Axion dark matter detection with quantum gyroscopes

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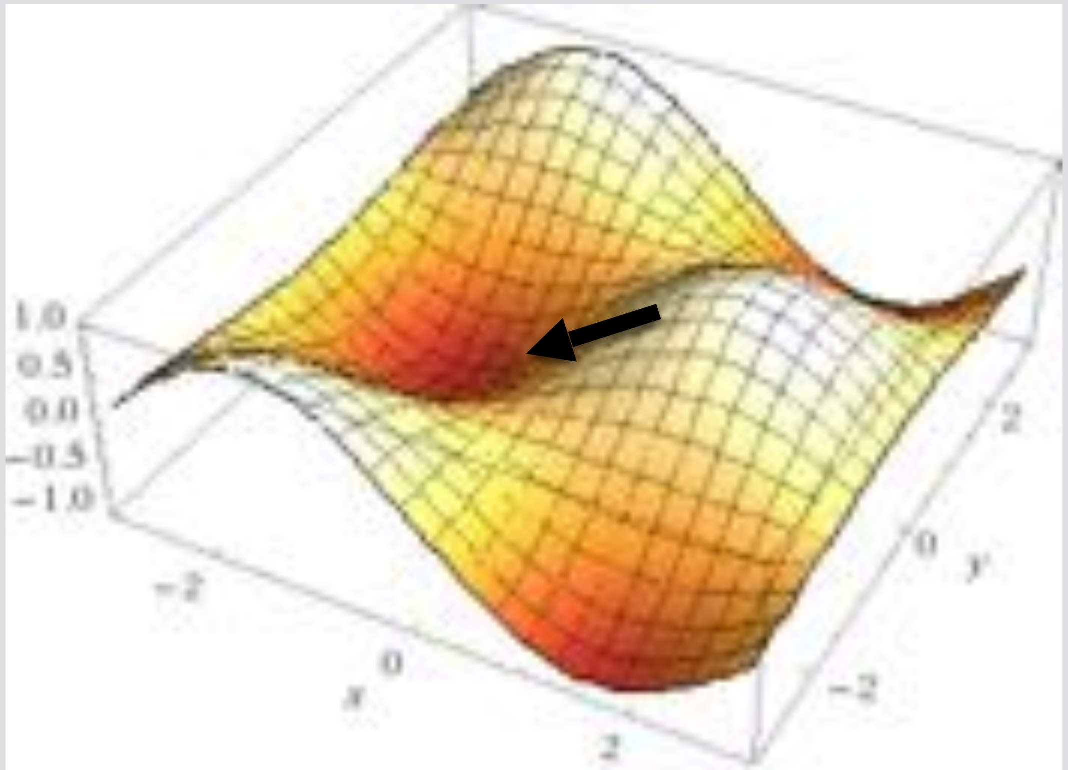
Princeton Axion Project

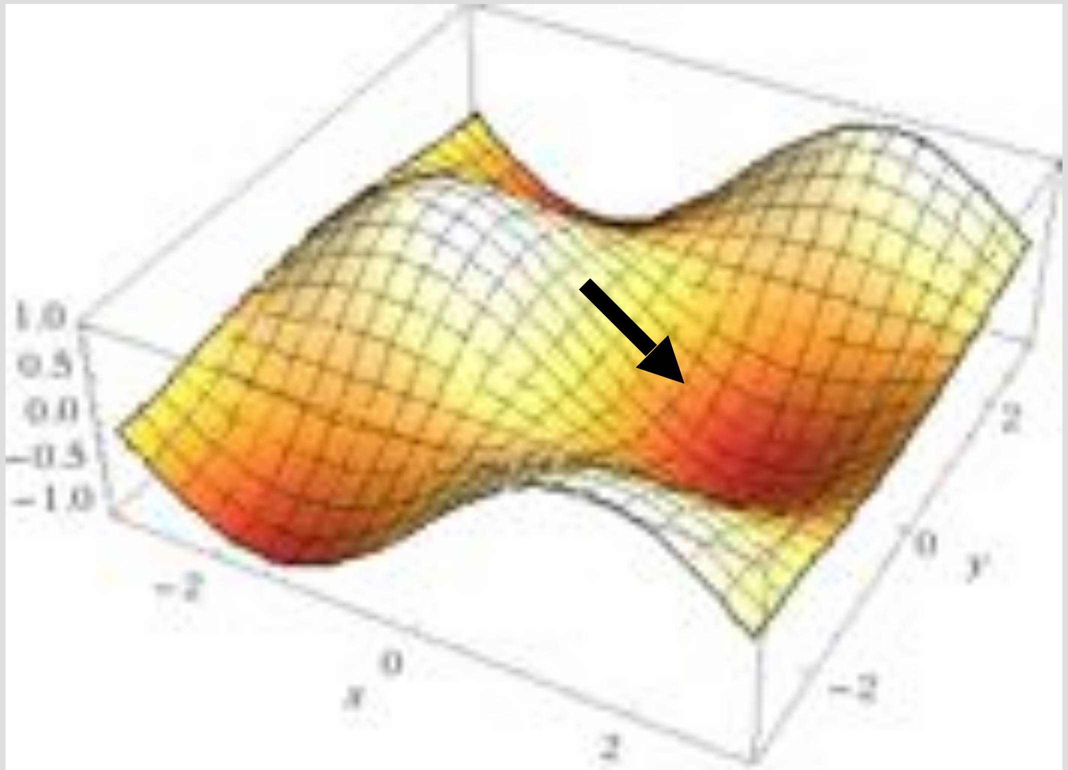
Axion splits
Spin Up & Down levels

$$\mathcal{L} = (\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$$

$$a = a_0 \cos\omega_C t$$



a at $t = 0$



a at $t = \pi/\omega_C$

Quantization axis defined by gradient of axion field
amplitude of splitting is oscillating

Axion splits Spin Up from Down

- magnitude determined by dark matter density, velocity and coupling strength

$$\vec{\nabla} a \sim \vec{p}_a a \sim m_a \vec{v} a_0 \cos m_a t. \qquad \rho_{DM} = \frac{1}{2} m_a^2 a^2$$

$$H_{ax} \sim 10^{-25}\ \mathrm{eV} \left(\frac{g_{a\bar{\psi}\psi}}{10^{-10}\ \mathrm{GeV}^{-1}} \right) \left(\frac{v}{10^{-3}} \right) \left(\sqrt{\frac{\rho_{DM}}{(0.04\ \mathrm{eV})^4}} \right) \cos m_a t$$

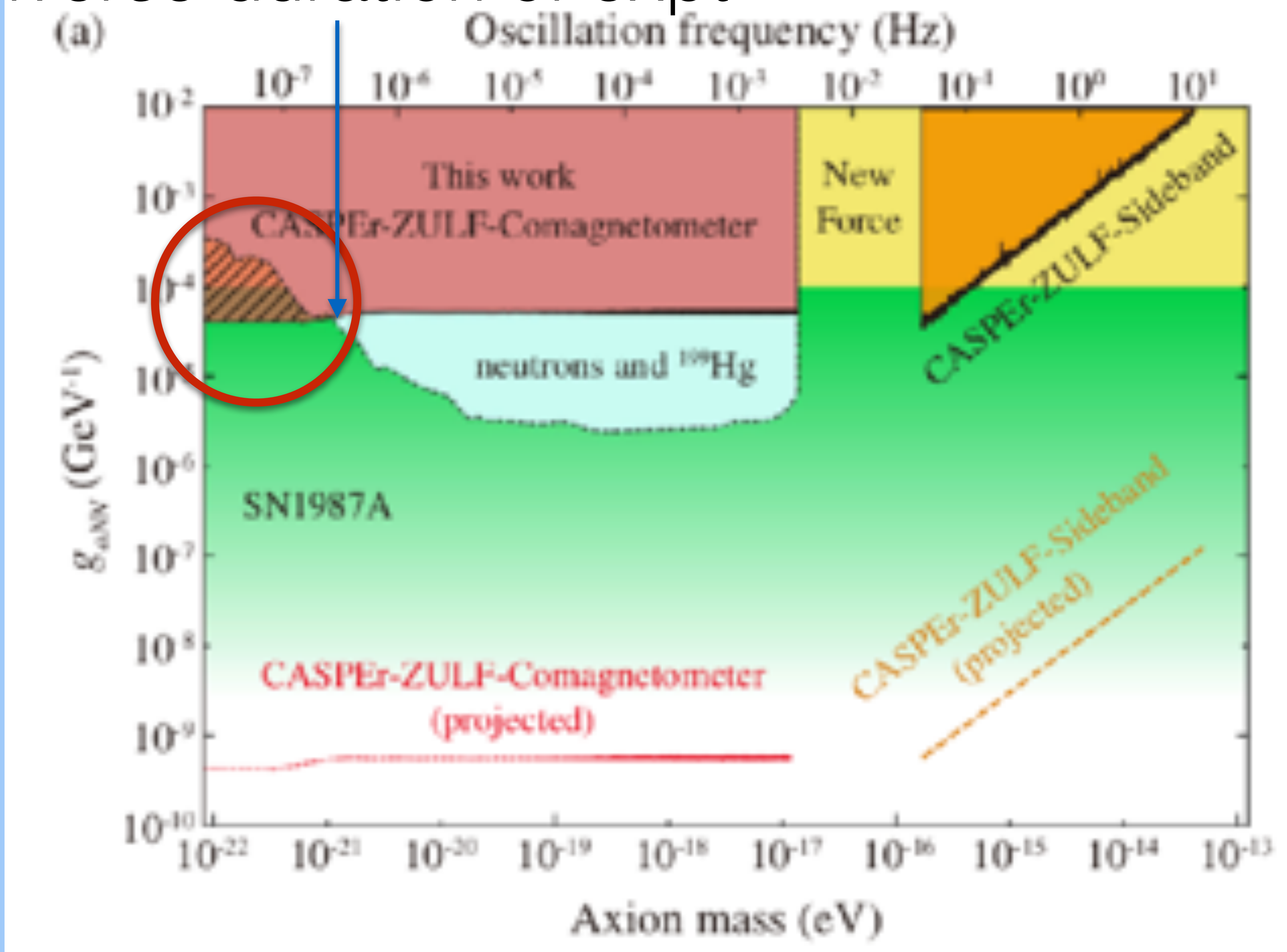
- Intuition: splitting of a magnetic moment in a magnetic field;

$$B \sim g_{a\bar{\psi}\psi} v \sqrt{2\rho_{DM}}/\gamma_\psi$$

- Spin-precession ✅ spin-flip ✅ spin-alignment ✅
  ⇒ Not shielded by magnetic shielding

Existing constraints on this coupling

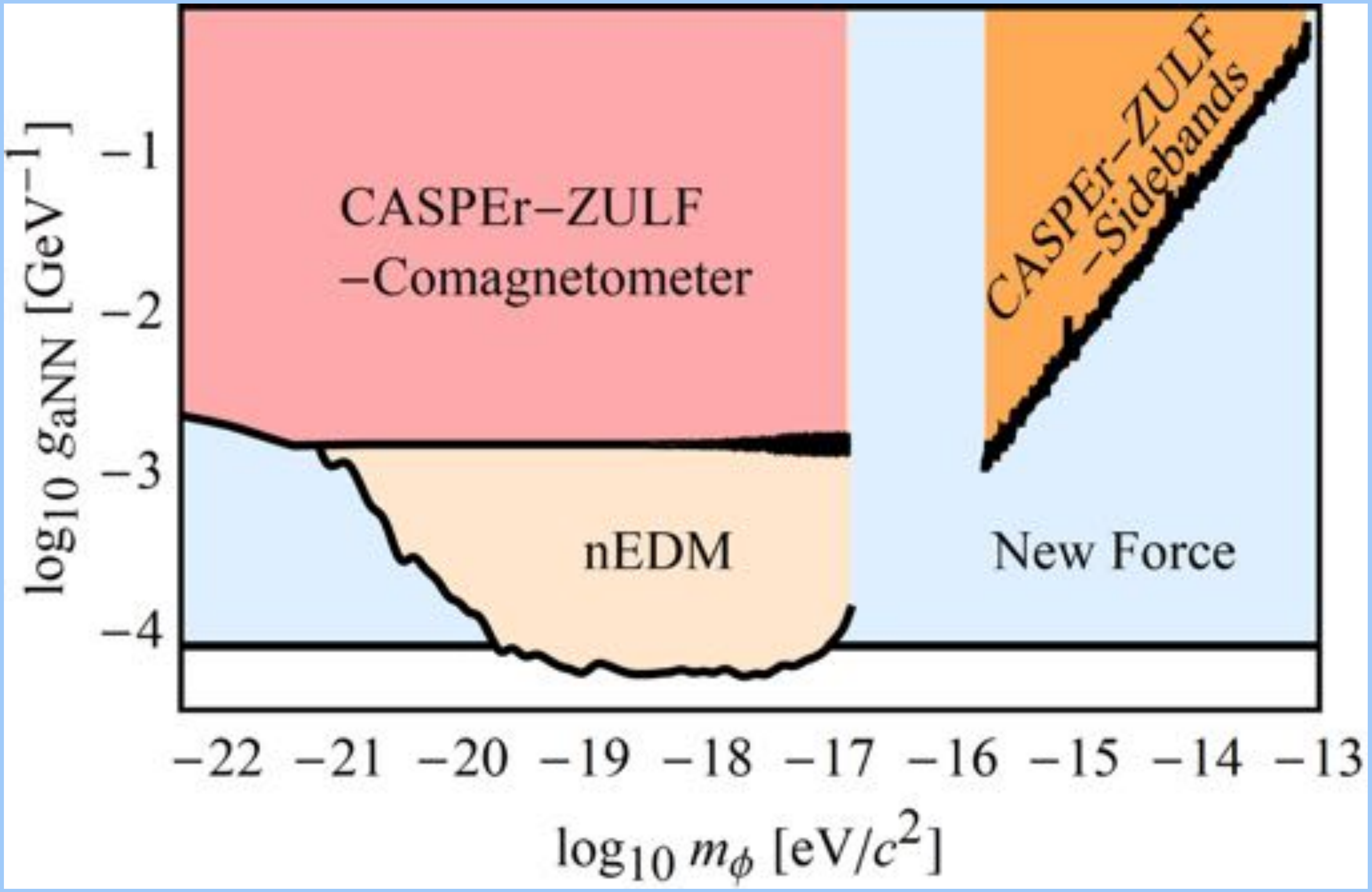
inverse duration of expt



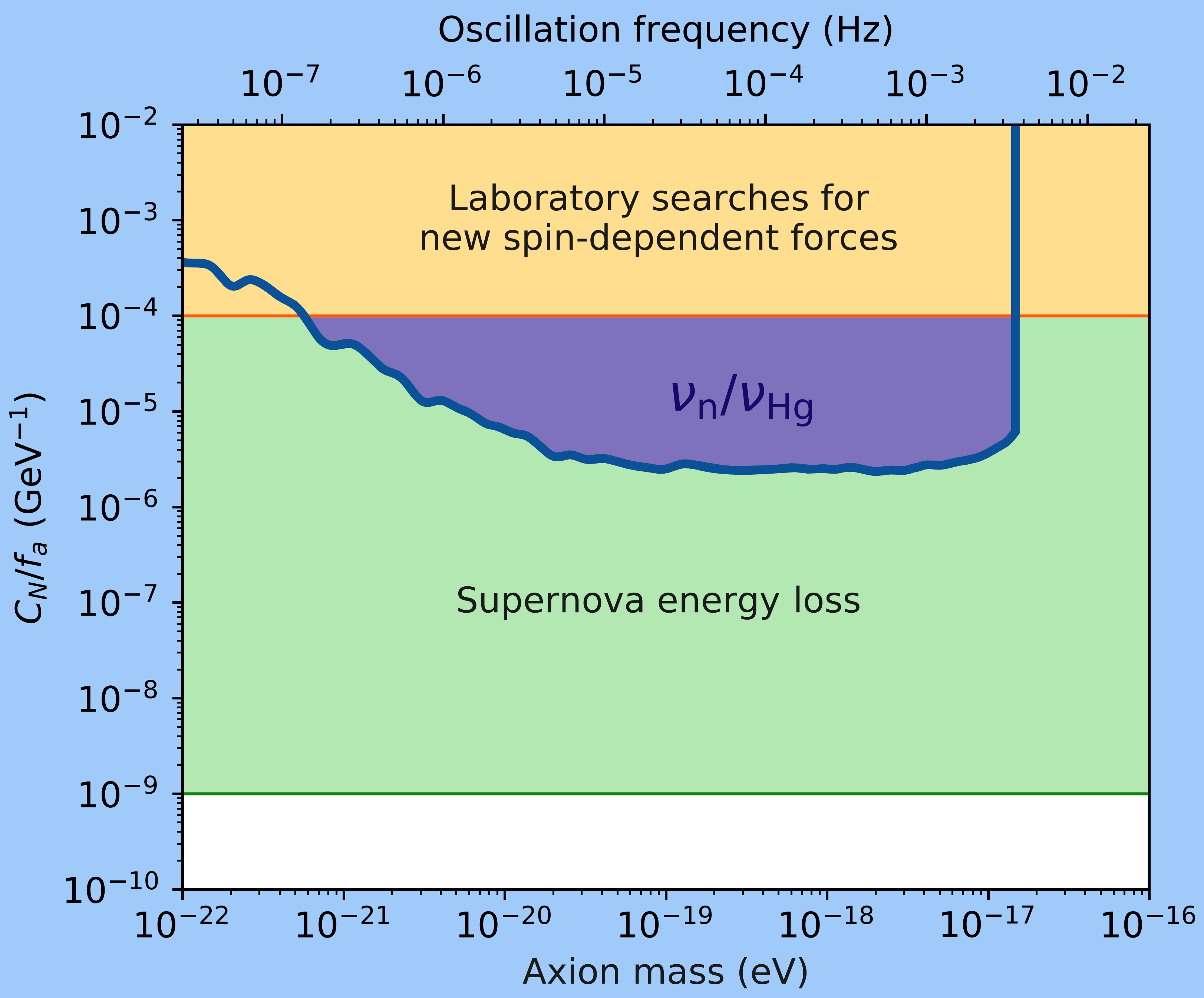
$$\sin(2\pi t/\tau) \approx 2\pi t/\tau$$

$$\cos(2\pi t/\tau) \approx 1 - (2\pi t/\tau)^2/2$$

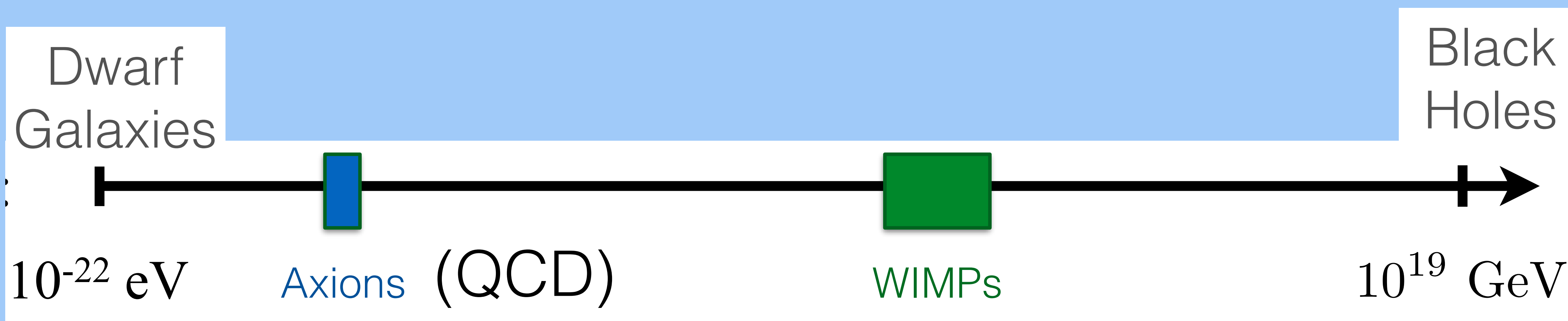
Updated constraints?

