Laboratory Search for New Spin-dependent Interaction
(at Center for Axion and Precision Physics)

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for the Axion Resonant InterAction Detection Experiment (ARIADNE)

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Outline

- Introduction
- Axion Search at CAPP, IBS
- Axion search with new spin-dependent interaction
- ARIADNE Collaboration
- CAPP contribution and future plan
- Summary

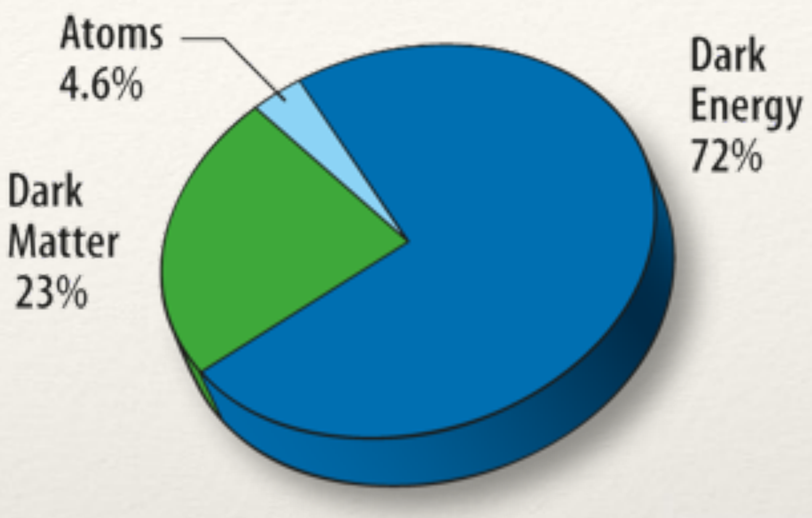
Particle Physics and Axion

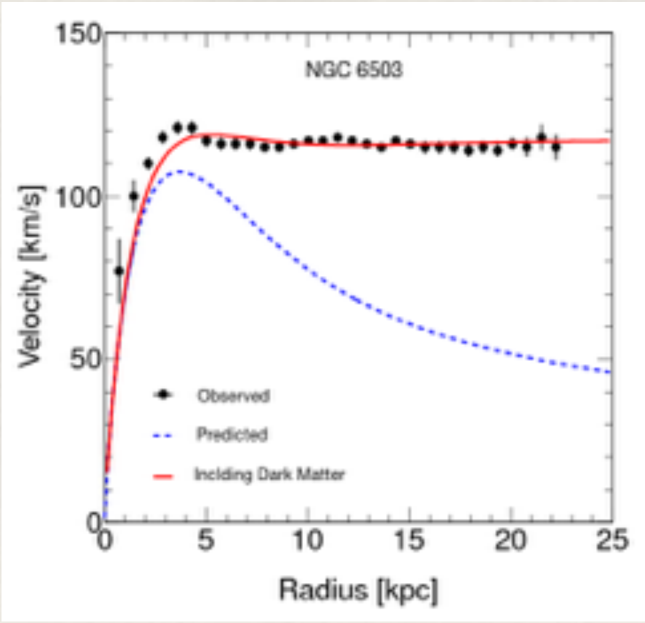
- The strong CP problem in QCD
  - ✓ CP violating term in Lagrangian: $L_\theta = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$
  - ✓ Vacuum Angle : θ
  - ✓ It gives neutron EDM of : $d_n \sim \frac{e}{M_n}\left(\frac{m_q}{M_n}\right)\theta \sim \theta \times 10^{-15} e \cdot cm$
  - ✓ But Current Experimental Limit of nEDM [1]: $d_n^{exp} \sim 3 \times 10^{-26} e \cdot cm$
  - ✓ Lack of explanation for why $\theta \lesssim 10^{-10}$ so small
- Axion field is introduced as a dynamical θ parameter[2]
  - ✓ a→a+constant, broken only by CP-anomalous term

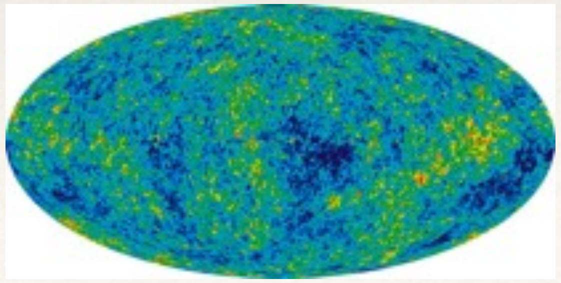
[1] C.A.Baker et al. Phys. Rev. Lett. 97, 131801 (2006)
[2] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)

Dark Matter and Axion

- A large fraction of our Universe: some how "Dark Matter"
- The evidence comes from a variety of sources at all scales
  - ✓ Galaxy Rotation Curves
  - ✓ CMB Observations
- Axion as a Dark matter candidate :
  - ✓ The coupling with matters suppressed by decay constant f_a :
    - $f_a \approx 10^9 \sim 10^{12}$ GeV
  - ✓ Non thermal production mechanism
    - $\theta \to 0$, $m_a \neq 0$: axion get mass
    - No damping mechanism for axion oscillation
    - Energy density freezes out until today
    - behaves like non-relativistic matter

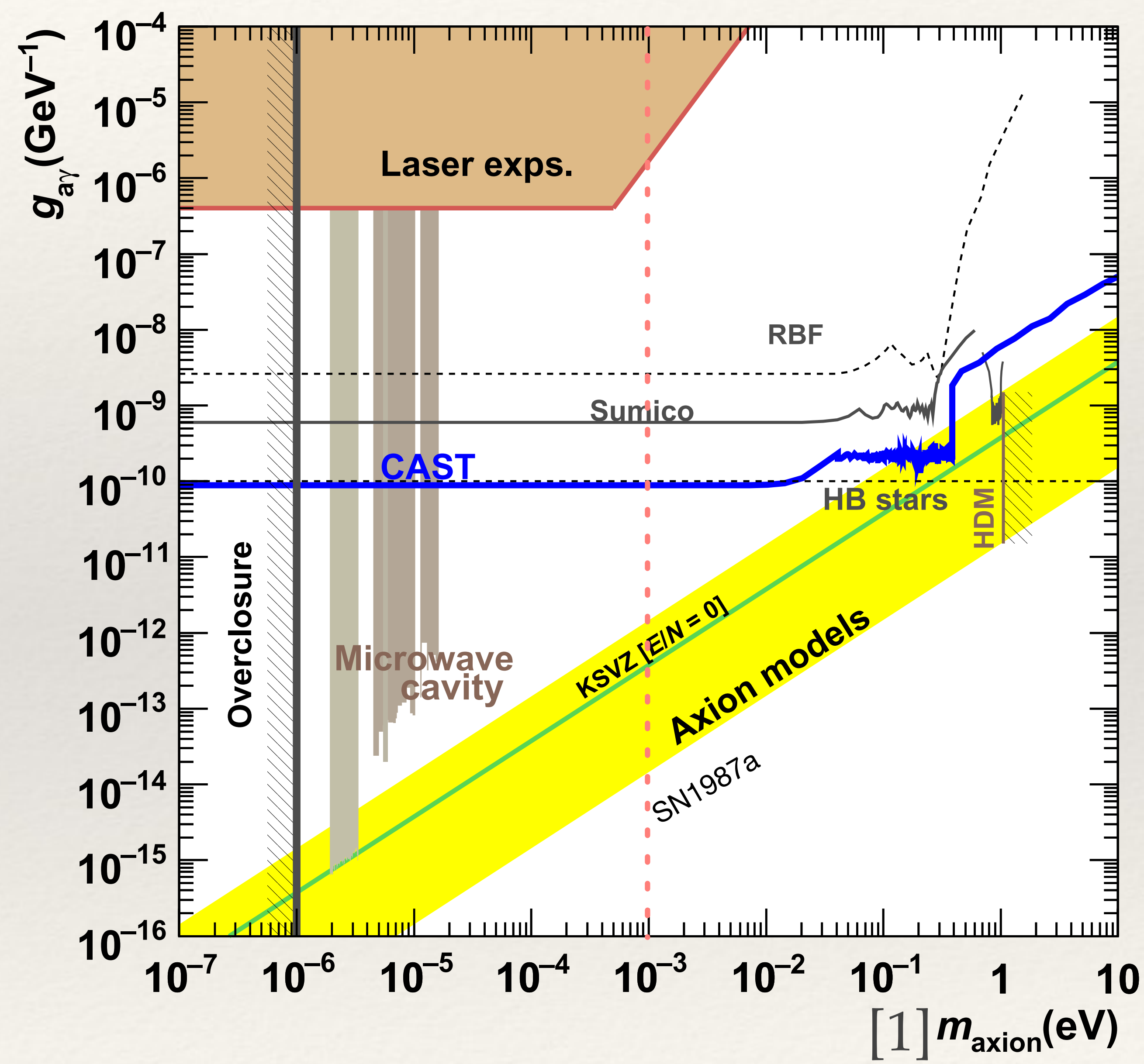






Dark Matter and Axion

- Cosmological boundary
  - ✓ relic energy density $\Omega_a \propto m_a^{-7/6}$
  - ✓ for the condition of $\Omega_a \lesssim 1$
  - ✓ No over-close of Universe
  - ✓ $1\mu eV \lesssim m_a \lesssim 10\mu eV \rightarrow m_a > 1\mu eV$
- Astrophysics boundary
  - ✓ $m_a < 1meV$
  - ✓ SN1987a stellar evolution

