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CONFERENCE ON FUNDAMENTAL SYMMETRIES AND FUNDAMENTAL CONSTANTS

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ATOMIC CLOCK TESTS OF LORENTZ AND CPT SYMMETRY

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Atomic clock tests of Lorentz and CPT symmetry

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In this talk…

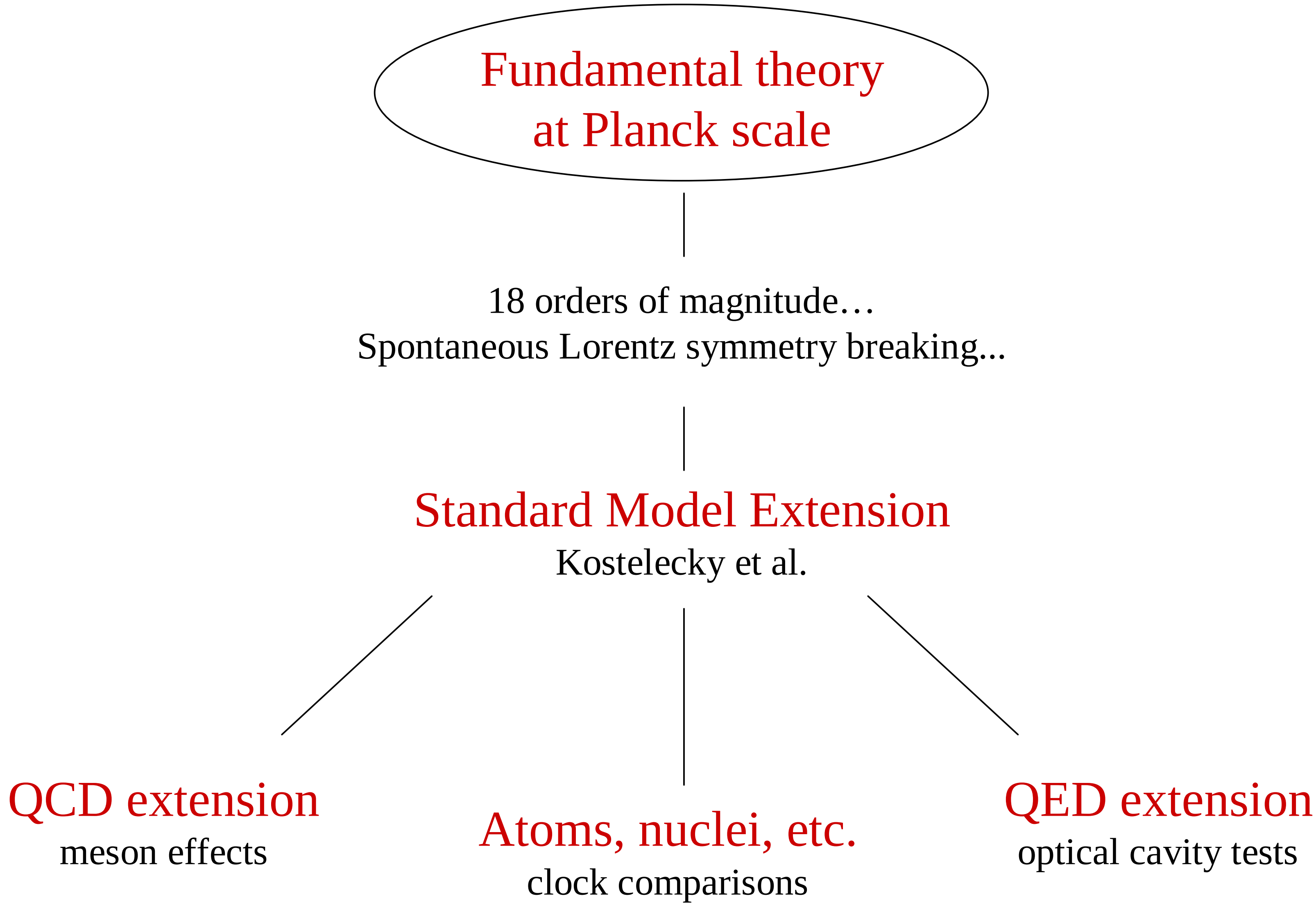
- An atomic physics experimentalist's view of the rationale for Lorentz and CPT symmetry tests
- What are the observable phenomena and experimental challenges?
- An incomplete survey of Lorentz/CPT tests to date:
  some have (naïve) Planck-scale sensitivity
- A look at my group's maser (atomic clock) experiments
  best limits so far for neutron and proton
- Coming attractions, challenges, and provocative comments…

Motivation and context

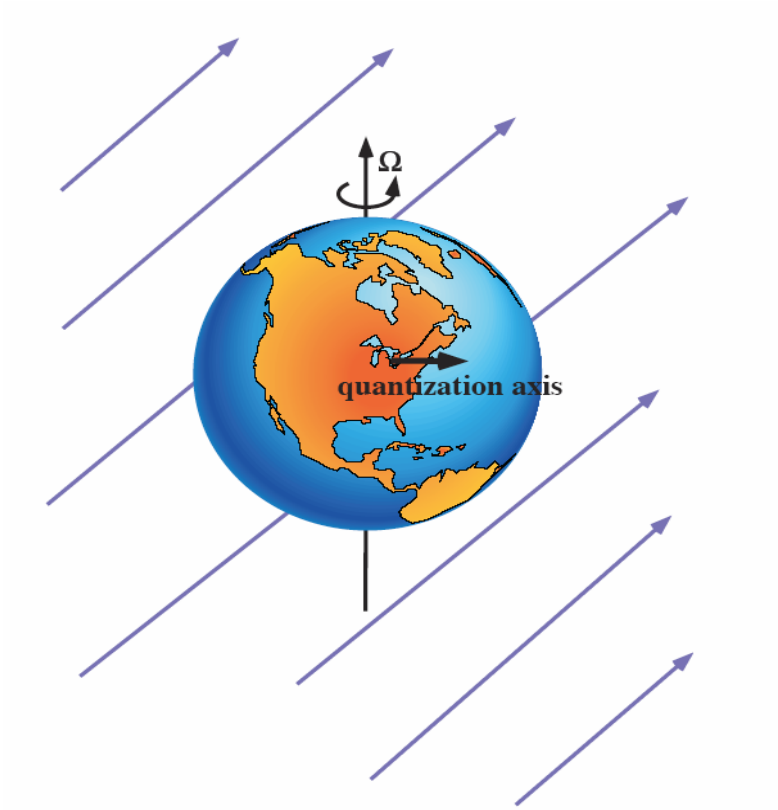
- Fundamental extended objects, cosmological dynamics
  —> low-energy violation of Lorentz (and hence CPT) symmetry

- Atomic clock comparisons are particularly sensitive to (small) Lorentz and CPT violations
  sensitivity for spin couplings ~ 10^{-31} GeV
  2 orders of magnitude improvement in next few years

- Standard Model Extension of Kostelecky et al. is the comprehensive formalism to interpret experiments


Fundamental theory
at Planck scale
18 orders of magnitude…
Spontaneous Lorentz symmetry breaking...
Standard Model Extension
Kostelecky et al.
QCD extension
meson effects
Atoms, nuclei, etc.
clock comparisons
QED extension
optical cavity tests

Implications of Lorentz-violation for "low energy" physics



Spins, mesons, photons, etc.
can couple (perhaps differently)
to background fields

—> orientation and boost dependent

- Zeeman splittings
- meson decays
- speed of light
- birefringence of vacuum

  etc.