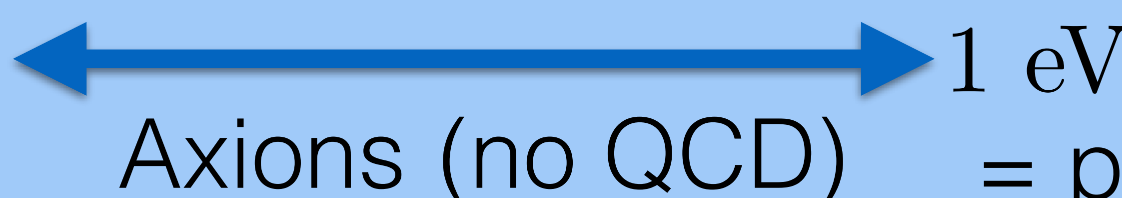


Existing constraints



‘Fuzzy’ Dark Matter





= pseudo-Goldstone boson

Fuzzy Dark Matter (Hu, Barkana, Gruzinov, 2001)

(Hui, Ostriker, Tremaine, Witten 2017)

Fuzzy Dark Matter

Light axion dark matter — mass $\mathrm{m} \sim 10^{-22}\,\mathrm{eV}$

Fuzzy dark matter
Hu, Barkana, Gruzinov

- A natural candidate for such a light particle is a pseudo Goldstone boson.

- Concrete realization: an angular field of periodicity $2\pi F$ i.e. an axion-like field with a potential from non-perturbative effects (not QCD axion).

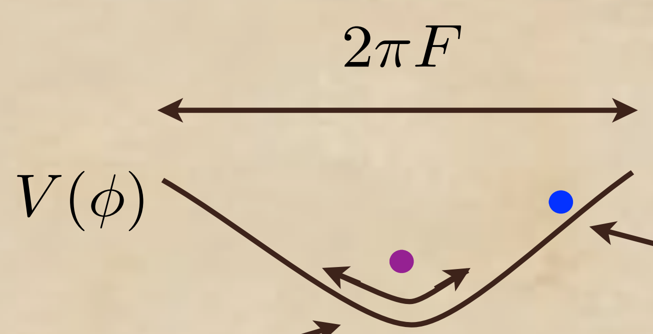
$$\mathcal{L} \sim -\frac{1}{2}(\partial\phi)^2 - \Lambda^4(1 - \cos[\phi/F])$$

$$m \sim \Lambda^2/F$$

(see Monday's talks)

- Relic abundance:

(standard story - see Kolb & Turner; review by Marsh)



$\phi \sim F$ at early times until $H \sim m$

$\rho_\phi \sim m^2 F^2$, $\rho_{\mathrm{rad.}} \sim H^2 M_{\mathrm{pl}}^2 \sim m^2 M_{\mathrm{pl}}^2 \sim T^4$

subsq. oscill. : $\rho_\phi \propto a^{-3}$

self – interaction can be ignored

$$\Omega_{\mathrm{matter}} \sim \left(\frac{F}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

(low scale inflation)

Slide from L. Hui

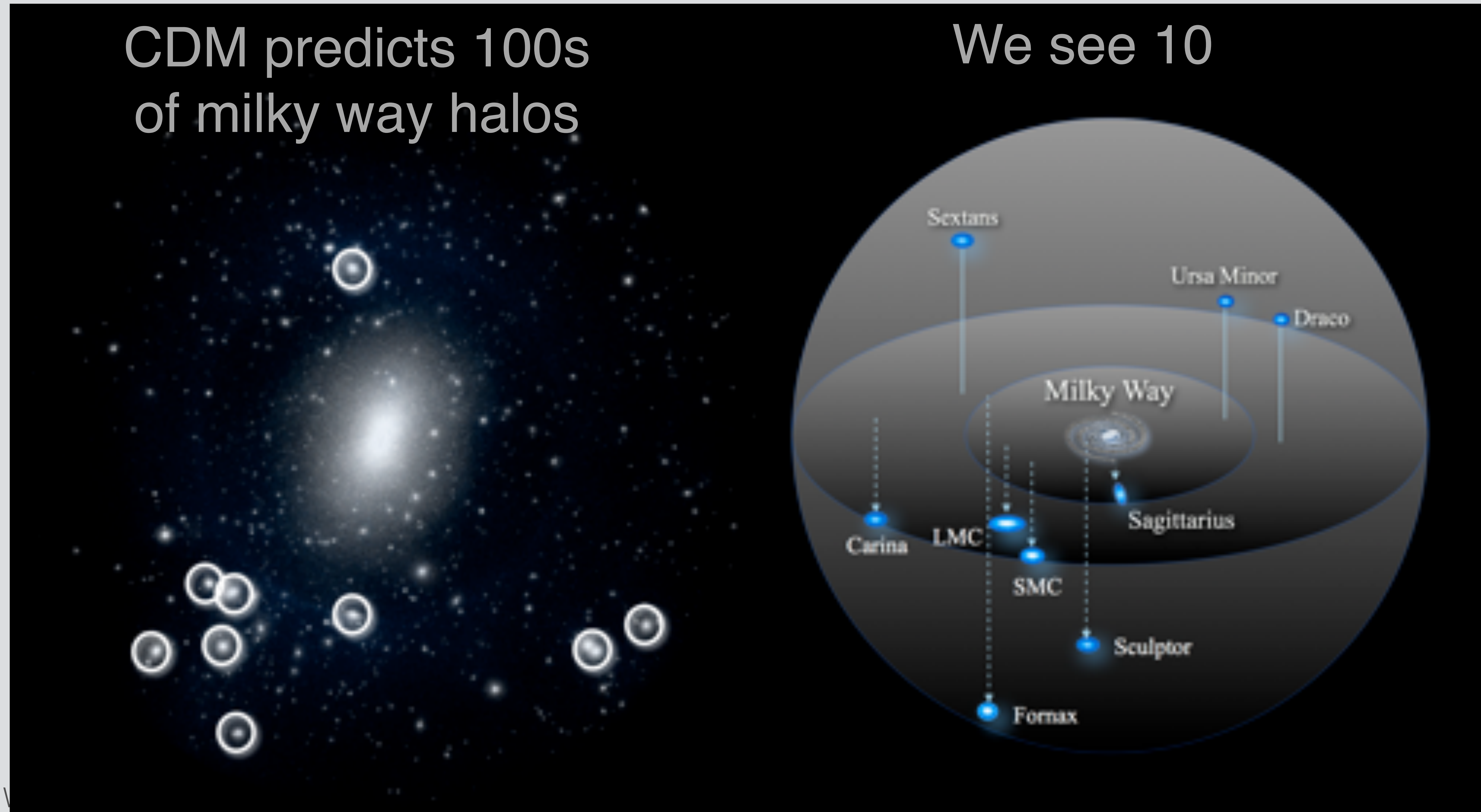
Why haven't Globular clusters collapsed?

Fuzzy dark matter reduces dynamical friction by x10

Dynamical friction issue: Tremaine 1976

Why isn't there more small scale structure?

Dwarf galaxies; Rotation curves

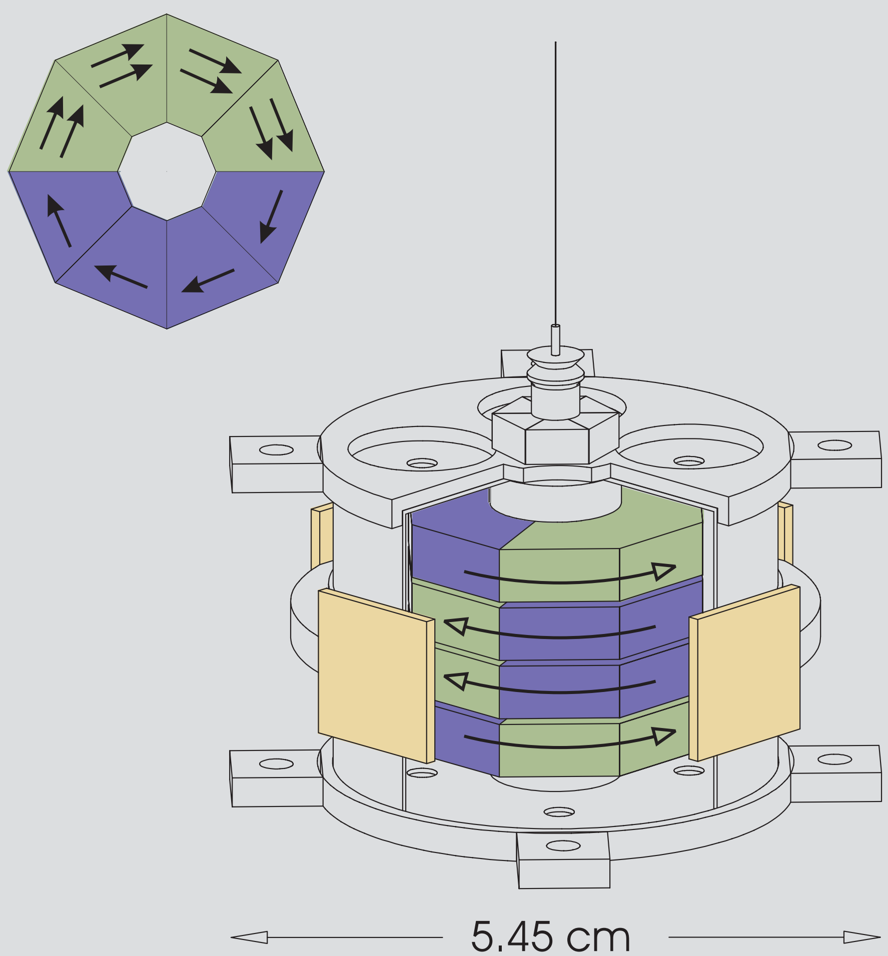


Quantum weirdness at galactic scales

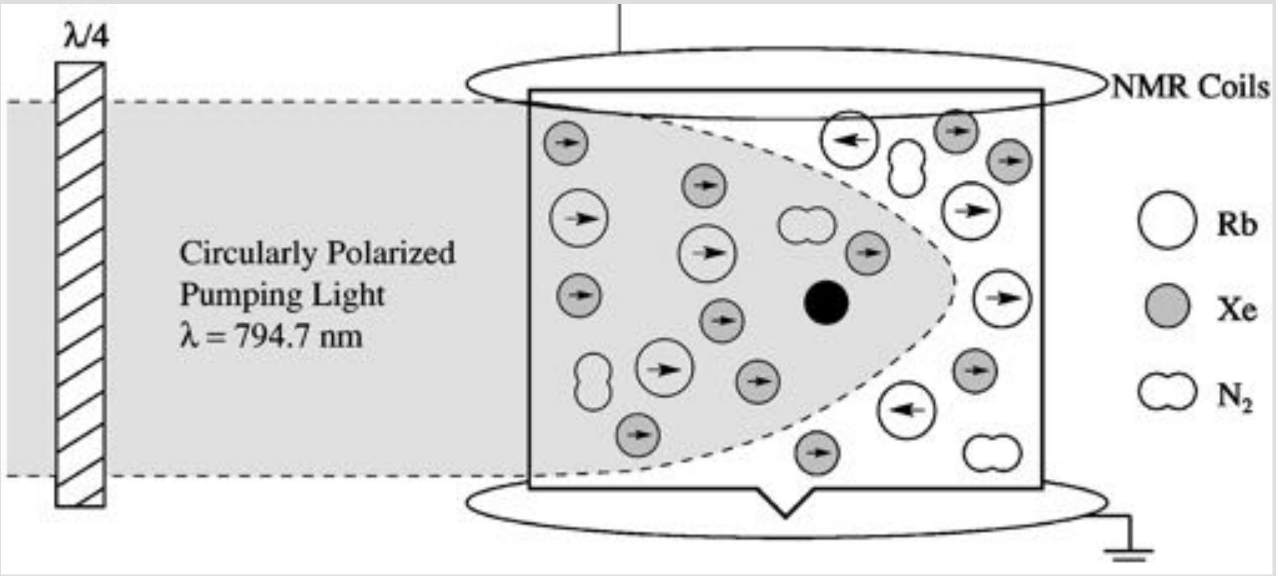
- Tunneling out of dwarf galaxies
- Soliton at center of galaxy
- Interference fringes

Quantum-mechanical (spin) Gyroscopes

Electronic Spins



Nucleonic Spins



Making a Spin Polarized Pendulum

- Alternating Alnico and SmCo5 magnets
  - At 1 Tesla, Alnico has a spin density of $\sim 7.8 \cdot 10^{22}$ spins/cc
  - At 1 Tesla, SmCo5 has a spin density of $\sim 4.2 \cdot 10^{22}$ spins/cc

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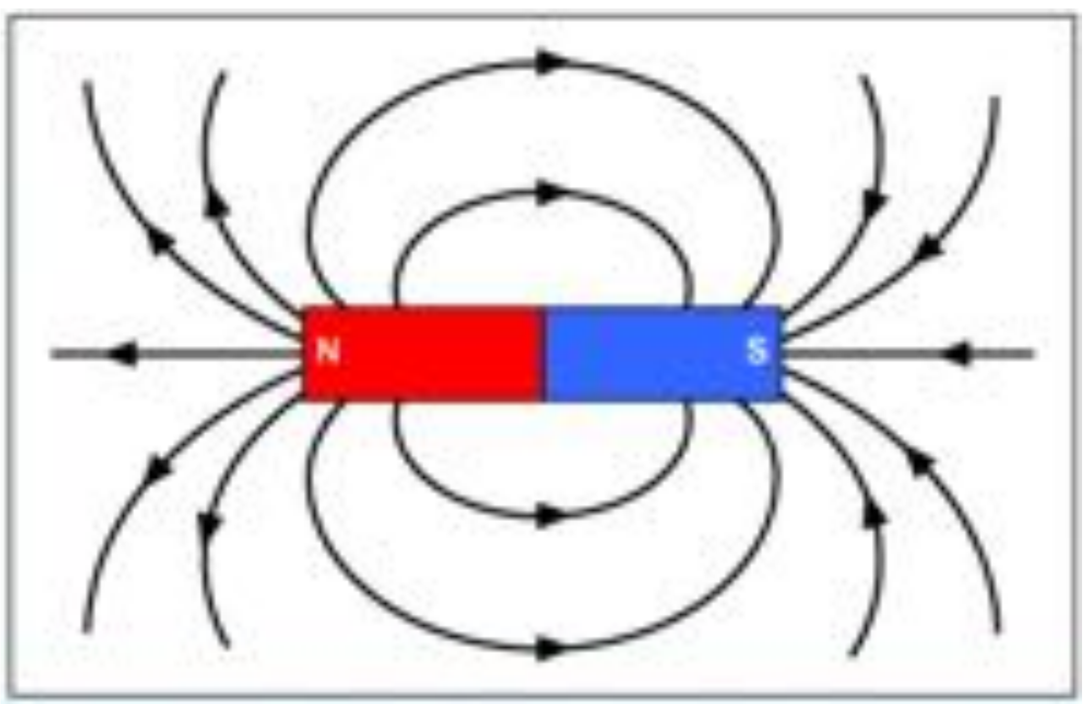

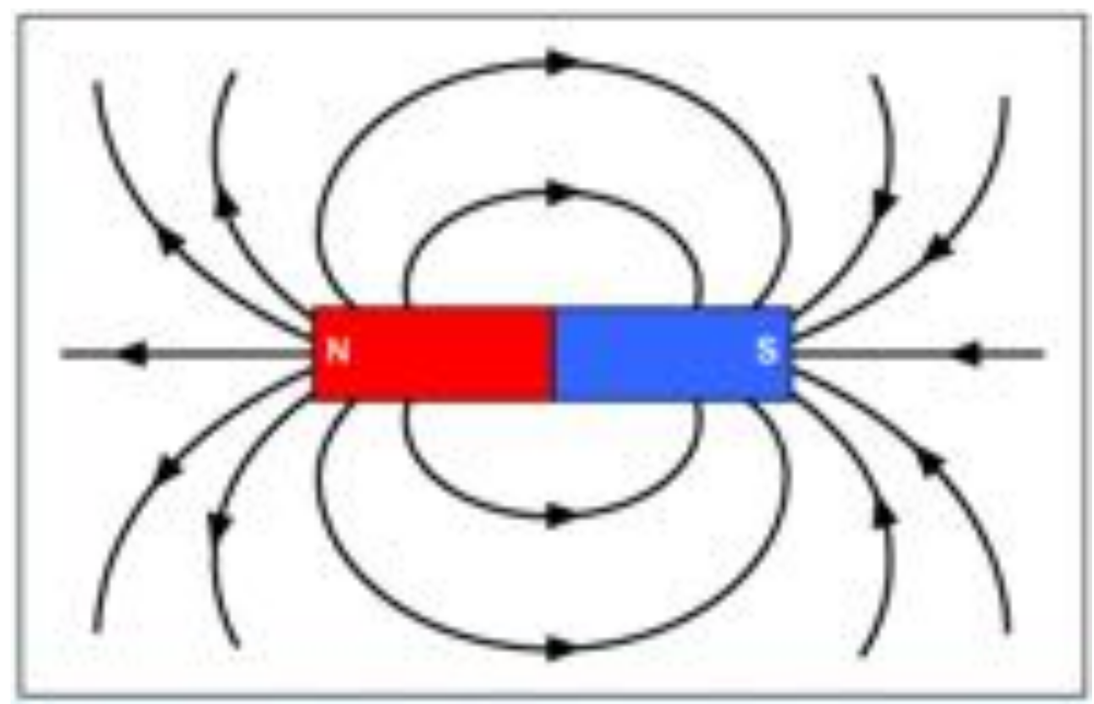

Making a Spin Polarized Pendulum

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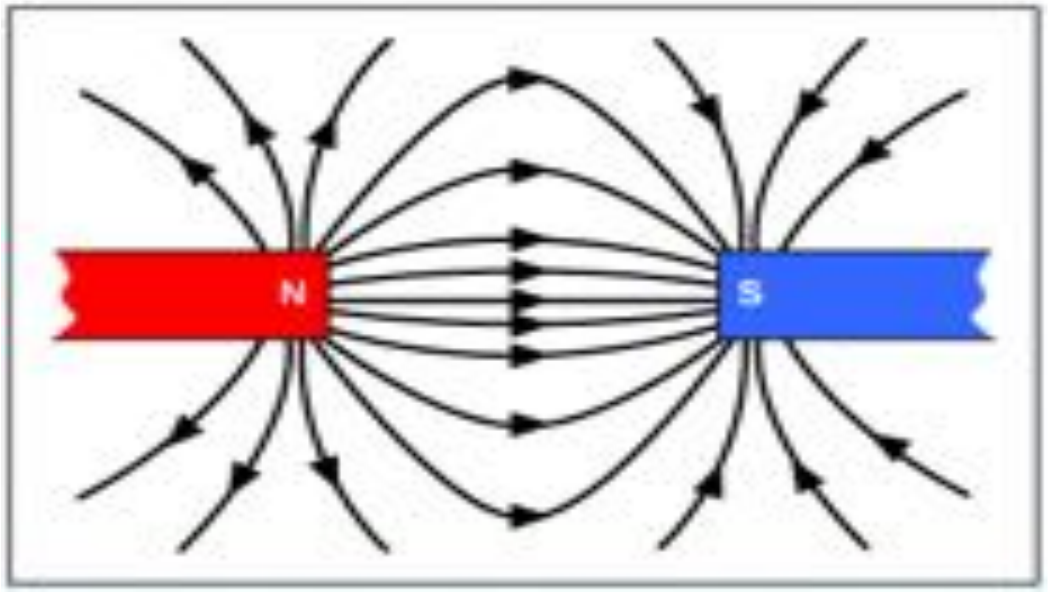
  - At 1 Tesla, $SmCo_5$ has a spin density of $\sim 4.2 \cdot 10^{22}$ spins/cc