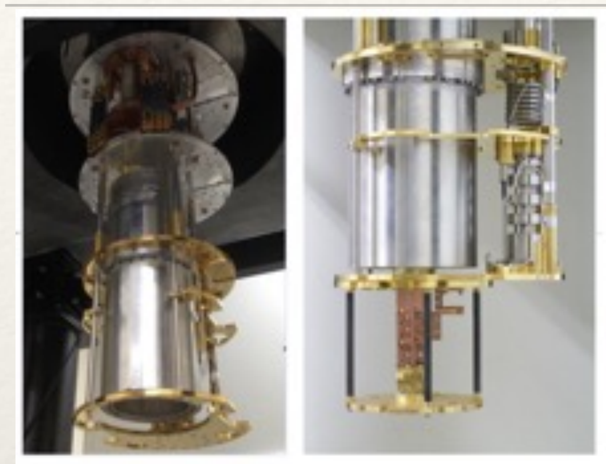


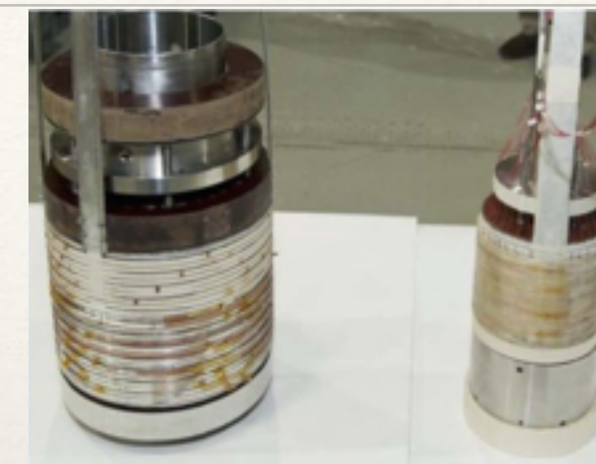
[1] K. Zioutas, et. al., New Journal of Physics, 11(10):105020 (2009)

Center for Axion and Precision Physics

- Established in 2013 through Institute for Basic Science in Korea (Director : Prof. Yannis Semertzidis)
- Focused on issues of modern particle and astrophysics
  - ✓ Nature of Dark Matter : Axion
  - ✓ Nature of Universe: Matter-antimatter asymmetry : pEDM

CAPP Axion program

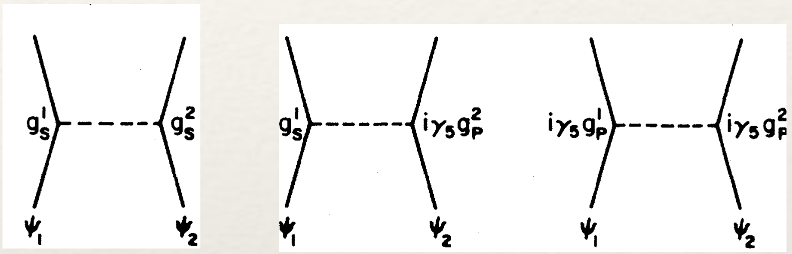




- Extensive R&D on axion dark matter experiments with
  - ✓ Microwave Cavity Experiment at T< 100mK (Chung)
  - ✓ CERN Axion Solar Telescope Collaboration (Miceli)
  - ✓ ADMX Collaboration (Ko)
  - ✓ R&D collaboration (with BNL) on High field SCM (Konikowska)
- Axion search from long-range, spin-dependent interaction with high precision NMR

New Spin-dependent Interaction

- Theoretical ideas imply weakly-coupled, long-range interaction[1][2] :
  - ✓ between macroscopic objects could exist
  - ✓ could be induced by the exchange of new light bosons
  - ✓ 16 interaction potentials : 8 parity-even, 8 parity-odd[2]



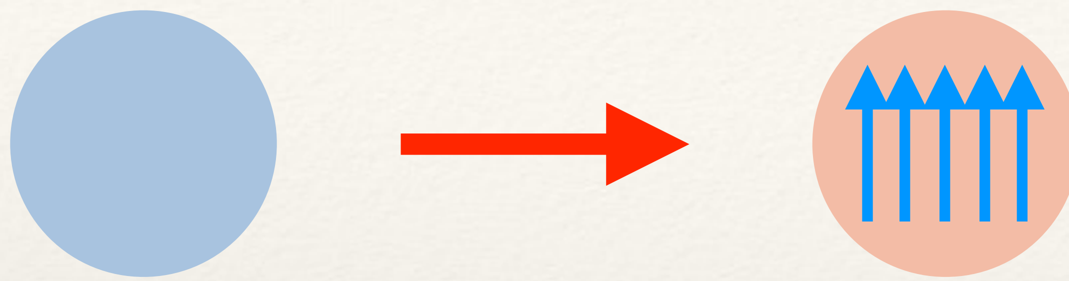
(a) (b) (c)

- The discovery of new force with a range longer than a micrometer :
  - ✓ tremendous impact on contemporary physics
  - ✓ few precision experiments have been conducted over “meso-scopic” ranges

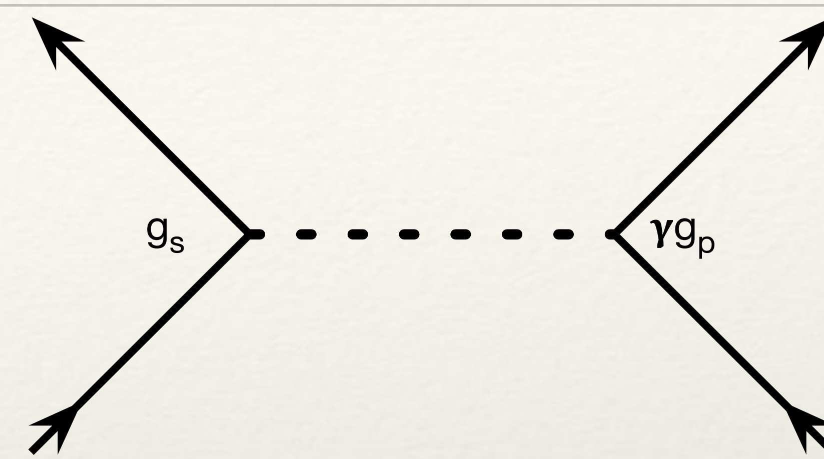
[1] J. E. Moody and F. Wilczek. Physical Review D, 30 (130), 1984

[2] B. A. Dobrescu and I. Mocioiu. Journal of High Energy Physics, 11(5), 2006

New Spin-dependent Interaction



monopole dipole



$$U_{sp}(r) = \frac{g_s g_p \hbar^2}{8\pi m_p}(\hat{\sigma}\cdot\hat{r})\left(\frac{1}{r\lambda_a}+\frac{1}{r^2}\right)\exp(-r/\lambda_a)$$ [1]

CP Violation in Standard Model

Coupling Constants g_s, g_p

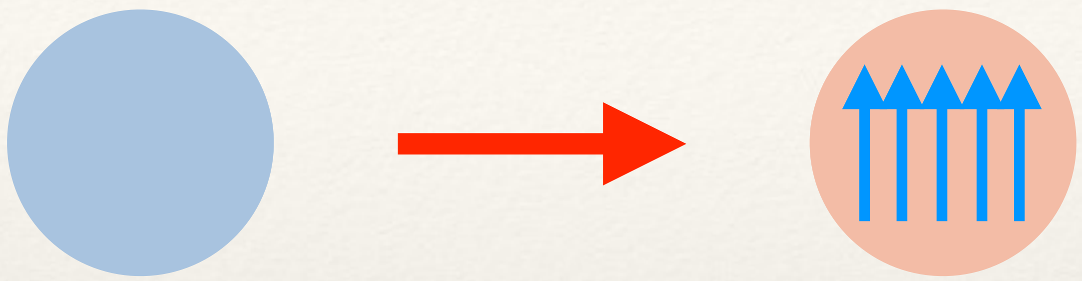
CP Violation allowed by experiment

$$\boxed{6\times 10^{-27}\left(\frac{10^9\ GeV}{f_a}\right)} < g_s \boxed{< 10^{-21}\left(\frac{10^9\ GeV}{f_a}\right)},$$

$$g_p = \frac{C_f m_f}{f_a} = C_f 10^{-9}\left(\frac{m_f}{1\ GeV}\right)\left(\frac{10^9\ GeV}{f_a}\right).$$

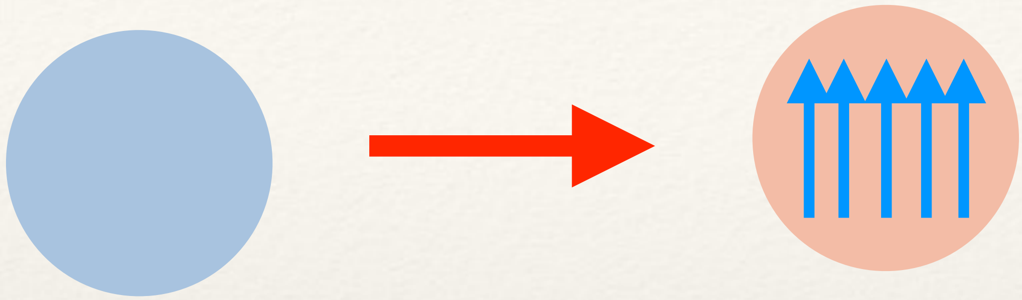
[1] J. E. Moody and F. Wilczek. Physical Review D, 30 (130), 1984

New Spin-dependent Interaction



$$
\begin{aligned}
U_{sp}(r) &= \frac{g_s g_p \hbar^2}{8\pi m_p}(\hat{\sigma}\cdot\hat{r})\left(\frac{1}{r\lambda_a}+\frac{1}{r^2}\right)\exp(-r/\lambda_a) \\
&= -\left(\frac{g_s g_p \hbar^2}{8\pi m_p}\right)\vec{\nabla}\left(\frac{1}{r}\exp(-r/\lambda_a)\right)\cdot\hat{\sigma} \\
&= -\vec{\nabla}V_a(r)\cdot\hat{\sigma} \\
&= -\vec{\nabla}V_a(r)\left(\frac{2}{\hbar\gamma_f}\right)\cdot\hat{\sigma}\left(\frac{\hbar\gamma_f}{2}\right) \\
&= -\vec{\mathrm{B}}_{\mathrm{eff}}\cdot\vec{\mu_f} \quad \text{(Magnetic potential Energy)}
\end{aligned}
$$

