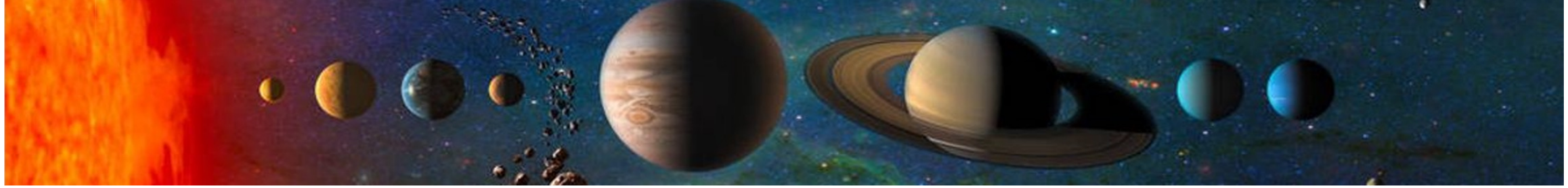


Cosmic Magnetic Monopole Searches with the SCEP experiment

Speaker：Qing Lin (qinglin@ustc.edu.cn)

(On behalf of SCEP collaboration)

University of Science and Technology of China

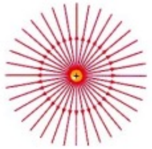
Deep Space Exploration Lab

NFMMS Workshop @ Beijing, 2026.09.14

Magnetic Monopole

Asymmetry of electromagnetism in Maxwell equation

$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$



$$\nabla \cdot \mathbf{B} = 0$$

$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_e$$

Standard Maxwell Equation

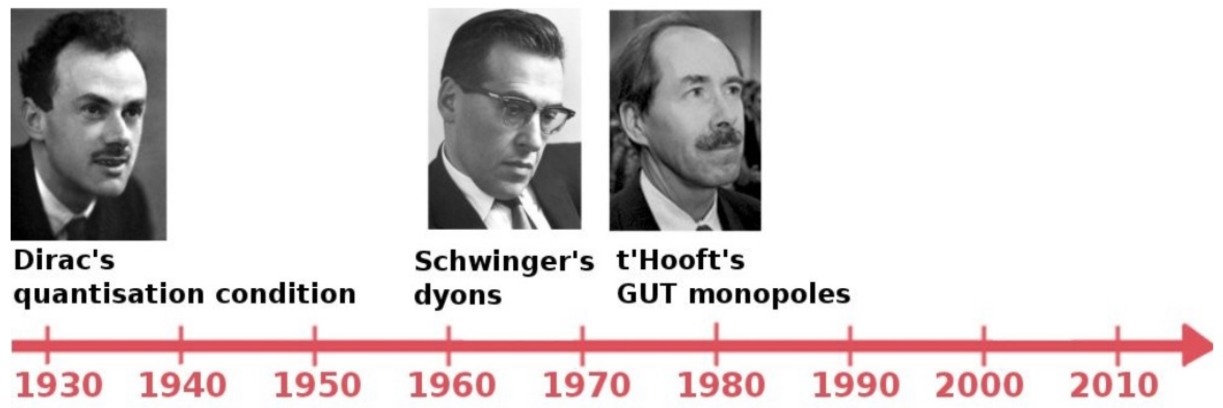
$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$

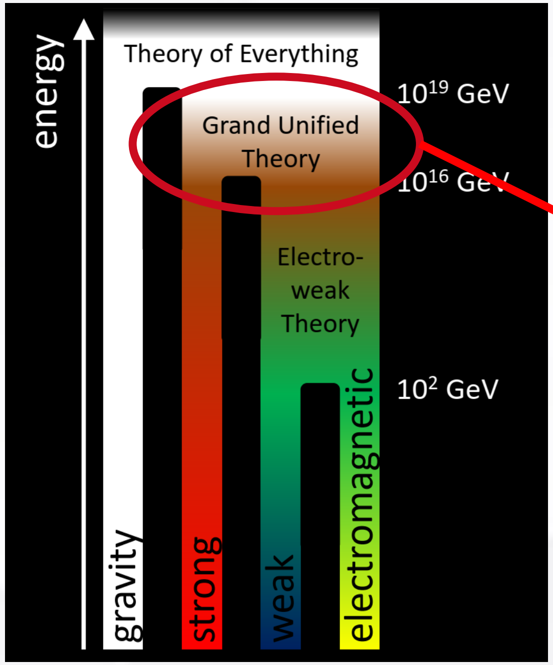
$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$

$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_m$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_e$$

Modified Maxwell Equation with magnetic charge

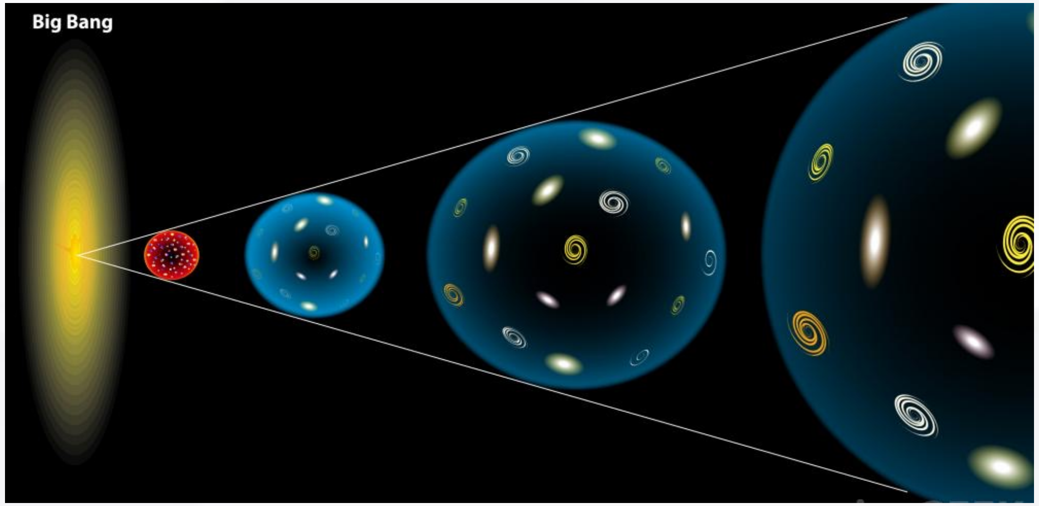




- ✓ GUT considers strong and EW unified at higher energy;
- ✓ GUT CAN explain the quantization of electric charge naturally;
- ✓ GUT also predicts the production of MM when strong and EW splitted;

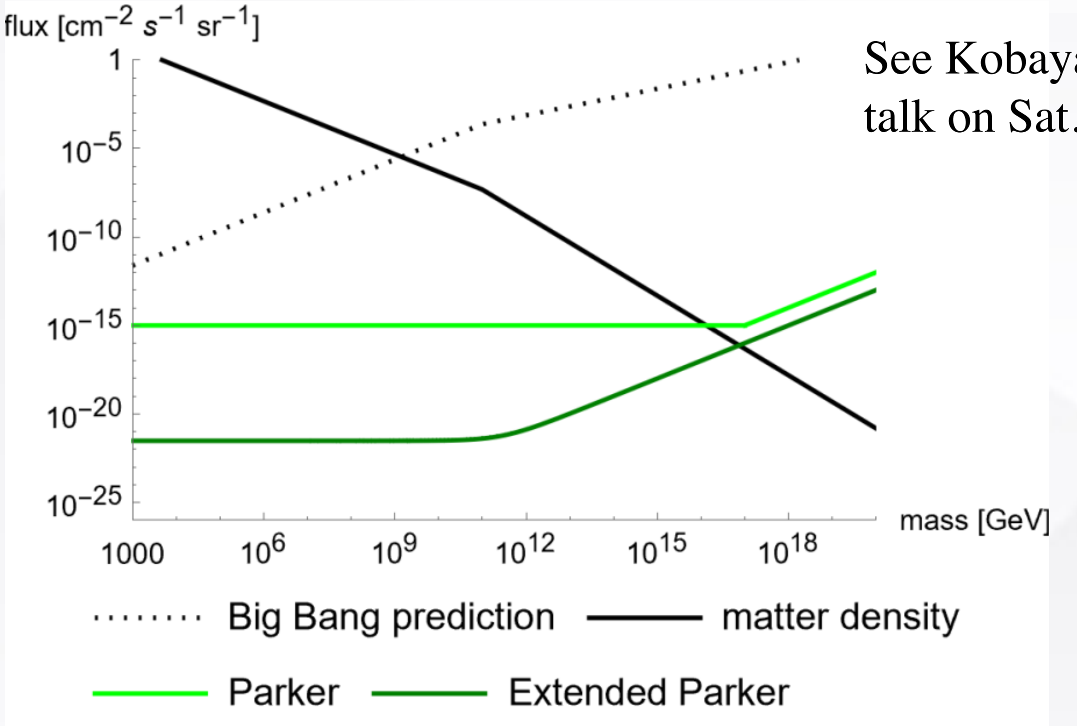
More details in talks in theory sessions!

Cosmic MM and its evolution



- MMs were produced right after the big bang, and diluted by the inflation. These GUT MMs have mass in order of ten to the several tens of GeV.
- Lighter MMs can also be produced by other less intense cosmic processes.

$$v_{\rm mag} \sim \begin{cases} c, & M \lesssim 10^{11}\,\mathrm{GeV}\,, \\ 10^{-3} c \left(\frac{10^{17}\,\mathrm{GeV}}{M}\right)^{1/2}, & M \gtrsim 10^{11}\,\mathrm{GeV}\,. \end{cases}$$

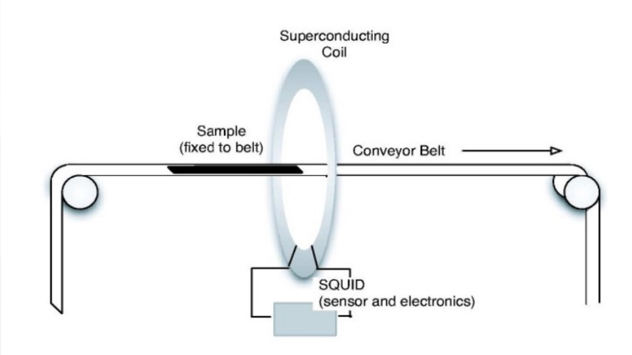


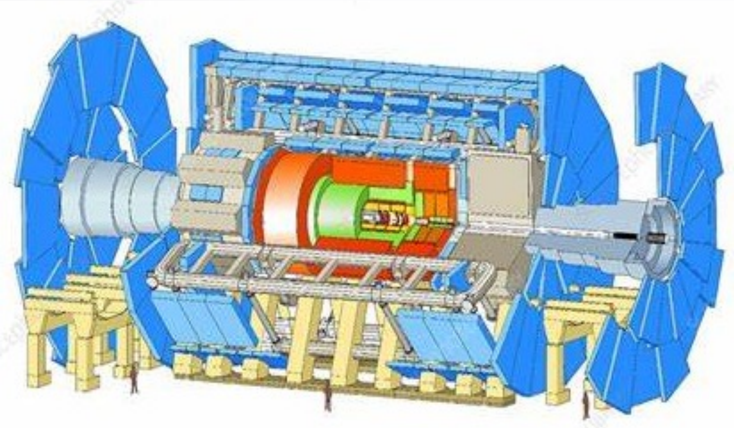
See Kobayashi's talk on Sat.

Parker: Excessive MMs could annihilate the magnetic field in space.
Density: Excessive MMs could conflict the gravitational observation.

Status of Experimental Searches

Samples from Moon and Meteorites

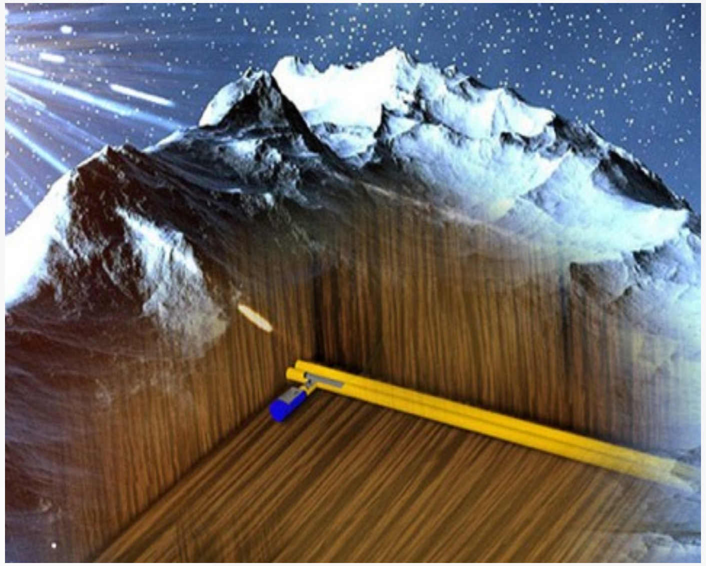




Collider experiments

See today's talks

Underground & CR Experiment



MACRO、IceCube

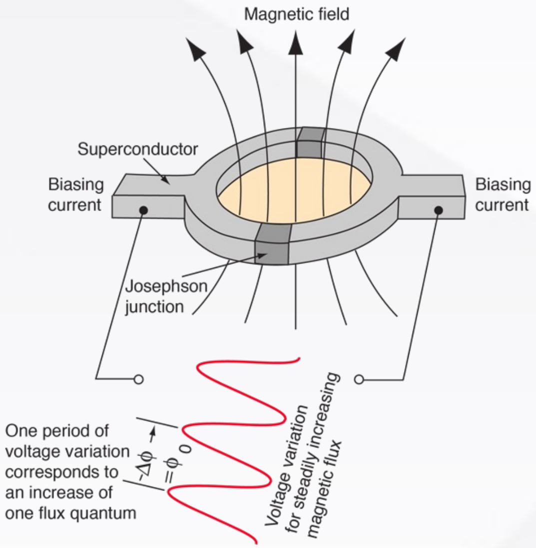
Ionization Signal

Pros： Large volume, high sens.

Cons： Need low-background,
Non-unique signal feature.