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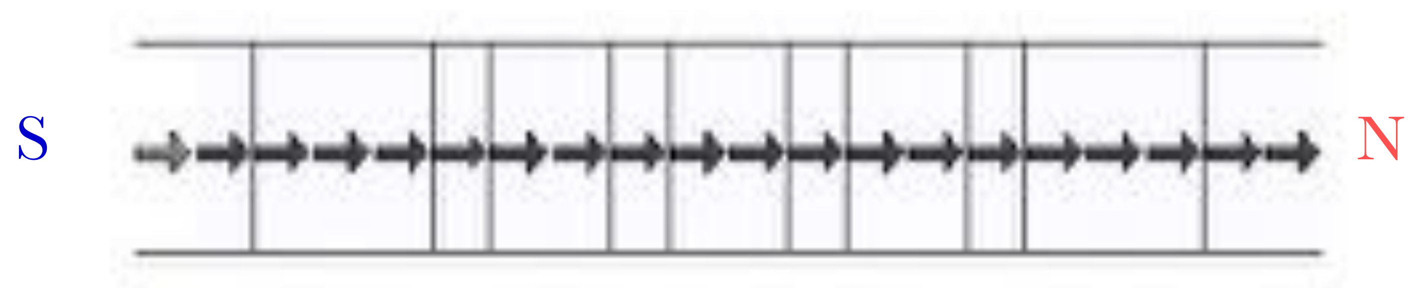
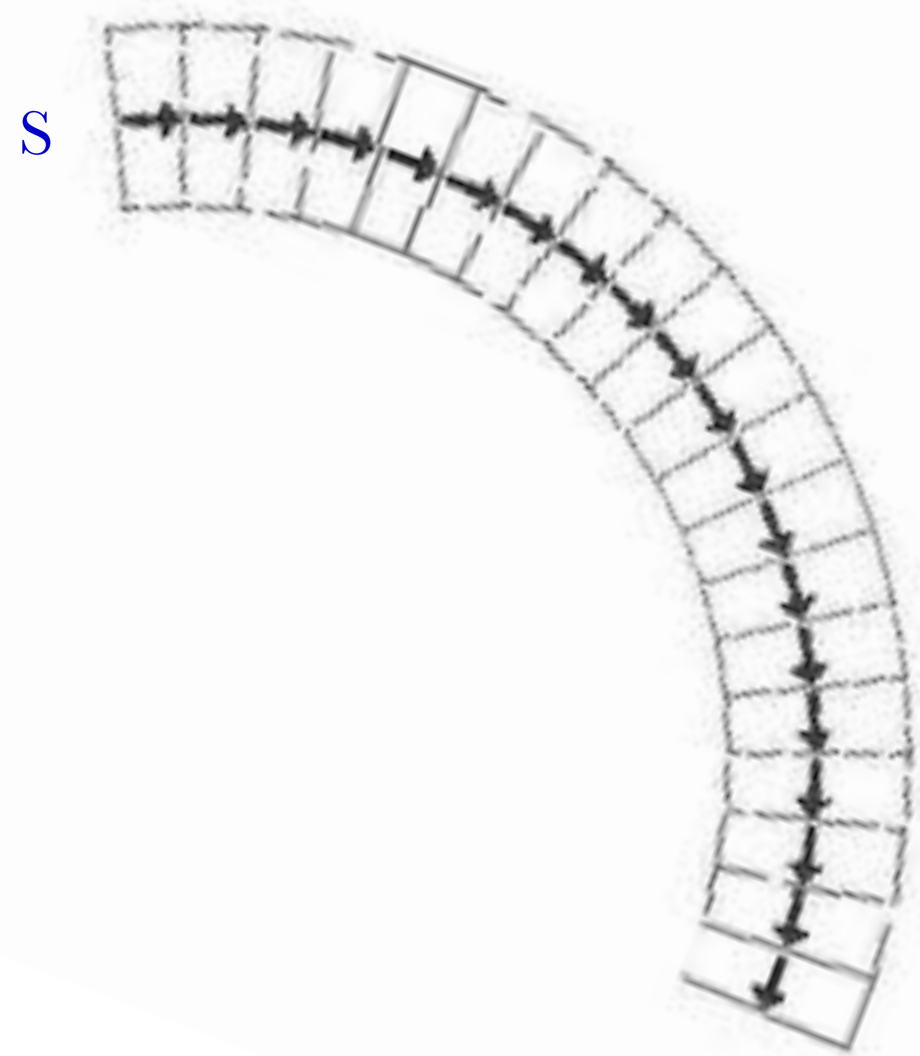


Making a Spin Polarized Pendulum

- Alternating Alnico and SmCo5 magnets
  - At 1 Tesla, Alnico has a spin density of ~ 7.8 $\cdot 10^{22}$ spins/cc
  - At 1 Tesla, SmCo5 has a spin density of ~ 4.2 $\cdot 10^{22}$ spins/cc



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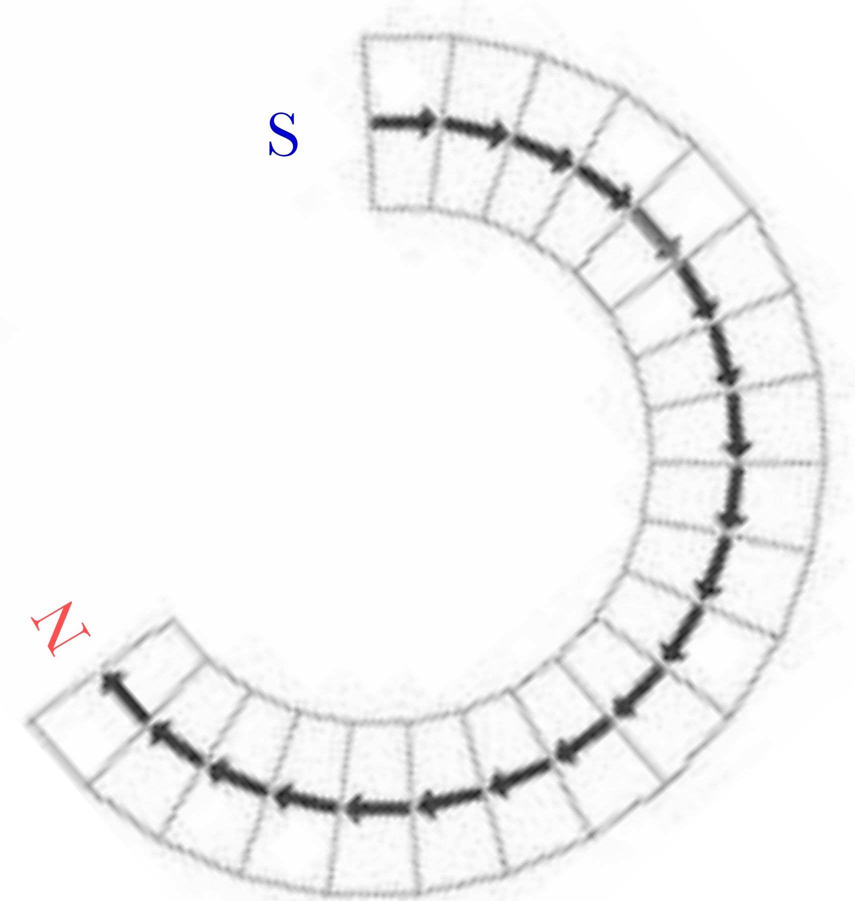

Making a Spin Polarized Pendulum

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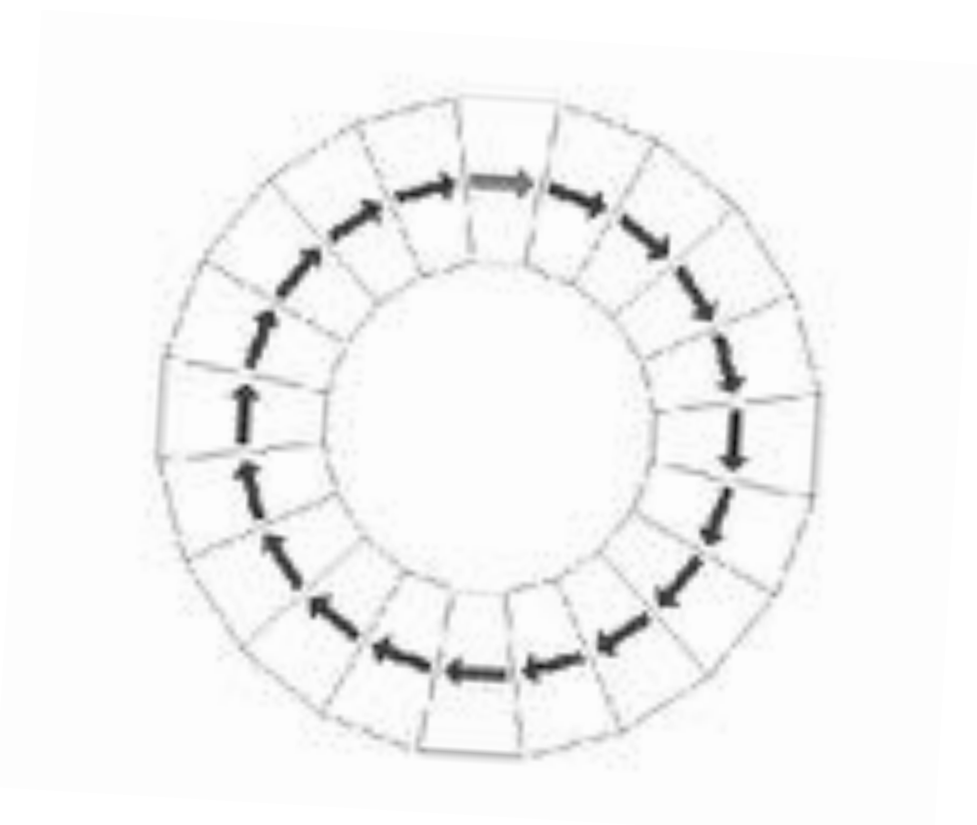
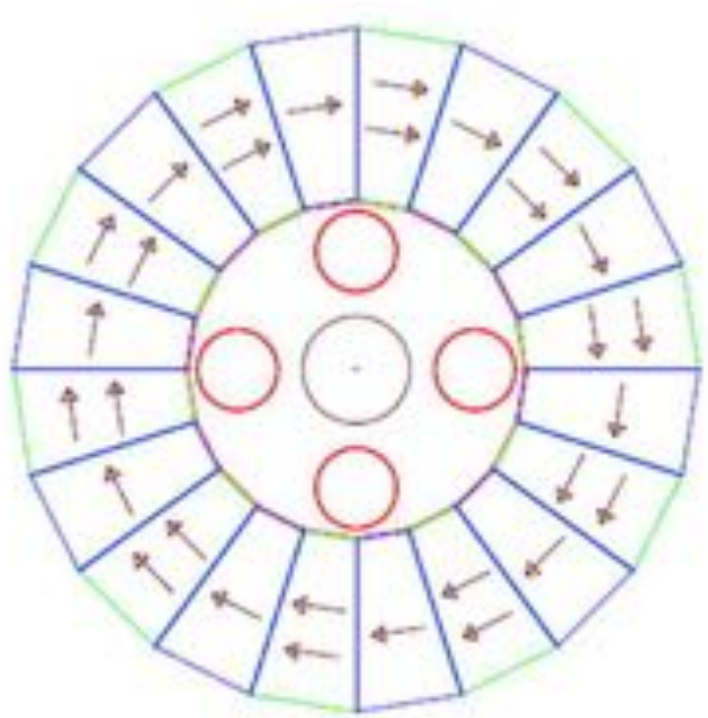
  - At 1 Tesla, Alnico has a spin density of $\sim 7.8 \cdot 10^{22}$ spins/cc
  - At 1 Tesla, SmCo5 has a spin density of $\sim 4.2 \cdot 10^{22}$ spins/cc
- Place them North pole to South Pole to contain the magnetic flux:

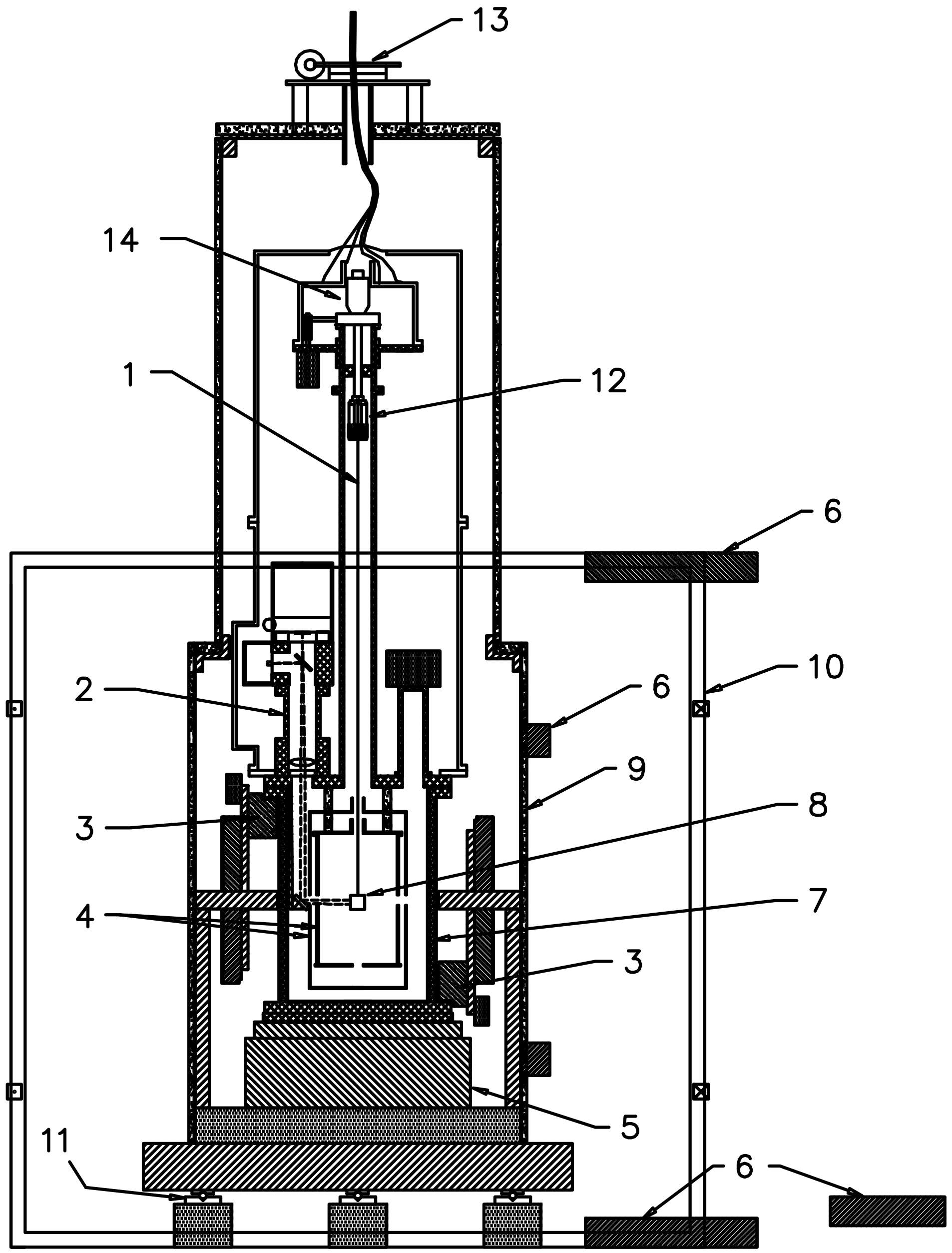


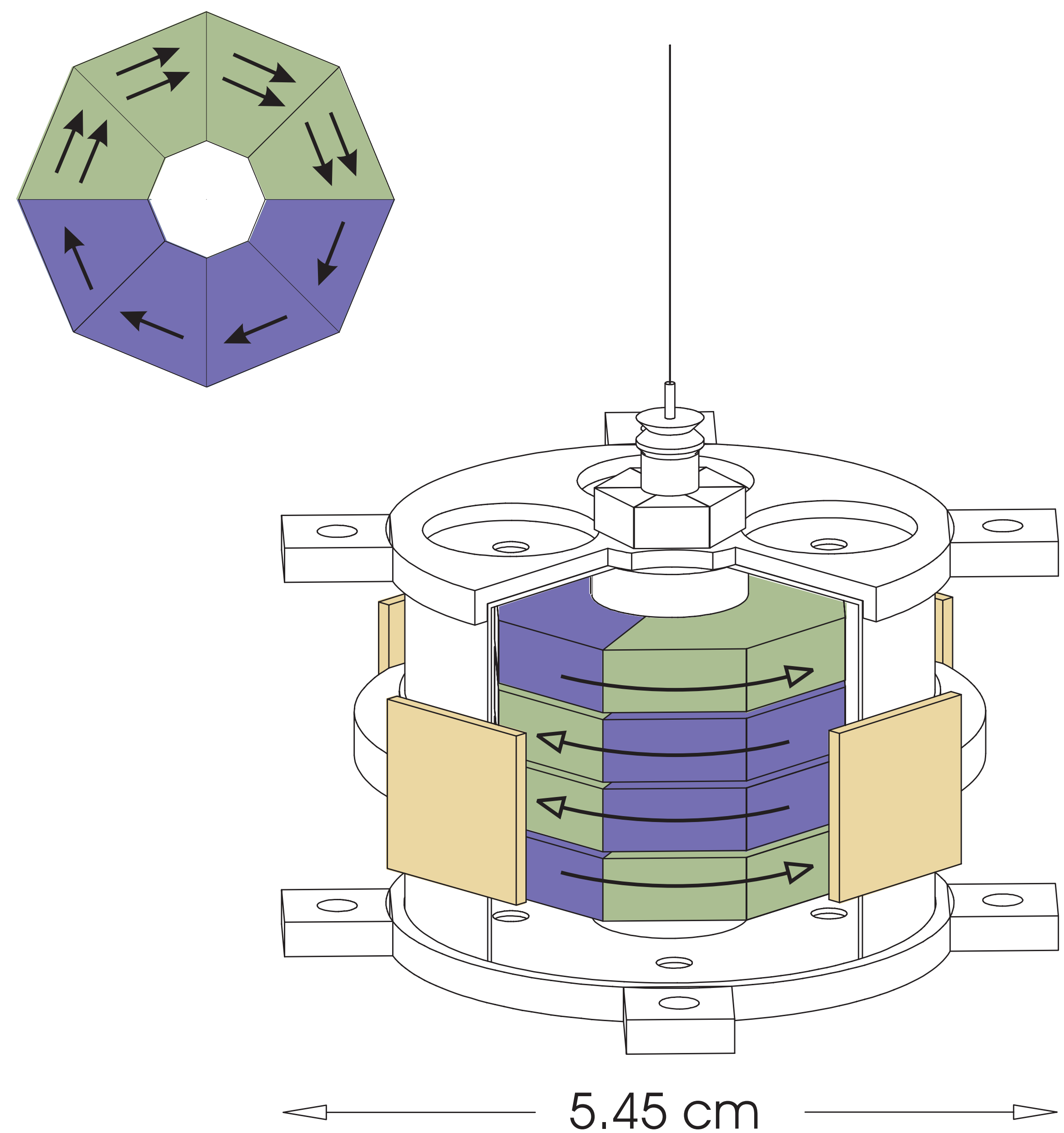
Making a Spin Polarized Pendulum

- Alternating Alnico and SmCo5 magnets
  - At 1 Tesla, Alnico has a spin density of ~ $7.8 \cdot 10^{22}$ spins/cc
  - At 1 Tesla, SmCo5 has a spin density of ~ $4.2 \cdot 10^{22}$ spins/cc
- Contains a Spin Gradient but no magnetic field!