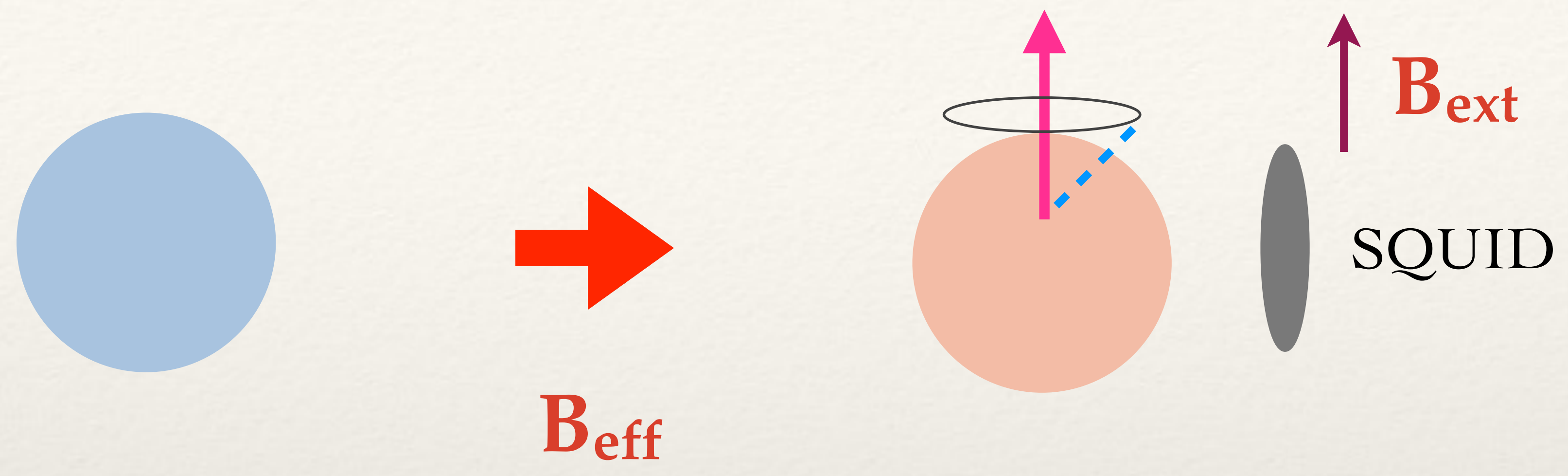
New Spin-dependent Interaction



$$\vec{\mathrm{B}}_{\mathrm{eff}} = \vec{\nabla} V_a(r) \left(\frac{2}{\hbar \gamma_f} \right)$$

- Different than normal electromagnetic field
- Independent from fermion's magnetic moment
- Does not couple to the angular moment or charge : No Maxwell equation ➜ can't be screened by magnetic shielding

ARIADNE Proposal



- Time varying $B_{\rm eff}$ drives spin precession

$$\vec{B}_{\rm eff} \approx \frac{1}{\hbar\gamma_N}\nabla V_a(r)(1+\cos(n\omega_{\rm rot}t)),$$

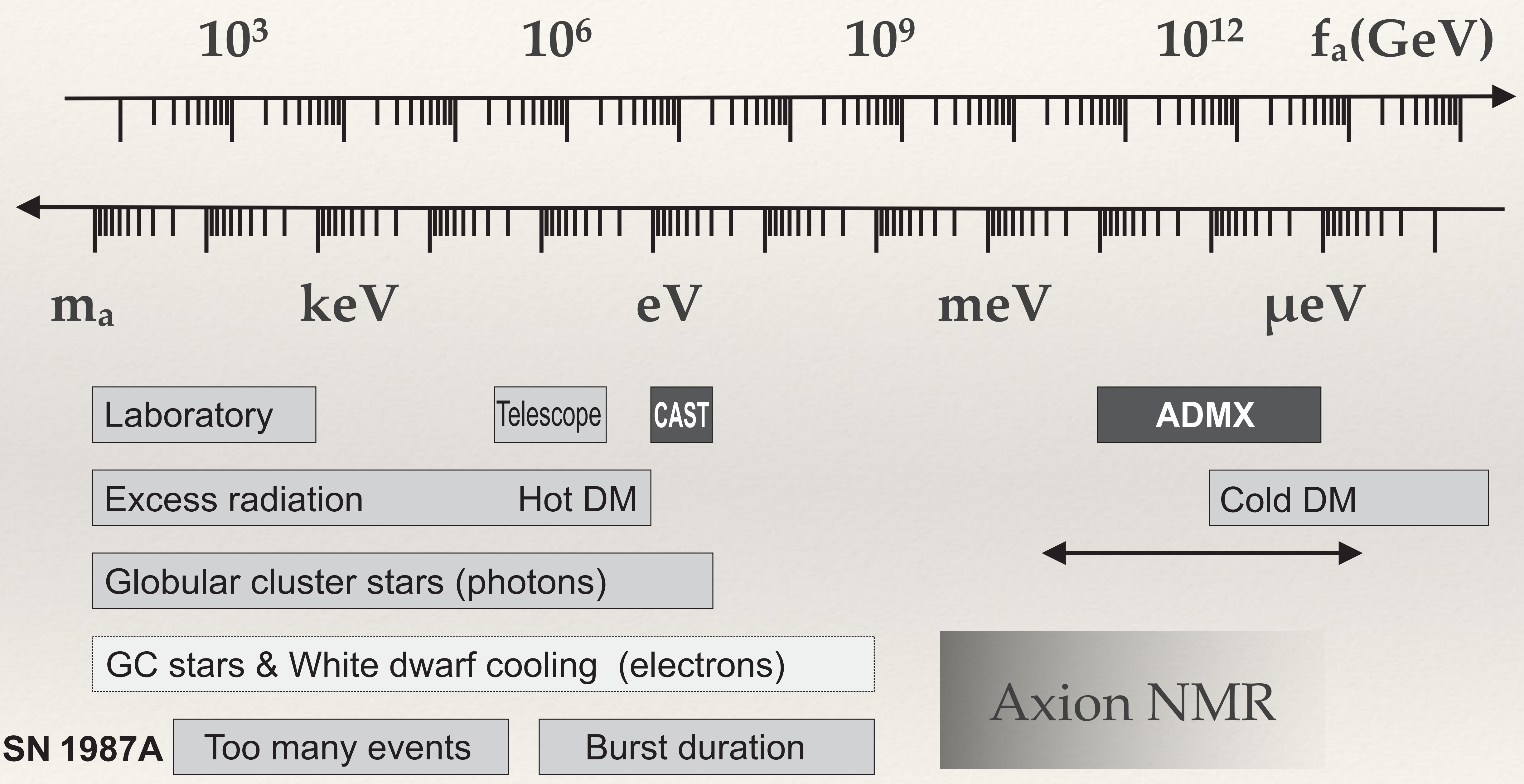
- Produce transverse magnetization [1]

$$M_x(t) \approx \frac{1}{2} n_s p \mu_N \gamma_N B_{\rm eff} T_2 (e^{-t/T_1} - e^{-t/T_2}) \cos(\omega t)$$

- Signal linearly grows until $t \sim T_2$: $Q \sim \omega T_2$

[1] p: polarized fraction, n_s: spin density of sample, T2: spin relaxation time

Searchable Regime

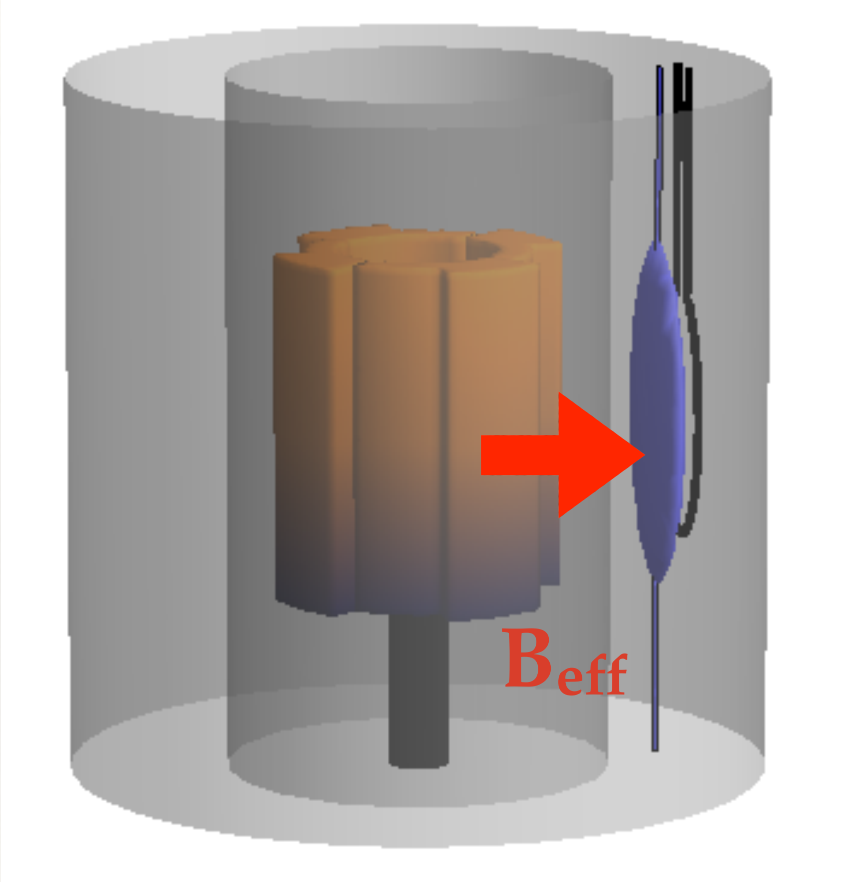


[1] J. Beringer et al. [Particle Data Group Collaboration], PRD 86, 010001 (2012)