Experimental challenges

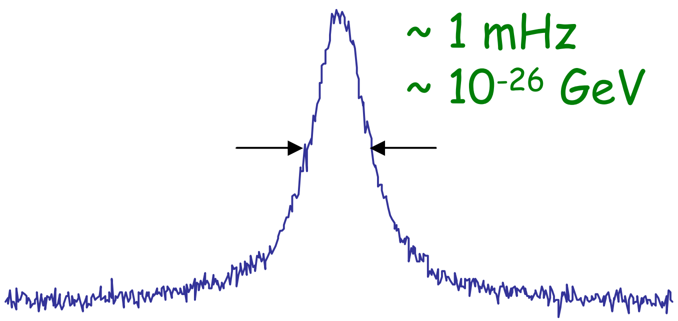
- Small effects !!
  —> need a narrow bandwidth observable,
  high-sensitivity detection (good S/N)

- Slowly-modulated signal (if using Earth's rotation)
  —> excellent long-term stability of apparatus

- Discrimination from confounding systematic effects
  good co-magnetometer (spins have magnetic moments)
  day/night thermal cycle (if using Earth's rotation)
  noise associated with a rotating platform
  variations in matter/antimatter loadings (meson sector)
  unknown astrophysical effects (photon sector)

What makes a good spin Lorentz symmetry test?

- *Clean:* simple spin structure (e.g., ^{3}He, H)
- *Sensitive to absolute energy changes:*
  Narrow bandwidth resonance
  Large signal-to-noise ratio
  Stable over sidereal modulation period
- *Suppress magnetic field effects:*
  E.g., co-magnetometer that does not eliminate
  Lorentz-violation sensitivity
- *Minimize systematics:*
  Differential measurements, environmental control, etc.



Hydrogen and noble gas masers meet criteria

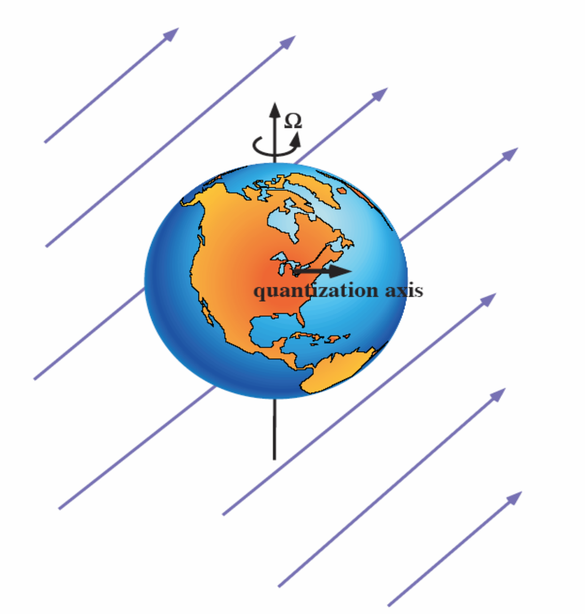
Current limits

Lorentz symmetry tests (CPT odd **and** even effects)		System	CPT tests	
Isotropy	Boosts		Isotropy	Boosts
10^{-24} GeV (Penning trap) *10^{-29} GeV (torsion pendulum)*		**e^-**	*10^{-25} GeV (e^+/e^- in Penning trap)*	
10^{-23} GeV (muonium, μ^+e^-) *10^{-24} GeV?? (BNL storage ring)*		**μ**	*10^{-22} GeV (μ^+/μ^- at CERN)* *10^{-23} GeV?? (BNL storage ring)*	
10^{-27} GeV (hydrogen maser)		**p**		
10^{-31} GeV	***10^{-27} GeV***	**n**		

(noble gas maser)

Lorentz symmetry tests (CPT odd **and** even effects): Isotropy	Lorentz symmetry tests (CPT odd **and** even effects): Boosts	System	CPT tests: Isotropy	CPT tests: Boosts
		D meson	*10^{-13} GeV* (FOCUS)	*10^{-13} GeV* (FOCUS)
		K meson	*10^{-21} GeV (KTeV)*	
		B meson	*10^{-16} GeV (BaBAR)*	
10^{-15} (cryogenic optical cavities)	*10^{-11}*	**speed of light**		
10^{-32} (spectral polarimetry of cosmological sources)		**birefringence of vacuum**	*10^{-42} GeV limit from cosmological data; strong arguments => must be zero*	

Search for Lorentz-violating coupling of spins to background fields



***Rotations**: sidereal day modulation of atomic Zeeman splittings?*

***Boosts**: sidereal year modulation of atomic Zeeman splittings?*

Assumptions

- Simple, additive effect of coupling to valence nucleon and electron spins
- Couplings do not scale with magnetic moments
- Large domain size for Lorentz-violating fields
- Conventional magnetic shields do not screen Lorentz-violating fields
- Interpret results in terms of Standard Model Extension of Kostelecky et al.

Hydrogen maser

Hydrogen masers are one of the most stable oscillators for periods of seconds to weeks:

$\Delta f/f \sim 10^{-15}$

CfA hydrogen masers are used throughout the world for spacecraft tracking, radio astronomy, atomic physics, etc.

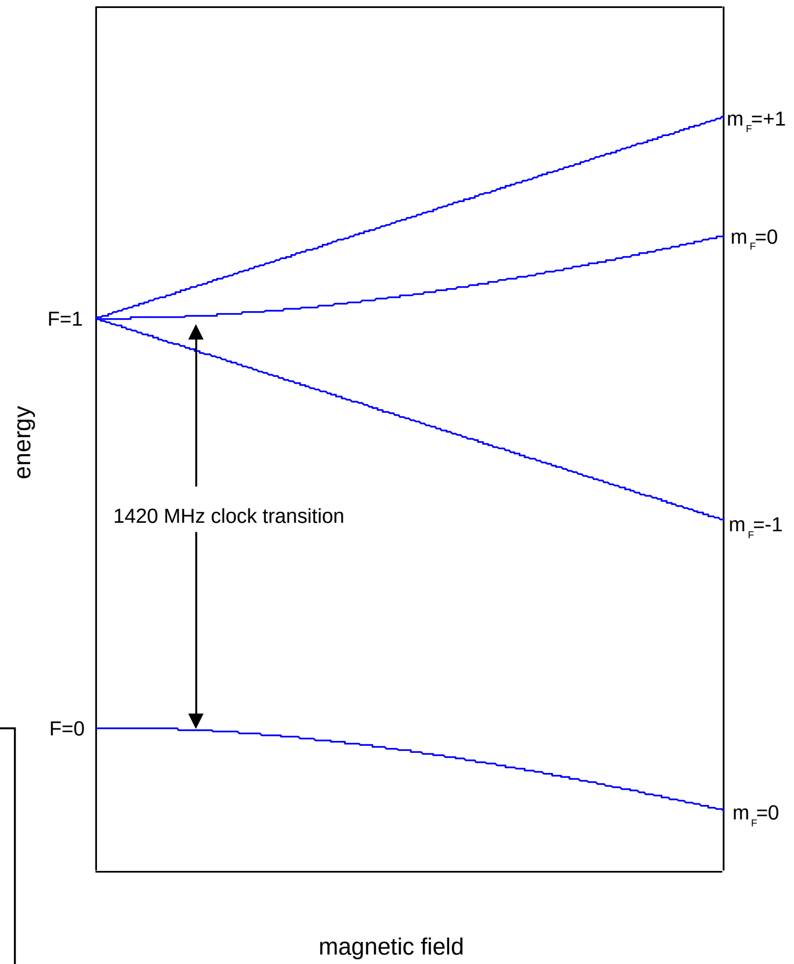
Test of Lorentz symmetry with H maser

Search for sidereal variations in difference of Zeeman and maser frequencies

- Zeeman transition:
  leading order dependence on Lorentz-violating couplings to electron and proton spins
- Maser clock transition:
  no leading order Lorentz-violating effects