See talks in CR sessions

Superconducting coils



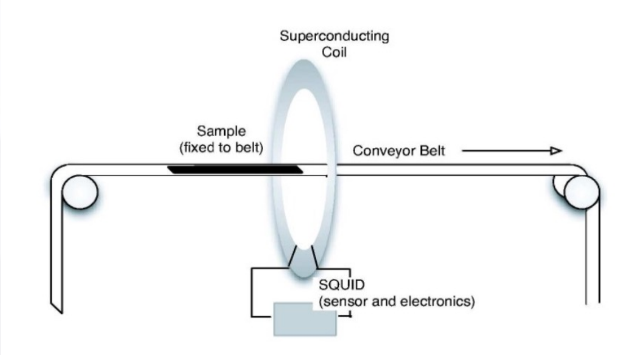
Induction Signal

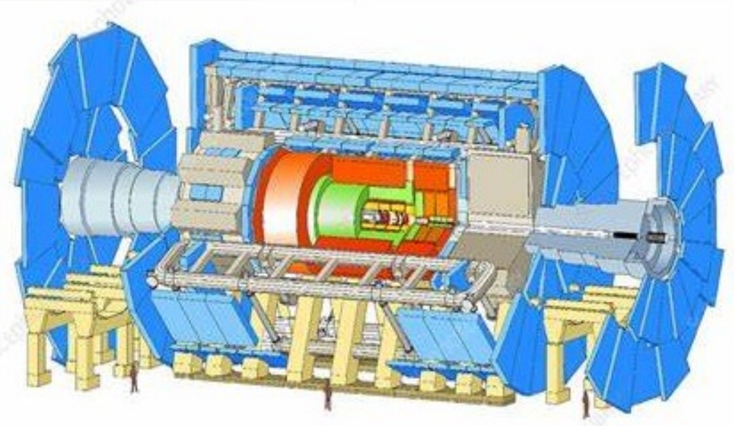
Pros： Smoking-gun signal;

Cons： Need superconducting temp;
Small volume

Status of Experimental Searches

Samples from Moon and Meteorites

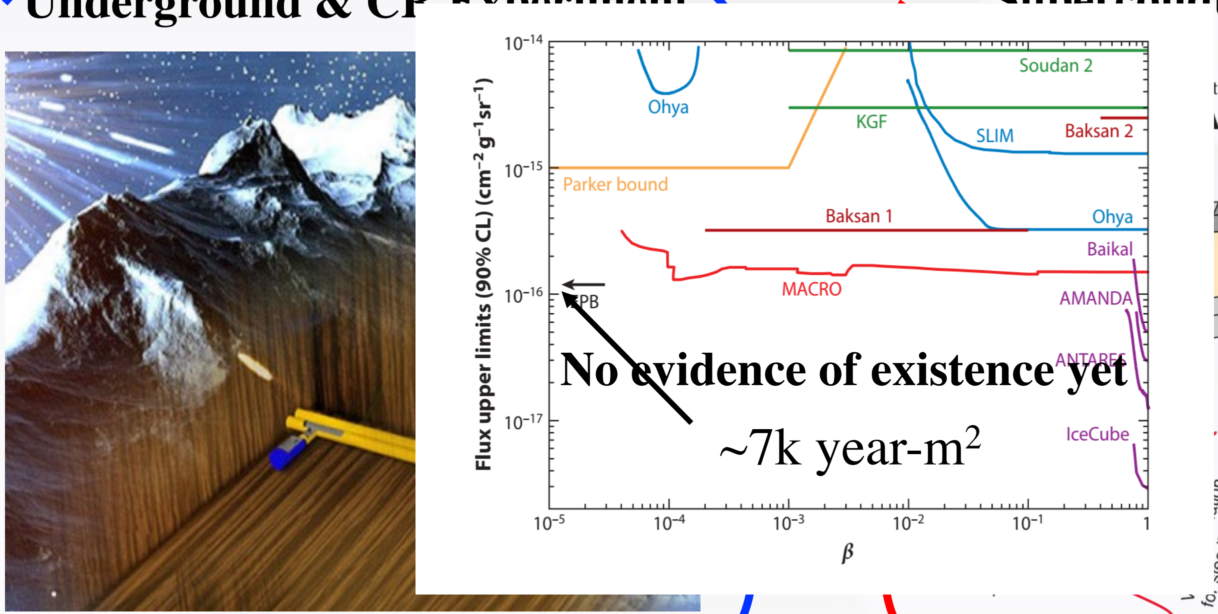




Collider experiments

See today's talks

Underground & CP Experiment



MACRO、IceCube

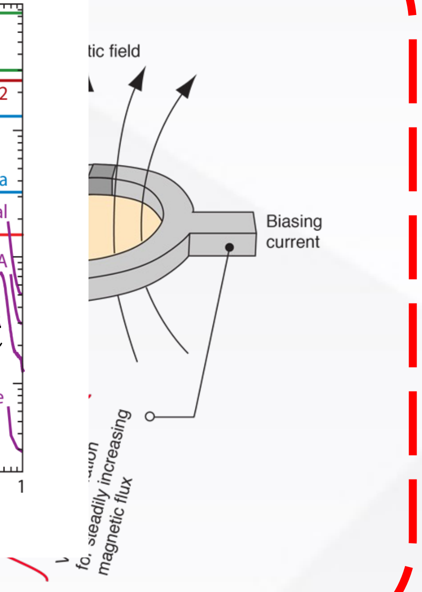
Ionization Signal

Pros： Large volume, high sens.

Cons： Need low-background,
Non-unique signal feature.

See talks in CR sessions

Superconducting coils



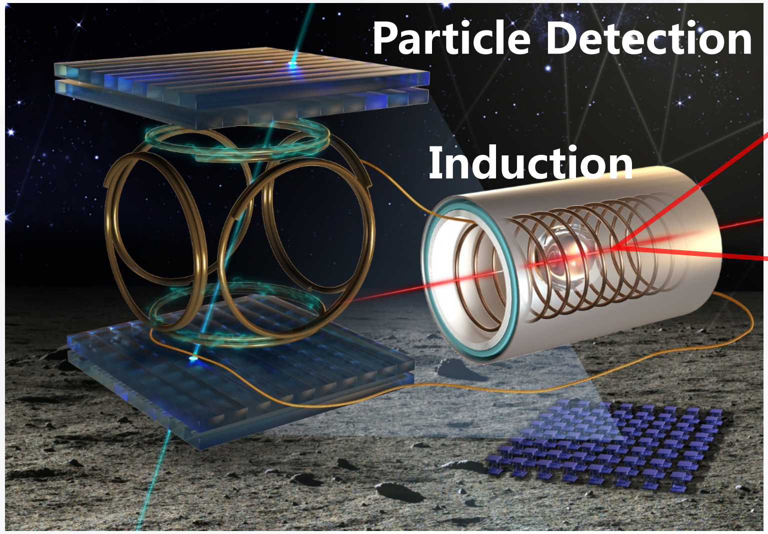
Induction Signal

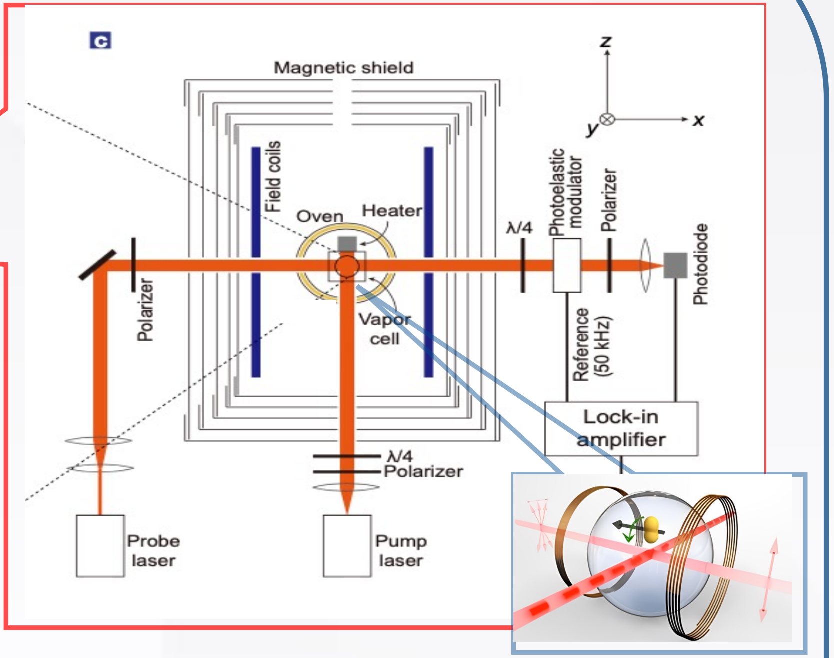
Pros： Smoking-gun signal;

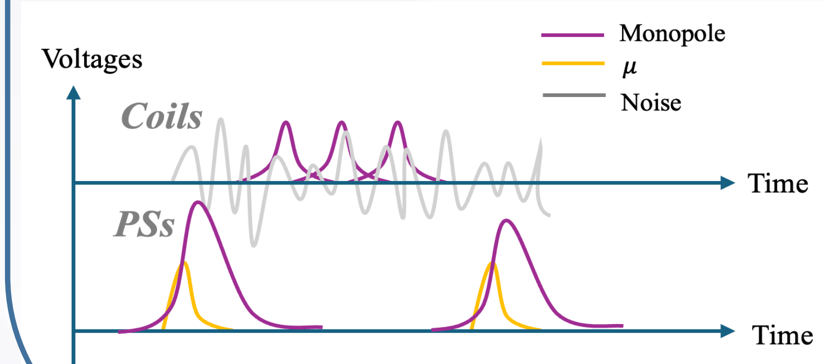
Cons： Need superconducting temp;
Small volume

SCEP concept

Schematic of the Detector



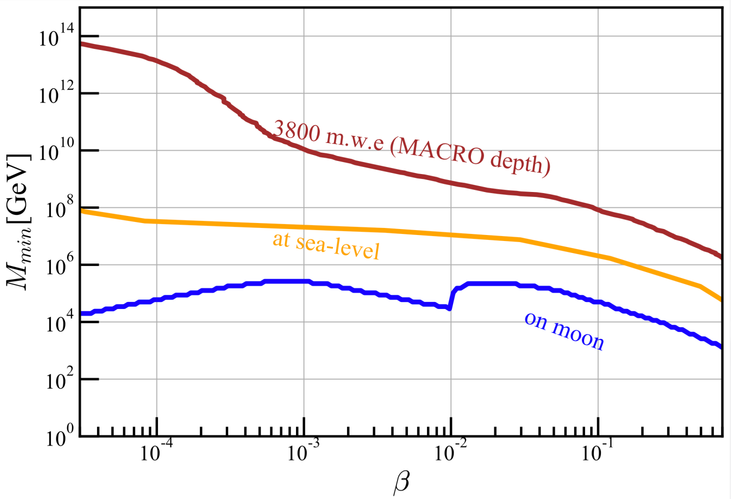




Signal Freq. ~kHz-100kHz

- Based on **room-temperature** induction readout, easy to scale-up;
- Simultaneous search for particle & induction signal, **reducing background**;

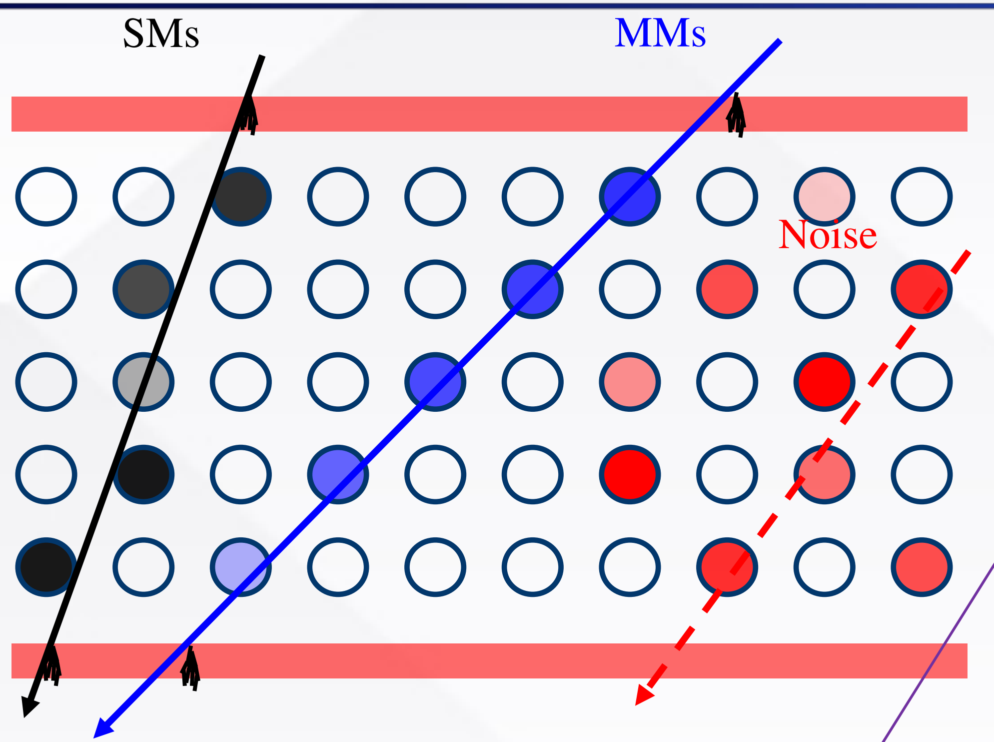
Long-time goal

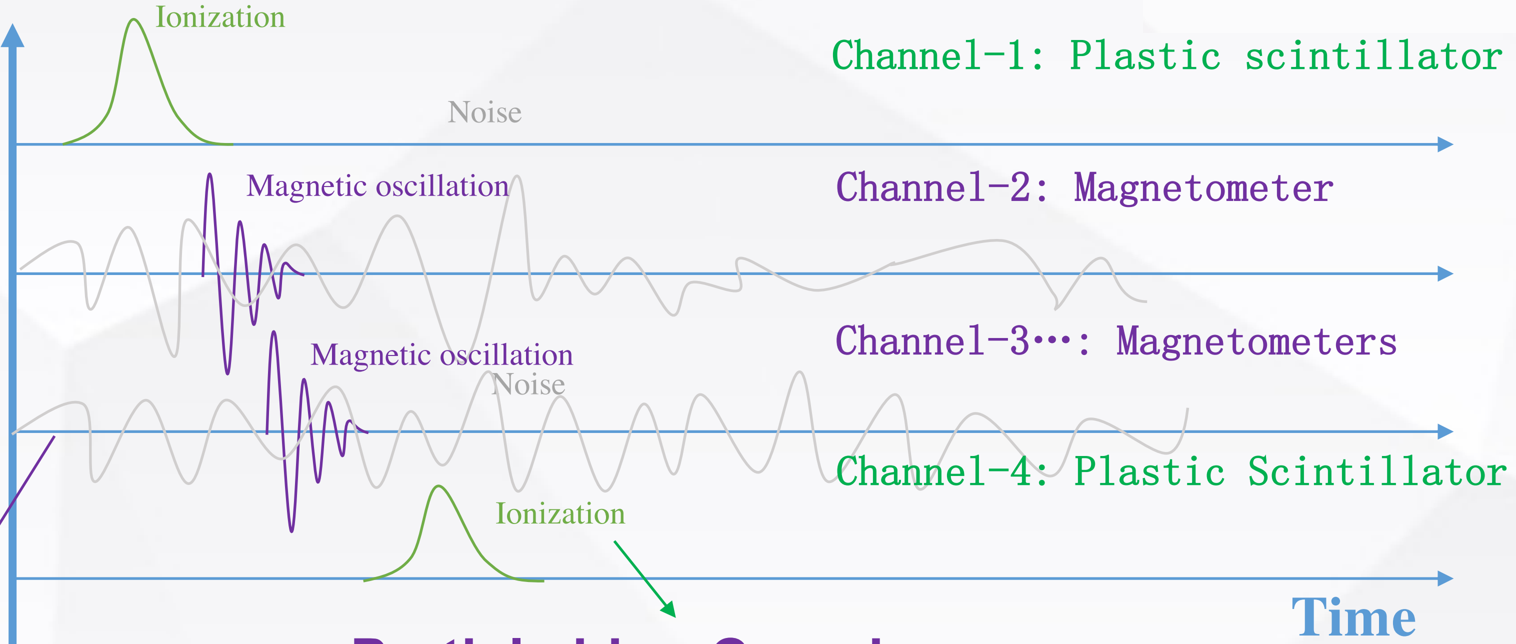


Long-time goals :