CPT, fifth force tests





Quantum Gyroscope:

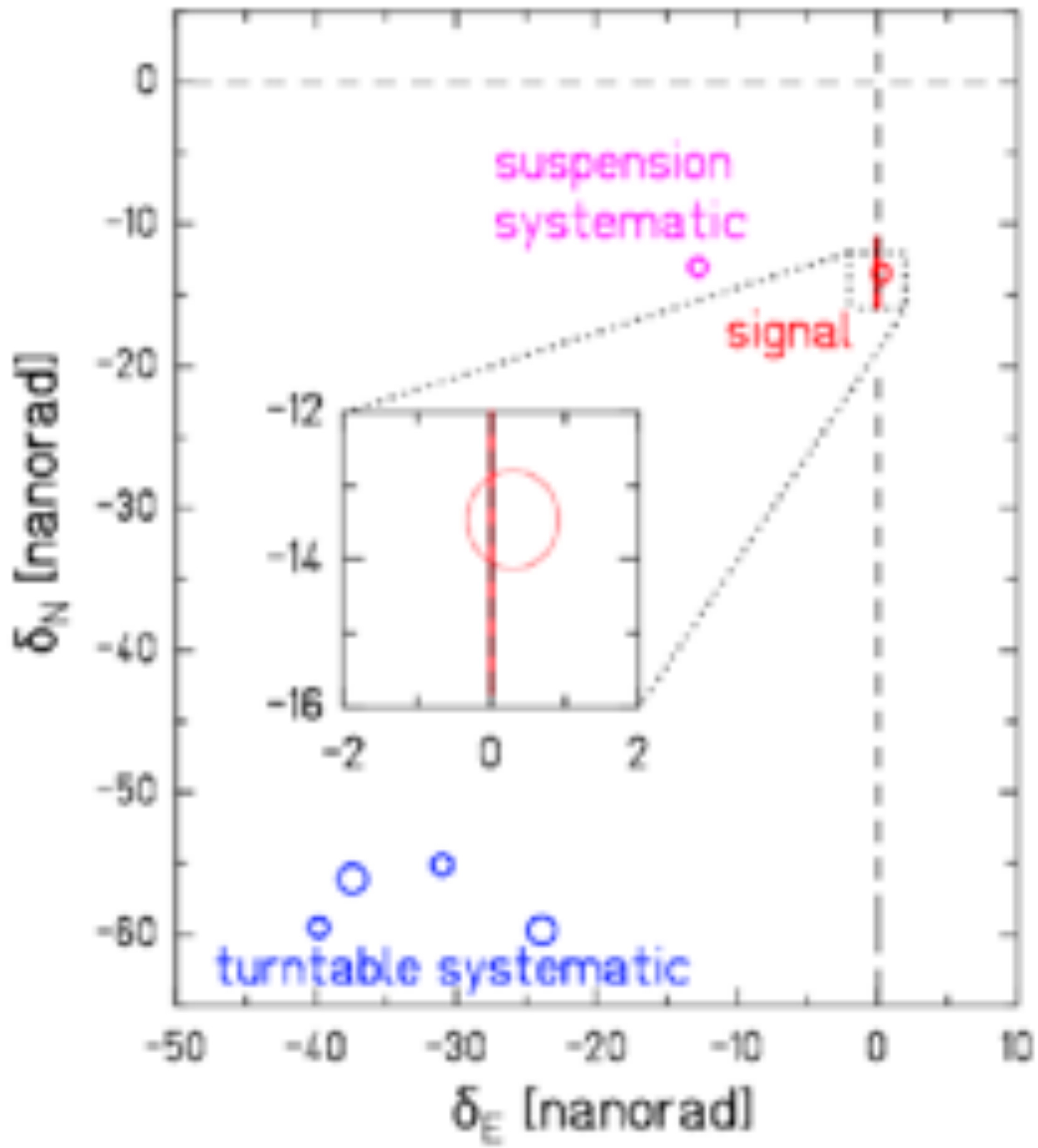
$$B_z(\mathrm{SmCo_5})/\mu_B = g_s S_z(\mathrm{SmCo_5}) + g_l L_z(\mathrm{SmCo_5})$$

$$B_z(\mathrm{Alnico})/\mu_B = g_s S_z(\mathrm{Alnico}) + g_l L_z(\mathrm{Alnico})\ ,$$

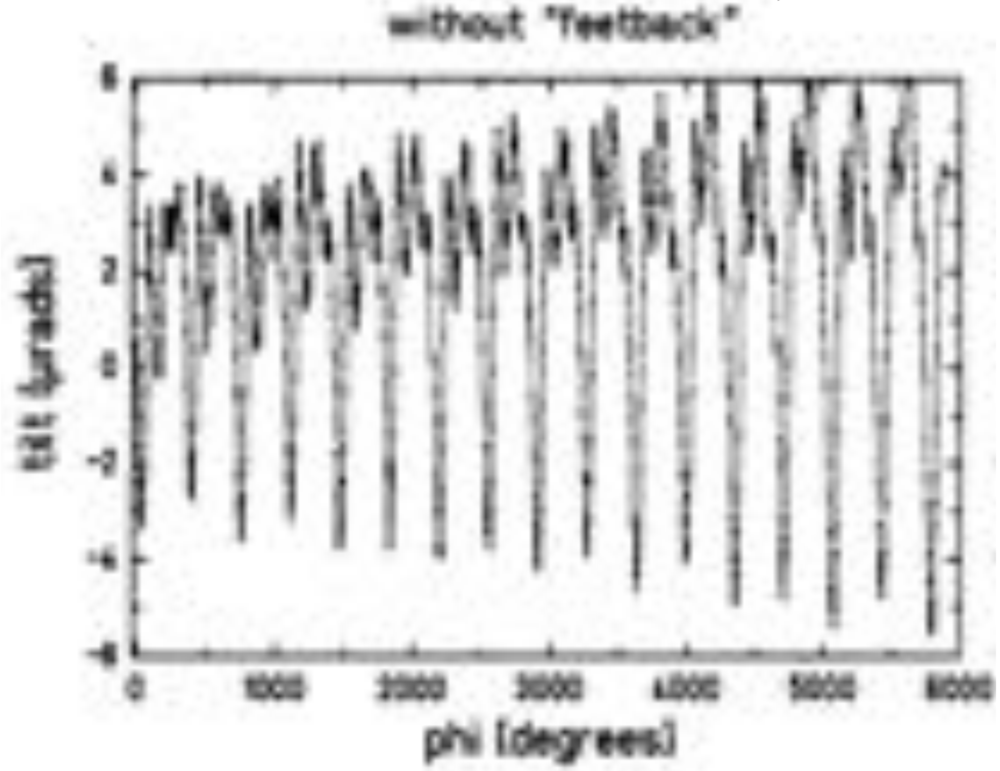
$$2\langle S_z^{\mathrm{tot}}\rangle + \langle L_z^{\mathrm{tot}}\rangle = 0$$

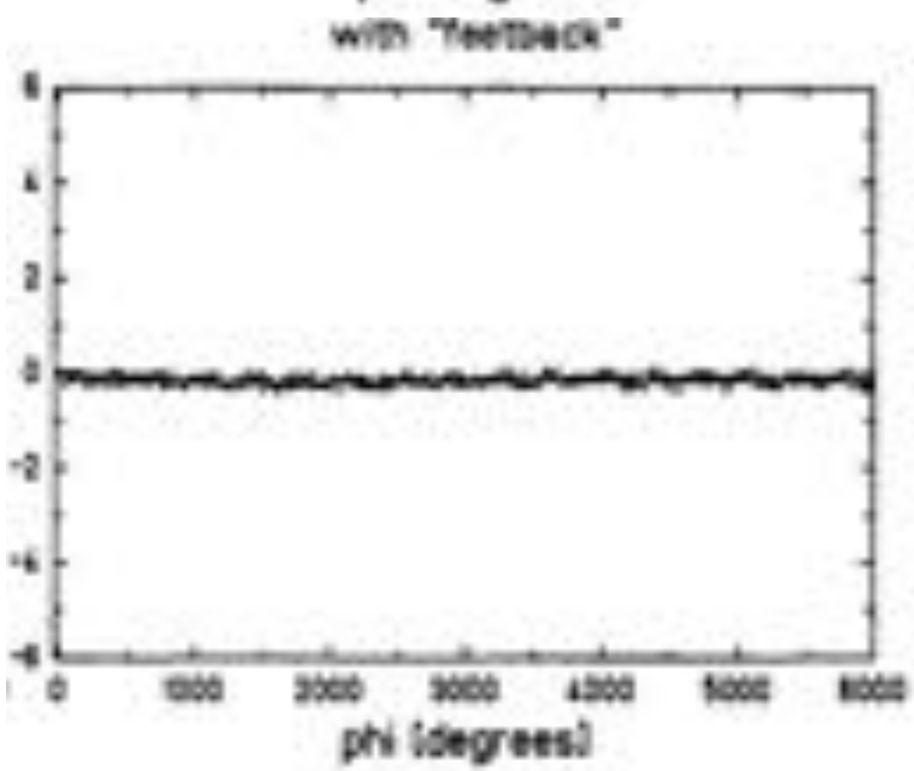
$$\langle J_z^{\mathrm{tot}}\rangle = -\langle S_z^{\mathrm{tot}}\rangle$$

$$\boldsymbol{T}\cdot\hat{\boldsymbol{n}} = |\boldsymbol{\Omega}_{\oplus} \times \boldsymbol{J}\cdot\hat{\boldsymbol{n}}|$$

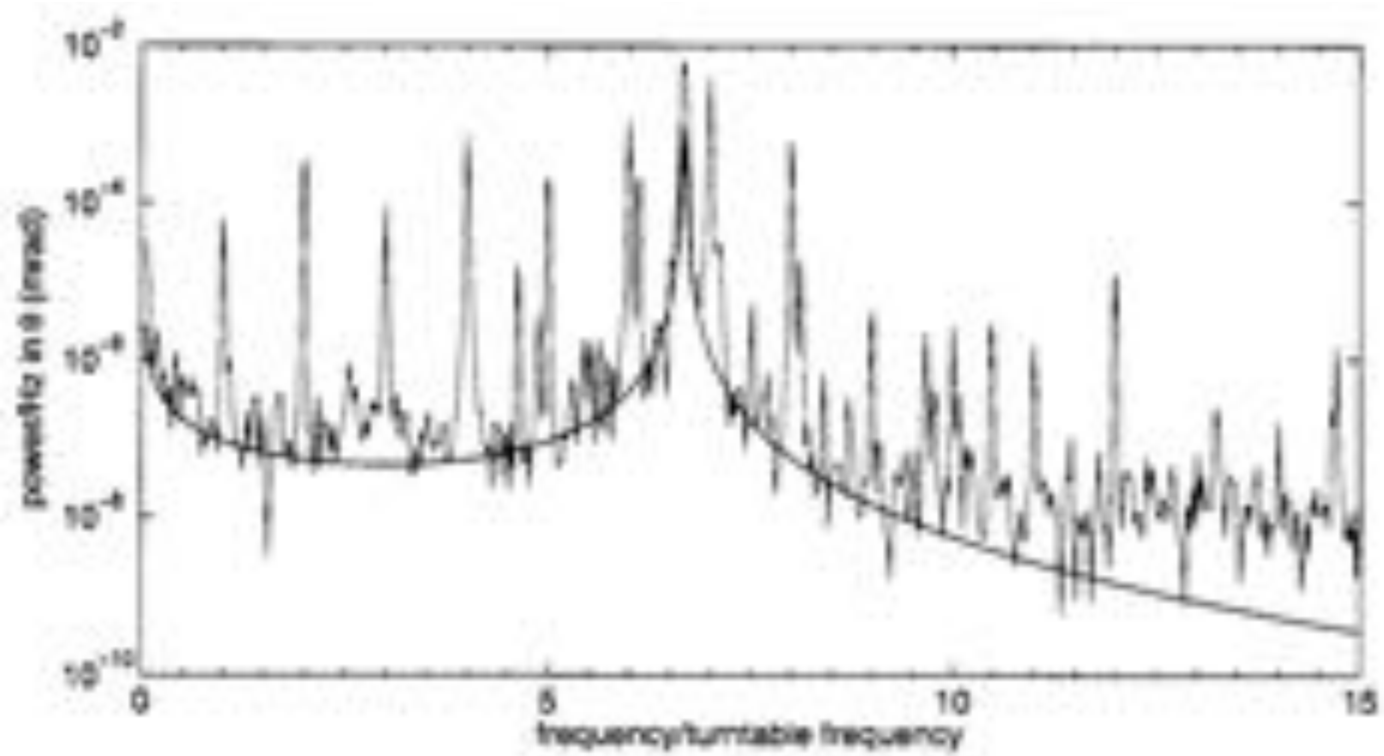


triply-modulated signal
Turntable; Earth rotation; Axion mass





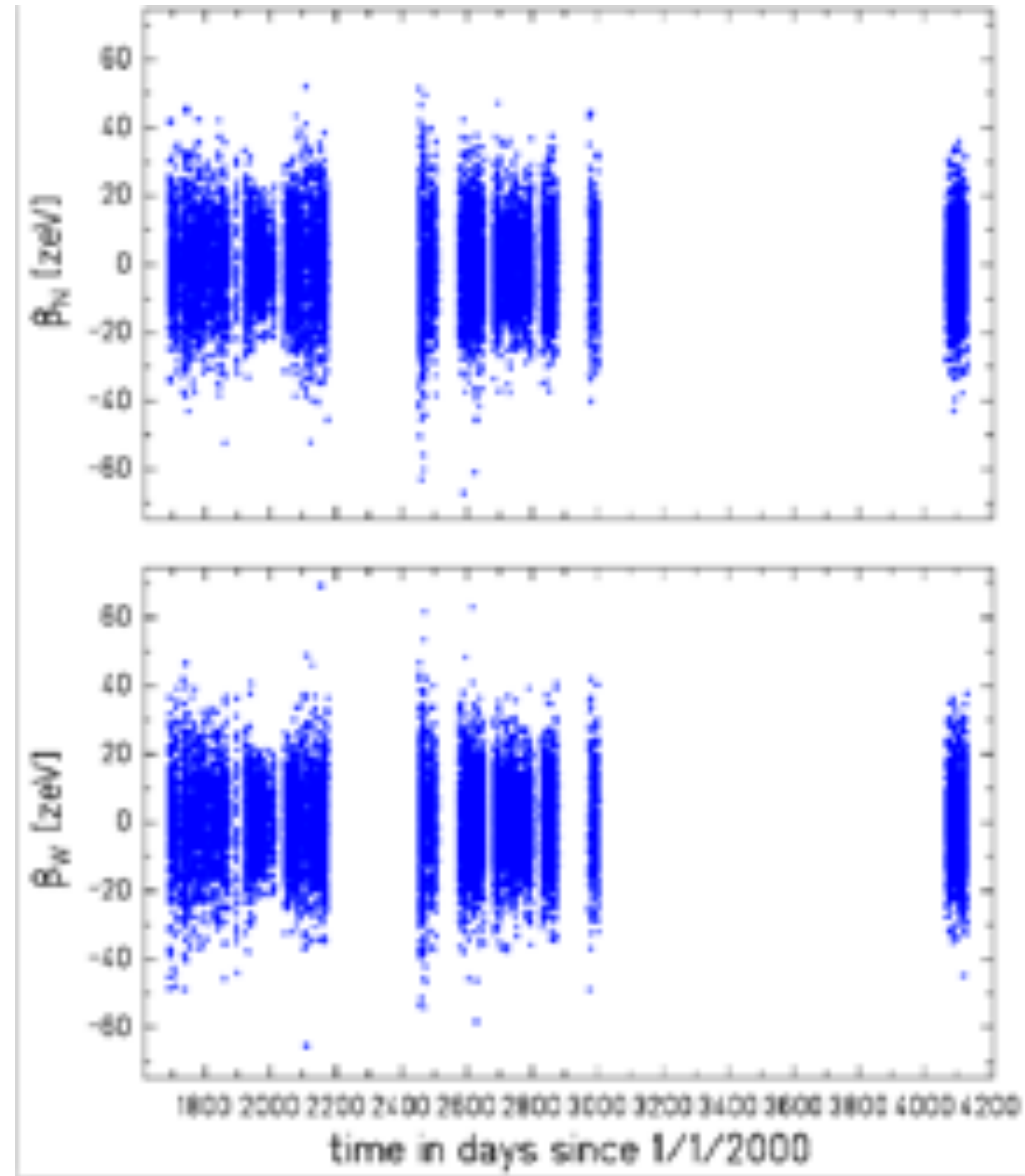
- Turntable reduces 1/f noise
- sidereal allows long-term stability



Analysis strategy

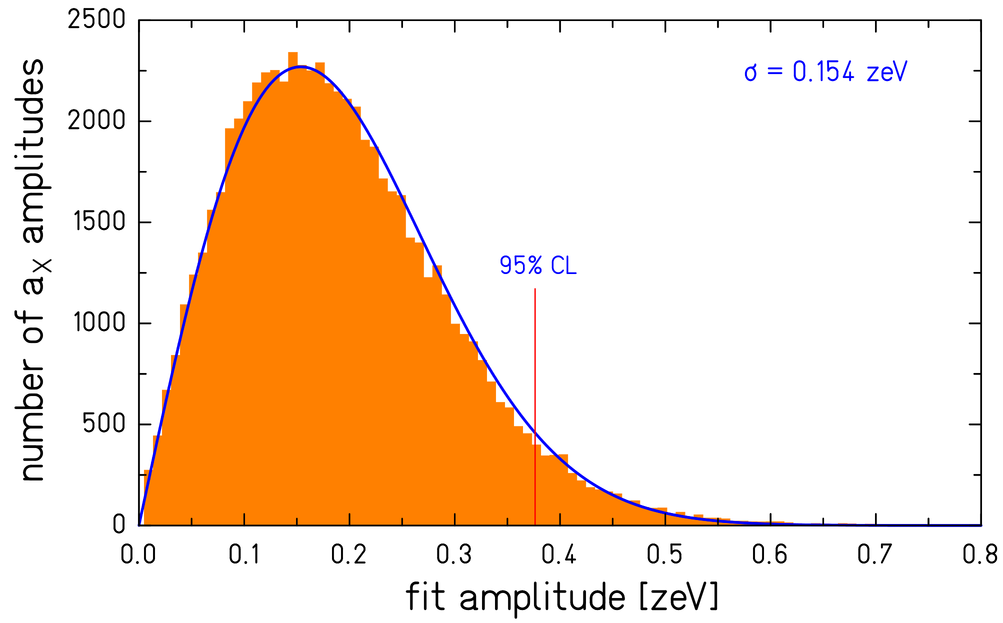
1. Extract pendulum torque at turntable frequency using 6.7 year span of data
2. Linear fit of resulting data to basis functions that include sidereal and axion oscillations
3. Repeat for 67,200 axion frequencies in our band (10^{-9} Hz — 3.2 10^{-4} Hz)

