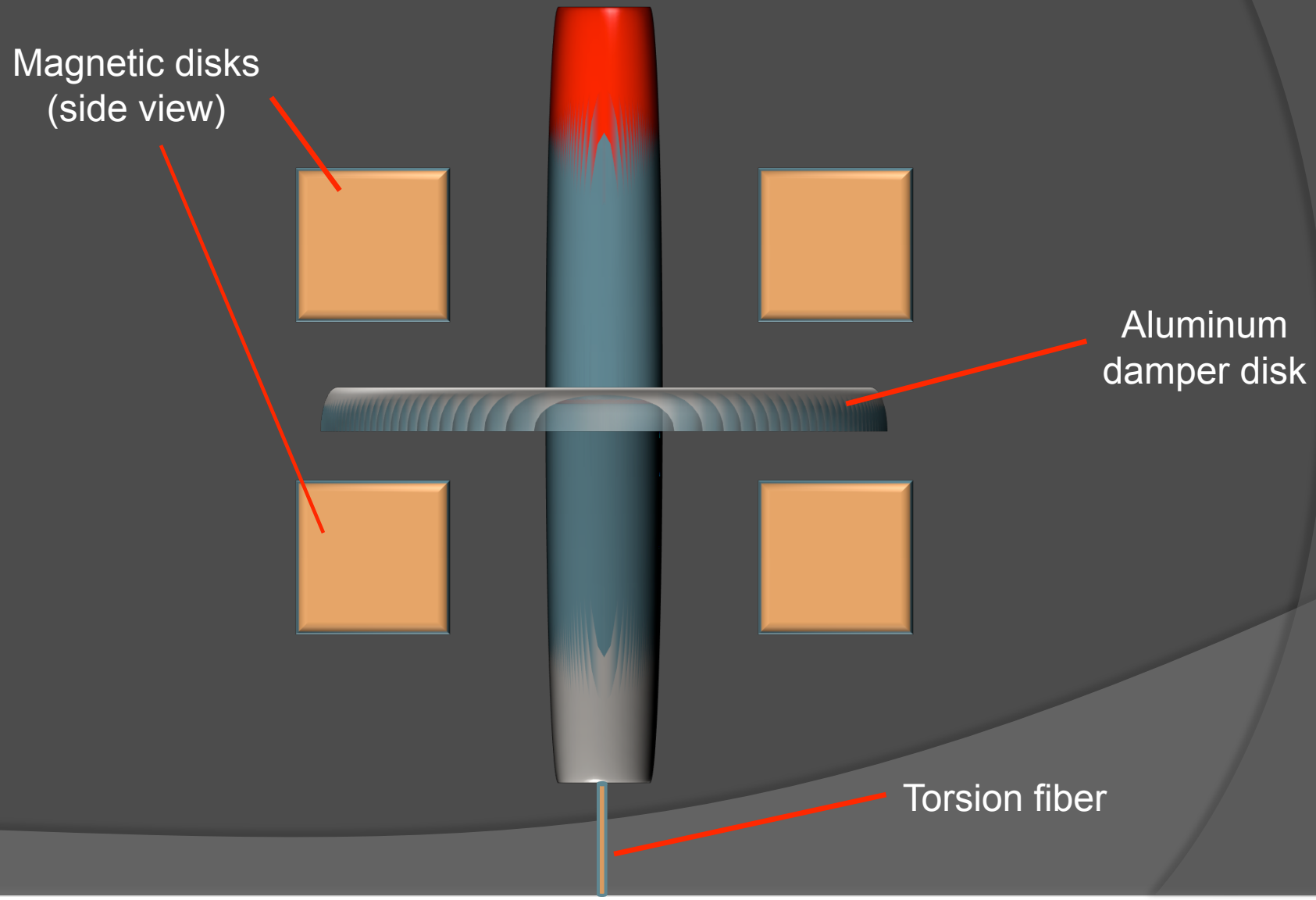


Design Features

- pendulum chamber cooled down to ~6 Kelvin
- independent support for pulse tube cooler
- air springs/flexible heat links help decouple vibration from pulse cooler
- uses Sun/galactic center as source mass