ARIADNE Proposal

PI: Andrew Geraci (U. Nevada Reno), co-PIs: Aharon Kapitulnik (Stanford),
Chen-Yu Liu (Indiana U.), Josh Long (Indiana U.),Mike Snow (Indiana U.),
Mina Arvanitaki (Waterloo), Yannis Semertzidis (CAPP Korea)
Senior Personnel: Eli Levenson-Falk (Stanford), Yunchang Shin (CAPP Korea)

- Polarized 3He gas at 4K with precession : ω_{3He}
- Rotating mass oscillates force in resonance at : n ω_{rot}
- Detect M_x with SQUID
- Limit : Transverse spin projection noise
- Longer T_2 and Higher $n_{3He\uparrow}$

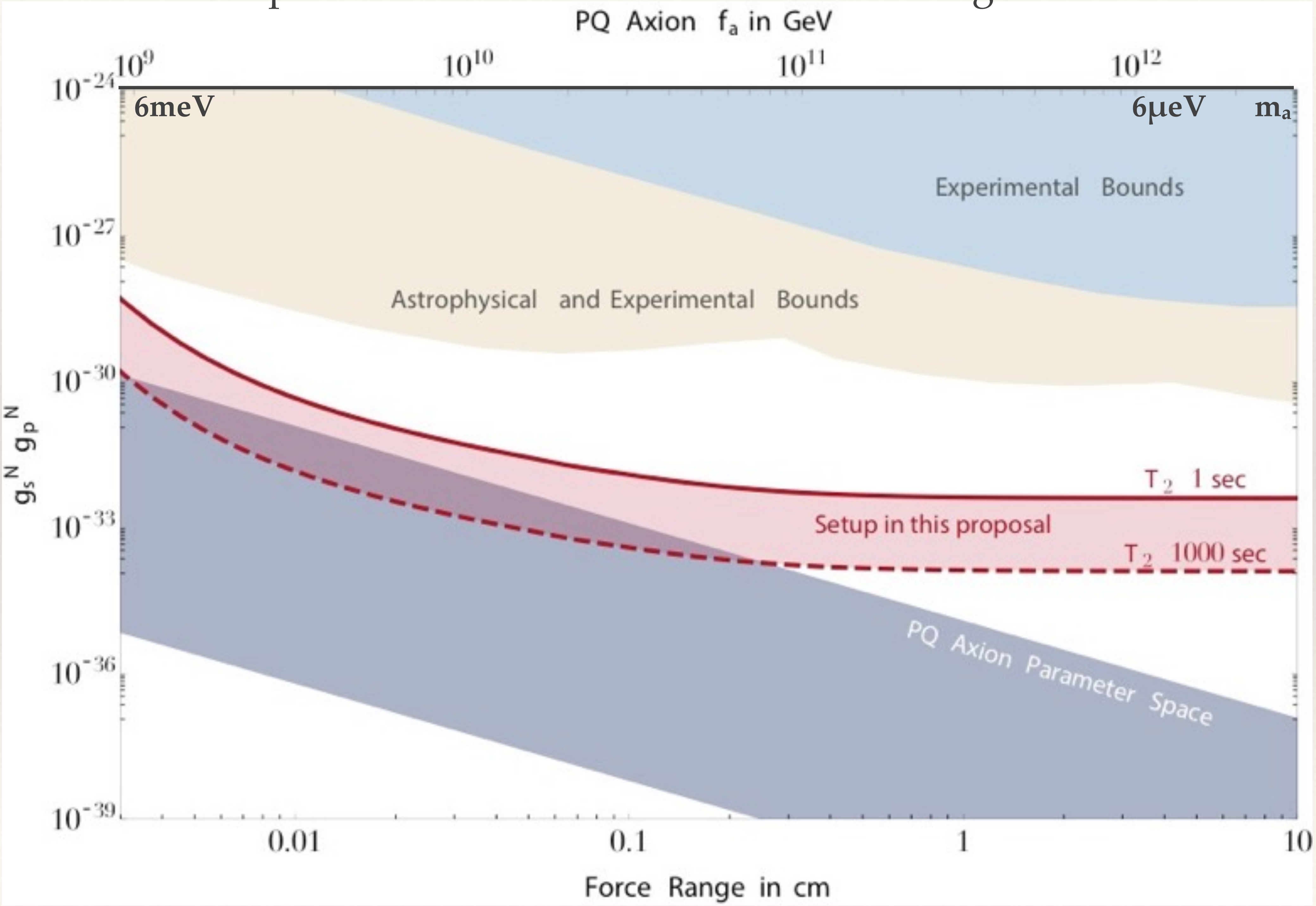


$$B_{min} \approx p^{-1}\sqrt{\frac{2\hbar b}{n_s \mu_{^3\mathrm{He}} \gamma V T_2}} = 3\times 10^{-19}\mathrm{T}\times\left(\frac{1}{p}\right)\sqrt{\left(\frac{b}{1\mathrm{Hz}}\right)\left(\frac{1\mathrm{mm}^3}{V}\right)\left(\frac{10^{21}\mathrm{cm}^3}{n_s}\right)\left(\frac{1000\mathrm{s}}{T_2}\right)}$$

[1] A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014).

Expected Reach

Unpolarized Source Mass with 10^6 sec integration

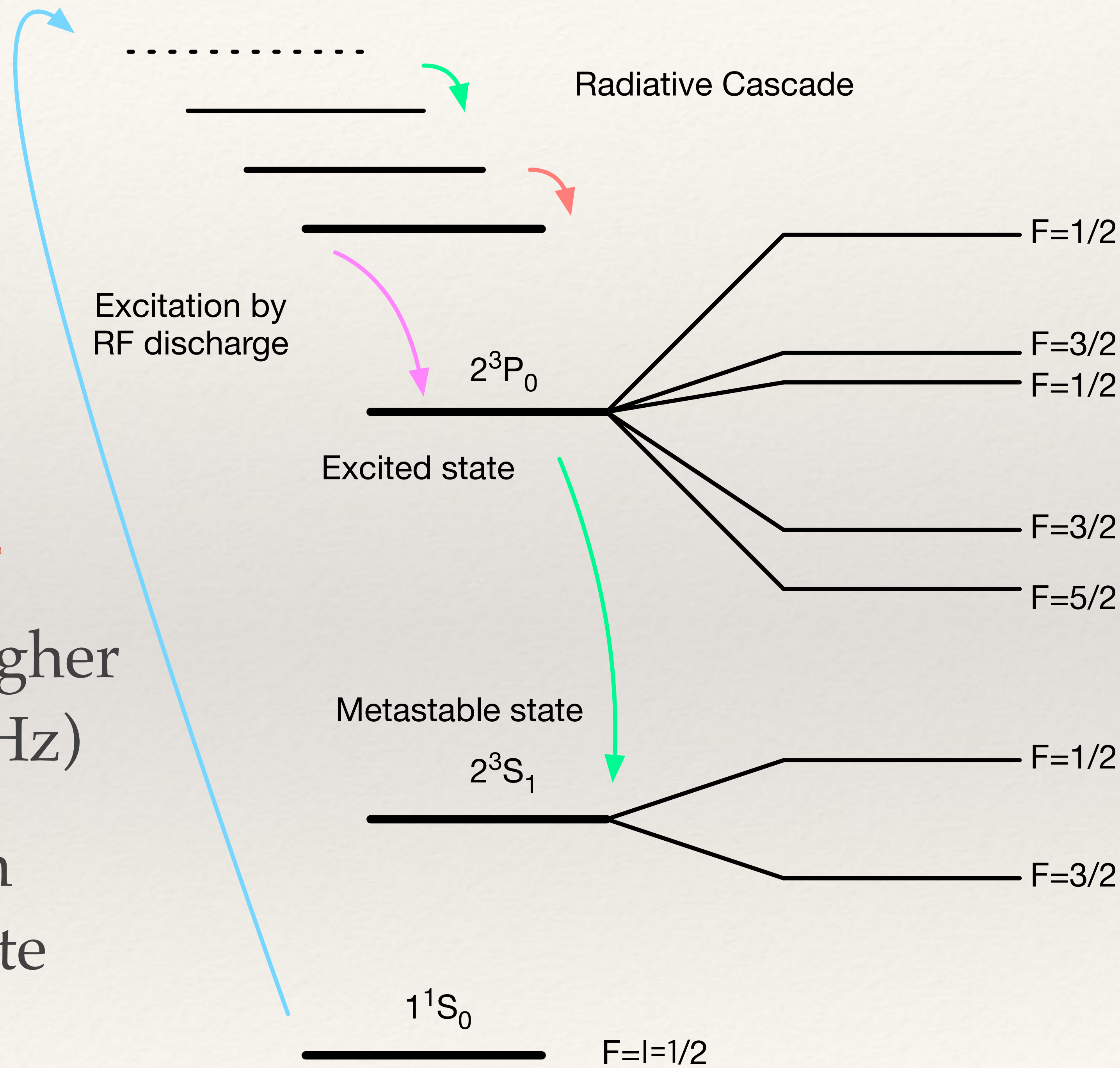


Technical Challenges

Systematic Effect/Noise source	Background Level	Notes
Magnetic gradients	3×10^{-6} T/m	Limits T_2 to ~ 100 s
		Possible to improve w/shield geometry
Vibration of mass	10^{-22} T	For 10 μm mass wobble at ω_{rot}
External vibrations	5×10^{-20} T/$\sqrt{\mathrm{Hz}}$	For 1 μm sample vibration (100 Hz)
Patch Effect	$10^{-21} (\frac{V_{\mathrm{patch}}}{0.1\mathrm{V}})^2$ T	Can reduce with V applied to Cu foil
Flux noise in squid loop	2×10^{-20} T/$\sqrt{\mathrm{Hz}}$	Assuming $1 \mu\Phi_0/\sqrt{\mathrm{Hz}}$
Trapped flux noise in shield	$7 \times 10^{-20} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$	Assuming 10 cm^{-2} flux density
Johnson noise	$10^{-20} (\frac{10^8}{f})$T/$\sqrt{\mathrm{Hz}}$	f is SC shield factor (100 Hz)
Barnett Effect	$10^{-22} (\frac{10^8}{f})$ T	Can be used for calibration above 10 K
Magnetic Impurities in Mass	$10^{-25} - 10^{-17} (\frac{\eta}{1\mathrm{ppm}})(\frac{10^8}{f})$ T	η is impurity fraction (see text)
Mass Magnetic Susceptibility	$10^{-22} (\frac{10^8}{f})$ T	Assuming background field is 10^{-10} T
		Background field can be larger if $f > 10^8$