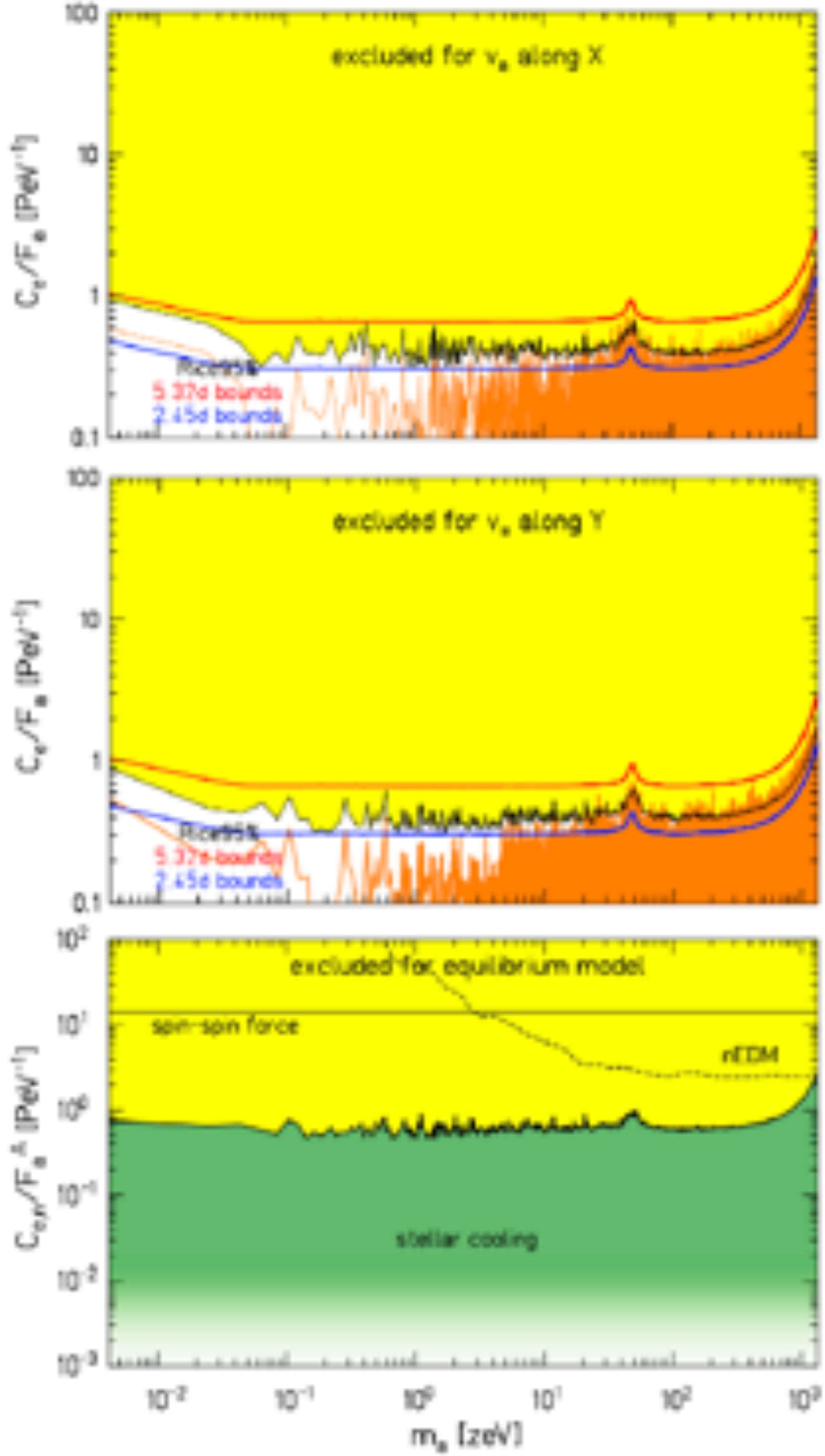
$$\beta^i_{\mathrm{N}} = b^i_{\mathrm{XNcos}}\, a_{X\mathrm{cos}} + b_{\mathrm{XNsin}}\, a_{X\mathrm{sin}}$$



Results:

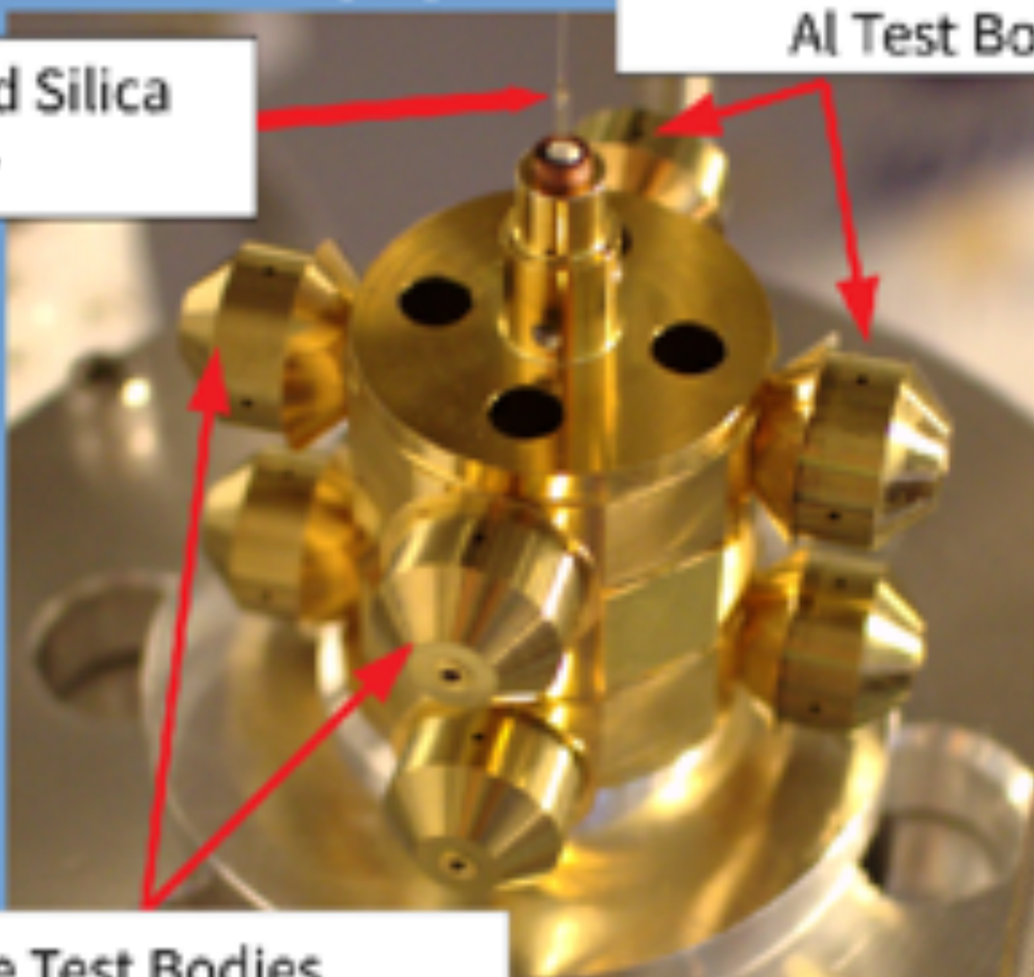
Error bar set by scatter of the 67,200 measurements





B — L (Erik Shaw)

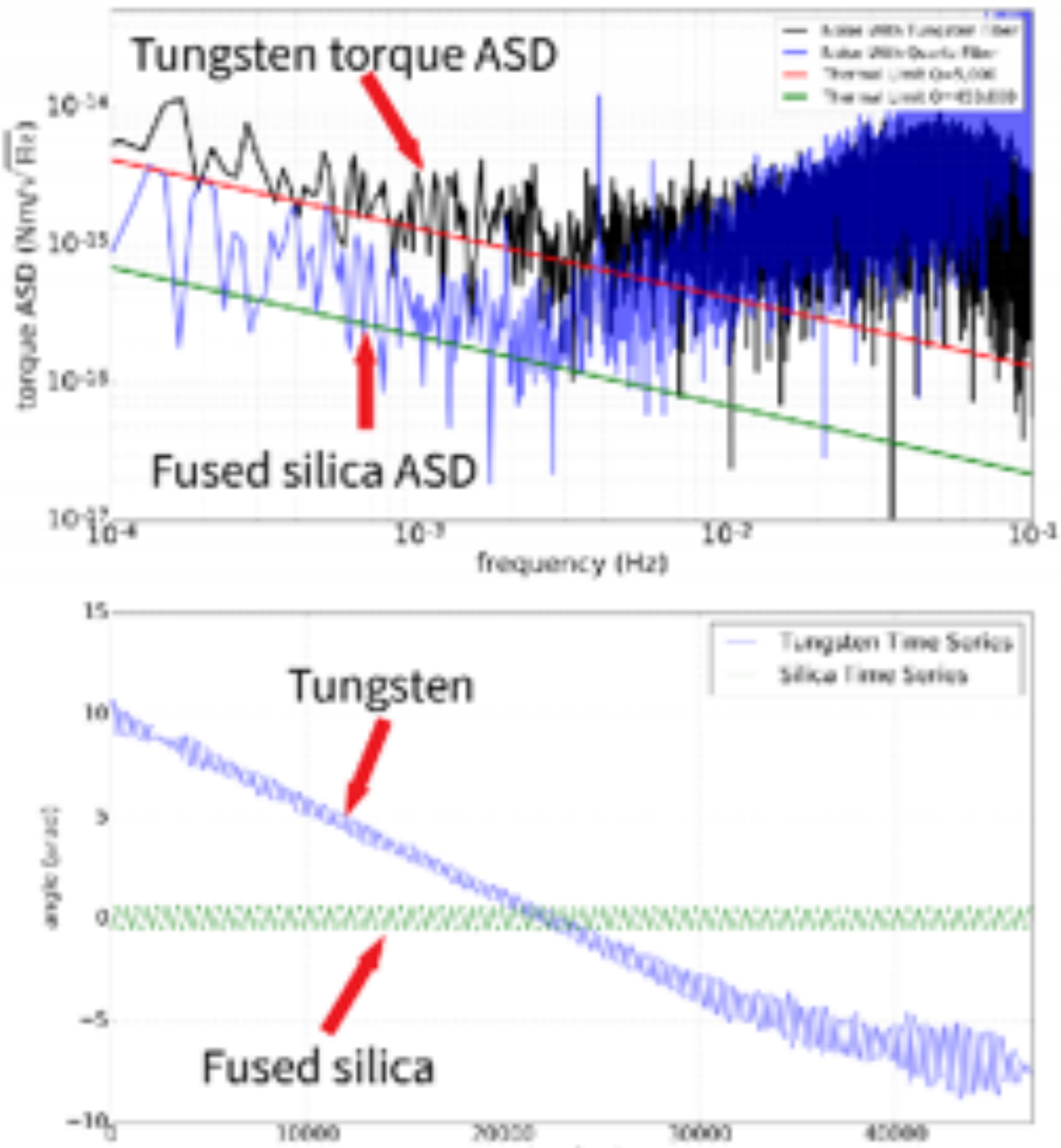
Non-Rotating Apparatus



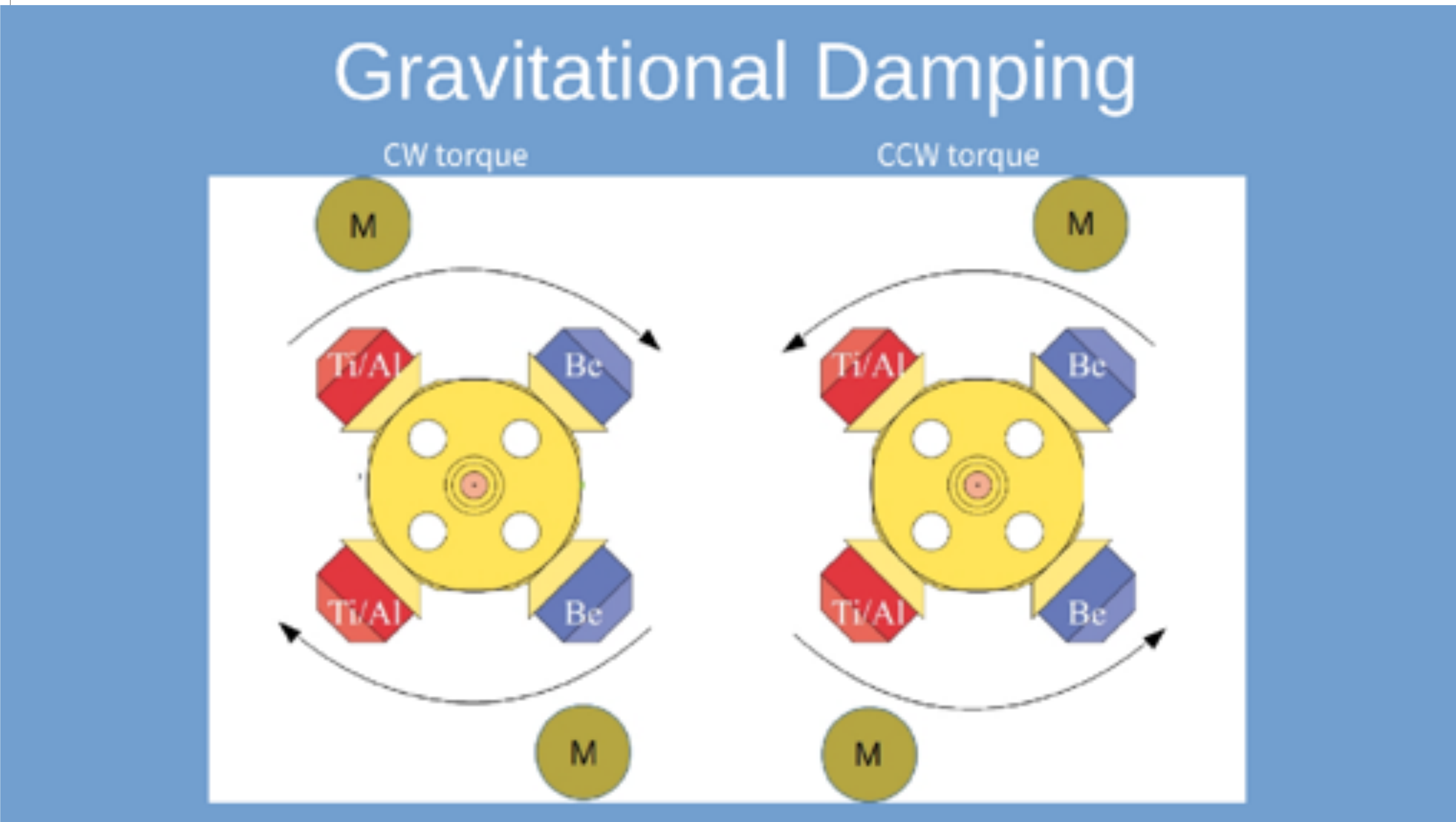
B – L (Erik Shaw)

Silica fibers

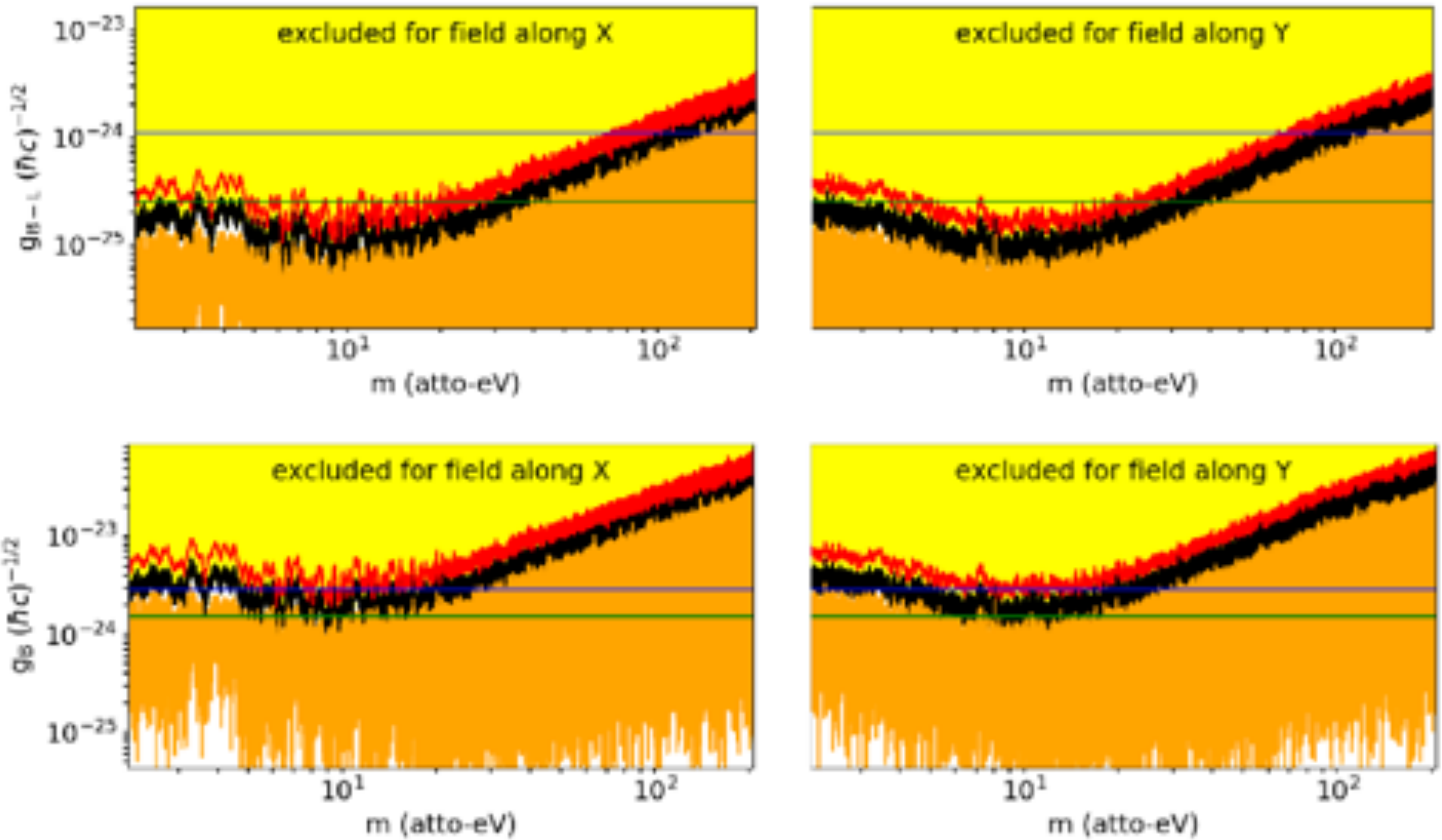
- High Quality factors improve sensitivity 5x
- Noise near thermal limit
- Fiber drifts reduced more than 10x
- More improvement is likely



B — L (Erik Shaw)


Gravitational Damping
CW torque
CCW torque
M
M
Ti/Al
Be
Ti/Al
Be
Ti/Al
Be
Ti/Al
Be
M
M

B — L (Erik Shaw)


excluded for field along X
excluded for field along Y
excluded for field along X
excluded for field along Y
10^{-23}
10^{-24}
10^{-25}
$g_{B-L}\ (\hbar c)^{-1/2}$
$g_B\ (\hbar c)^{-1/2}$
10^1
10^2
m (atto-eV)

B — L (Erik Shaw)

Moving Forward

- There are a variety of ways to expand this search:
  - Improve apparatus sensitivity with improved fibers and angular readout
  - Use pendulum with better composition dipole
  - Use rotating apparatus to extend search to lower masses