- Kilo-meter-square terrestrial surface array for heavy MM search;
- Meter-square lunar array for light MM search;

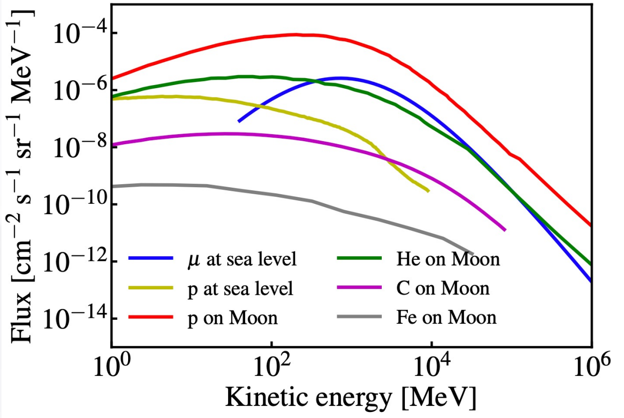
SCEP signal and background

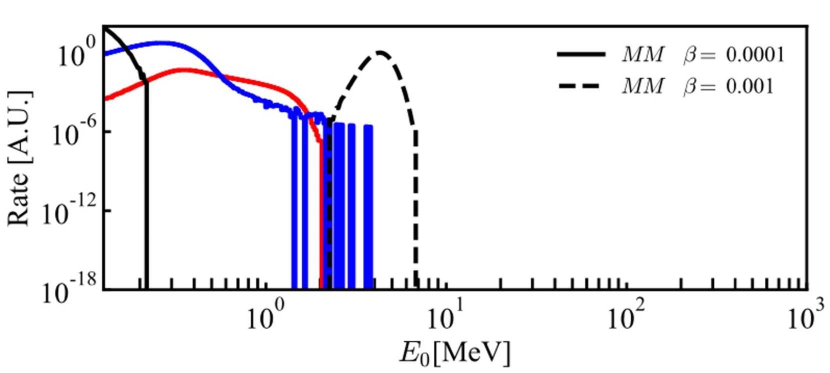




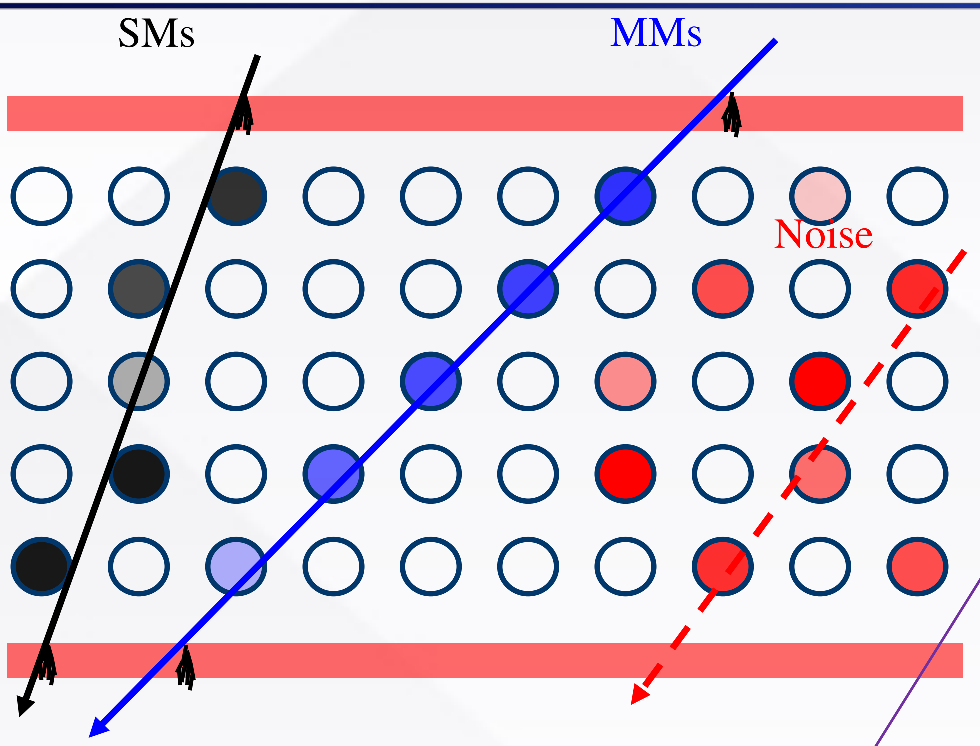
Particle bkg: Cosmic rays

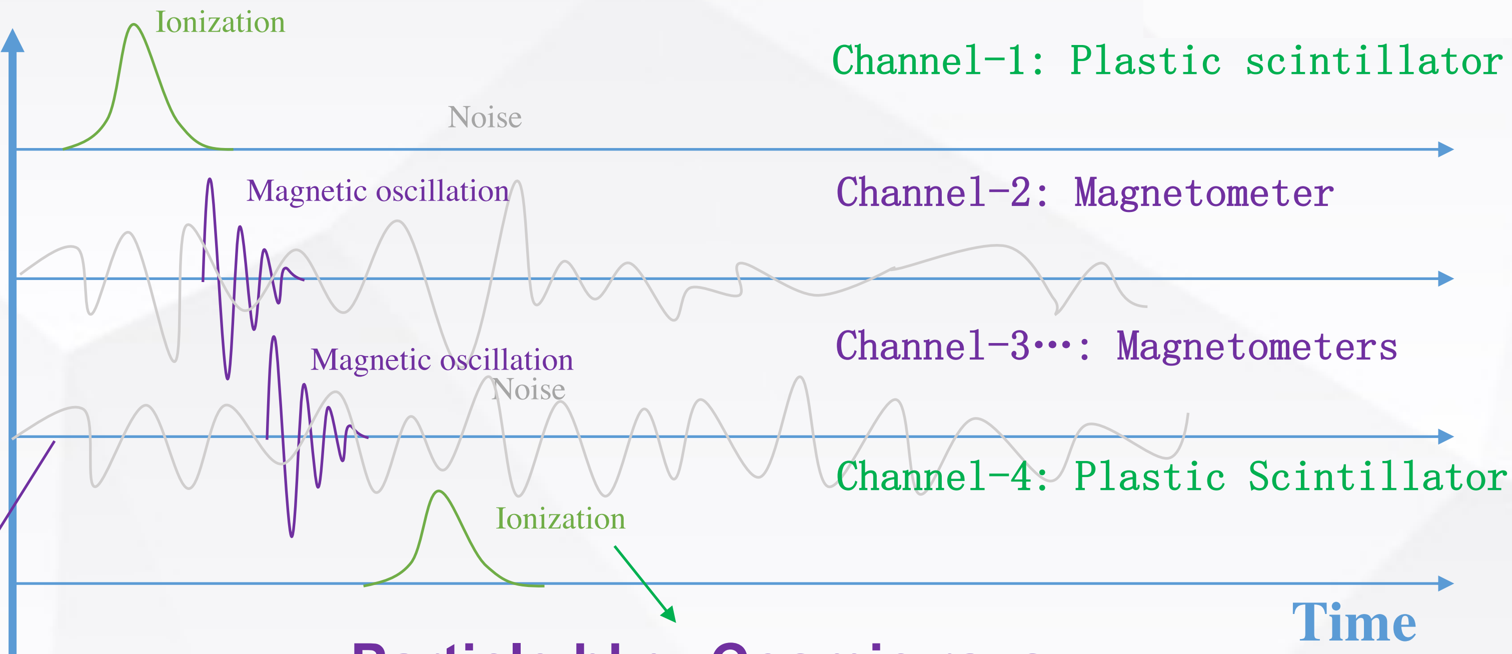
Induction bkg: Thermal noise





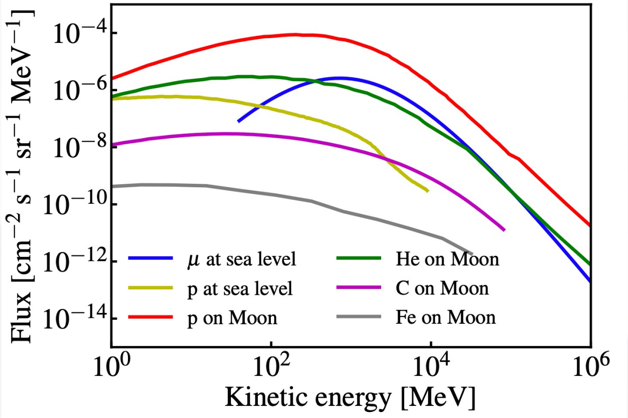
SCEP signal and background



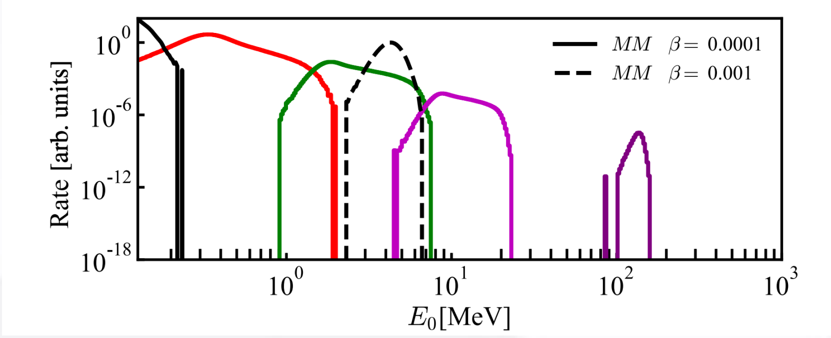


Particle bkg: Cosmic rays

Induction bkg: Thermal noise



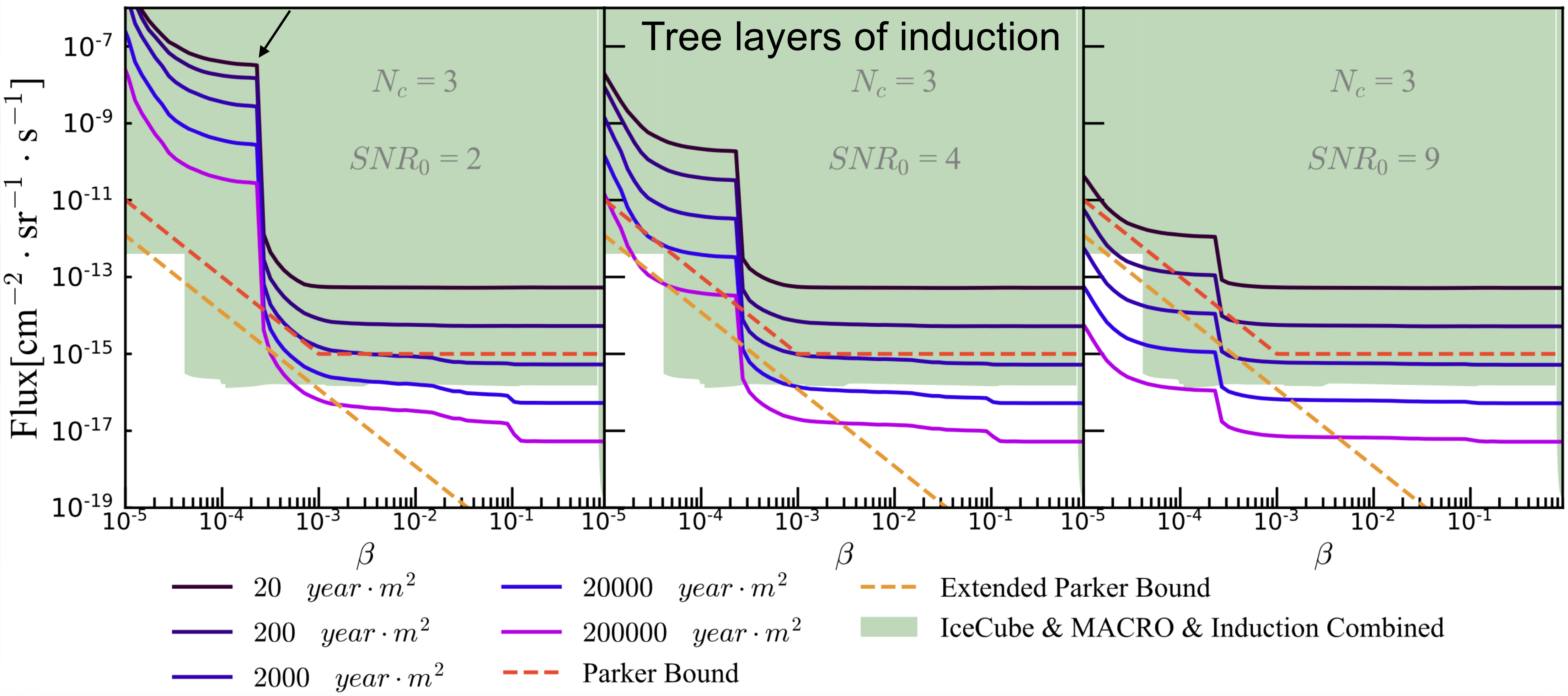
Moon-based



Sensitivity (Terrestrial)

PS threshold

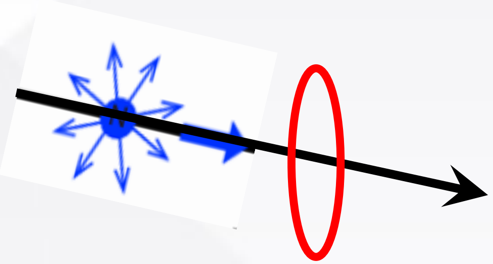
Changqing Ye, et al., Phys. Rev D 111, 023020 (2025).