Zeeman frequencies
~ 700 Hz ~ 0.5 mG

Differential splitting between two Zeeman transitions < 1 mHz

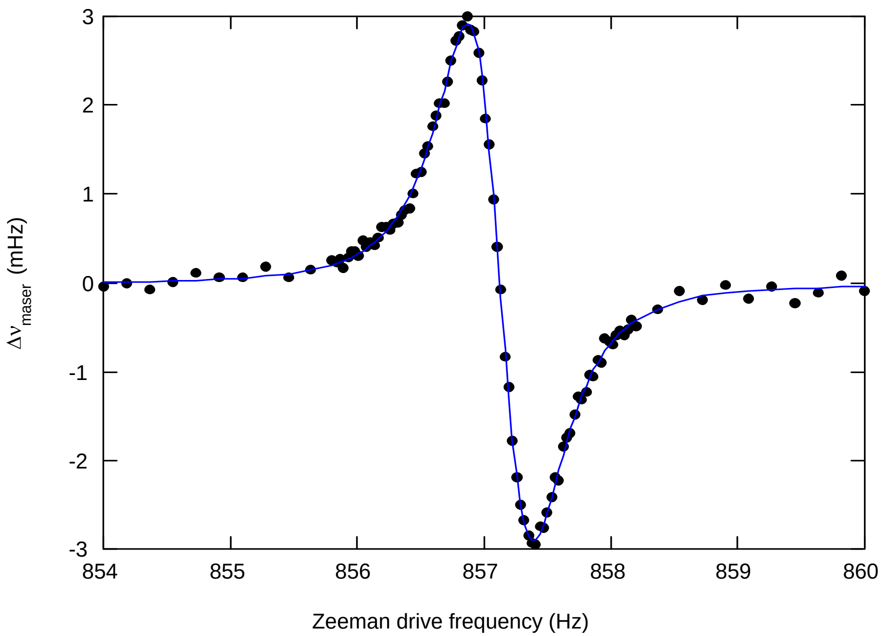


Zeeman frequency measured with a <u>double-resonance technique *(Andresen effect)*</u>

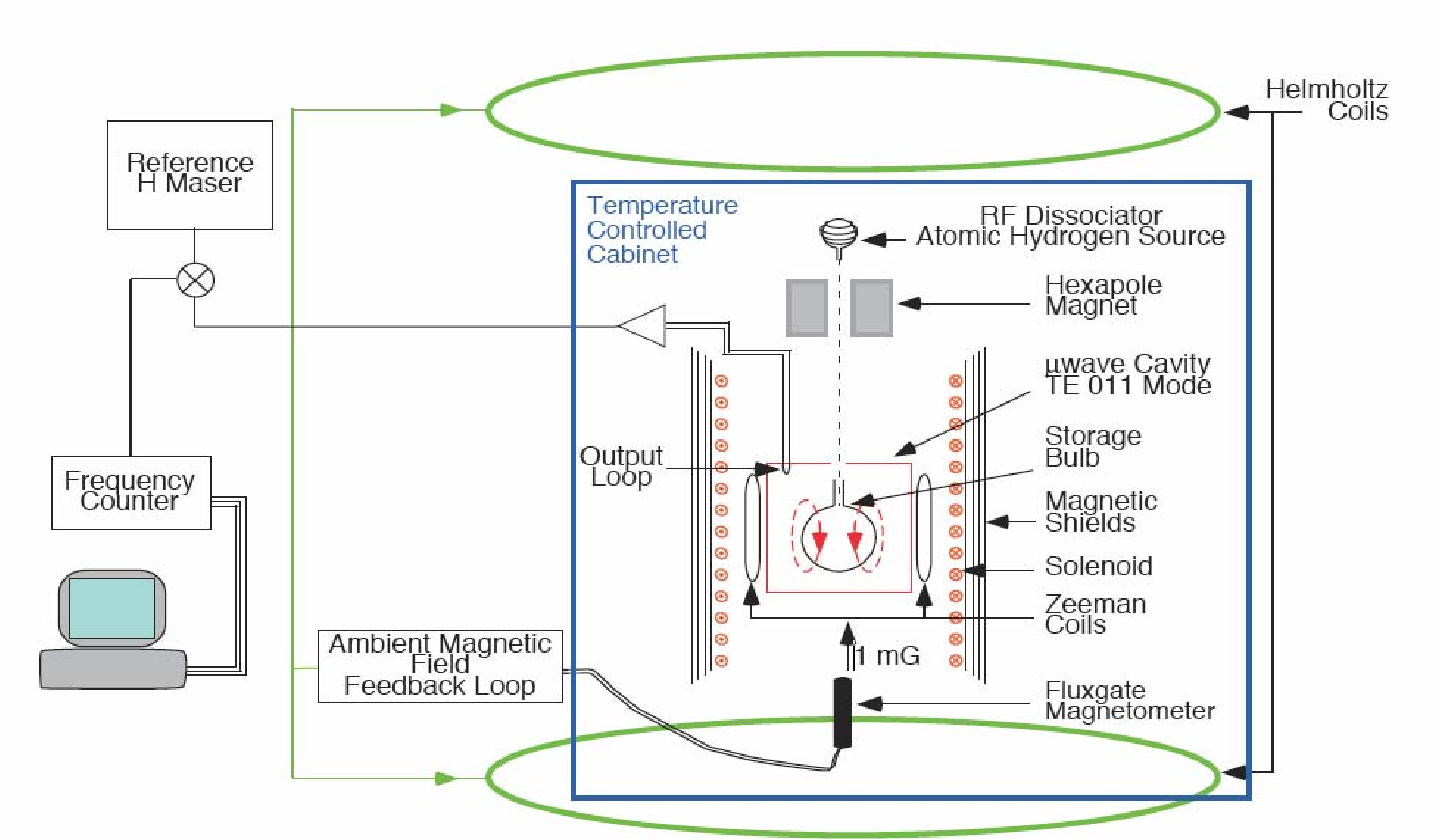
- Very weak Zeeman excitation pulls maser frequency observably with negligible change in state populations

- Zeeman frequency resolution ~ 1 mHz in single sweep of resonance

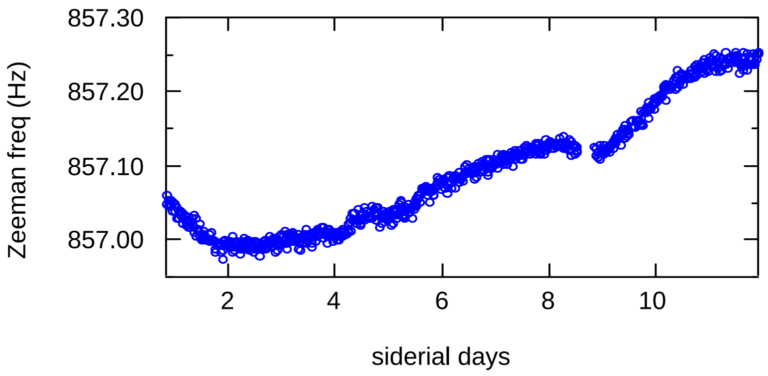
- Maser and Zeeman frequency measurements alternated continuously over many days



Experiment schematic

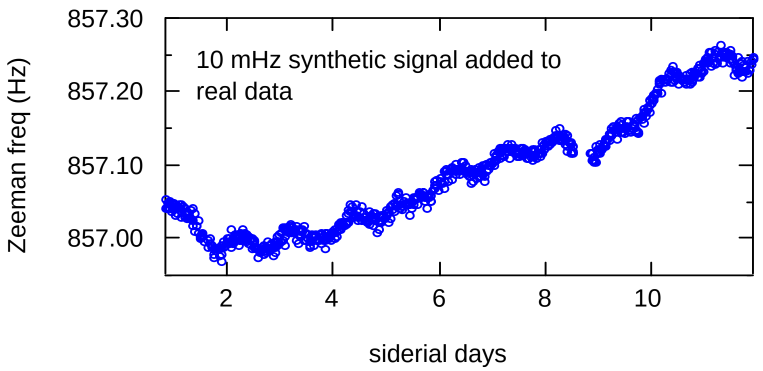


Example hydrogen Zeeman frequency data



Fit model includes:

- *piecewise linear function to account for frequency drift (slope varied for each day)*
- *sinusoid with sidereal period*