Nuclear-spin interactions

- Much larger spin/magnetic ratio
- Probes higher energy scales for given coupling

$$g_{\rm p} = \frac{m_\psi}{F}$$

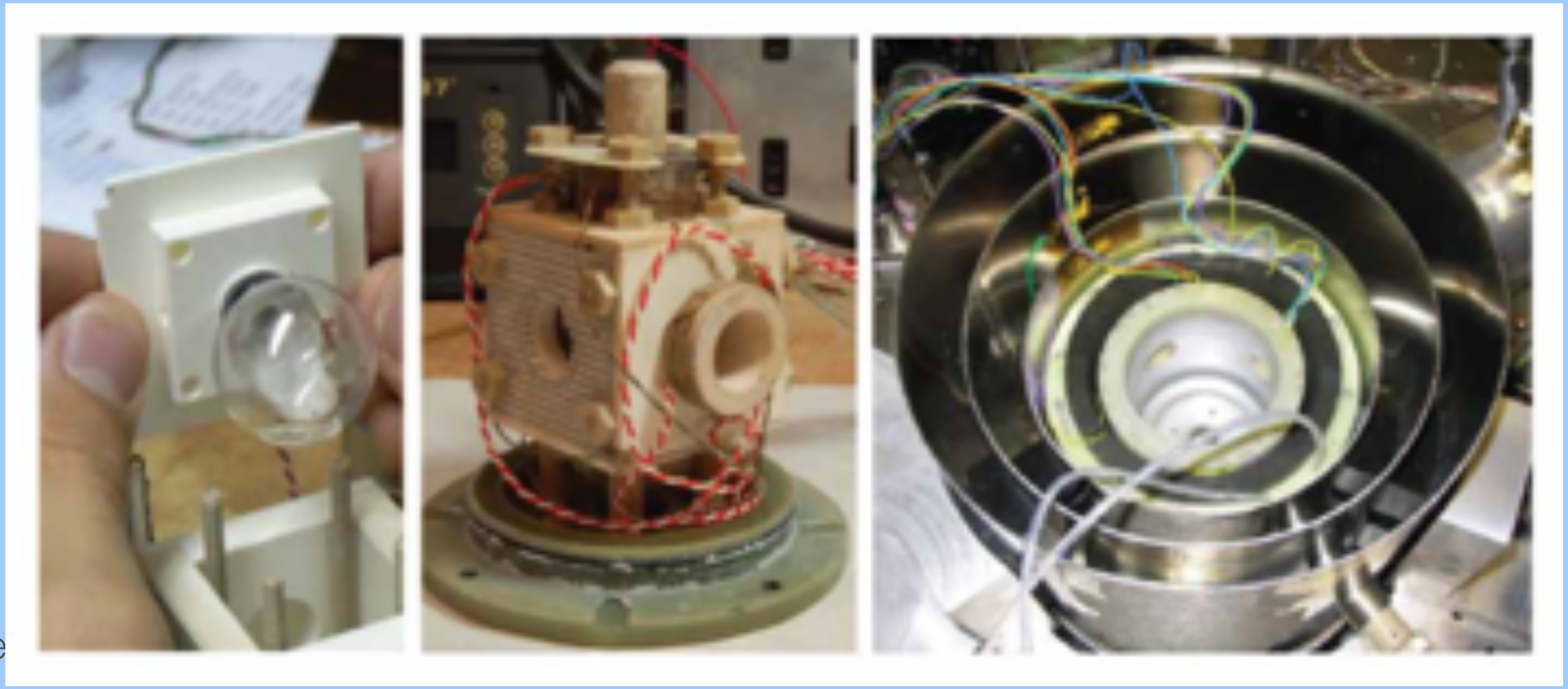
- Thermal polarizations (earths field) ~10^{-10}
- hyper-polarization provides ~ O(10-50%)

Princeton Axion Project

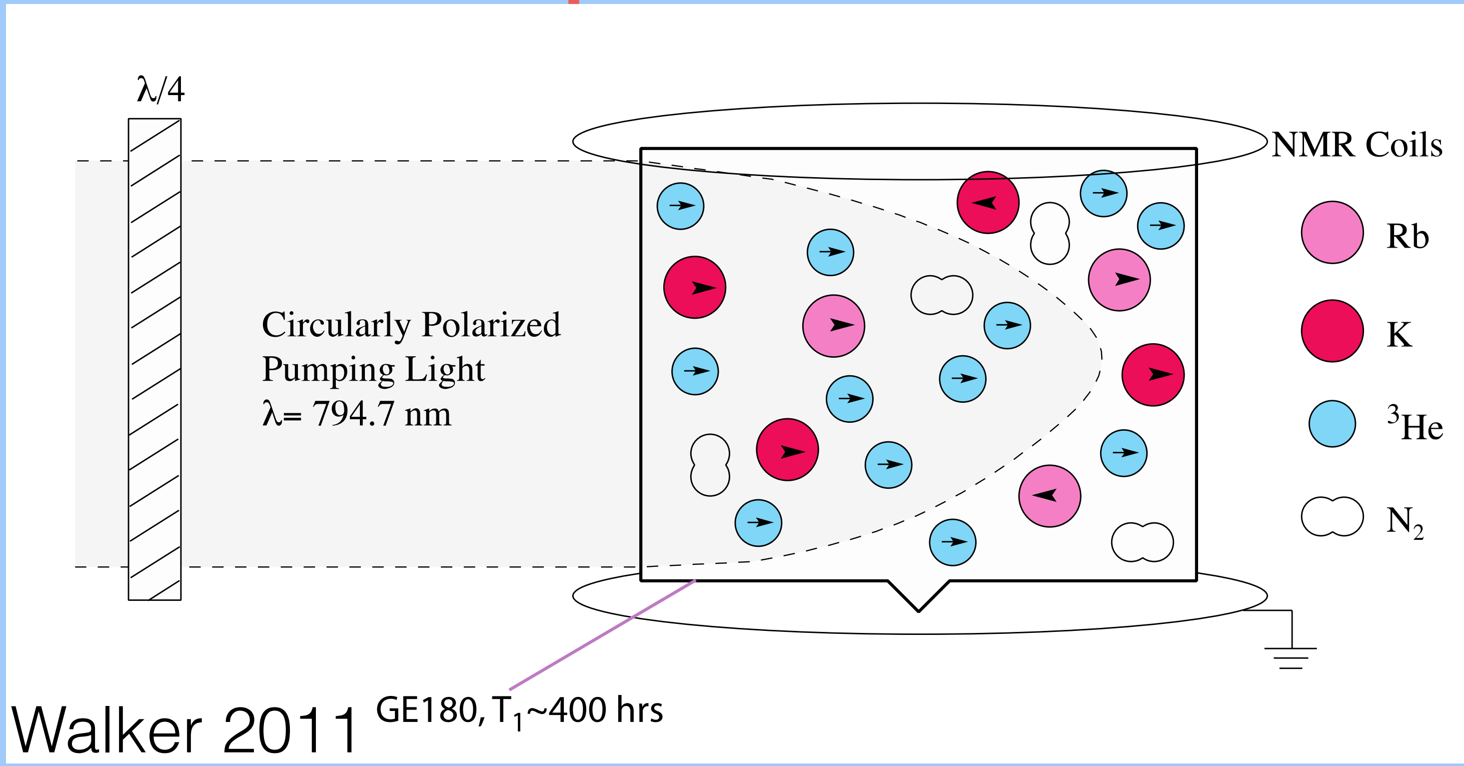
- Main issues:
  1. cancel magnetic perturbations
  2. keep sensitivity to non-magnetic interactions

I. Compare two nuclear spins in same volume

II. Compare electron-spin to nucleon spin

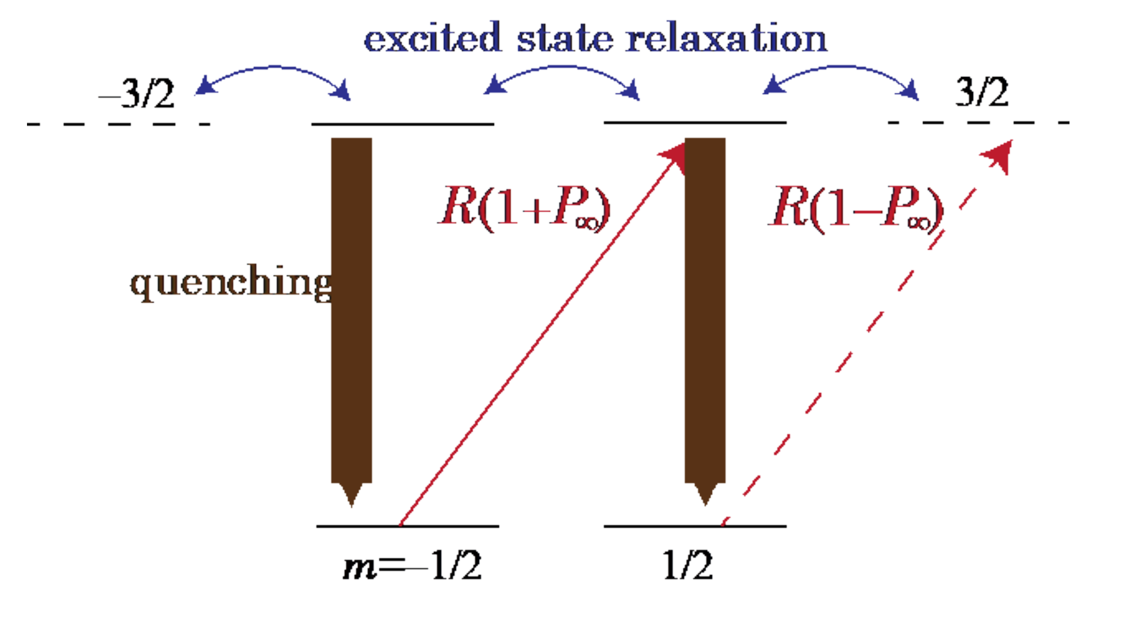


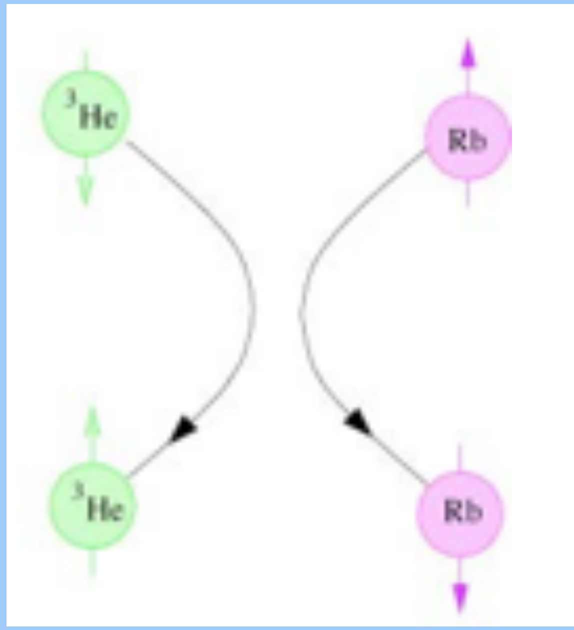
Nuclear spin hyper-polarization

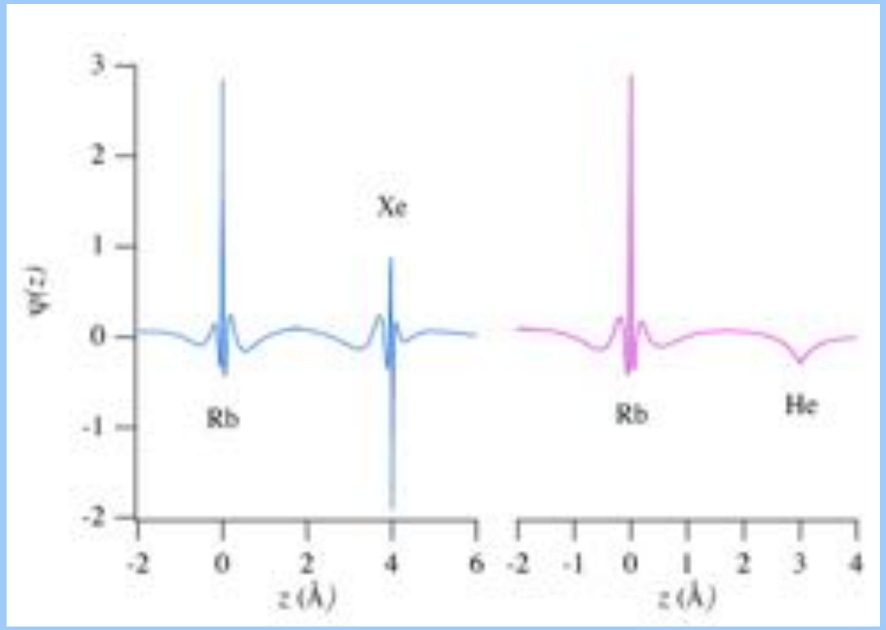


Walker 2011

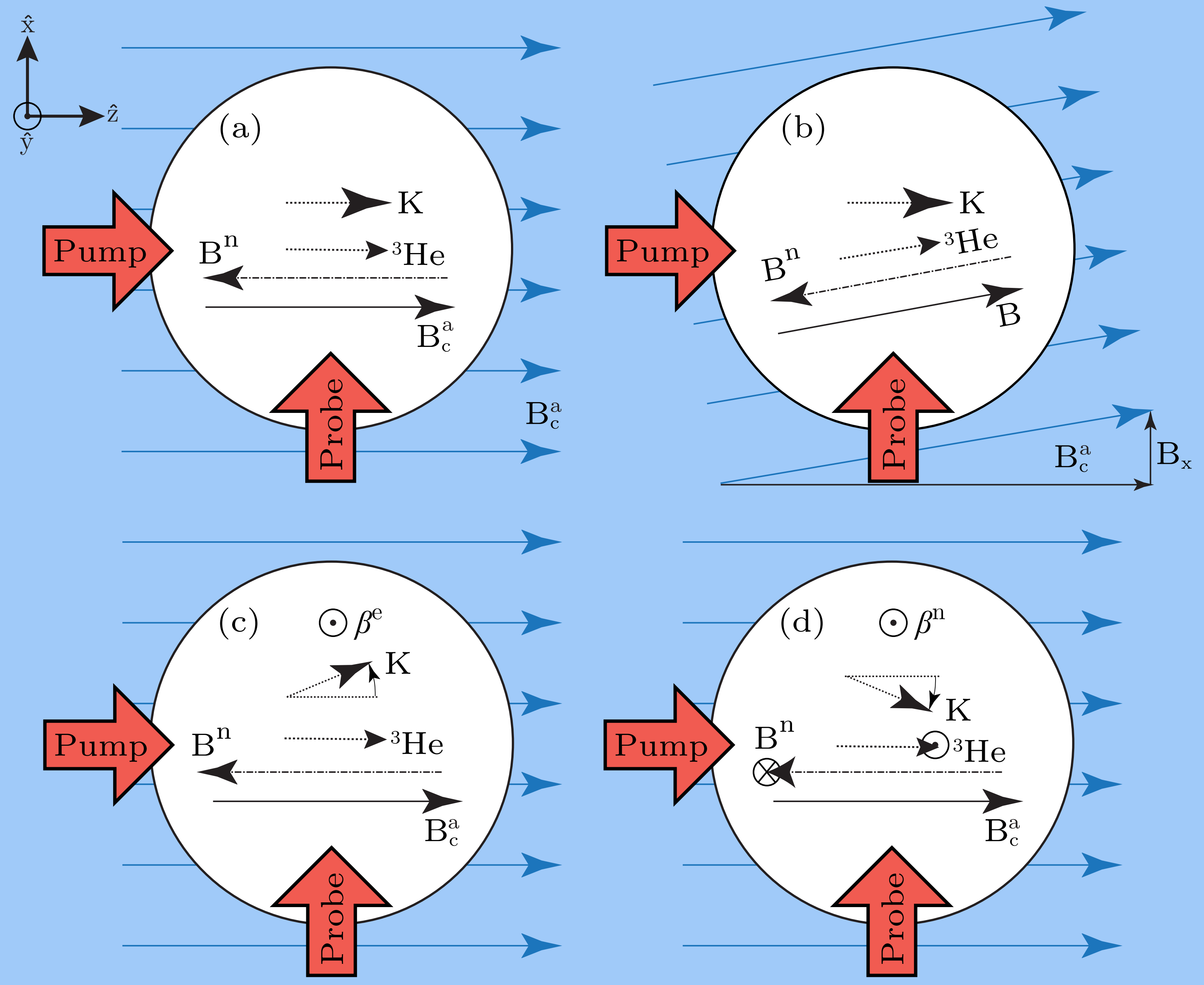
angular momentum from laser -> electron -> nucleon