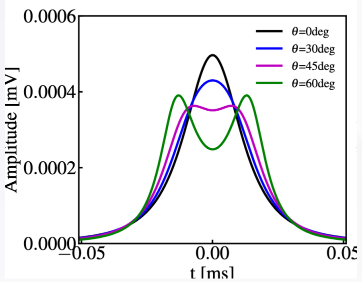


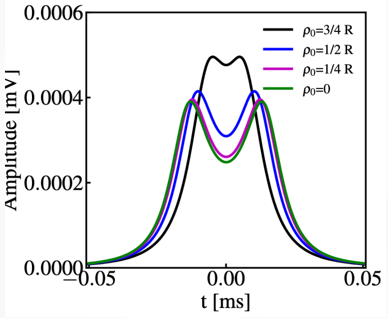
➢ **The signal-to-noise ratio (SNR) needs to reach certain level (>~4.5);**

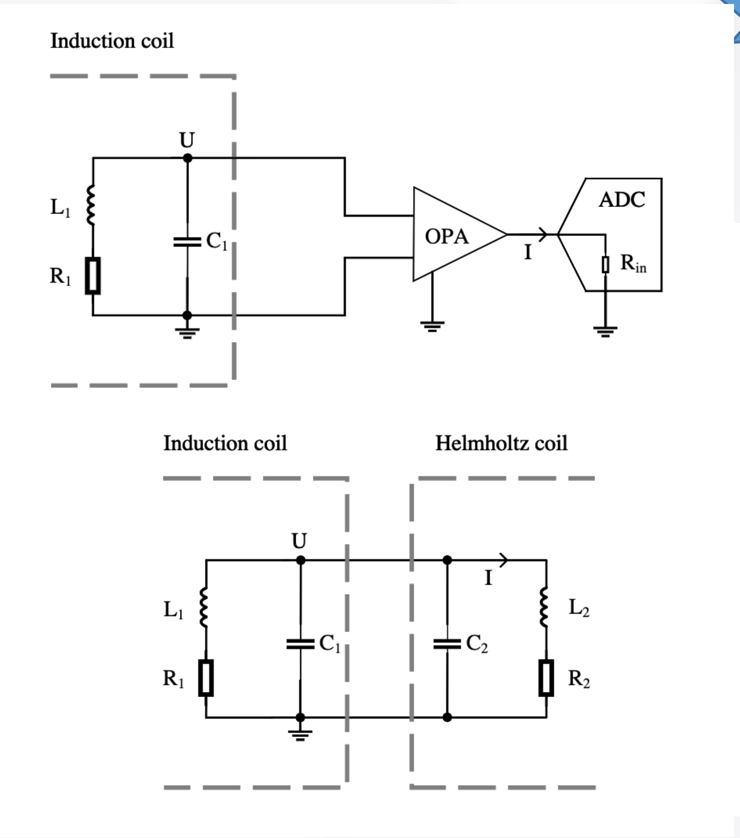
Induction Signal Shaping

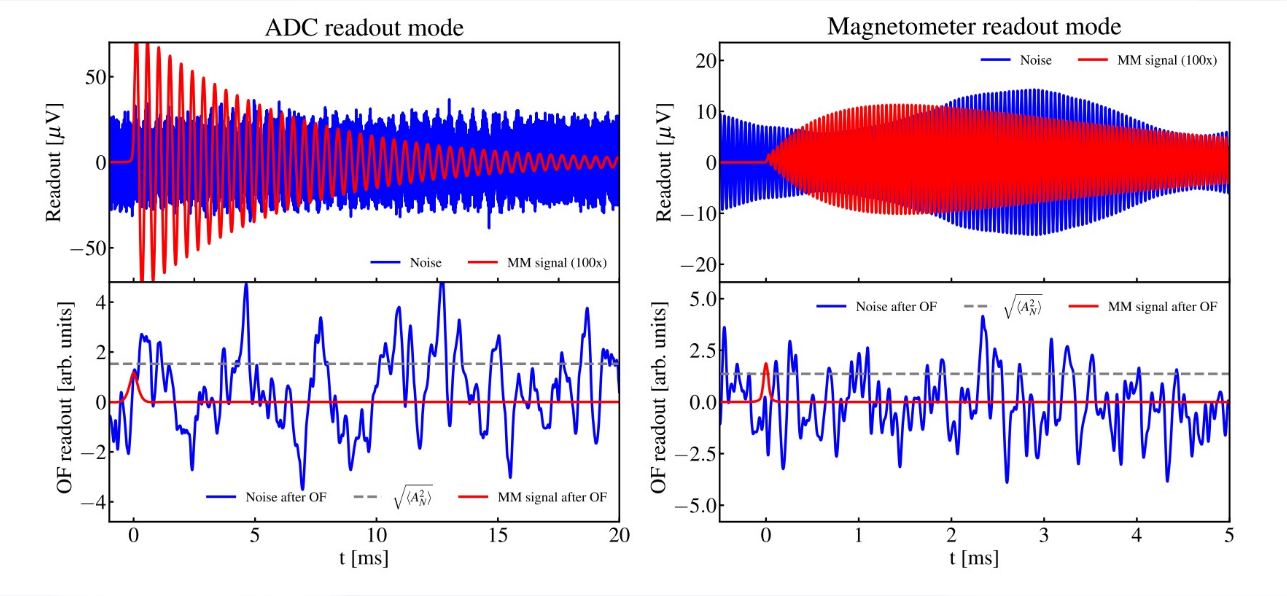
Induction Voltage → Circuit shaping → Mag.-readout / ADC-readout → Optimal filter











SNR=0.57

SNR=1.92

Thermal noise of Induction coil

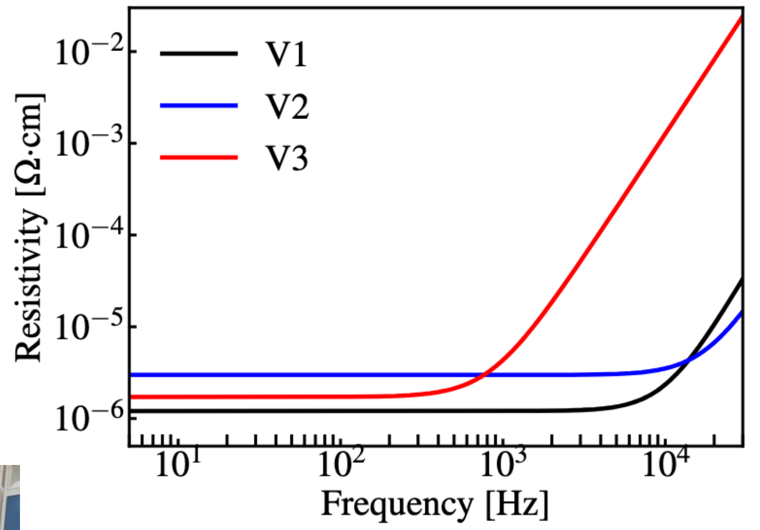
Coil	Wire type	Wire diameter [mm]	Minimal coil radius [cm]	Maximal coil radius [cm]	Turn number	Optimized SNR_0 ADC readout	Optimized SNR_0 Mag. readout
V1	Simple	0.11	5.7	7.2	4320	0.16	0.16
V2	Litz	1.35	5.7	7.2	720	0.02	1.92
V3	Simple	0.55	10.0	14.5	12500	0.57	0.82

Key pars for SNR:

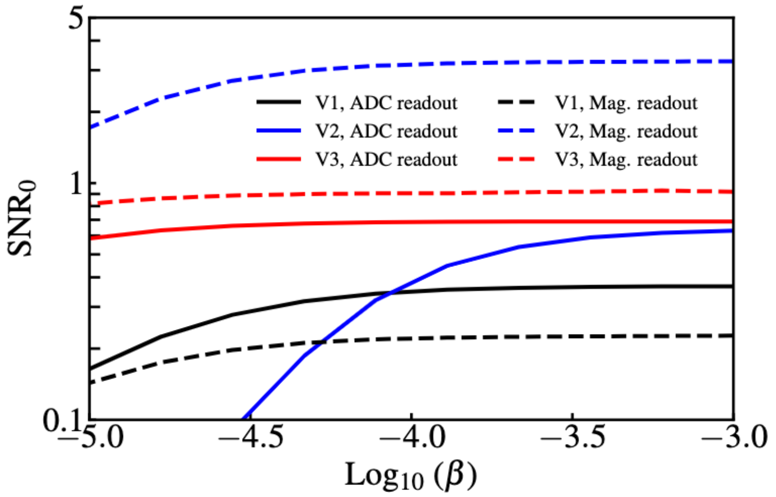
- Circuit C, L, R;
- Alternating R of coil (source of thermal noise)

We perform tests of the three prototype coils with distinct geometric parameters.

Resistivity of V3 skyrockets



Monopole speed affects SNR



V1

V2

V3

Thermal noise of Induction coil

Coil	Wire type	Wire diameter [mm]	Minimal coil radius [cm]	Maximal coil radius [cm]	Turn number	Optimized SNR_0 ADC readout	Optimized SNR_0 Mag. readout
V1	Simple	0.11	5.7	7.2	4320	0.16	0.16
V2	Litz	1.35	5.7	7.2	720	0.02	1.92
V3	Simple	0.55	10.0	14.5	12500	0.57	0.82

Key pars for SNR：

- Circuit C, L, R；
- Alternating R of coil (source of thermal noise)

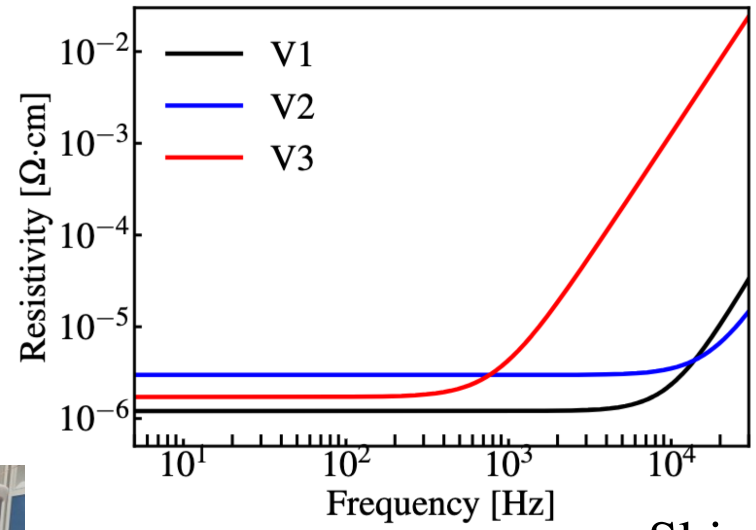
We perform tests of the three prototype coils with distinct geometric parameters.

V1

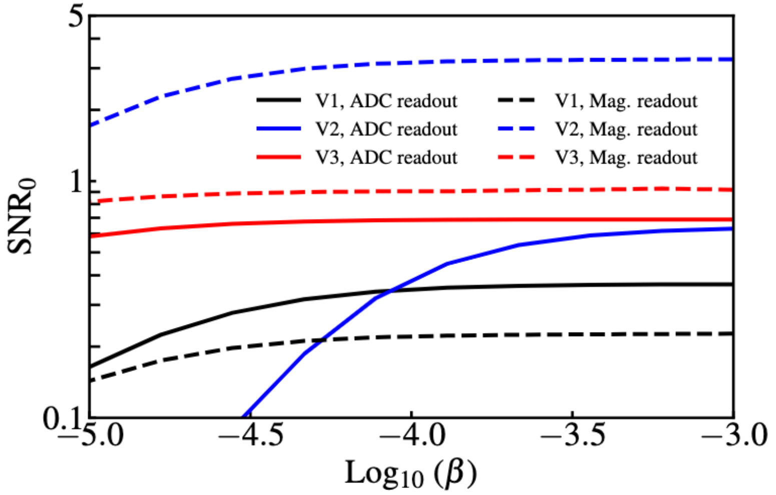
V2

V3

Resistivity of V3 skyrockets



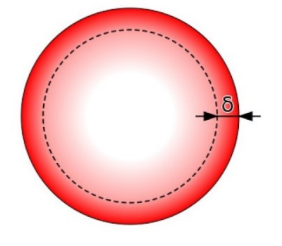
Monopole speed affects SNR



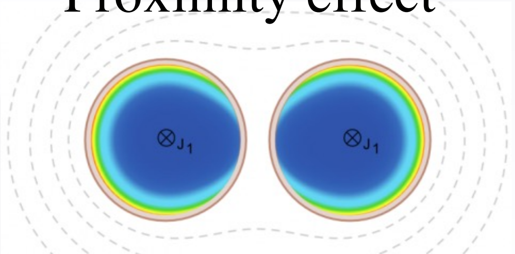
Two contributors:

Both depend on B field

Skin effect



Proximity effect



Thermal noise of Induction coil

Coil	Wire type	Wire diameter [mm]	Minimal coil radius [cm]	Maximal coil radius [cm]	Turn number	Optimized SNR_0 ADC readout	Optimized SNR_0 Mag. readout
V1	Simple	0.11	5.7	7.2	4320	0.16	0.16
V2	Litz	1.35	5.7	7.2	720	0.02	1.92
V3	Simple	0.55	10.0	14.5	12500	0.57	0.82

Key pars for SNR：

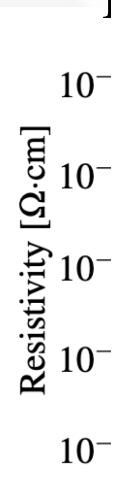
- ➢ Circuit C, L, R；
- ➢ Alternating R of coil (source of thermal noise)

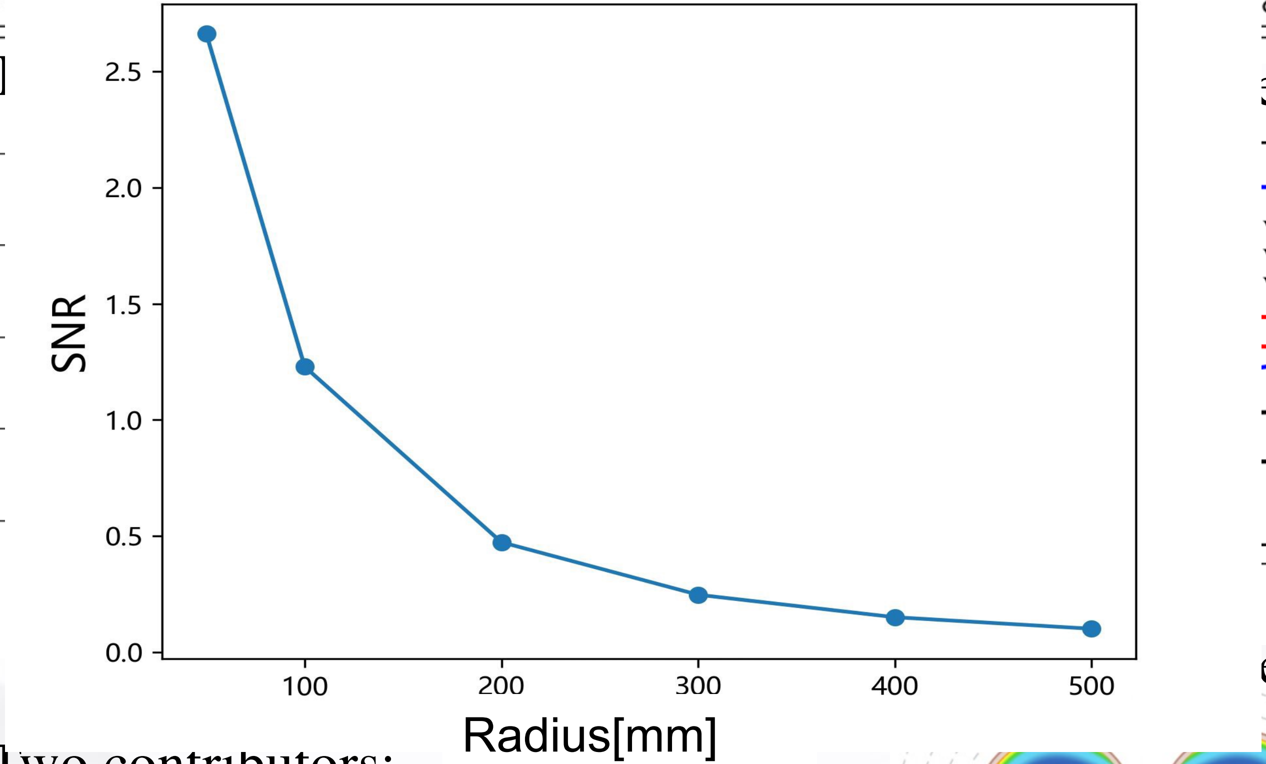
We perform tests of the three prototype coils with distinct geometric parameters.