10 mHz faux sidereal modulation observable by eye

Fitting gave better than 1 mHz sensitivity to sidereal modulation with small data set from first generation experiment

1–2 orders of magnitude improvement possible with engineering upgrades & more data taking

Data analysis for 2000 H maser experiment

- Three runs: 19 useful days over 5 months

  1-sigma limit: $|\Delta\nu_{Zeeman}|$ = 0.49 ± 0.34 mHz

- Clean bound on Lorentz-violating isotropy effects:

$$\left|\tilde{b}^{e^-}_{X,Y} + \tilde{b}^{p}_{X,Y}\right| \leq (3 \pm 2) \times 10^{-27}\ GeV$$

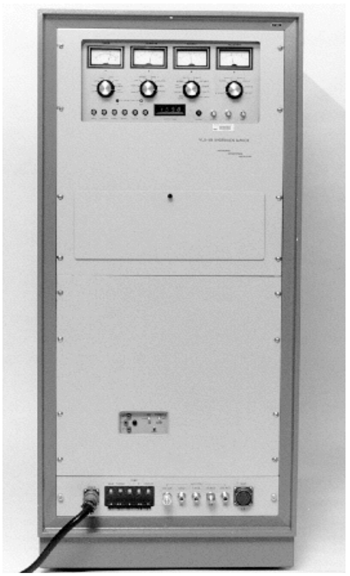
$$\tilde{b}^w_J = b^w_J - m_w d^w_{J0} - \tfrac{1}{2}\varepsilon_{JKL} H^w_{KL}$$

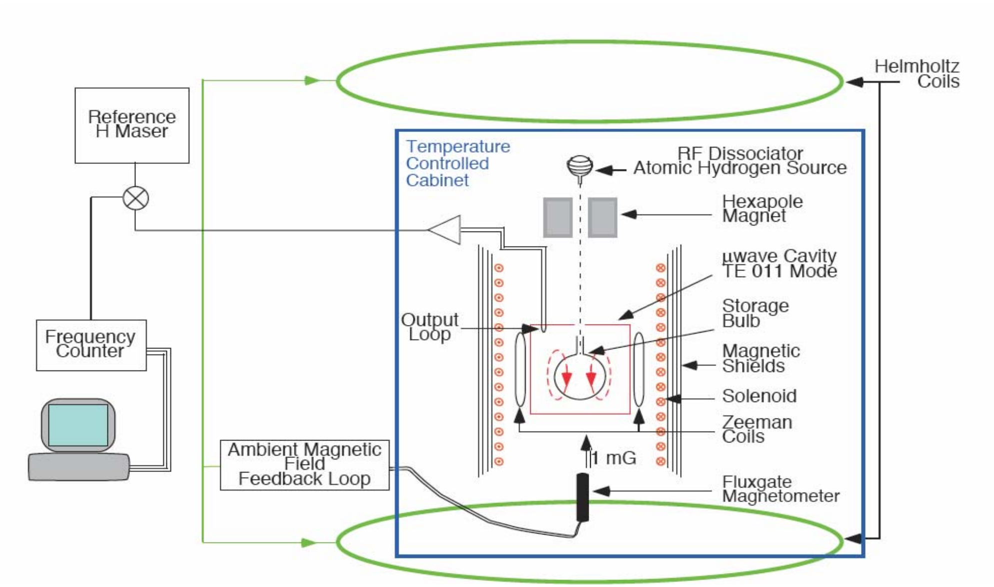
D. Phillips et al., PRD **63**, 111101 (2001)
M. Humphrey et al., PRA **62**, 63405 (2000)
M. Humphrey et al., PRA **68**, 63807 (2003)

Next-generation H maser experiment (ongoing)

Optimized/dedicated H maser for Lorentz symmetry test:

- Improved magnetometry
- Rebuilt internal heater and other systems to reduce meander of internally-generated magnetic fields
- Operation in lab with improved environmental control
- Much greater data taking





Dual noble gas maser

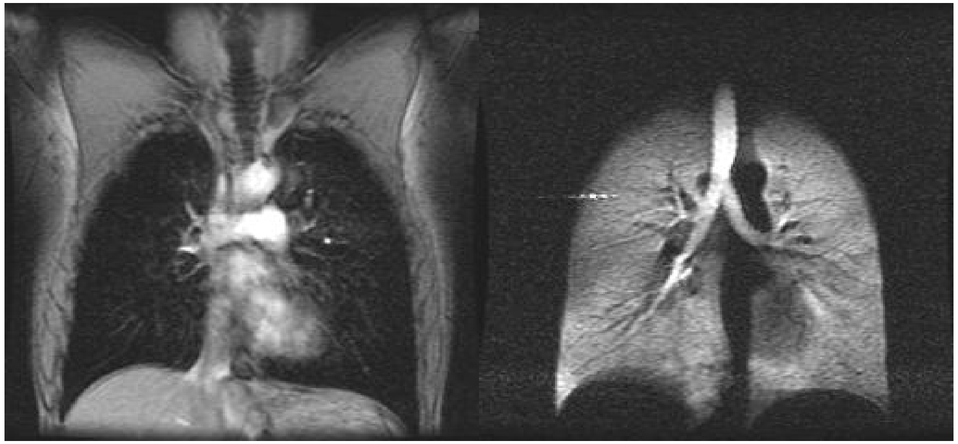
Spin-polarized noble gas NMR

The nuclear spin 1/2 noble gases, ^3He & ^{129}Xe, can be given large spin polarization (~ 50%) via spin-exchange optical pumping

=> inert, magnetized gases, detectable with NMR

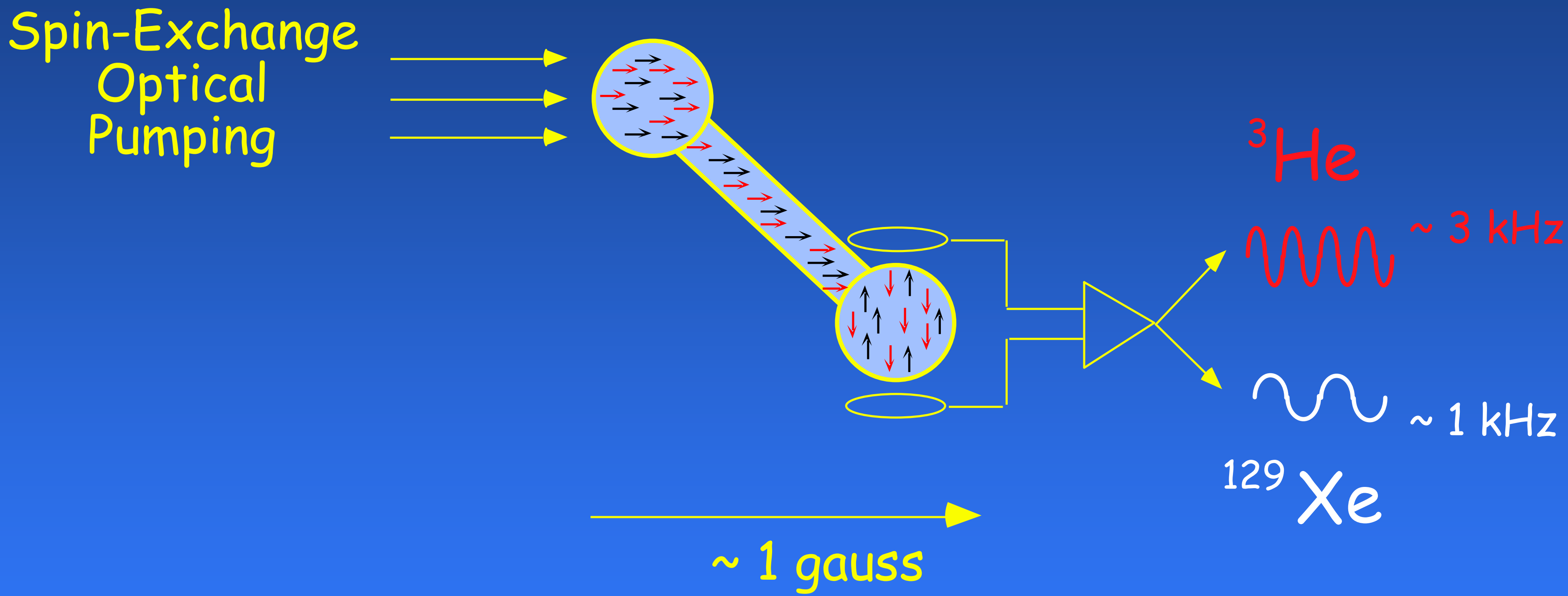
=> biomedical imaging, probing porous media