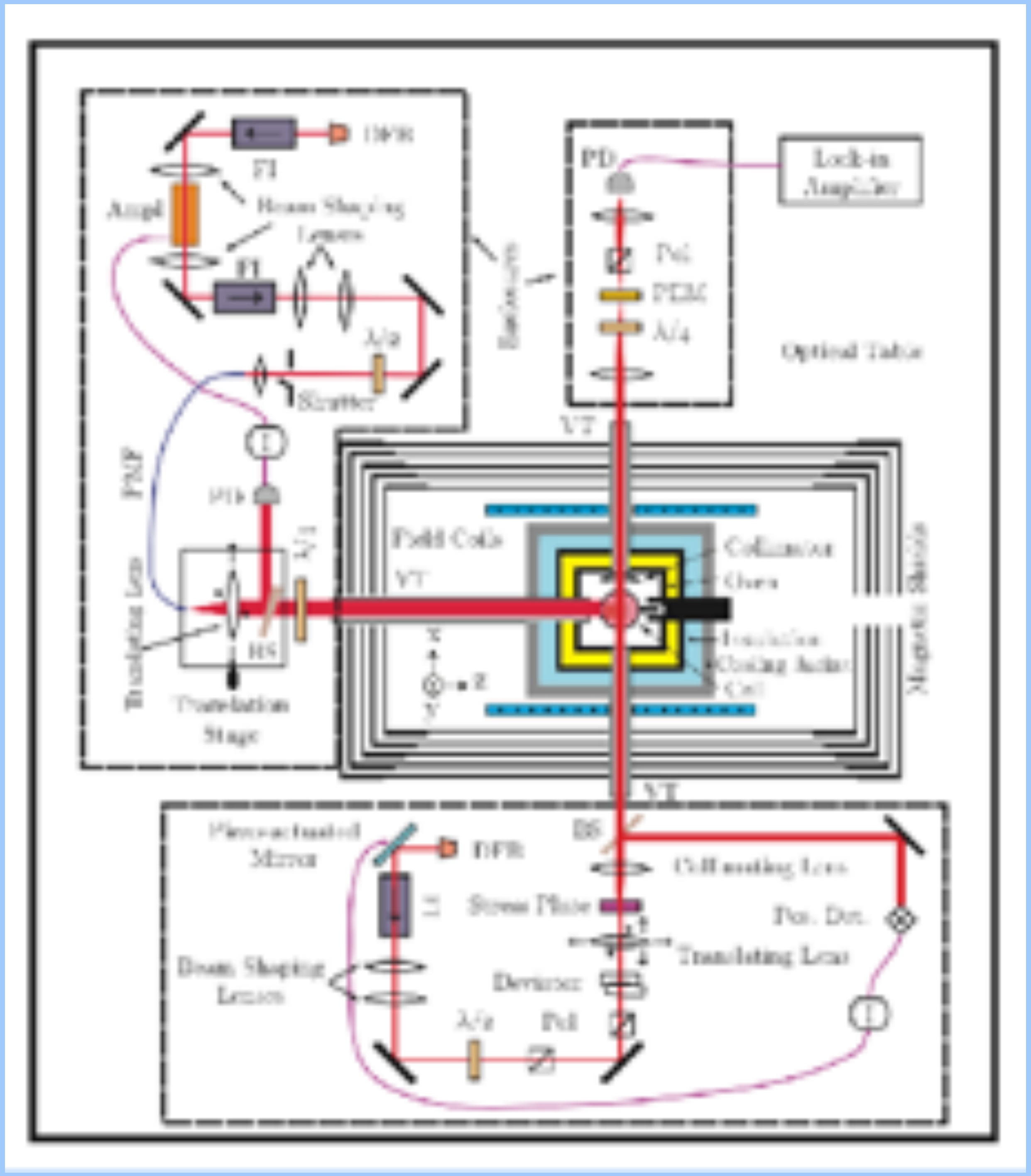




electron-nucleon comagnetometer

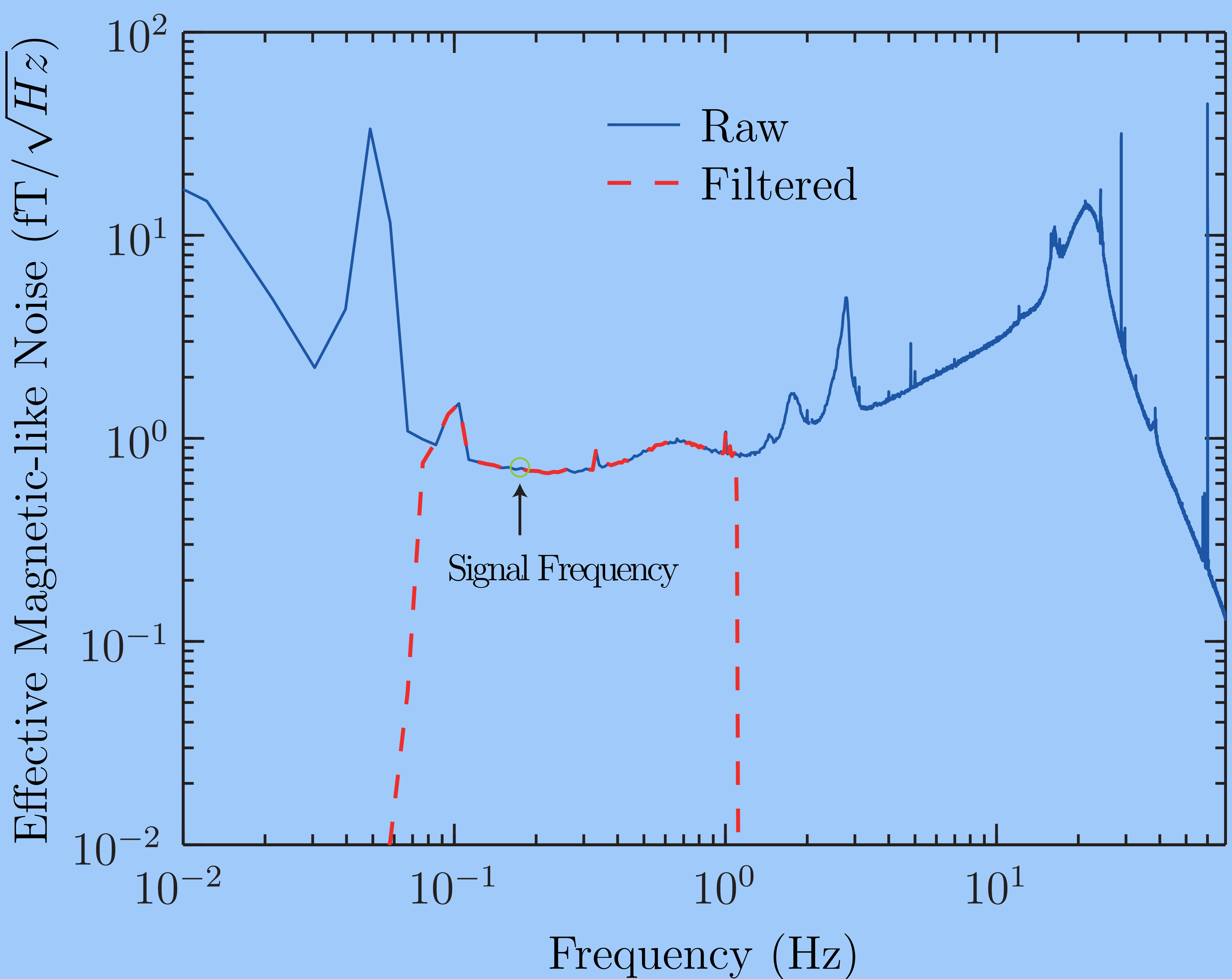


electron-nucleon comagnetometer



So simple!

Existing data

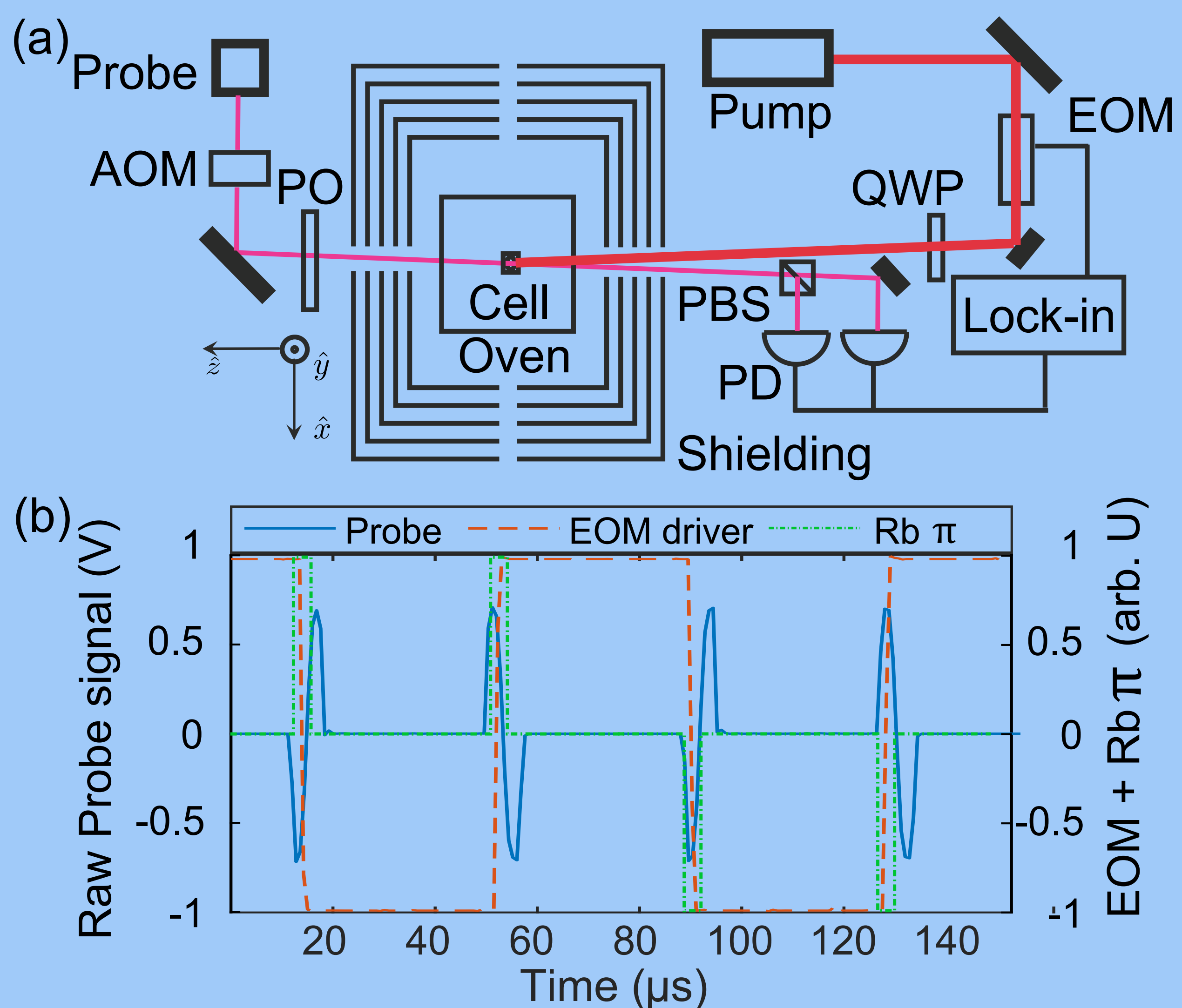


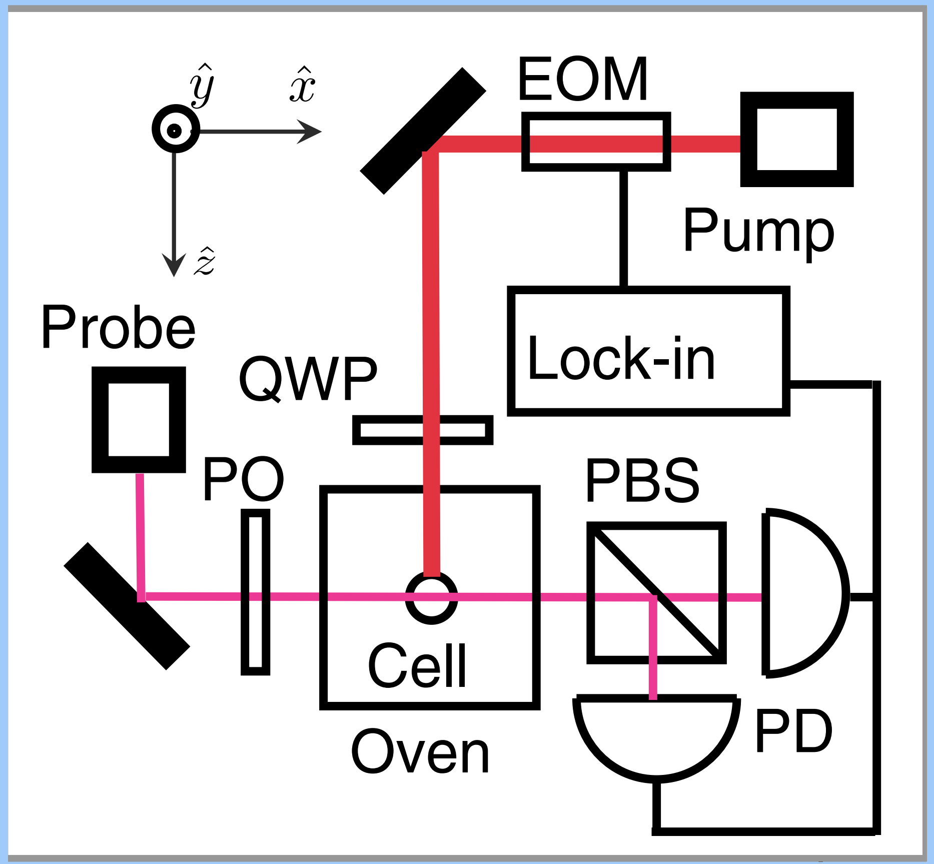
Supernova cooling

If Integrated over whole data set

He-? gyroscope with Rb pump & Rb read-out

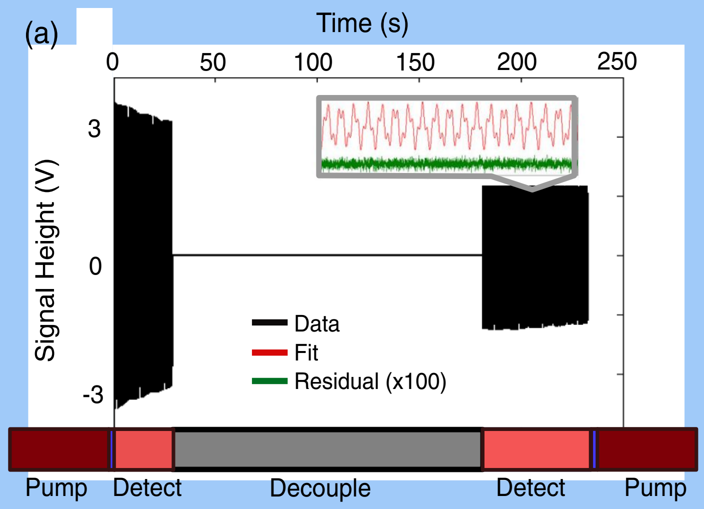
Developed with Xenon, now using Neon



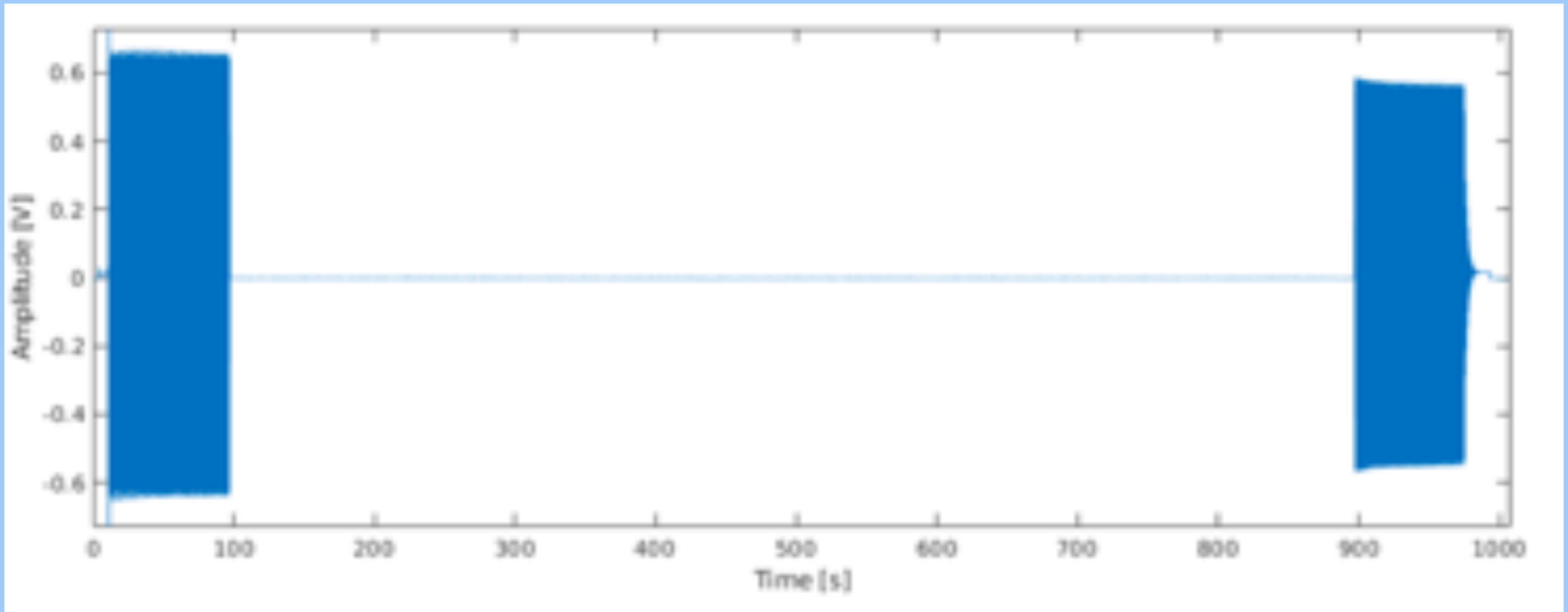


Limes et al 2017

Current status

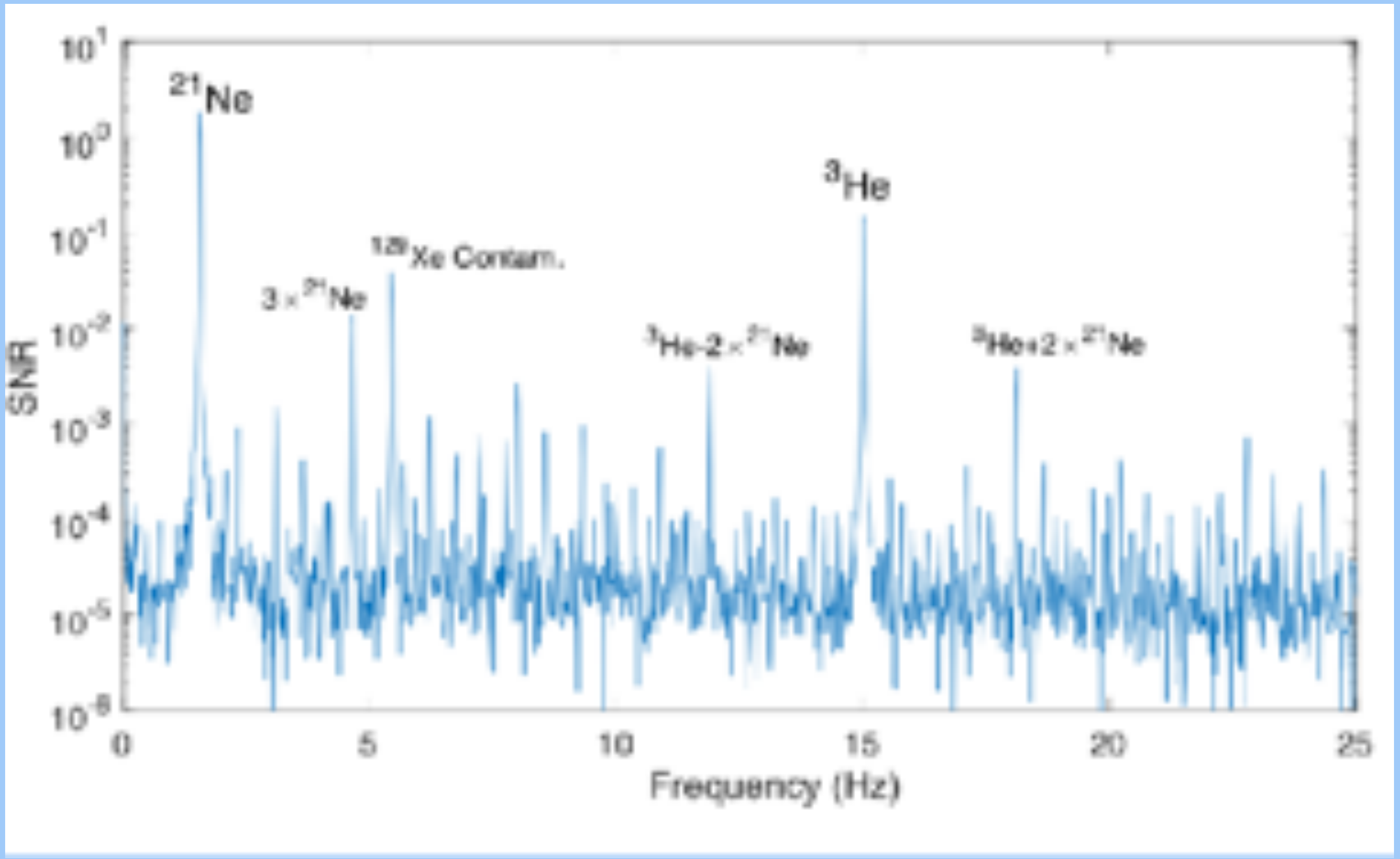


Replaced Xenon with Neon (lower Rb interactions)