V1

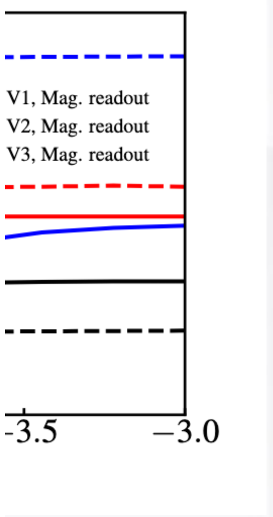
V2

V3





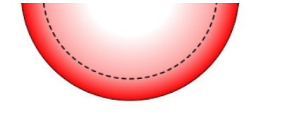
ects SNR

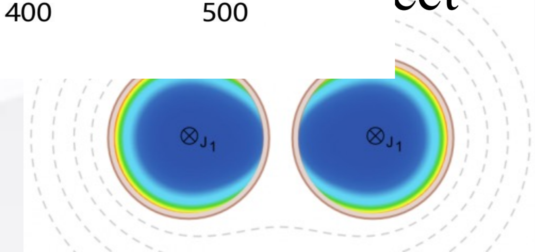


ect

Two contributors:

Both depend on B field

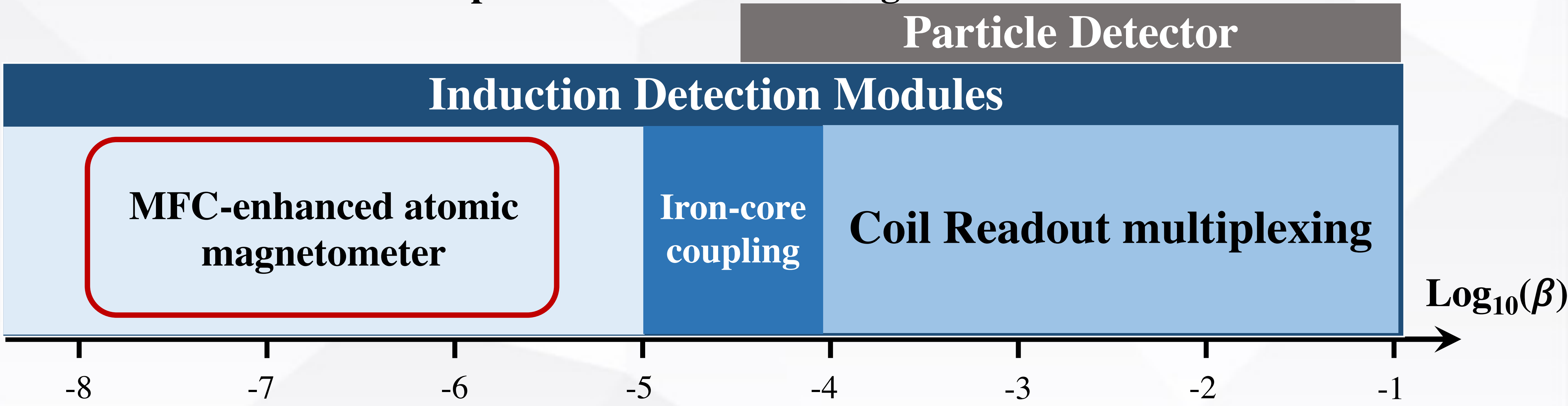




Optimization of Induction

Challenges:

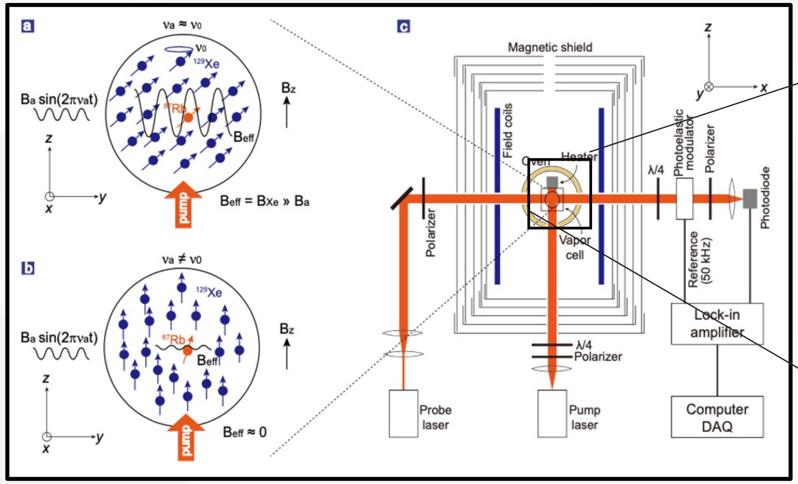
- **How to cover a wide speed parameter space?**
- **How to increase the acceptance in cm2 sr of a single module?**

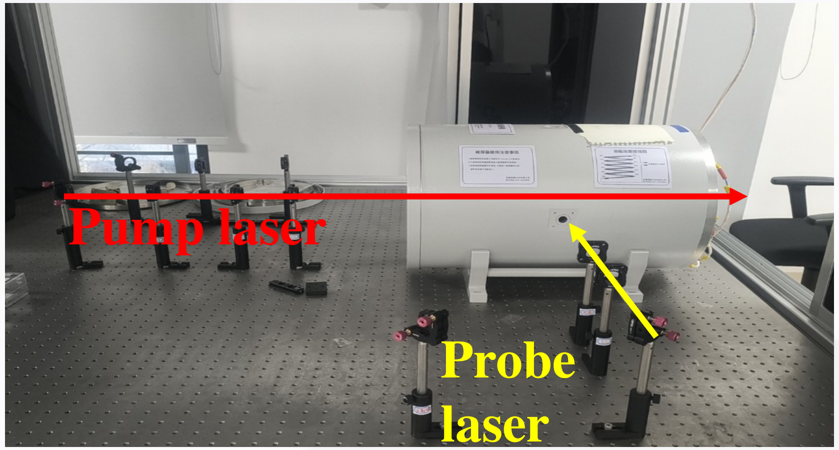


How to maximize acceptance? **How to suppress noise?**

MFC enhanced atomic magnetometer

Traditional atomic magnetometer

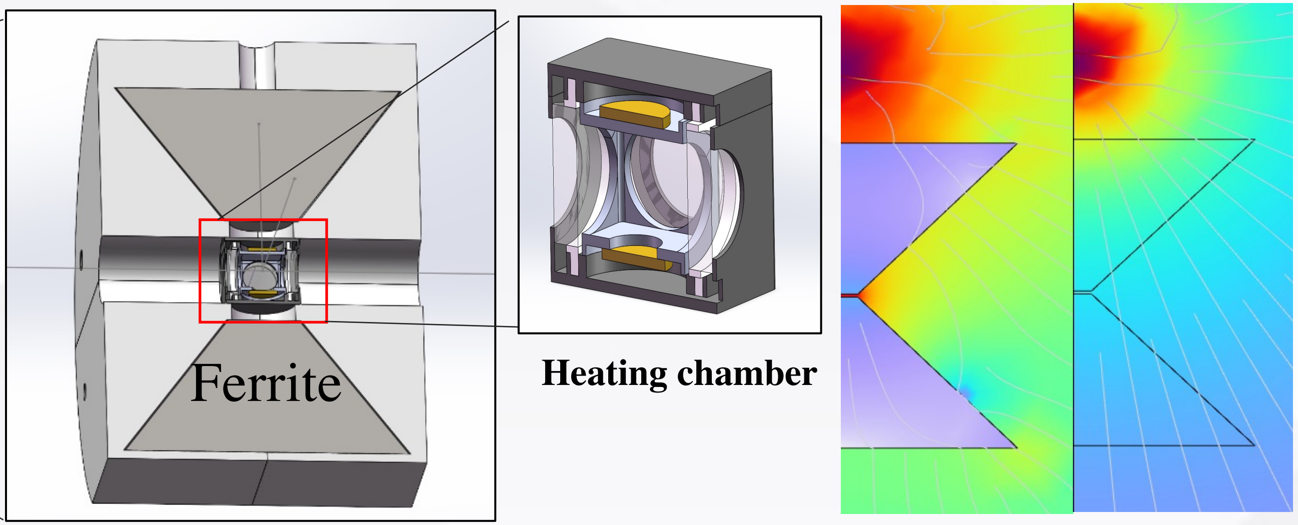




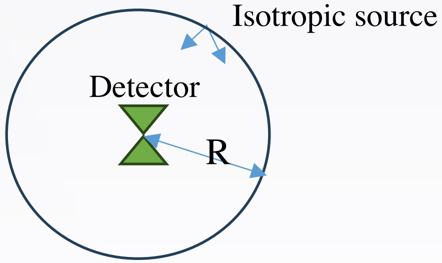
Sensitity $\sim 10 fT/\sqrt{Hz}$;

Detection r~1cm; SNR > 10

MFC enhanced magnetometer

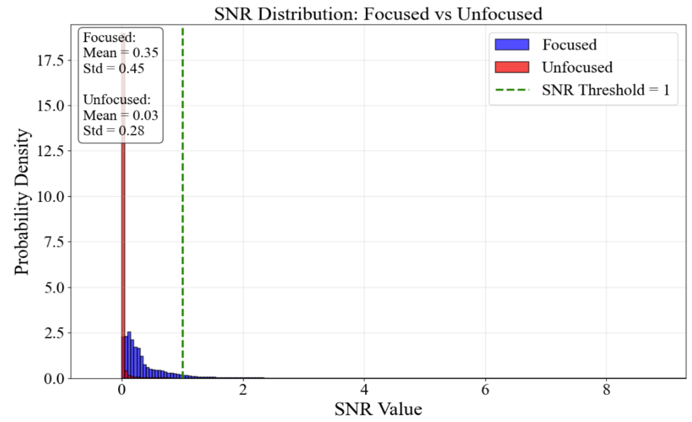


Acceptance can be increased by an order!!

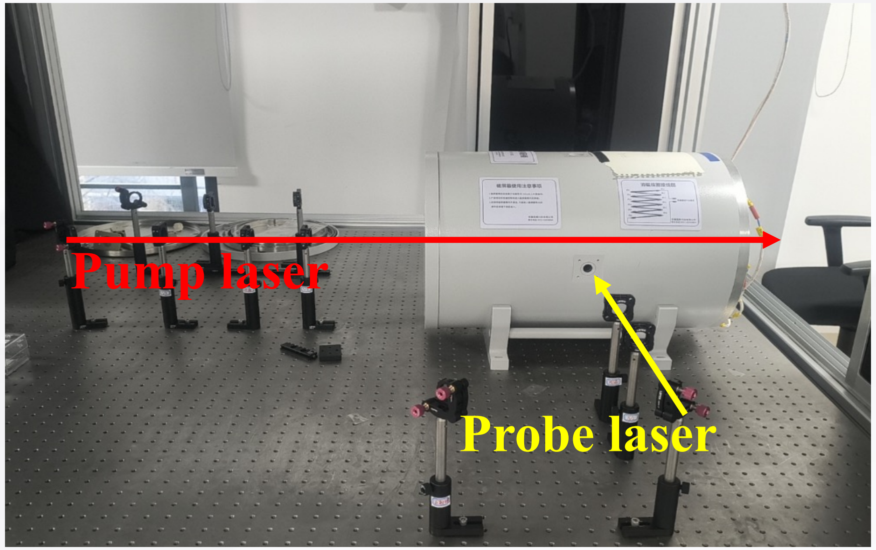


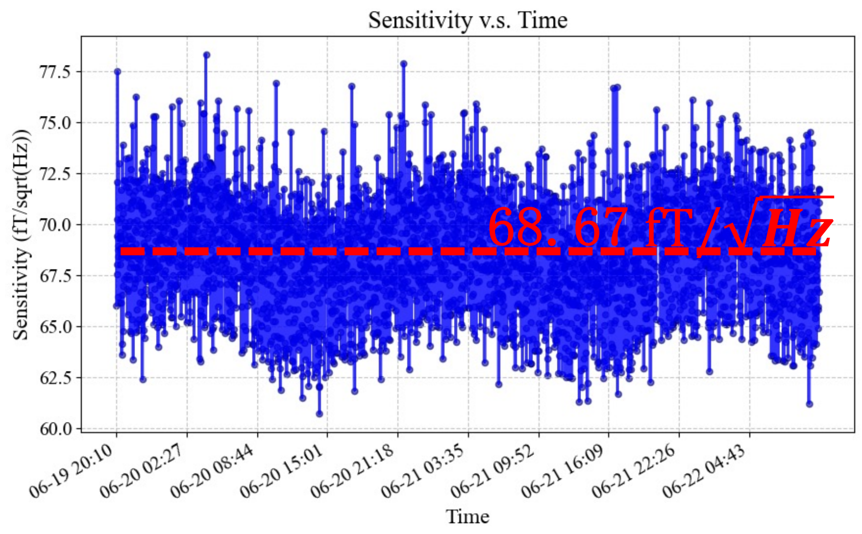
Without MFCs, A~15.9cm^{2}sr, For a benchmark MFC, **A~280.0 cm^{2}sr**