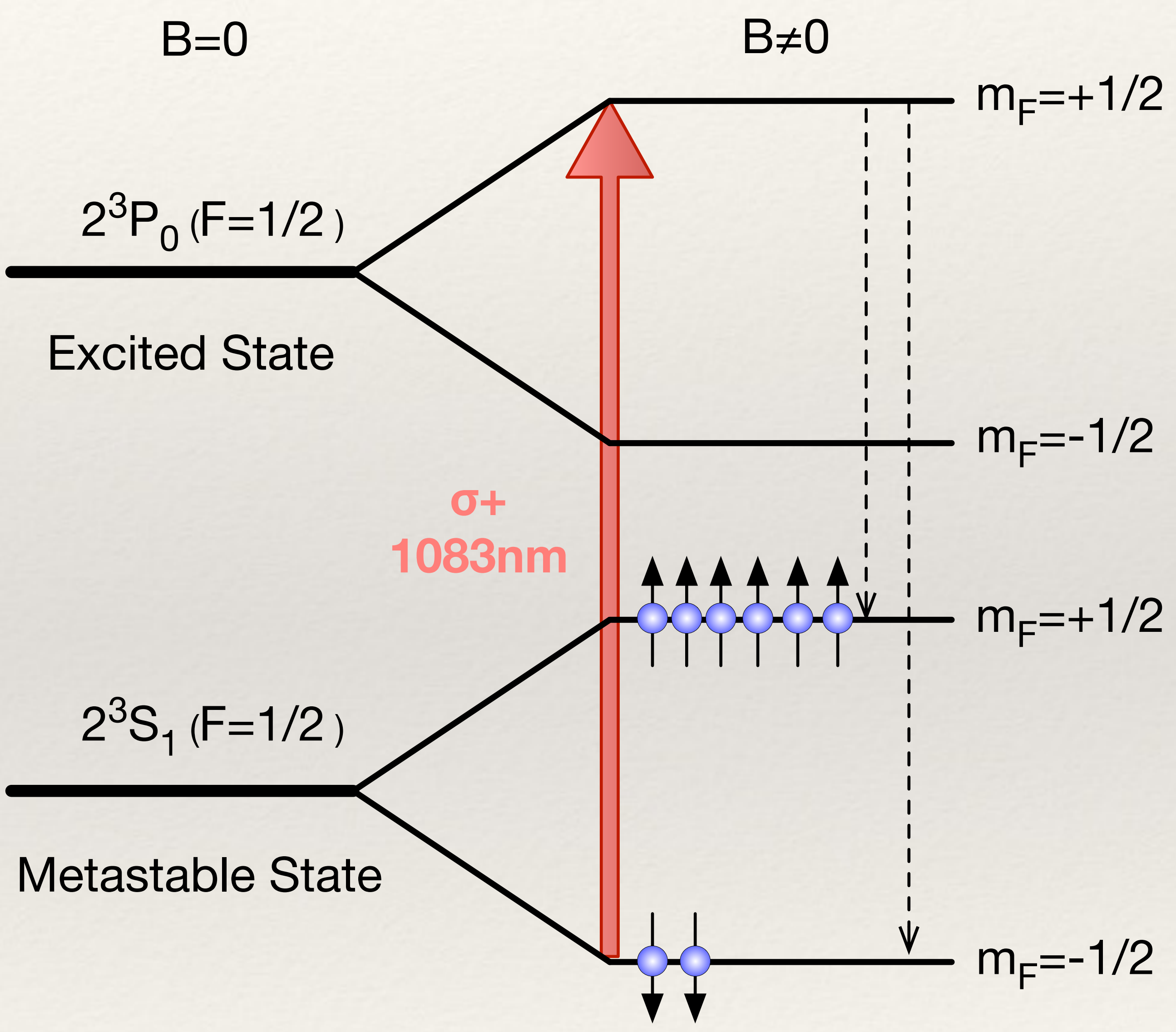
Metastability Exchange Optical Pumping

- The ground state (1^1S_0)
  - ✓ singlet with L=0 (orbital)
  - ✓ total electron J=0
- Total angular moment
  - ✓ **purely nuclear F=I=1/2**
- RF discharge to populate higher excited states (50W, 1~10MHz)
- small faction of the atoms in 2^3S_1 (~ppm) : metastable state



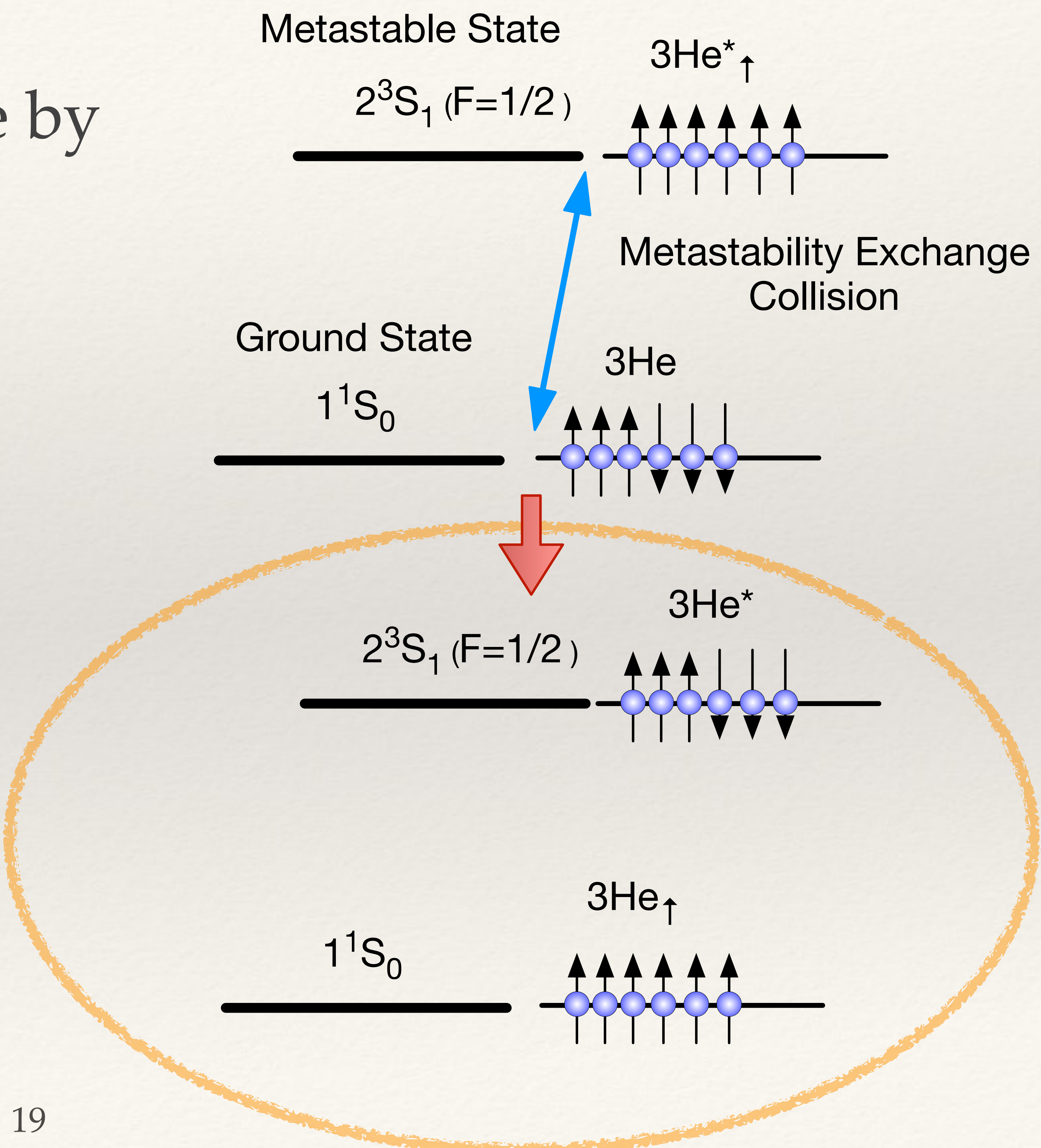
MEOP in standard condition

- OP with σ^+ light at 1083nm enables transitions between 2^3S_1 and 2^3P_0 (C8) with angular momentum selection
- Population of m_F=-1/2 is depleted relative to m_F=1/2
- The electronic optical orientation enforces nuclear orientation : hyperfine coupling
- Net polarization of total angular momentum