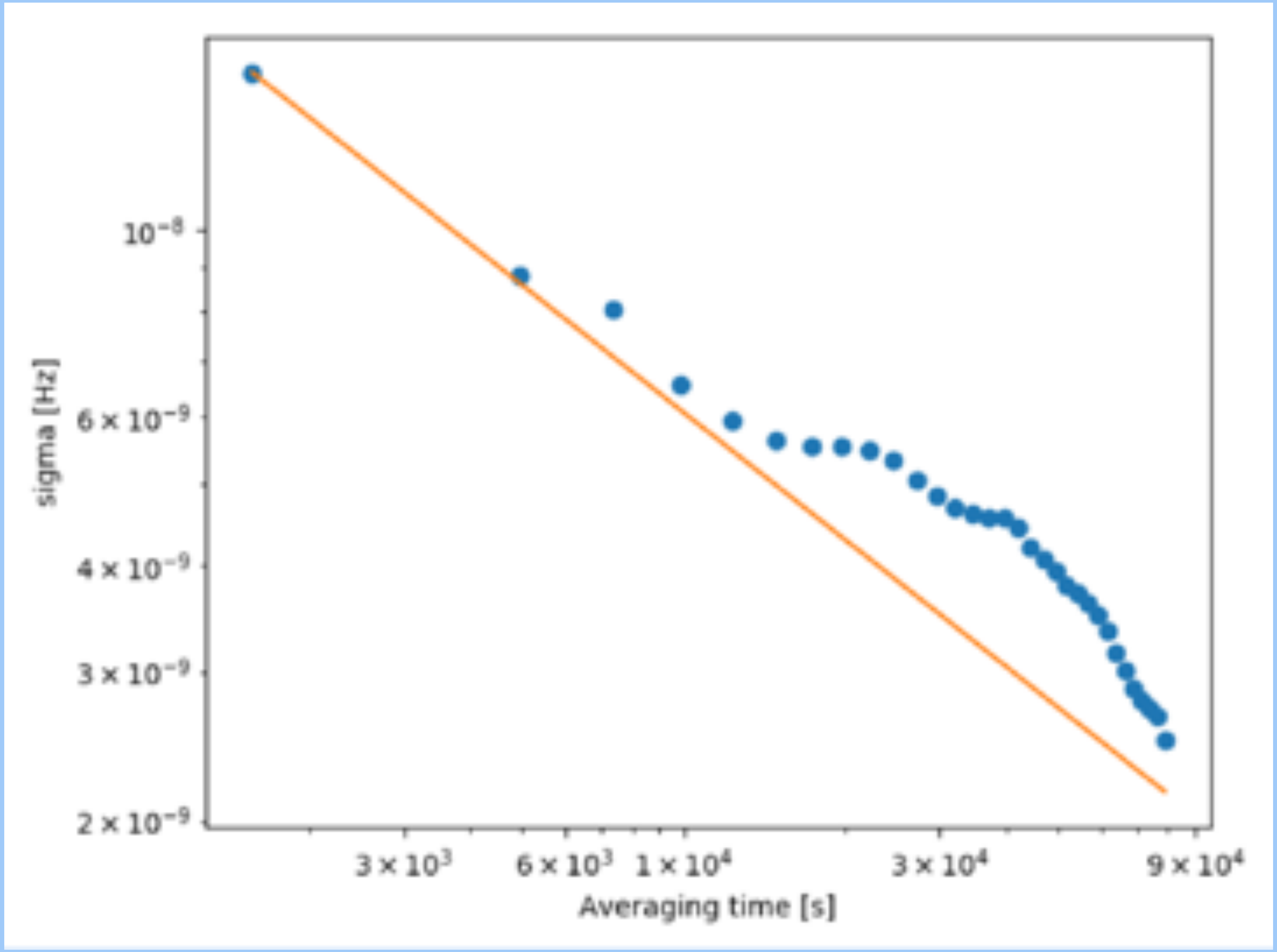


SNR is not a problem

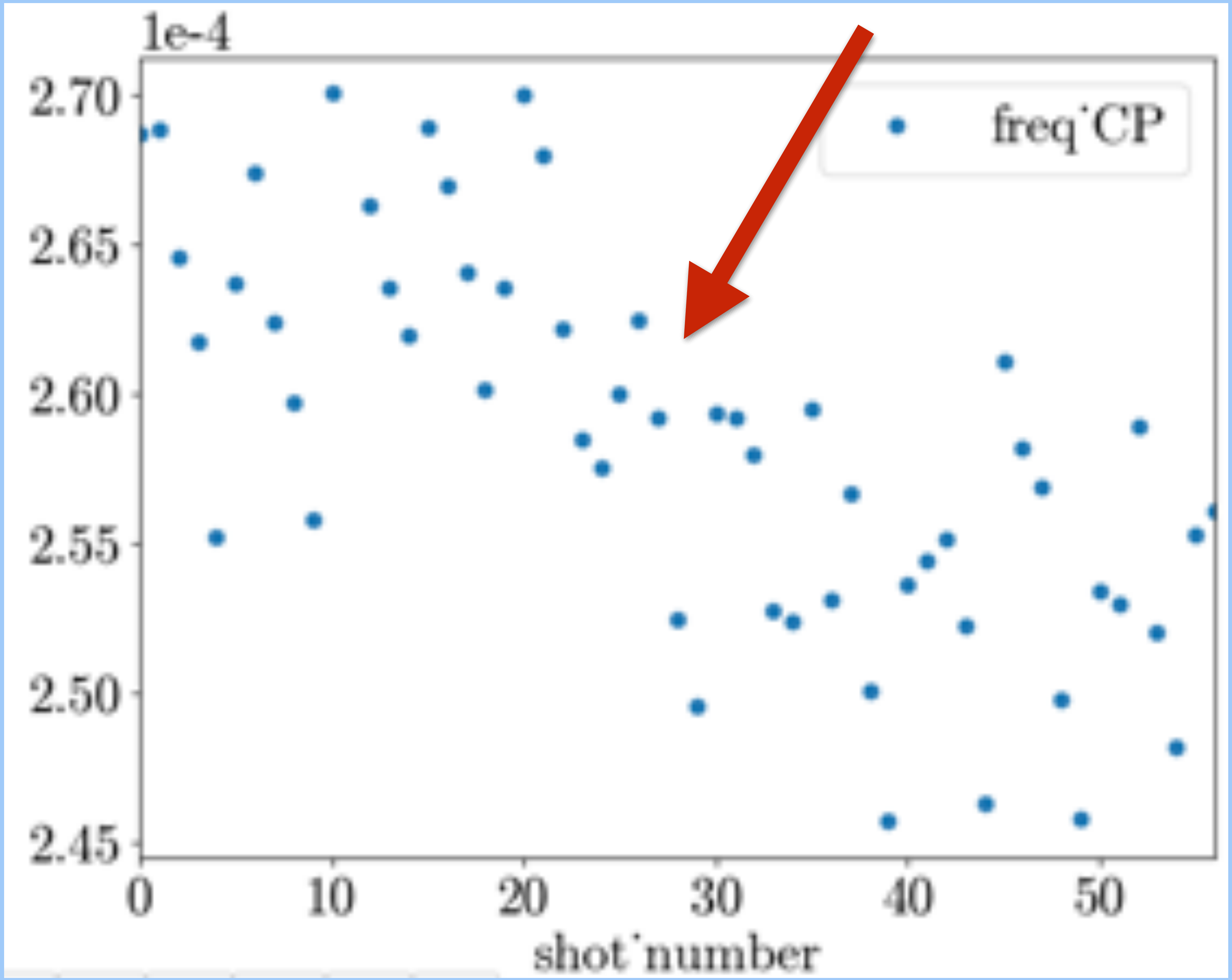
SERF - magnetometer non-linear response



Current stability



Current Problem



What changed?

Plenty of fun to have

1. Rb - pump laser
2. Rb - probe laser
3. Rb - RF pulses

Measure in the Dark?

Operate at an extremum?

4. He/Ne - Rb
5. He/Ne - RF pulses

Optically depolarize Rb?

6. He - Ne contact interaction
7. He-He/Ne-Ne long-range geometric interactions
8. Ne quadrupole interactions

Design cell to cancel these?

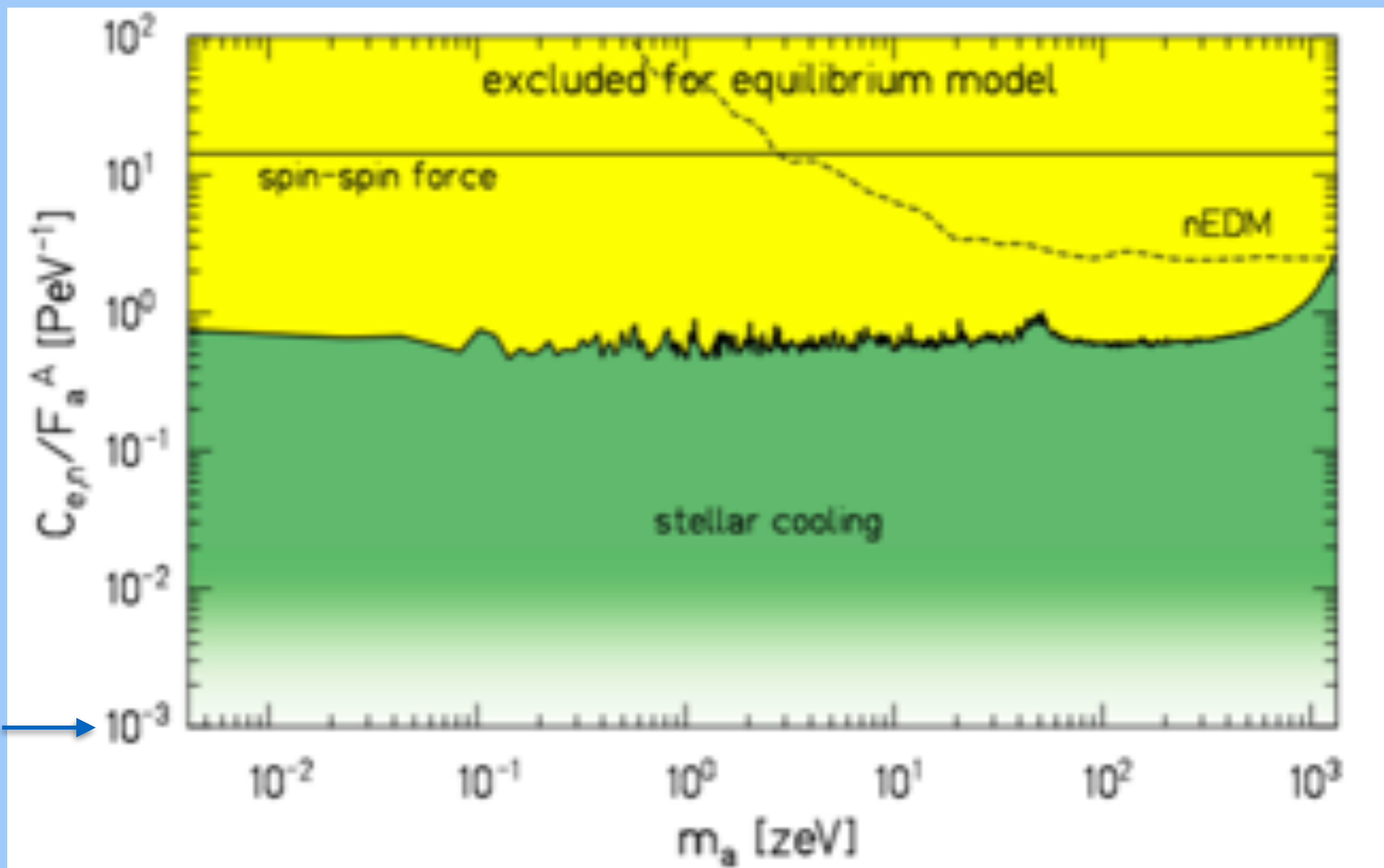
Zooming out on the problems

O(10^{-3})
Suppresion Required

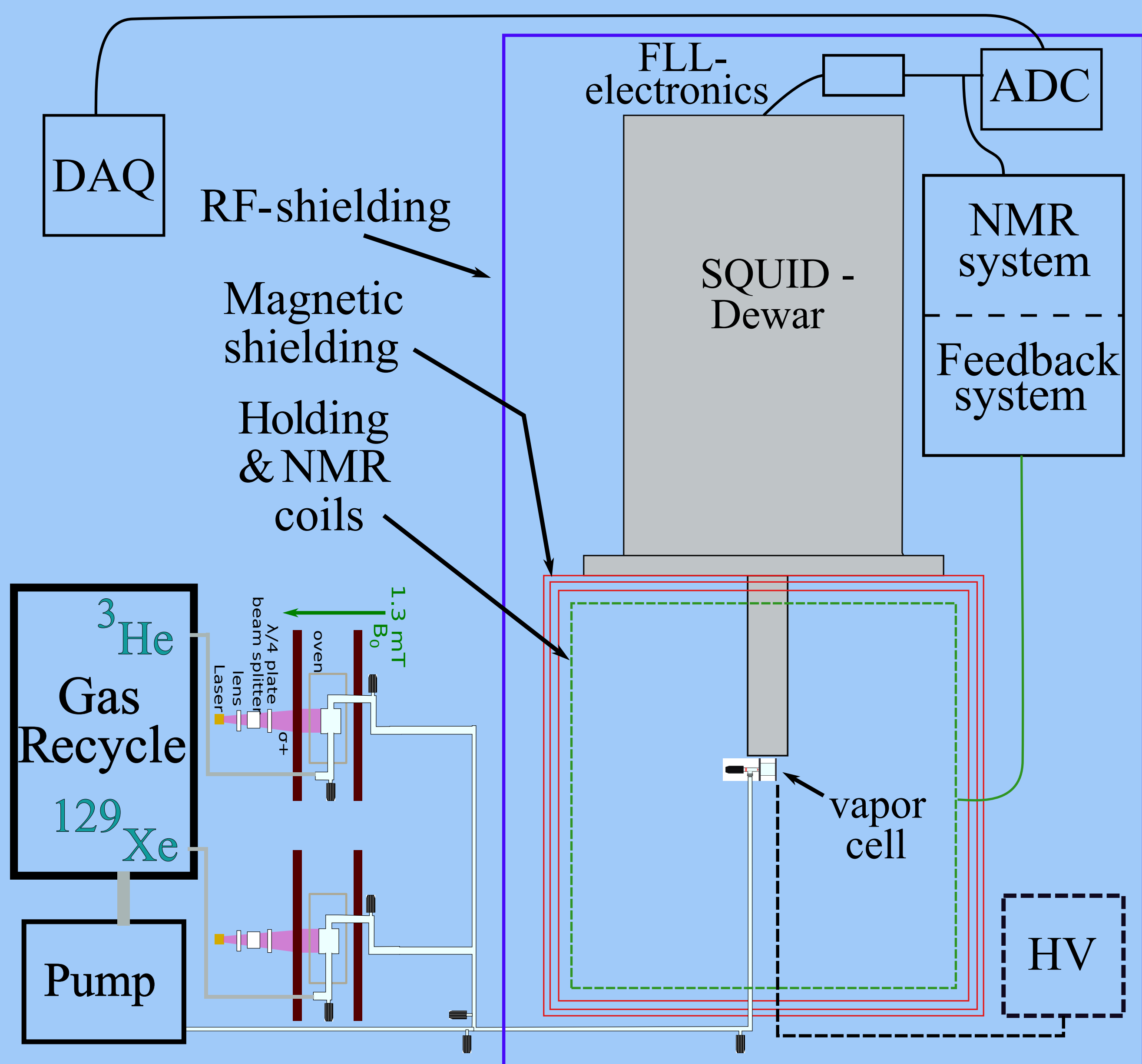
- Self-interacting system:
  Energy splitting depends
  on the superposition you are in.

$$\mathcal{H}_{\mathrm{ex}} = -\sum_{i<j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

10^9 GeV


excluded for equilibrium model
spin-spin force
nEDM
stellar cooling
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
C_e,n/F_a^A [PeV^-1]
m_a [zeV]

Rb-interaction free system



Potential for Ultra-light Axion search

Reach F_{DM}

Astro-physics — 10^9 GeV

He-Ne Goal — $2 \cdot 10^{10}$ GeV

2nd Gen — $1.2 \cdot 10^{14}$ GeV

Commercial Gear

Density: 1 amagat

Polarization: 10%

Cell size: 5 x 4.285 cm

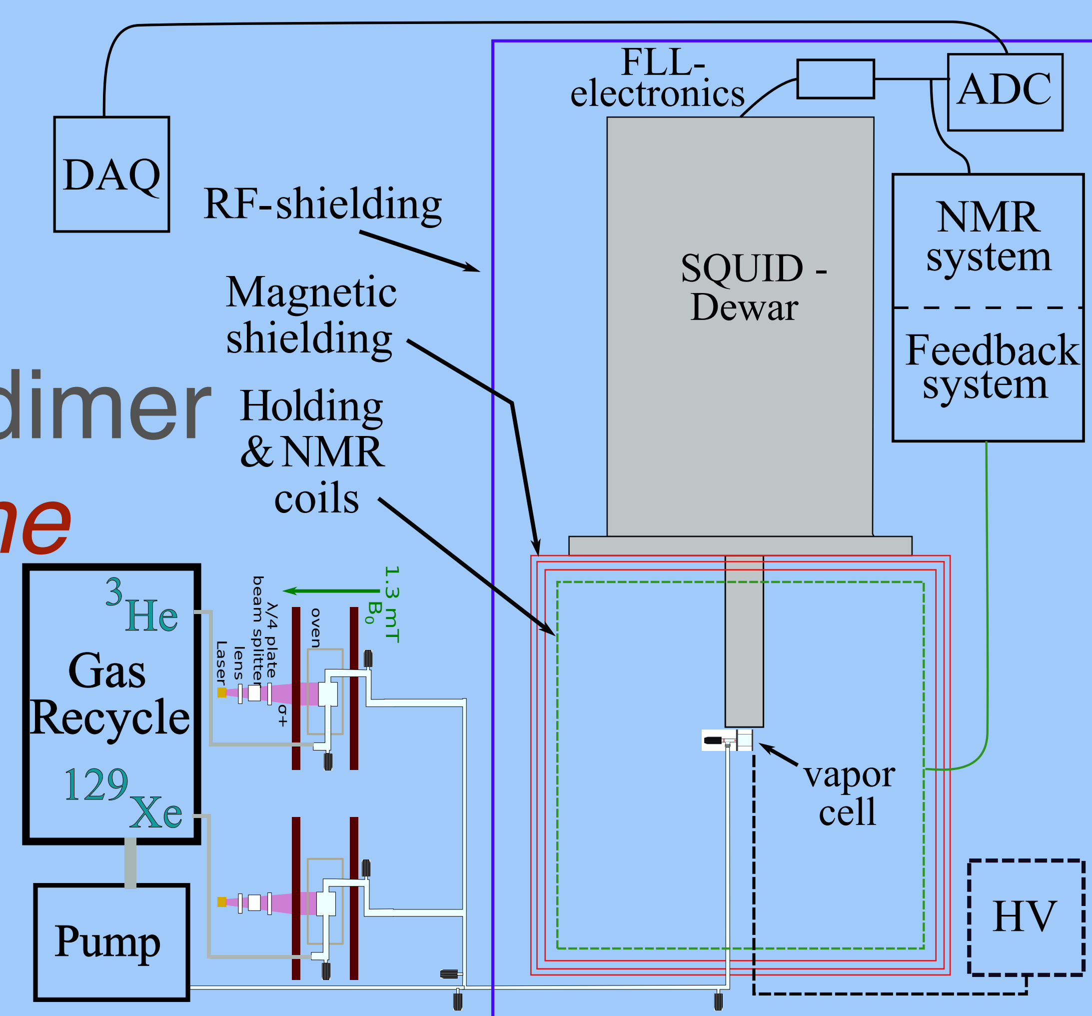
SQUID noise: 0.180 fT

SQUID distance: 4 cm

2nd Gen

T2 5hrs: Xenon-dimer

Adjustable volume (ppm) and fidelity (ppm)



Towards GUT scale

Reach	F_{DM}
Astro-physics	$10^9\,\mathrm{GeV}$
He-Ne Goal	$2 \cdot 10^{10}\,\mathrm{GeV}$
2nd Gen	$1.2 \cdot 10^{14}\,\mathrm{GeV}$

<u>Beyond</u>

Decay time T2 limited by Xenon-dimers
— Run hotter (T2 x10?) or
— Higher pressure (x20)

SQUID noise limited by pickup-loop inductance:
— Custom SQUID coil (x7) &
— Better coupling (x5)

Big hammer:
— 50 cm cell (x20), gradients at nEDM levels

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