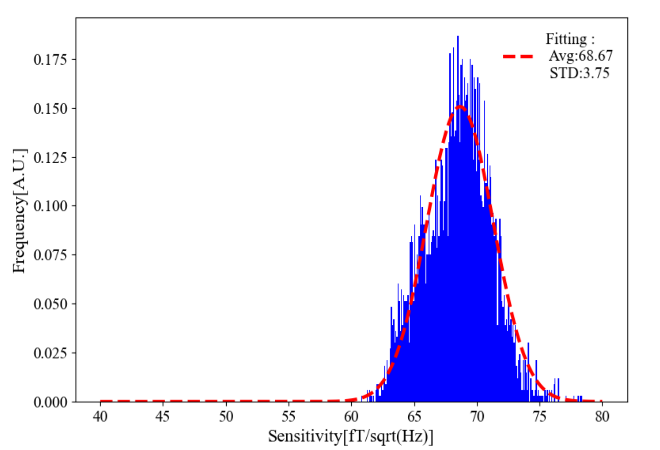
($\beta \sim 1e^{-6}$)



MFC enhanced magnetometer prototype test - Noise





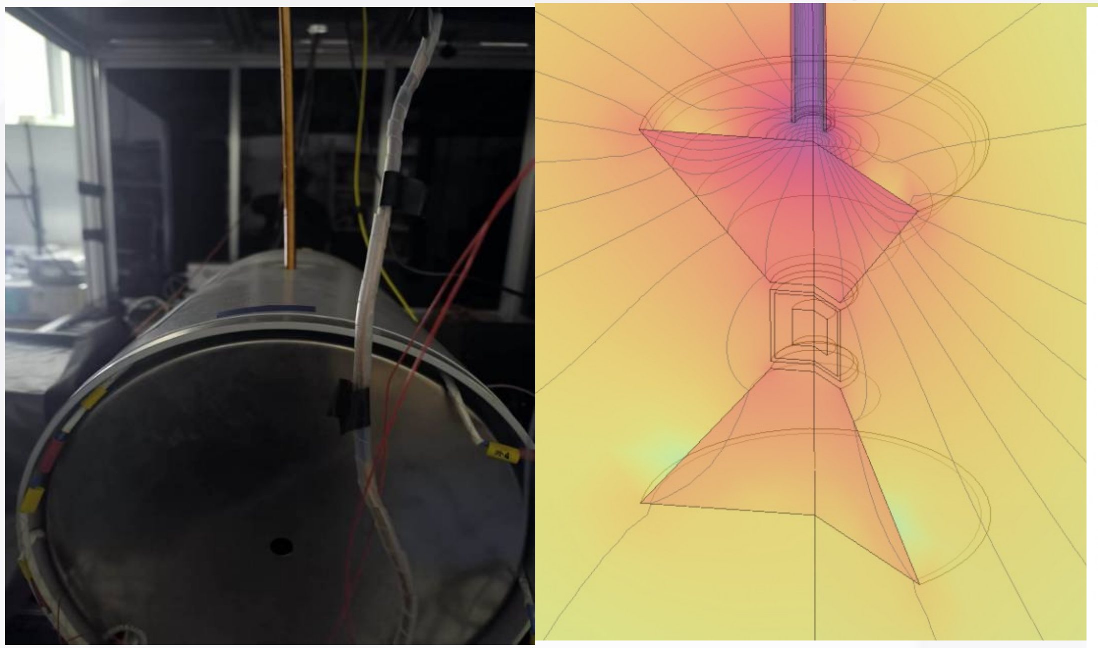


Noise contribution	Estimated noise level ($fT/\sqrt{Hz}$)
Magnetometer noises (laser, photon shot etc.)	~67
Thermal noise from MFC	<1
Environmental EM	~100(W/O shielding), <1(shielded)
Seismic	<1
Total	<69(shielded)
Measured	**68.67(3-day long monitoring)**

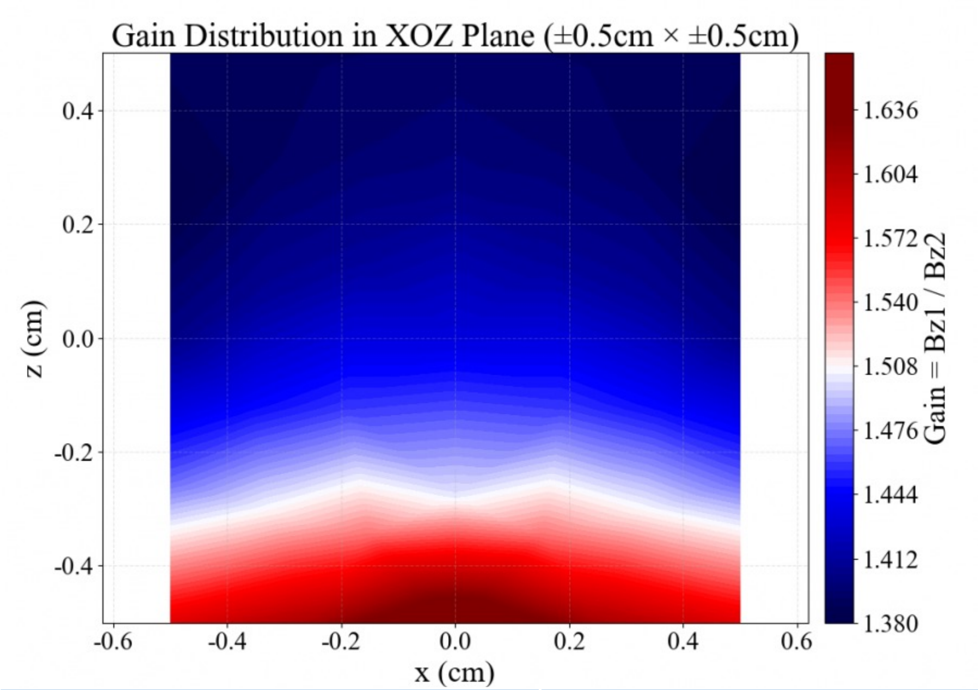
MFC DOES NOT contribute significantly to noise!

MFC enhanced magnetometer prototype test - Signal

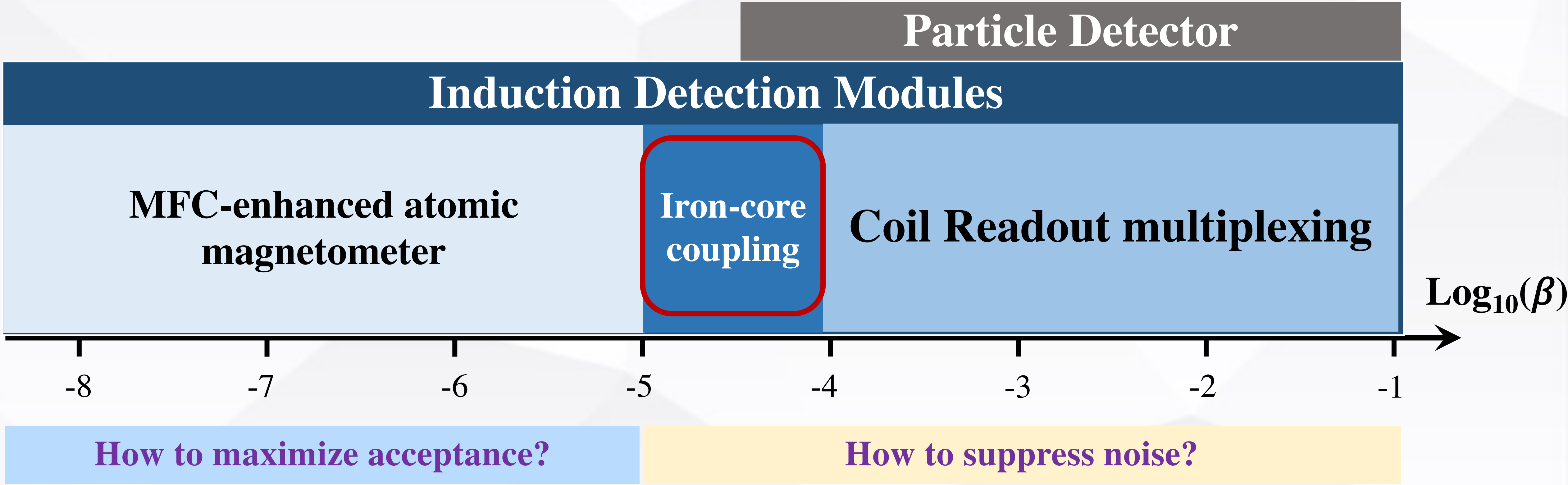
Stimulation coil to mimic signal



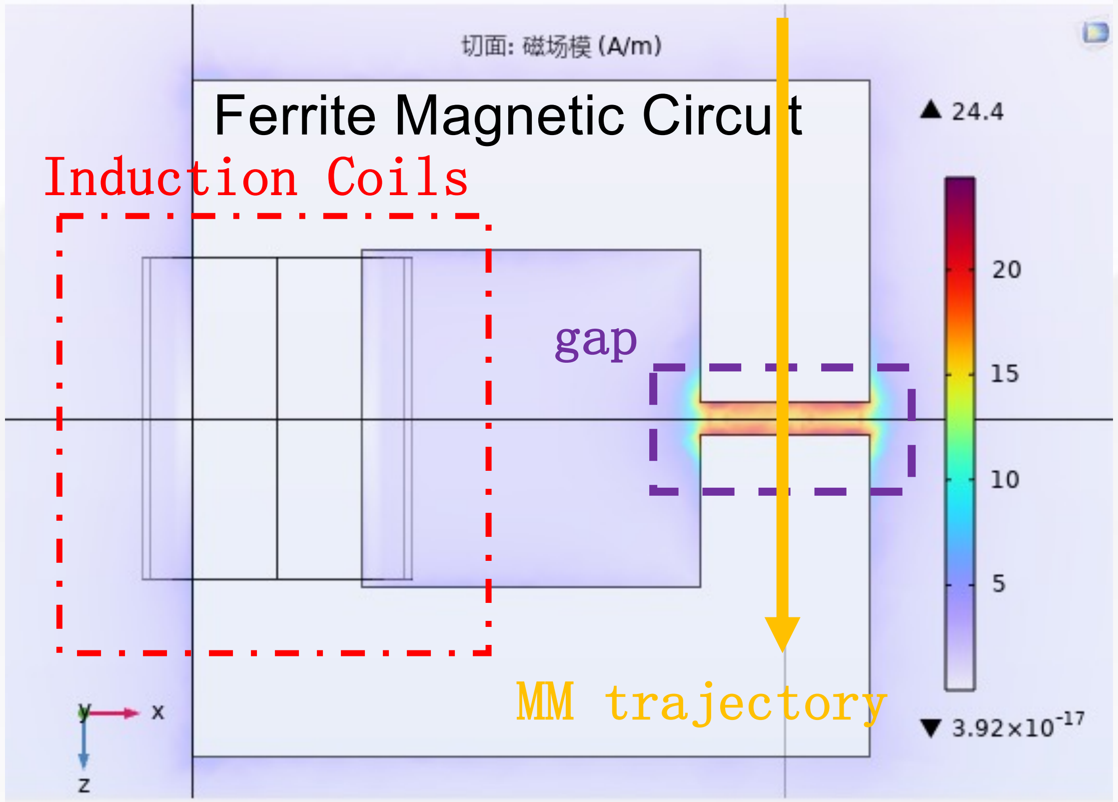
Temperature non-uniformity within gas chamber

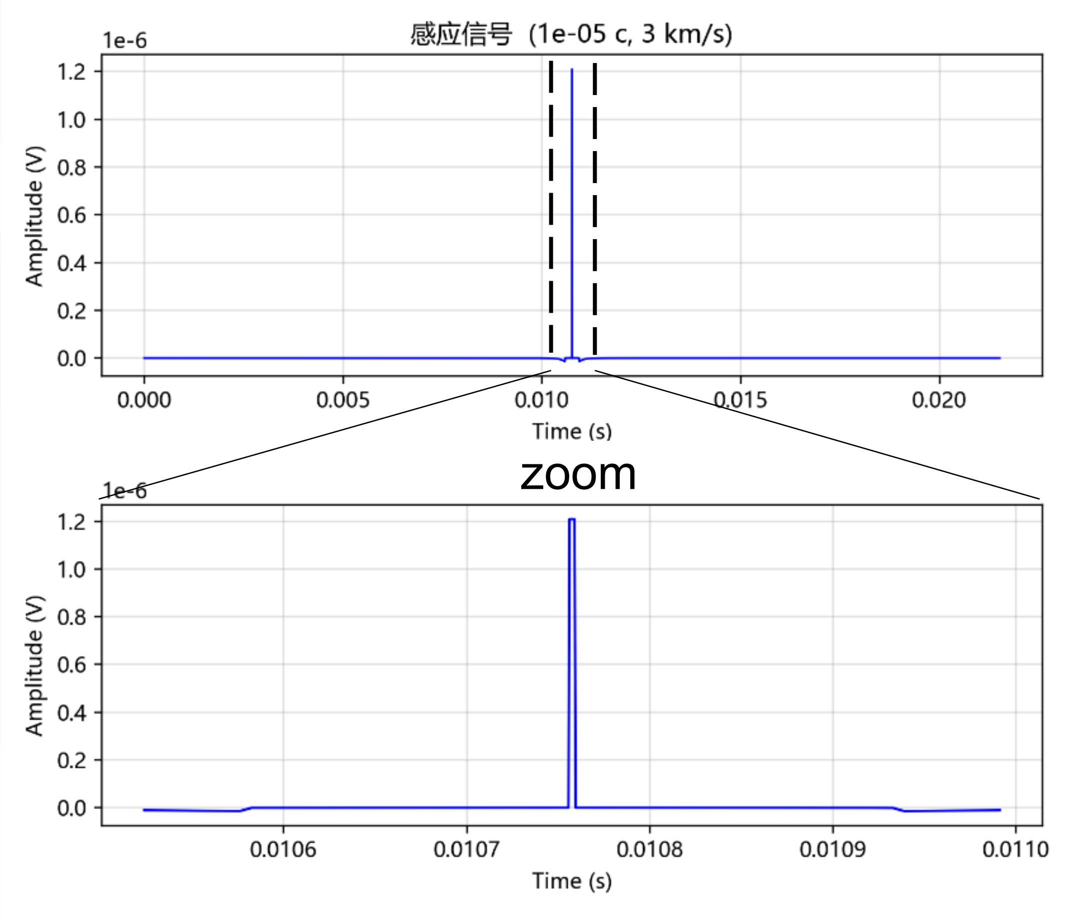


Case	Sample 1&2	Sample 2&3	Sample 1&3
Simulation	1.54±0.15	1.37±0.15	1.37±0.15
Measurement	1.42±0.24	1.43±0.19	1.31±0.20


Particle Detector
Induction Detection Modules
MFC-enhanced atomic magnetometer
Iron-core coupling
Coil Readout multiplexing
$\mathrm{Log}_{10}(\beta)$
-8
-7
-6
-5
-4
-3
-2
-1
How to maximize acceptance?
How to suppress noise?