Pulse tube cooler
Air springs
Autocollimator view hole
Vacuum chamber
Vacuum pump

Close-up: Magnetic Damper



Challenges

- Vibrations from pulse tube cooler (and other sources)
- With Sun/galactic center as source mass, daily environmental changes cause problems (temperature, human traffic, etc.)
- Gravity gradients

Gravity Gradients

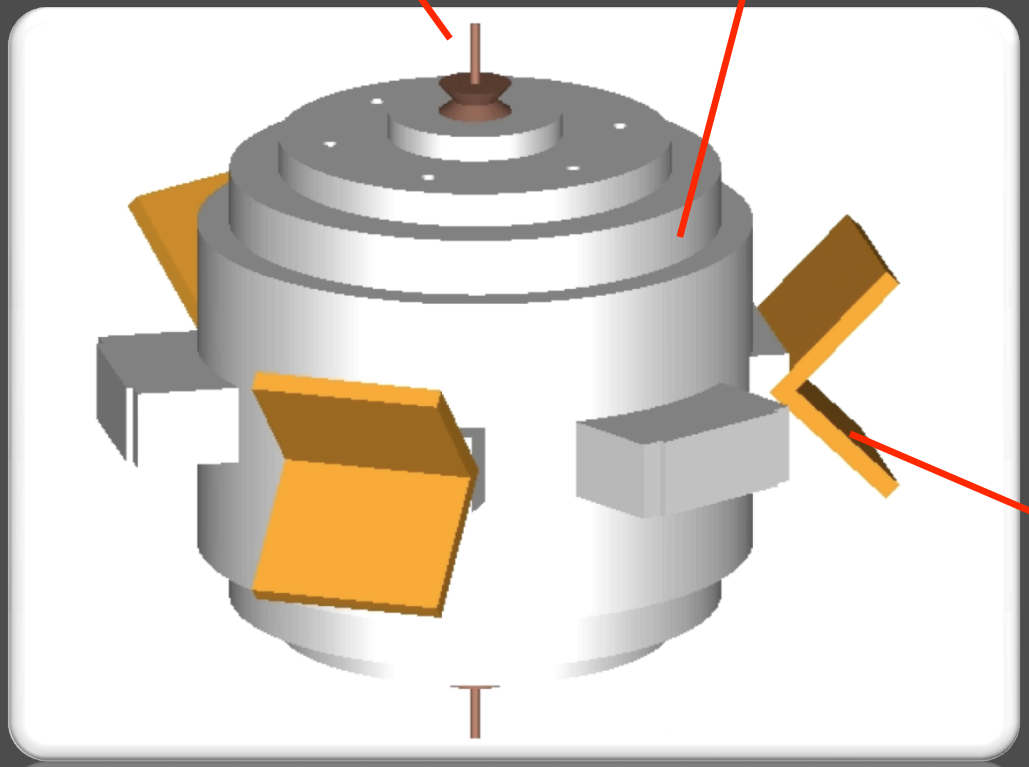
- When gravity field is *not* uniform, there *can* be torques on pendulum (even without EP violation)
- Must design pendulum so coupling to nearby gradients as weak as possible

$$-G\int d^3\,r\rho_p(\vec{r})\int d^3\,r'\rho_S(\vec{r}')\frac{1}{|\vec{r}-\vec{r}'|} = -4\pi G\sum_{l=0}^{\infty}\frac{1}{2l+1}\sum_{m=-l}^{+l} q_{lm}\,Q_{lm}$$

Source: Su, Yue. “A New Test of the Weak Equivalence Principle.” 1992 p.19.

Test Pendulum

- Check to see if apparatus working as expected (only deflection should be from thermal noise)
- No composition dipole
- Small low-order multipole moments



Design Features

- 120° rotational symmetry
- Symmetric across x-y plane
- Hollow

Future of Experiment

- Use test pendulum to check noise levels, make modifications to experiment as necessary
- Design experiment pendulum with composition dipole
- Make new measure of EP violation

Thank you everybody!

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