Conventional proton MRI of chest



MRI of inhaled laser-polarized 3He gas

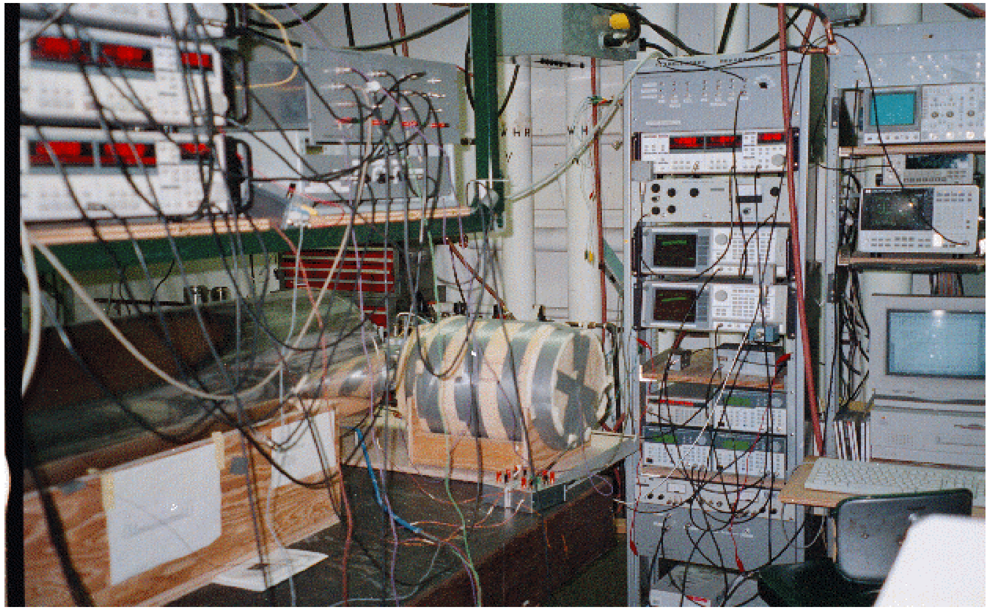
Dual Noble Gas Maser

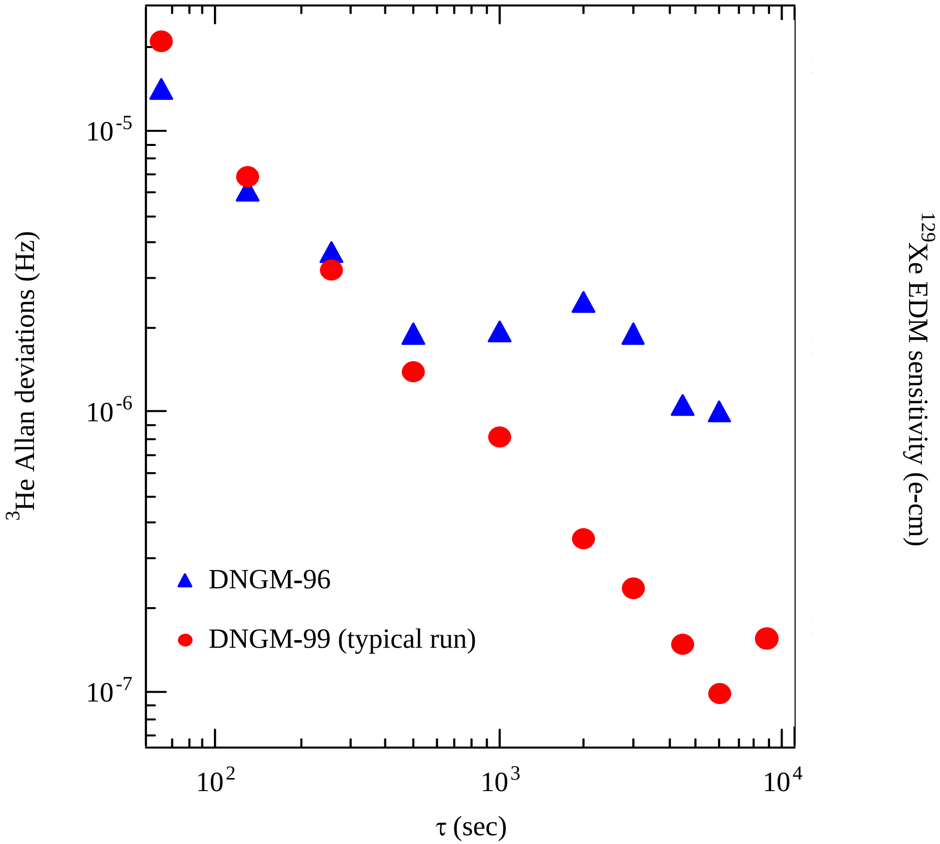


~100 nanohertz frequency sensitivity on timescale of hours

Best test to date of Lorentz and CPT symmetry of the neutron

Testing Lorentz symmetry with noble gas masers





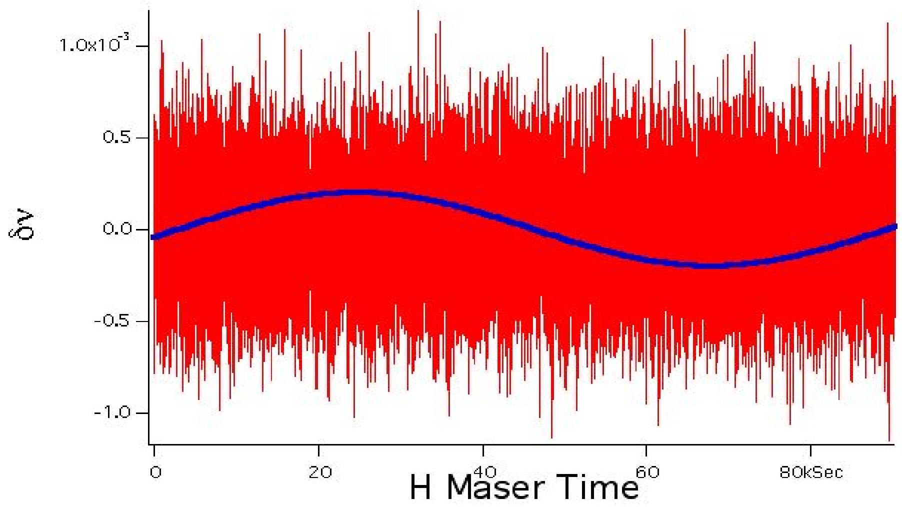
- Lorentz violation couples similarly to ^{3}He and ^{129}Xe (valence neutron)
- ^{3}He/^{129}Xe magnetic moment ratio ~ 3

Data analysis for 2000 isotropy symmetry test

- Fit free-running ^{3}He maser phase data for each sidereal day to model including Larmor precession and sinusoid with sidereal periodicity.
- Runs performed for three cells in both east and west orientations.
- Bound isotropy-violation from weighted means of sidereal modulation coefficients.