Iron-core coupling





- ➢ Highest induction voltage when MM passing gap;
- ➢ Large area of gap -> High acceptance area;
- ➢ Magnetic circuit guide signal to induction coil -> smaller coil with less resistance can be used!

Magnetic-Core Coil: Detection Principle

☐ Signal

- Magnetic core: concentrates magnetic flux; modifies the rate of flux change without generating additional flux variation
- Lorentz reciprocity theorem:

$$V_{ind}(t) = -\frac{g}{I_B}\boldsymbol{v}(t)\cdot\boldsymbol{H_B}[r_m(t)]$$

- Signal waveform: rectangular-like due to the nearly uniform H-field in the air gap

☐ Noise

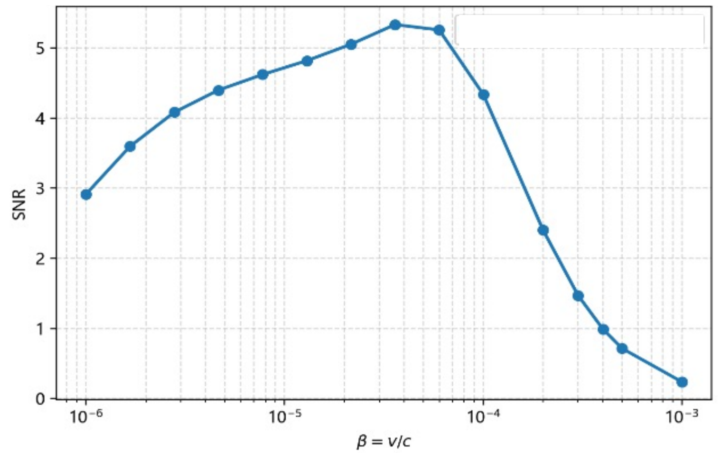
Coil thermal noise: the dominant noise source

- Leakage flux: fringing fields near the air gap and split-core joints introduce additional loss
- Hysteresis loss
- Eddy-current loss

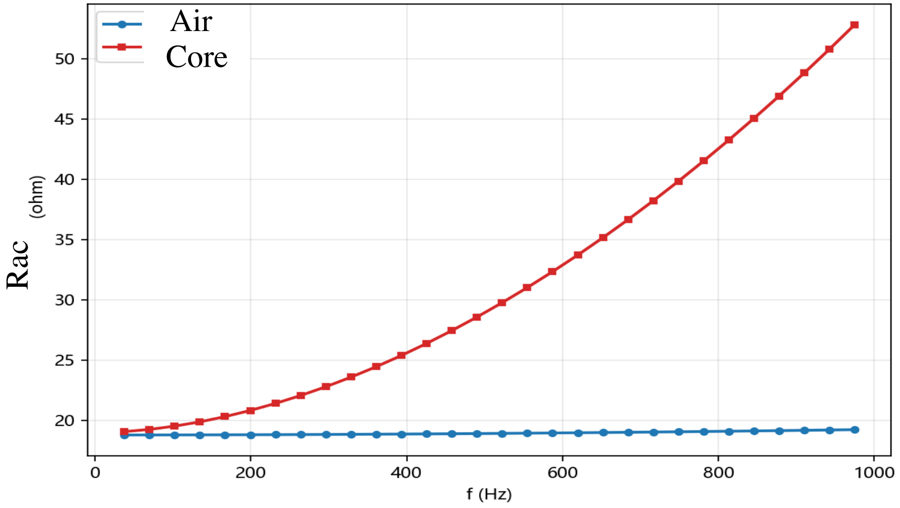
Design implication:
keep the coil winding away from the air gap

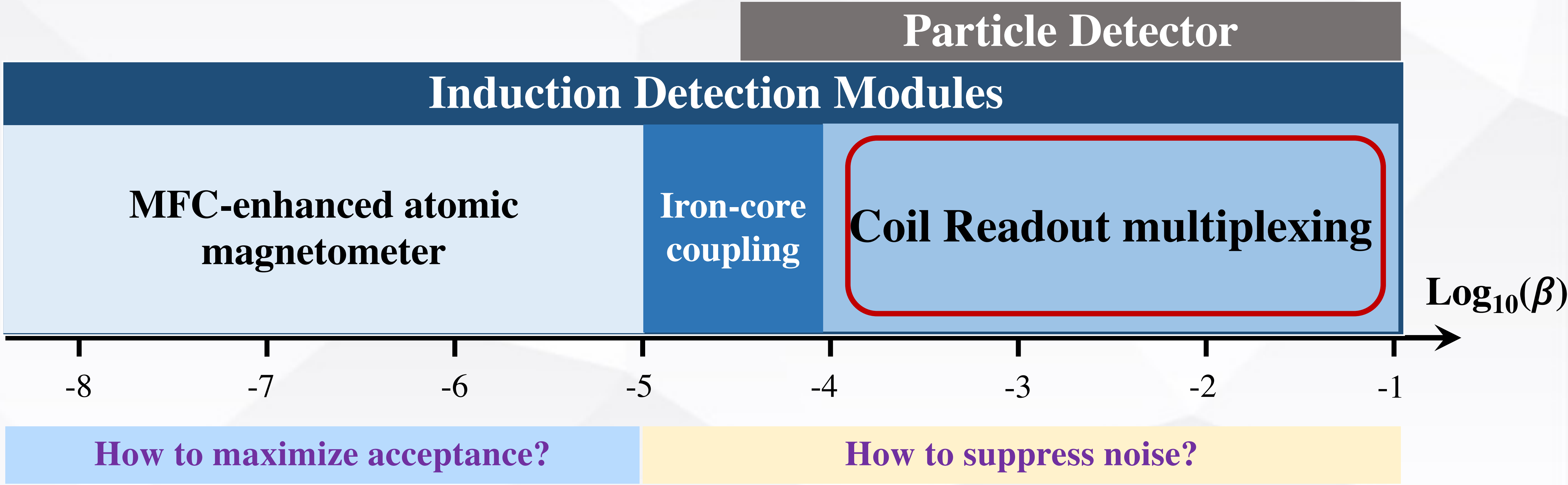
Negligible for ferrite at low frequencies

☐ SNR: Dedicated to low-speed magnetic monopole detection



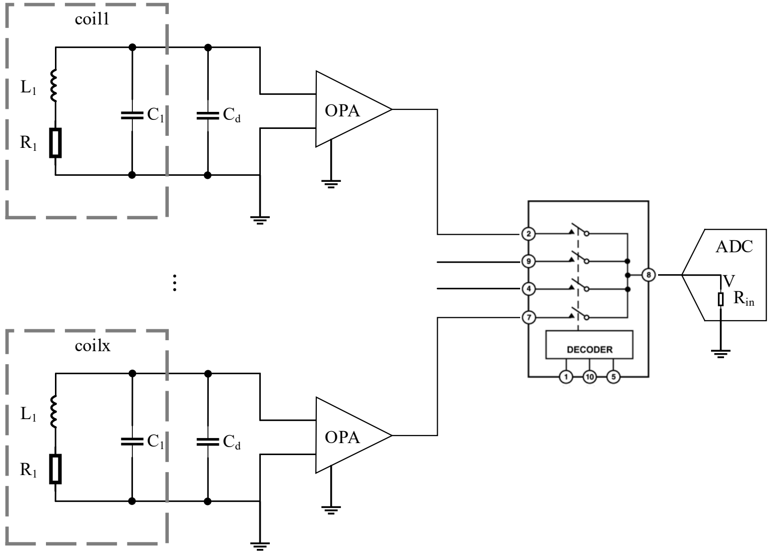
☐ Noise measurement: Higher than expected! Field leakage?




Particle Detector
Induction Detection Modules
MFC-enhanced atomic magnetometer
Iron-core coupling
Coil Readout multiplexing
$\mathrm{Log}_{10}(\beta)$
-8
-7
-6
-5
-4
-3
-2
-1
How to maximize acceptance?
How to suppress noise?

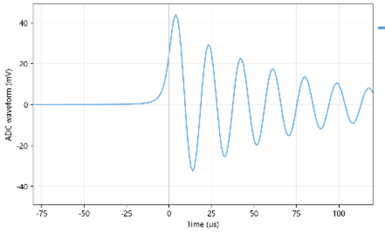
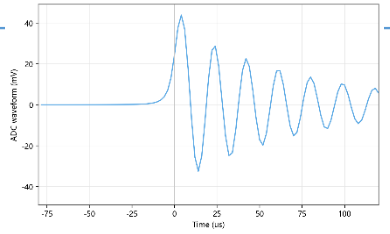
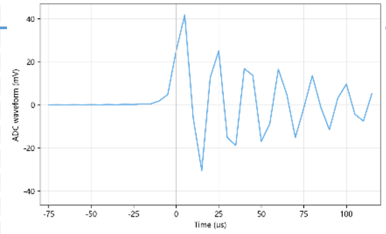
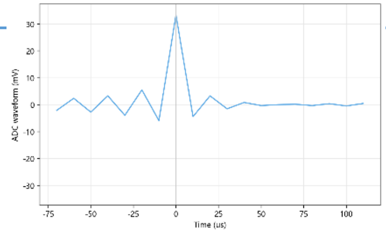
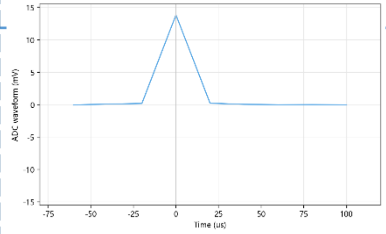
Multiplexed Readout

A high-speed analog multiplexer sequentially routes signals from multiple coils to a shared ADC