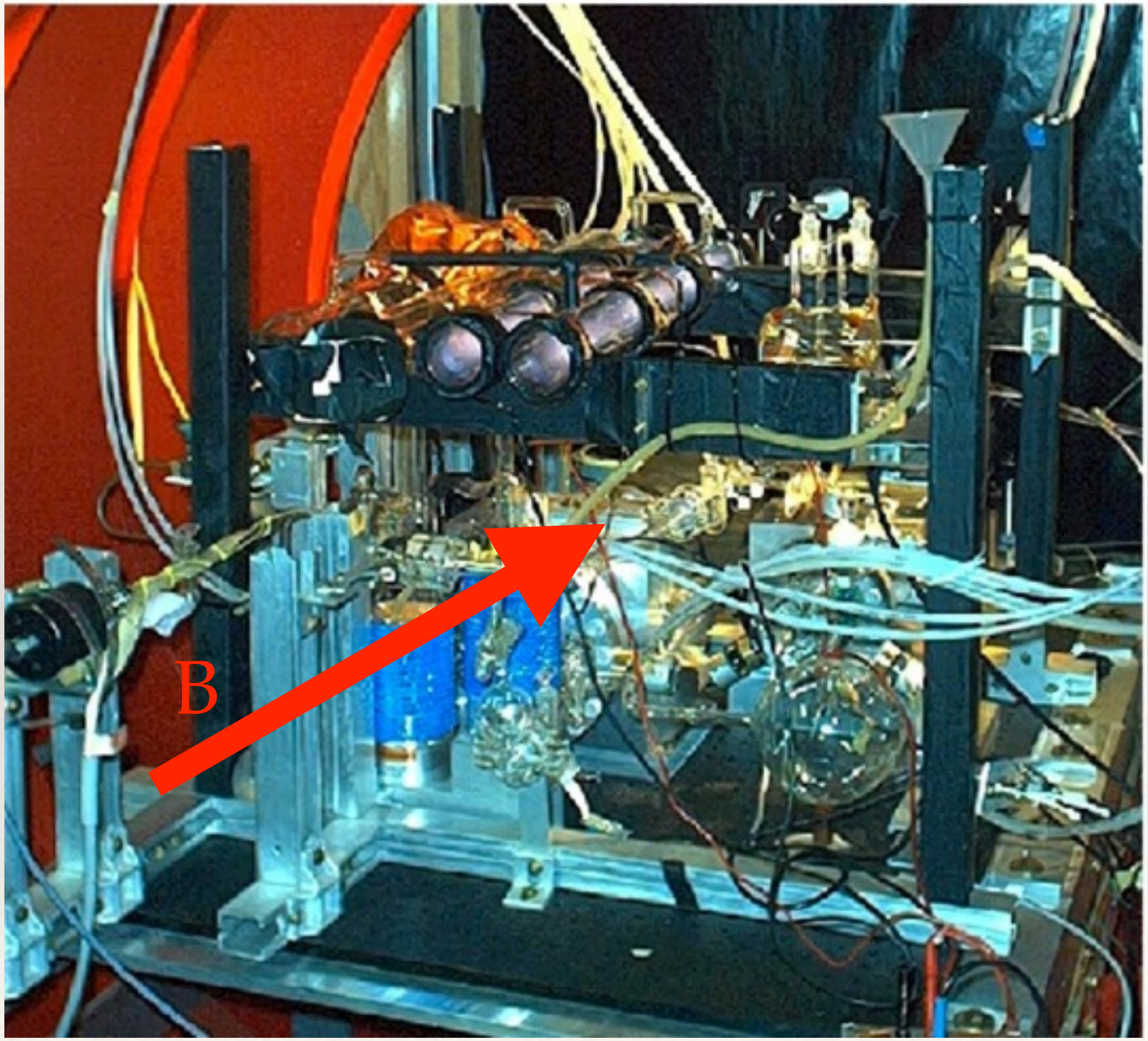
MEOP in standard condition

- Nuclear polarization of 3He by metastability exchange collision
- 3He+3He*↑→ 3He*+3He↑
- Net transfer of nuclear orientation from 2^3S_1 to 1^1S_0
- Repeat whole process to accumulate more 3He polarization



3He Polarization System

- at Indiana University
- Polarization of 3He and 3He/4He mixtures by MEOP at 1 mbar pressure
- Compression system can produce polarized 3He unto 1bar
- Can deliver arbitrary pressure of 3He or 3He/4He between 1mbar to 1bar
- Complication of polarized 3He transport



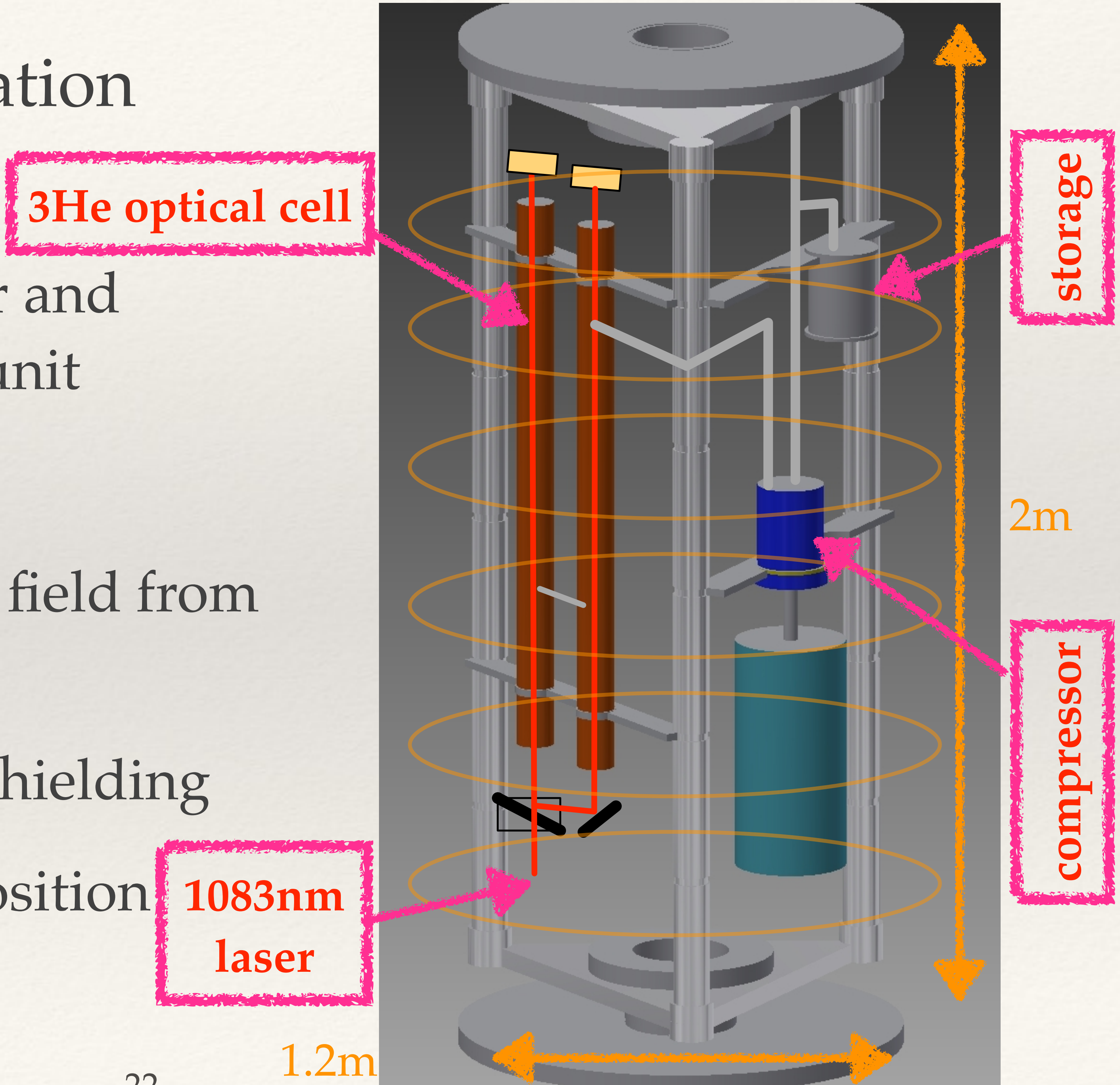
[1] D. S. Hussey et. al, Review of Scientific Instruments, 76(5),053503 (2005)

CAPP's contribution

(Yun Shin, Dong-Ok Kim)