$$\delta\nu^{\exp} = \delta\nu_X \sin\omega_{\oplus} t + \delta\nu_Y \cos\omega_{\oplus} t$$

sidereal day frequency



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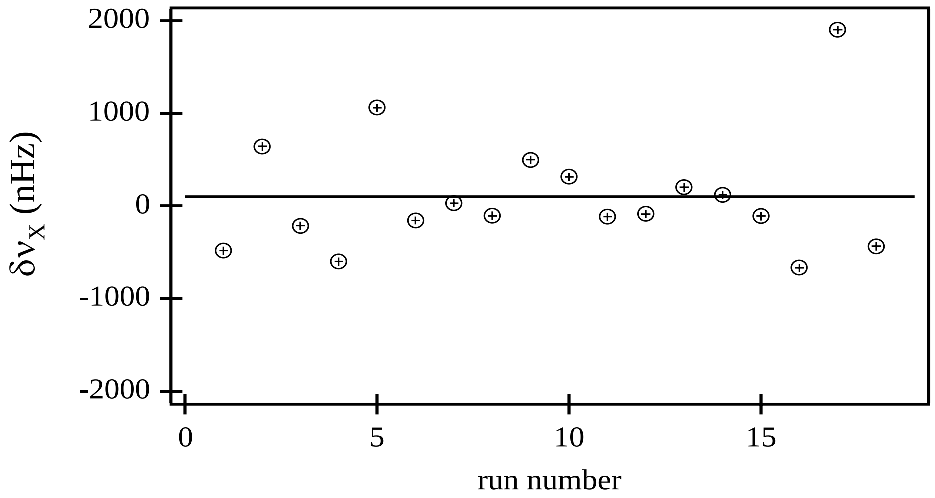


Results for sidereal modulation coefficient $\delta\nu_X$ with cell SE3/east

Result of 2000 isotropy symmetry test

- Eight runs: 90 useful days over 13 months

1-sigma limit: $|\Delta\nu_{^3He\ Zeeman}|$ = 53 ± 45 nHz

- Bound on Lorentz-violating orientation effects assuming only valence neutron is important in ^{3}He & ^{129}Xe:

$$\left|\tilde{b}^{n}_{X,Y}\right| \leq (6 \pm 5) \times 10^{-32}\ GeV$$

$$\tilde{b}^{w}_{J} = b^{w}_{J} - m_{w} d^{w}_{J0} - \tfrac{1}{2}\varepsilon_{JKL} H^{w}_{KL}$$

D. Bear et al., PRL **85**, 5038 (2000)

Best bounds on isotropy-violation (coupling to spins)

Experiment	electron	proton	neutron
^{199}Hg and ^{133}Cs precession frequencies (Hunter, Lamoreaux et al.)	10^{-27} GeV	10^{-27} GeV	10^{-30} GeV
spin-polarized torsion pendulum (Adelberger, Heckel et al.)	10^{-29} GeV	—	—
H maser double resonance (Harvard-Smithsonian)	**10^{-27} GeV**	**10^{-27} GeV** *(clean test)*	—
^{129}Xe/^{3}He maser (Harvard-Smithsonian)	—	—	**10^{-31} GeV**

Naive Planck-scale sensitivity ~ 10^{-19} GeV for neutron & proton

New ^{129}Xe/^{3}He maser result: sensitive test of ***boost***-symmetry for the neutron

- In the **lab frame**, the net effect of Lorentz-violation includes both **rotations** ($b_{X,Y}$) and **boosts** (b_T):

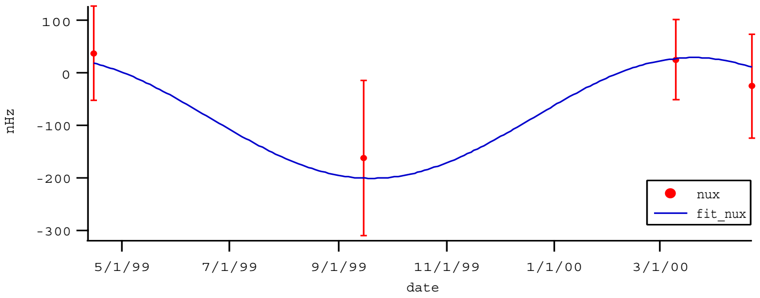
$$b_2 = b_T \beta_L - (b_X + b_T \beta_\oplus \sin \Omega_\oplus T) \sin \omega_\oplus T_\oplus + (b_Y - b_T \beta_\oplus \cos \Omega_\oplus T) \cos \omega_\oplus T_\oplus$$

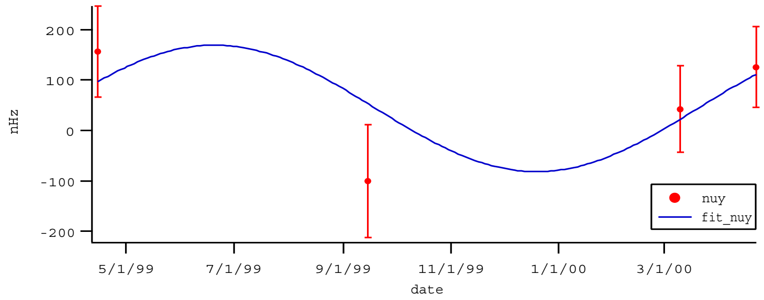
sidereal year frequency

$v_{orbit}/c \sim 10^{-4}$

sidereal day frequency

- We analyzed ^{129}Xe/^{3}He maser data with 3 free parameters b_X, b_Y, b_T





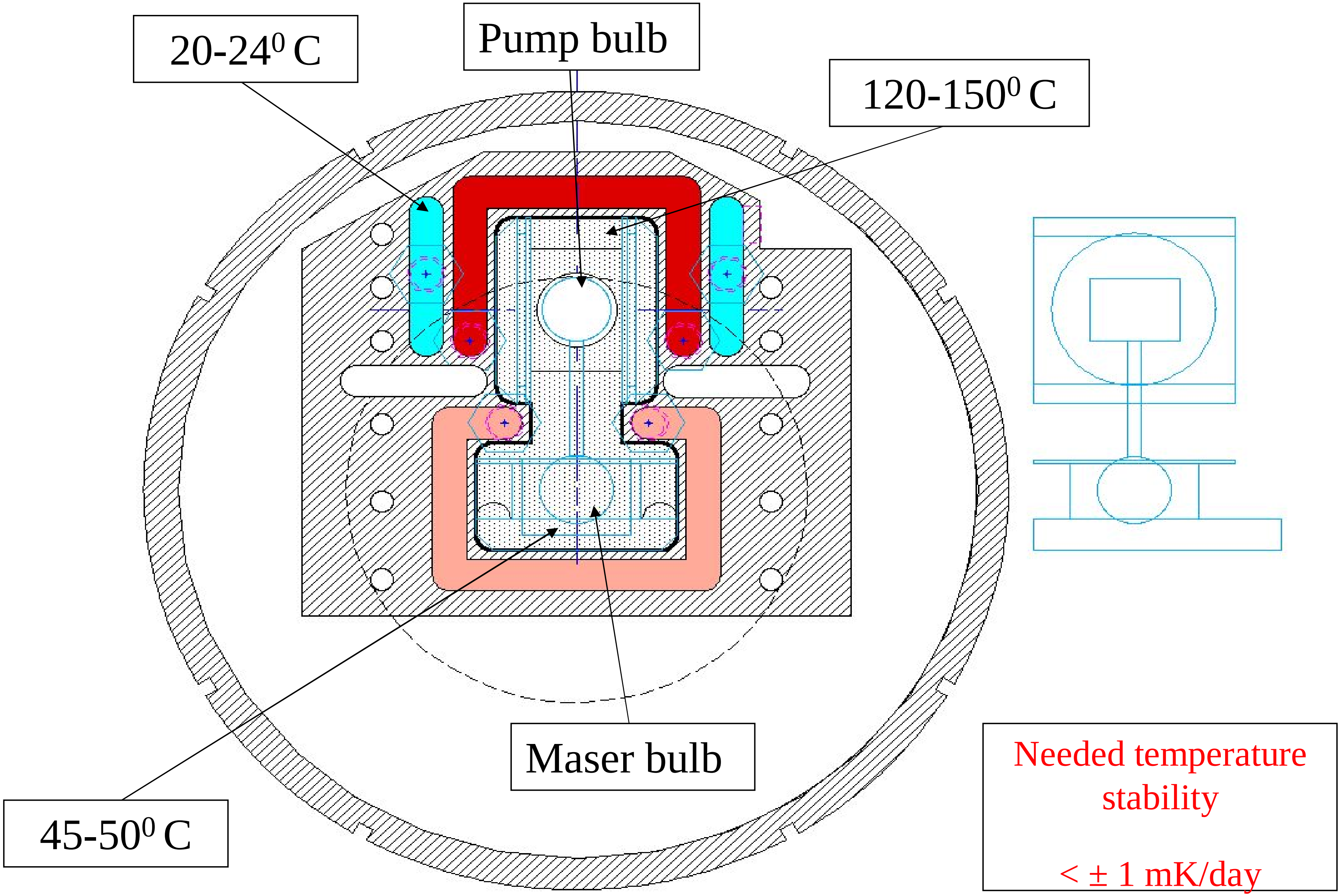
$$b_T^n = (1.5 \pm 0.9)\ 10^{-27}\ GeV$$

F. Cane et al., PRL (2004)

Next-generation noble gas maser experiment (ongoing)

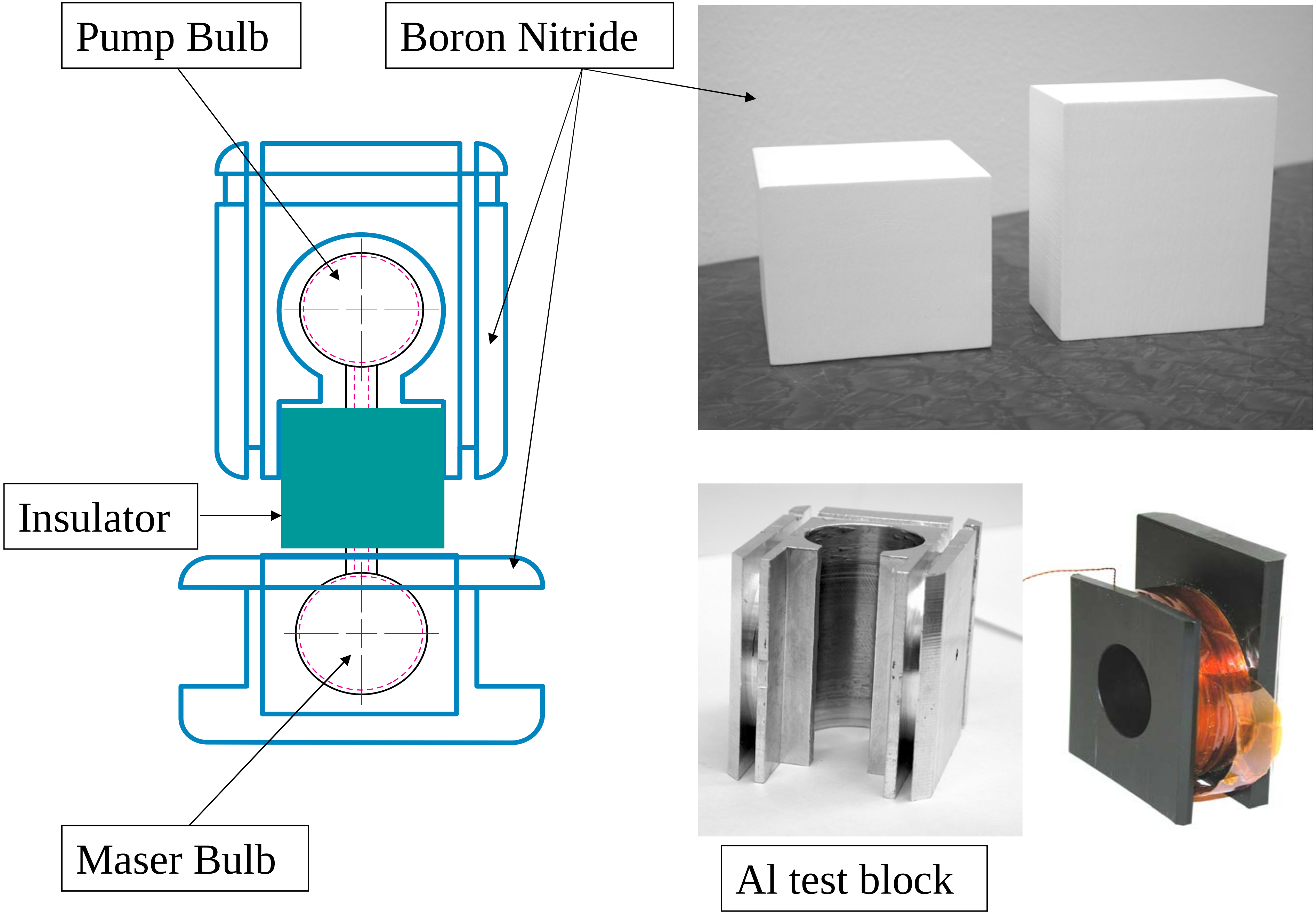
- Optimize cell geometry & gas pressures
- Improve temperature control
- Improve mechanical and thermo-mechanical stability
- Narrow-spectrum optical-pumping laser

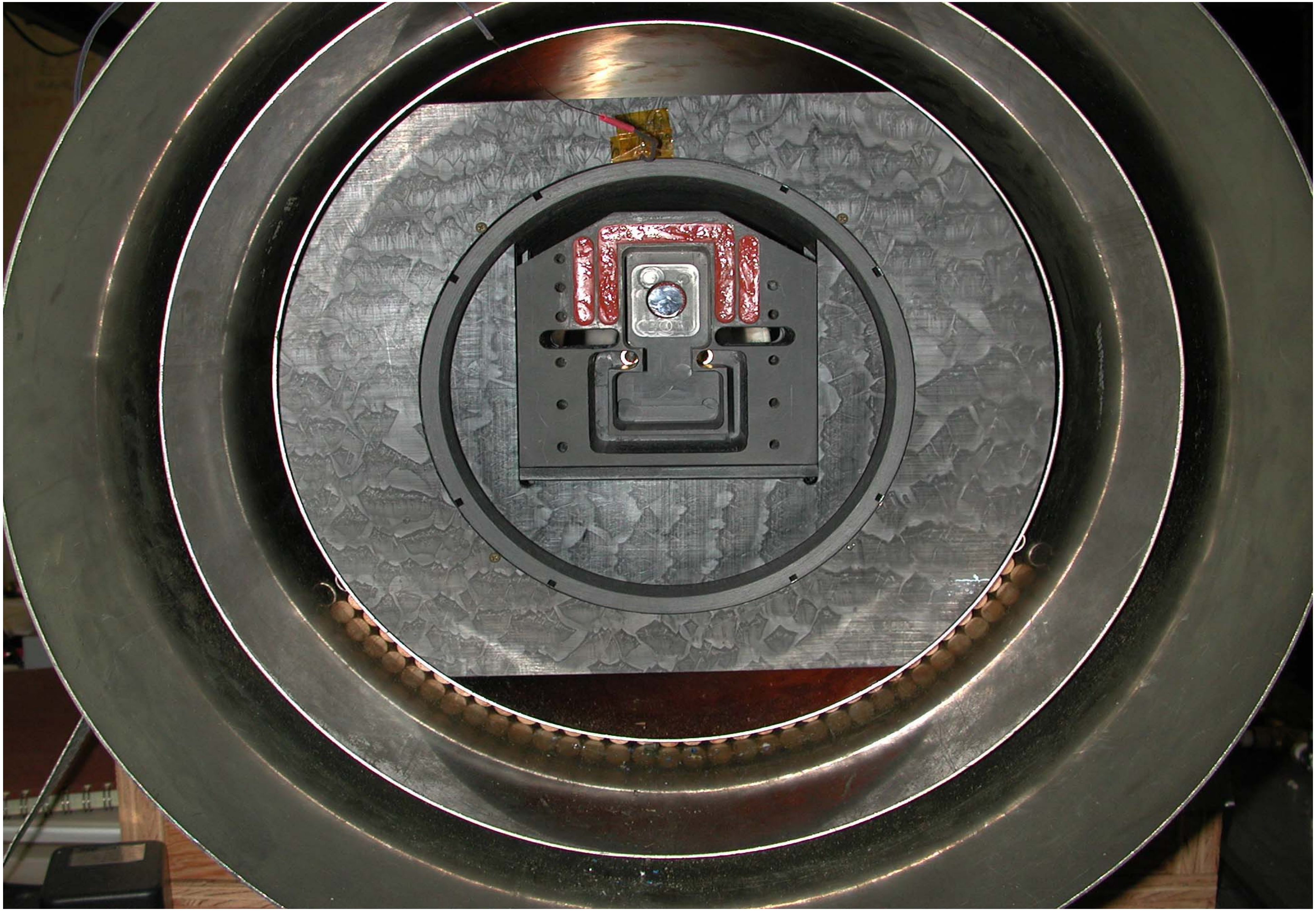
—> improved co-magnetometry
& reduced medium-term frequency noise