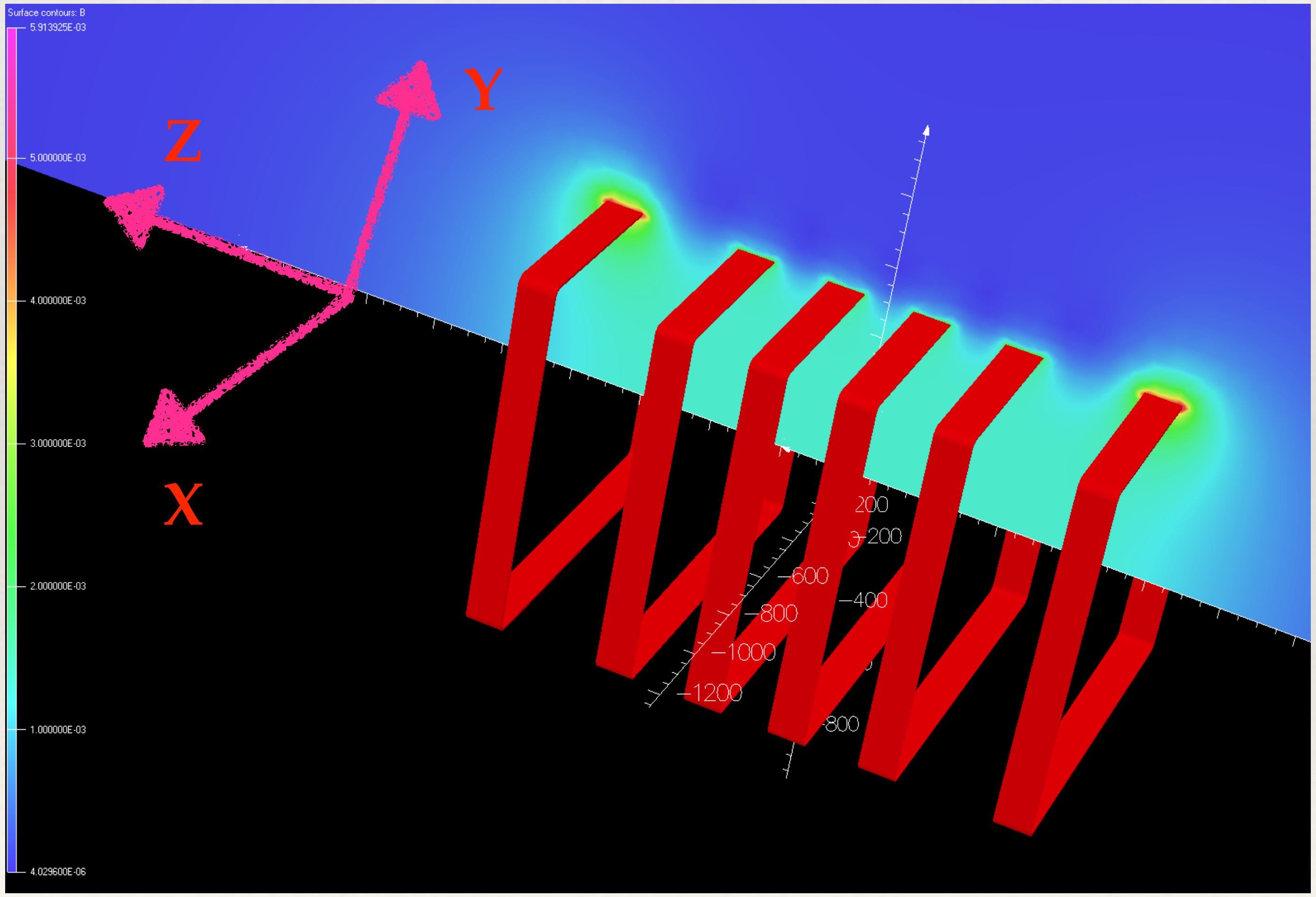
Compact 3He Polarization Unit

- Integrated 3He polarization system with
  - ✓ pumping cell, compressor and storage are in one single unit
  - ✓ non-magnetic parts
  - ✓ integrated uniform guide field from multi coil set
  - ✓ within layers of μ-metal shielding
  - ✓ can be mounted in any position
  - ✓ no field complication

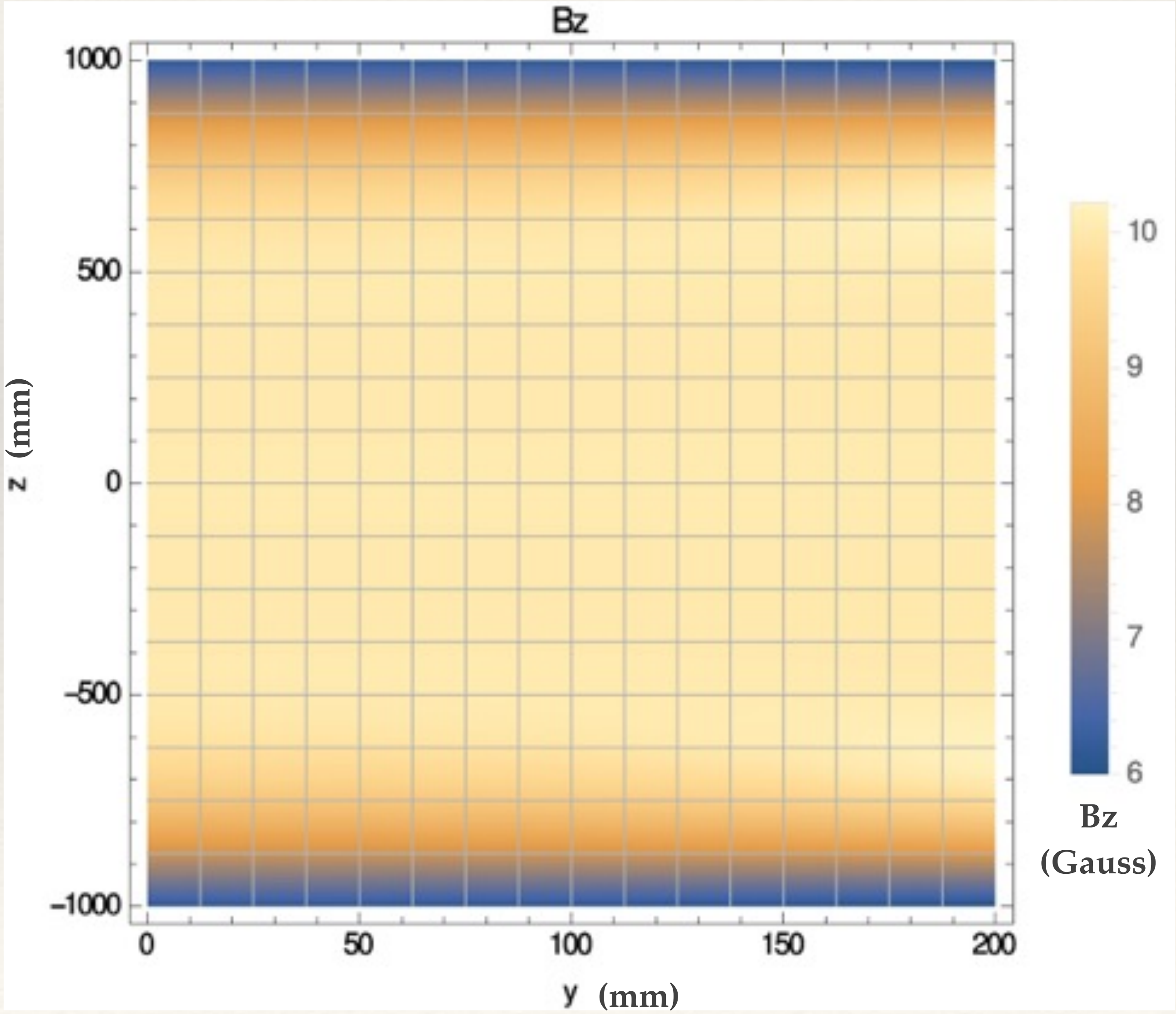


Uniform Guiding Field

- Uniform guide field simulation with OPERA 3D
  - ✓ six square coils configuration : more volume
  - ✓ less than 1% of field fluctuation with different number of turns for each coil and distances