20-24^0 C
Pump bulb
120-150^0 C
Maser bulb
45-50^0 C
Needed temperature stability
< ± 1 mK/day

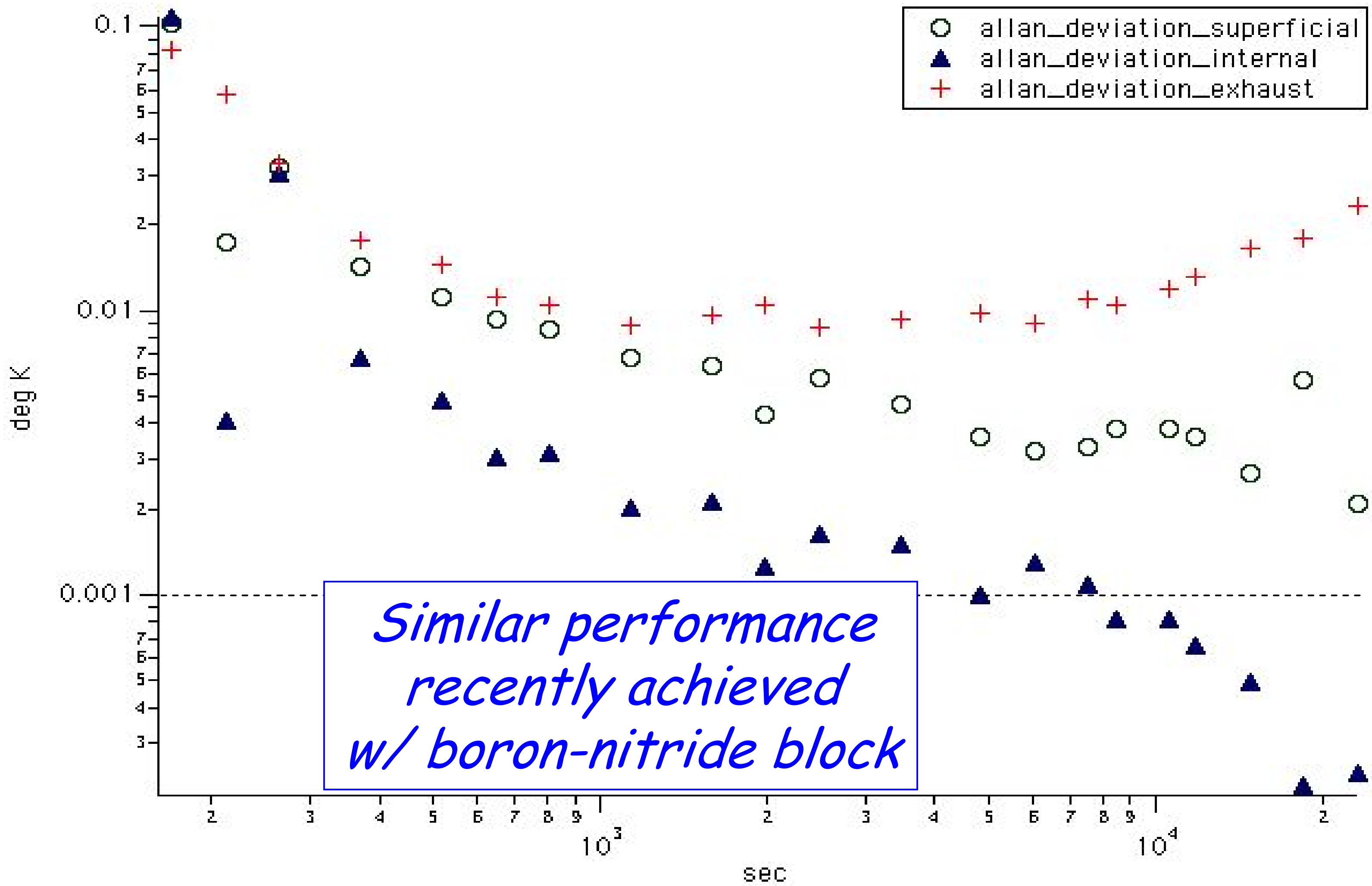
Thermal properties of materials

Material	**Density** (Kg/l)	**Specific Heat** (J/Kg-K)	**Thermal Conductivity** (W/m-K)	**Coefficient of Thermal Expansion** (K^{-1})	**Continuous Service in Air** (Max °C)
Ultem® 1000 PEI, Polyetherimid, unfilled, extruded	1.28	-	**0.12**	$0.56\ 10^{-4}$	**171**
Nylatron® GS Nylon, MoS2 filled, extruded	1.16	-	**0.24**	$0.72\ 10^{-4}$	**104**
Boron Nitride (Grade AX05)	1.9	809	**78/130**	$0.3\text{-}1\ 10^{-6}$	850
Aluminum	2.68	897	**240**	-	-


Pump Bulb
Boron Nitride
Insulator
Maser Bulb
Al test block



Double temperature lock tested with Al block



Target isotropy-violation sensitivity of new experiments

Experiment	electron	proton	neutron
^{199}Hg and ^{133}Cs spectroscopy on rotating table (Amherst)	*10^{-29} GeV*	*10^{-29} GeV*	*10^{-32} GeV*
Optimized spin-polarized torsion pendulum (U. Washington)	*10^{-31} GeV*	—	—
K/^{3}He spectroscopy (Princeton)	*10^{-30} GeV*	—	*10^{-33} GeV*
Optimized H maser double resonance (Harvard-Smithsonian)	***10^{-29} GeV***	***10^{-29} GeV*** *(clean test)*	—
Upgraded noble gas masers (Harvard-Smithsonian)	—	—	***10^{-33} GeV***

How much better can one do?

Experimental challenges

- Narrow bandwidth, high S/N spin resonance
- Good co-magnetometry
- Excellent long-term stability and immunity from environment

Current limitations

- Thermal noise
  (2-5 orders of magnitude worse than shot noise)
- Properties of materials
  (thermal expansion and conductivity, magnetic permeability, etc.)
- Slowness of Earth's rotation

Modest proposals

- Develop facilities to aid Lorentz symmetry experiments:
  e.g., a low-noise rotating platform for (modest-sized) experiments

- Community commitment to support 2+ experiments (of roughly comparable sensitivity) in each sector
  —> a systematic attack on problem

How ?

Immodest questions

- What is the relative magnitude of Lorentz-violating effects between different sectors?
- Relative magnitude *within* a sector?
  "Enhancement factors" to aid experimentalists?