work from PhD Student :Dong-Ok Kim

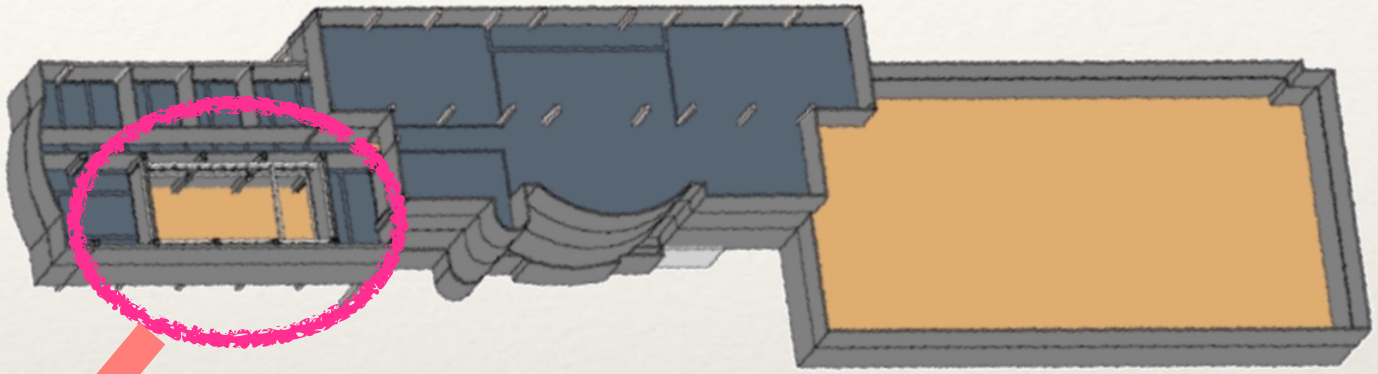


Magnetic Shielding Room

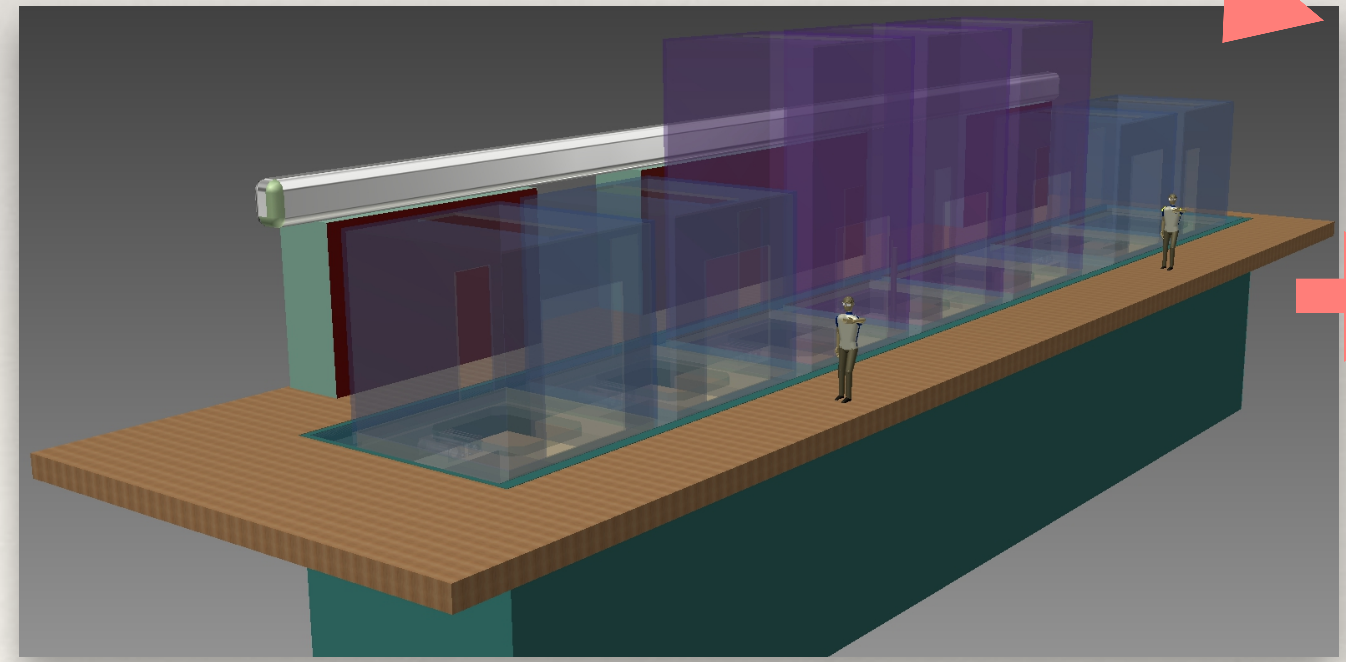
- Dimension : 2.8m×2.5m×2.5m(H)
- Built with Coam-Tech in S. Korea
- Shielding performance
  - ✓ 0.01 Hz: 200 times or more
  - ✓ 0.1 Hz: 300 times or more
  - ✓ 1 Hz: above 2000 times or more
  - ✓ 10 Hz ~ 400 MHz: more than 10,000 times
  - ✓ 400 MHz ~ 1000 MHz: more than 1,000 times
- Residual Field : 2nT
- Field gradient : 0.5nT
- will be installed in Creation Hall
- plan to improve : with Prof. Fierlinger at TMU

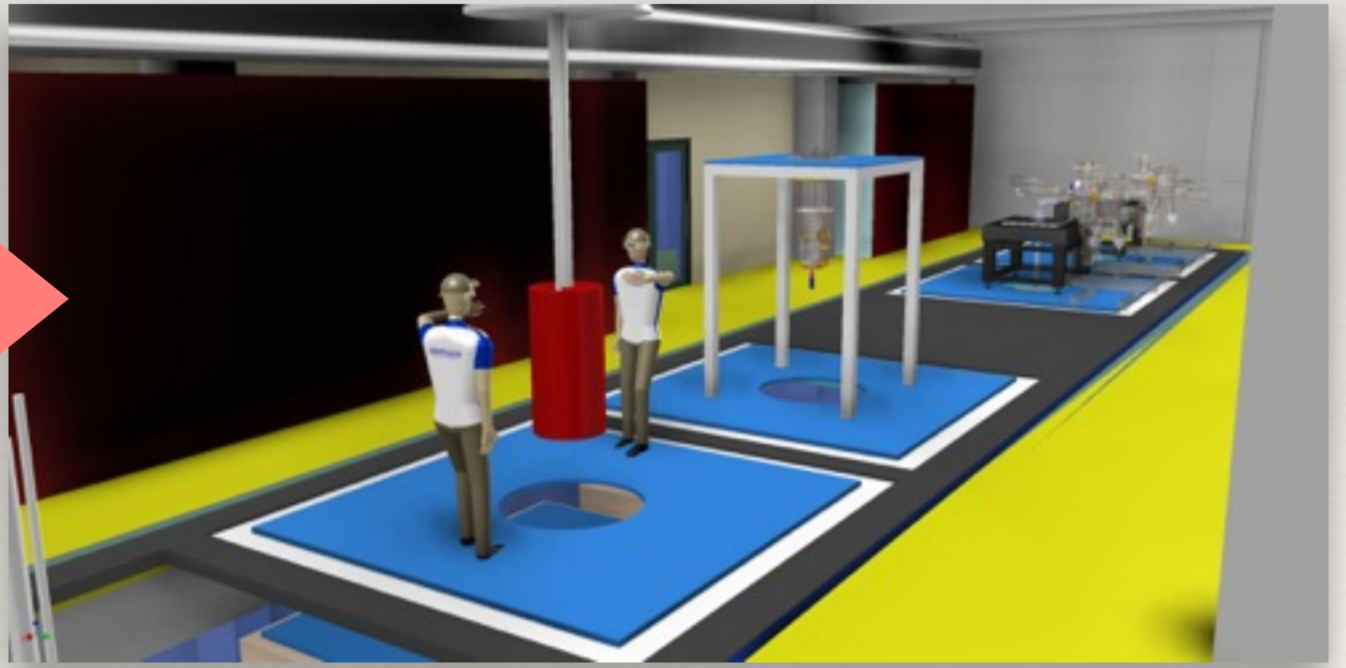
PIT (Anti-vibration platform)

- Creation Hall Experimental area
  - ✓ Located at KAIST Munji Campus
  - ✓ Seven anti-vibration platforms

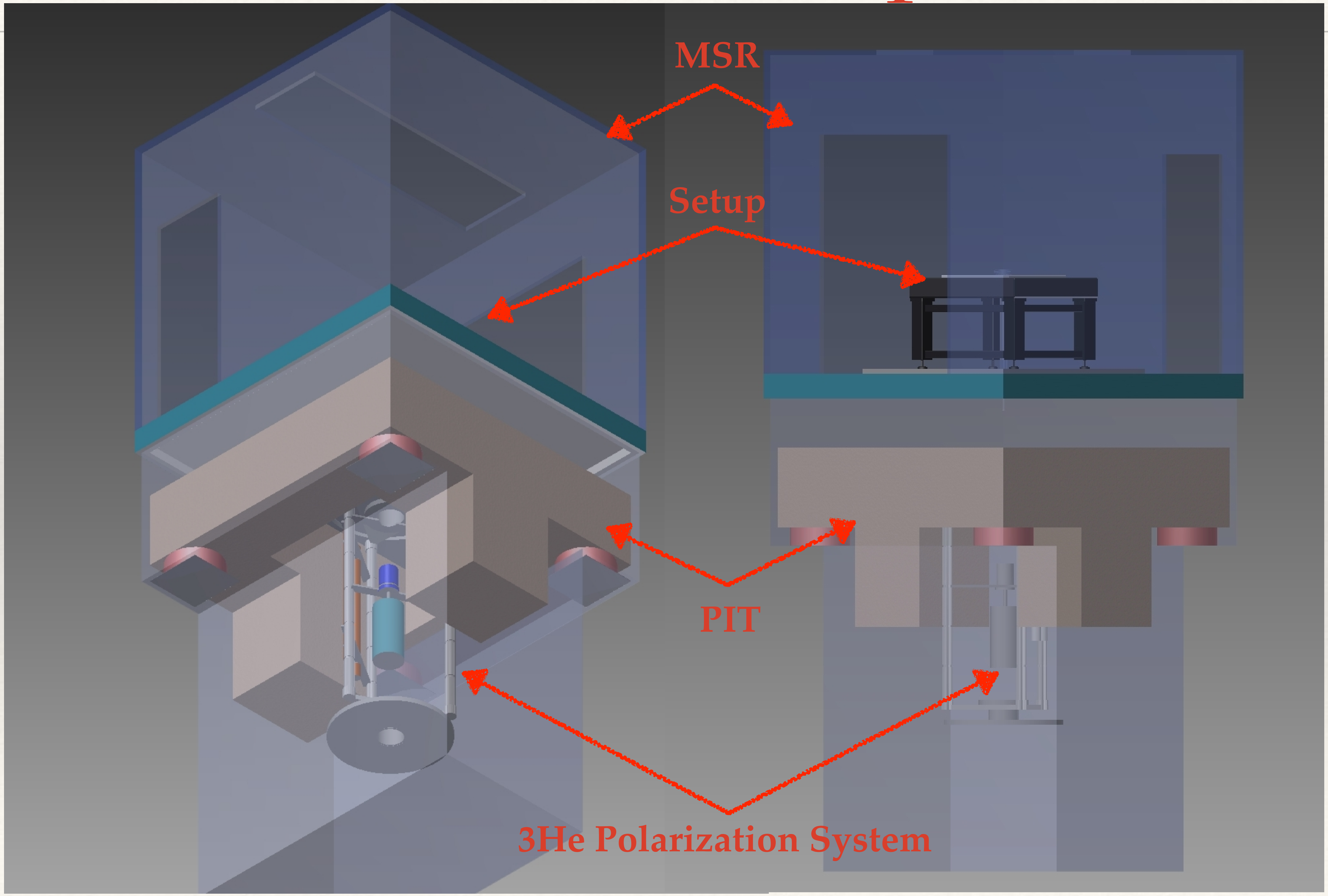


Frequency	Supression Efficiency (dB)
10Hz	> -15
20Hz	> -25
>30Hz	> -35





CAPP Concept



Plan at CAPP

- Ongoing R&D in ARIADNE Collaboration
  - ✓ prototype cryostat cold test at Indiana University
- Contribute with
  - ✓ Compact 3He polarization system
  - ✓ Magnetic Shielding (with Coam-Tech)
  - ✓ SQUID (with help from Dr. Yong-Ho Lee at KRISS)
  - ⋆ Anti-vibration platform (at CAPP at KAIST Munji Campus)
  - ✓ Other improvements
- Launch the experiment at CAPP

Summary

- Various approaches to look for axions at CAPP
- Laboratory search for axion from long range spin-dependent interaction can be very complementary
- Improvement in sensitivity can be made from new spin-dependent interaction experiment