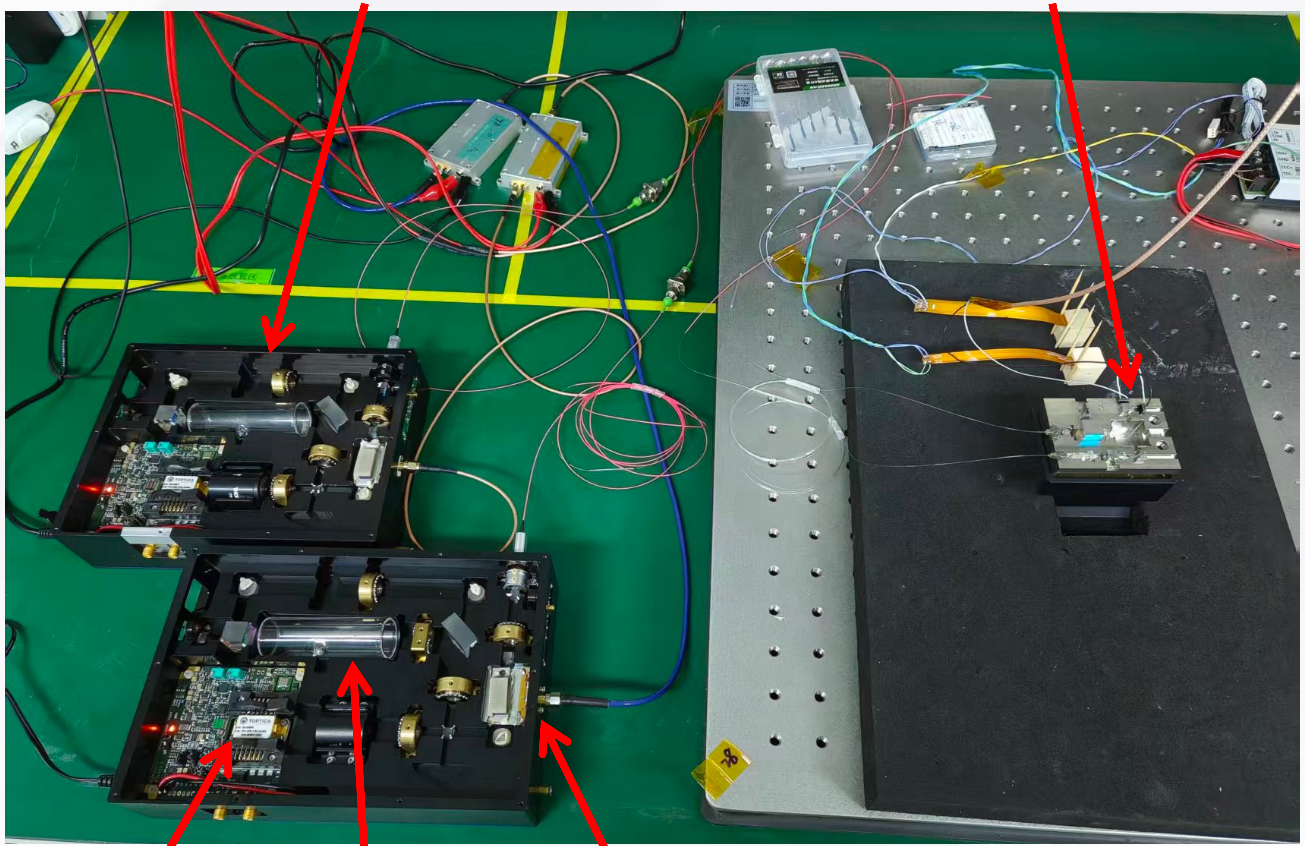


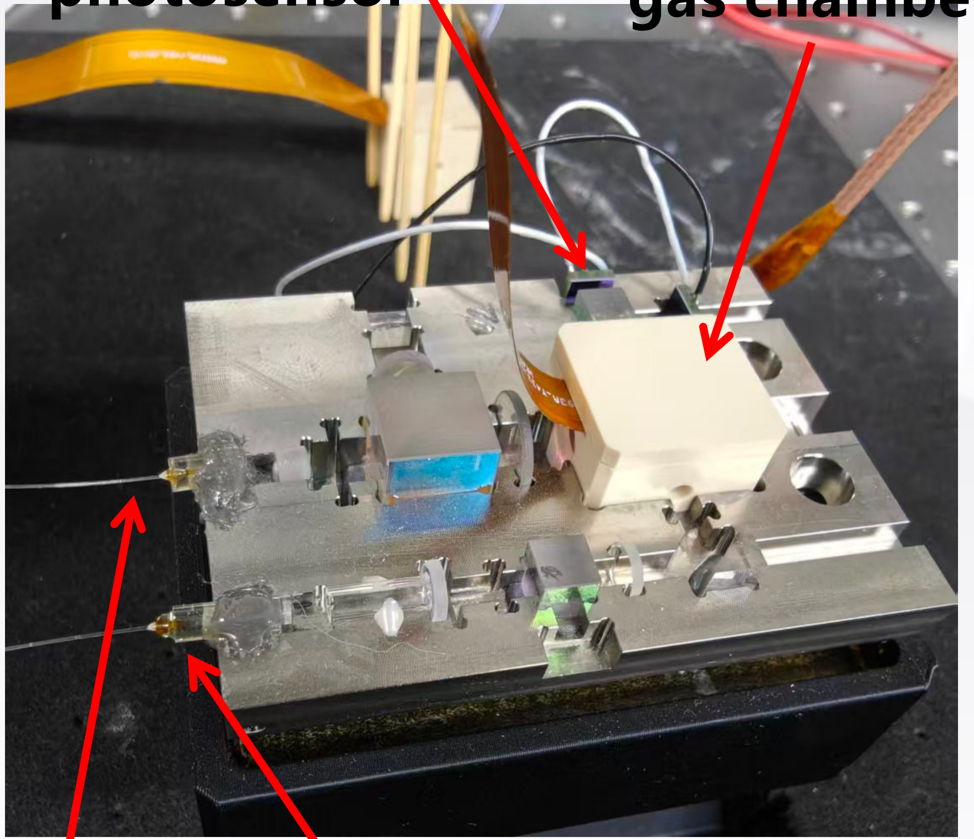
☐ Time budget

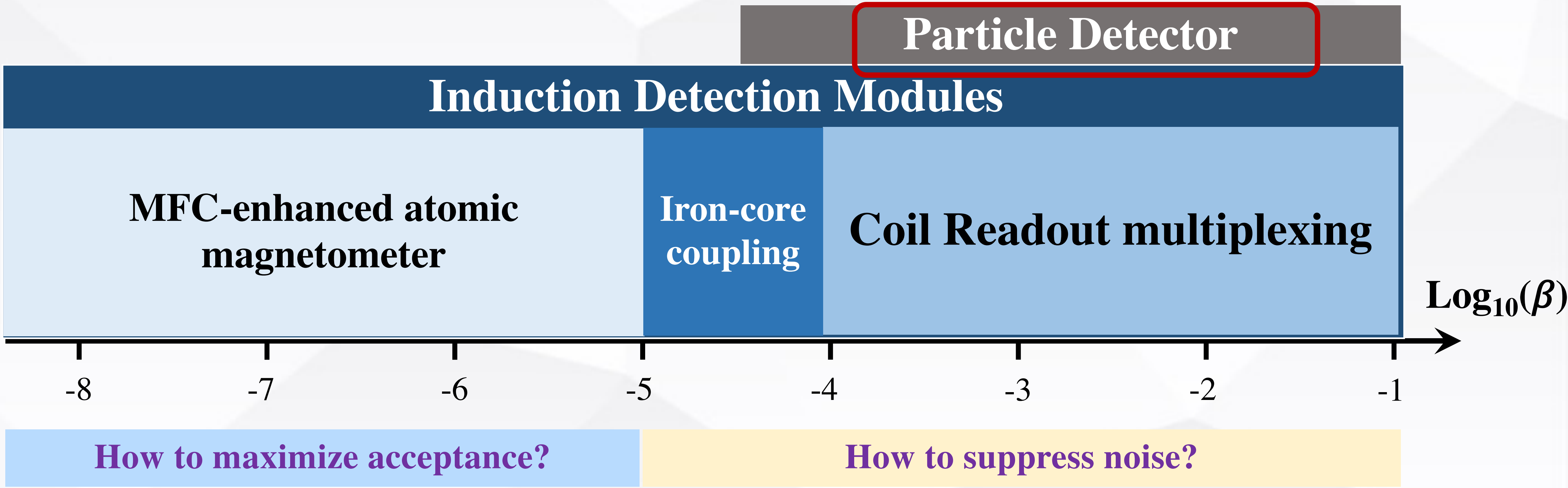
- Sampling requirement: **50 kSPS** per channel, corresponding to a **20 µs** sampling period
- SPICE simulation: switching and ADC input-capacitance charging time **120 ns**
- Ideal timing-only limit: $\frac{20\mu s}{120ns} = 166\ channels$

Sample rate	1 MSPS	500 kSPS	200 kSPS	100 kSPS	50 kSPS
Waveform					
SNR	3.589	3.588	3.586	3.541	3.221

Miniaturization of magnetometer

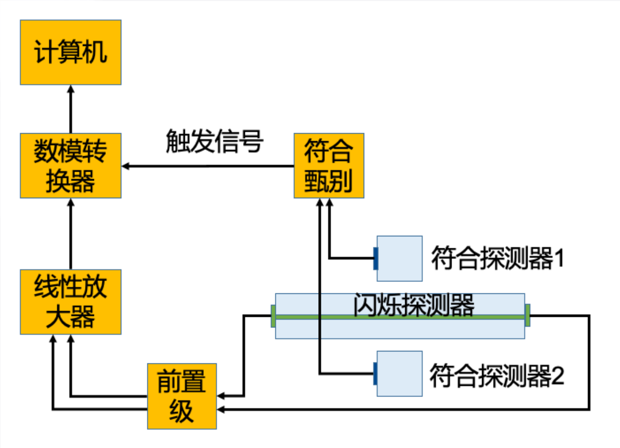


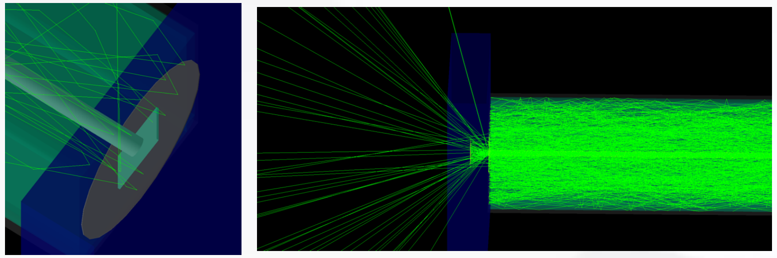



Particle Detector
Induction Detection Modules
MFC-enhanced atomic magnetometer
Iron-core coupling
Coil Readout multiplexing
$\mathrm{Log}_{10}(\beta)$
-8
-7
-6
-5
-4
-3
-2
-1
How to maximize acceptance?
How to suppress noise?

Scintillator sample test

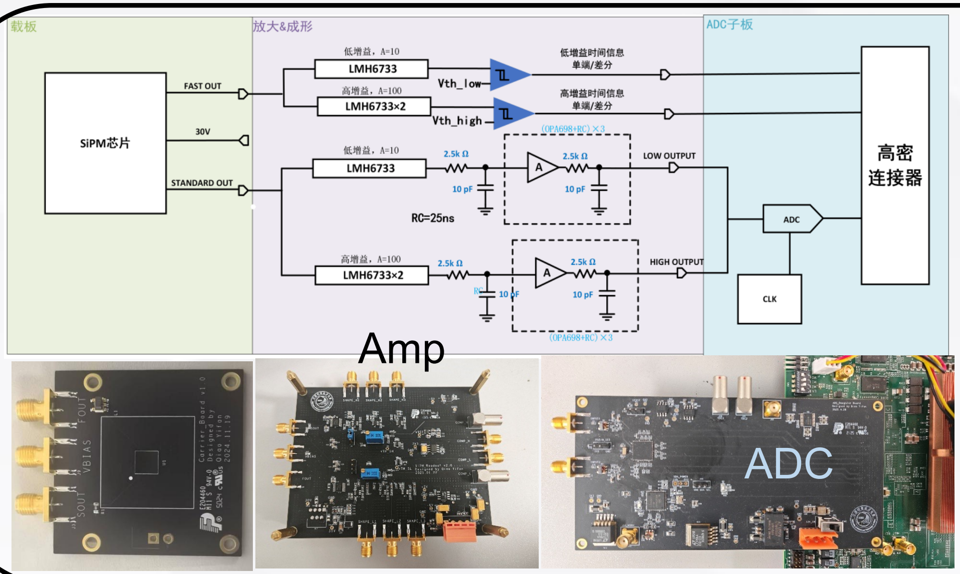
PS test



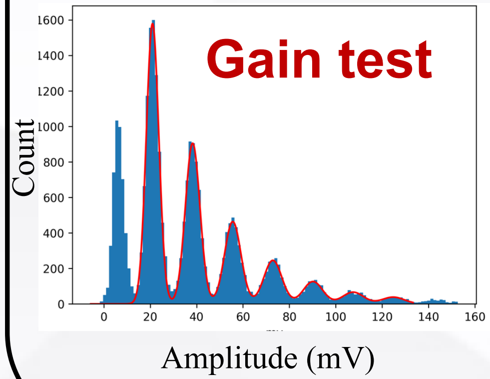


- PS + PMT or PMT+WLS+SiPM；
- Two small PS as coin. detectors for muon tagging;

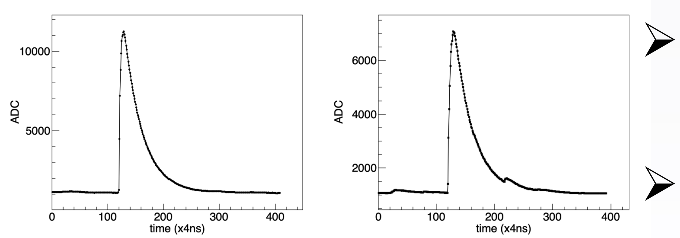
SiPM electronis



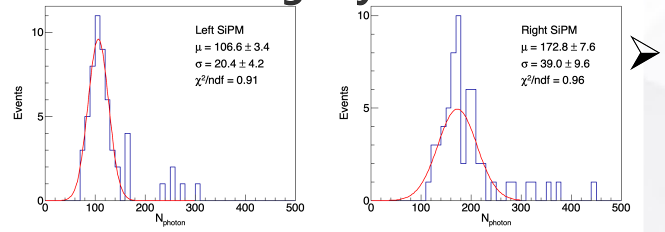
- Area 6×6 mm^2 ;
- Time info ;
- Sampling rate 125Msps;
- Dual readout，Dynamic range ~1-230MeV; ;



Muon signal waveform



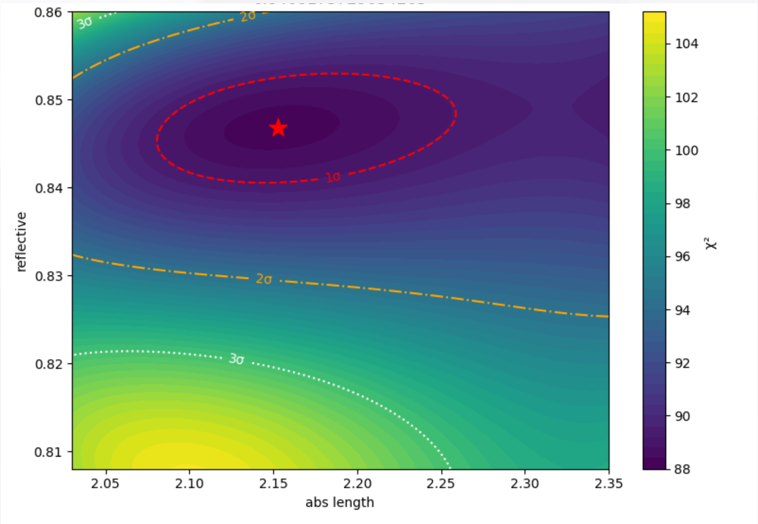
Muon light yield



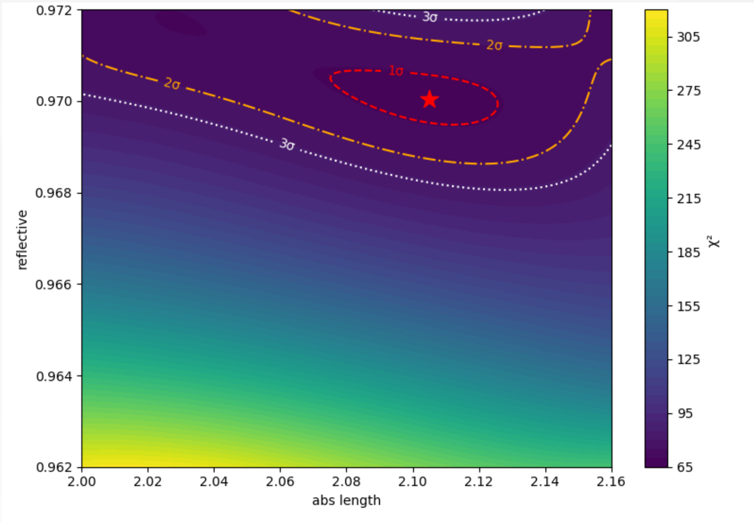
- Time response ~36 ns;
- 1-side light yield ~140 ph/muon
- Muon energy resolution ~20% ;

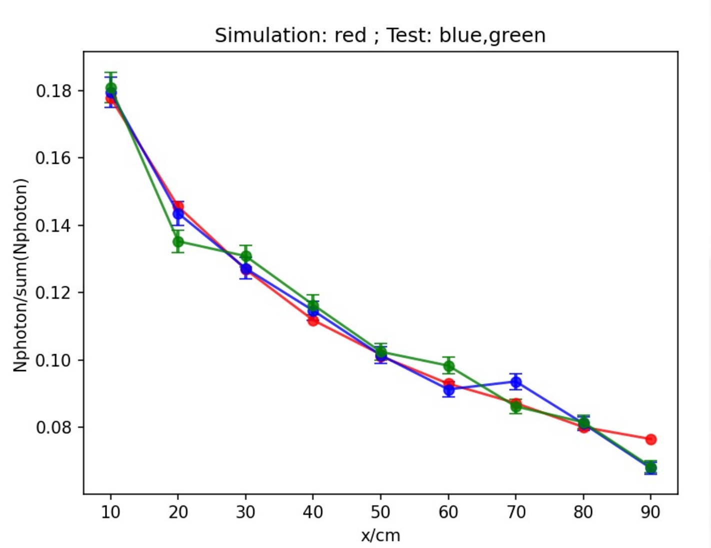
Parameterization of PS

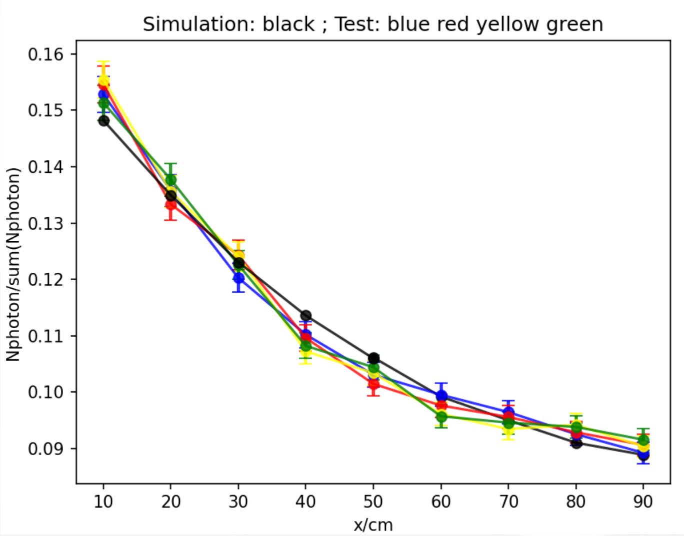
PS + WLS + SiPM



PS + PMT



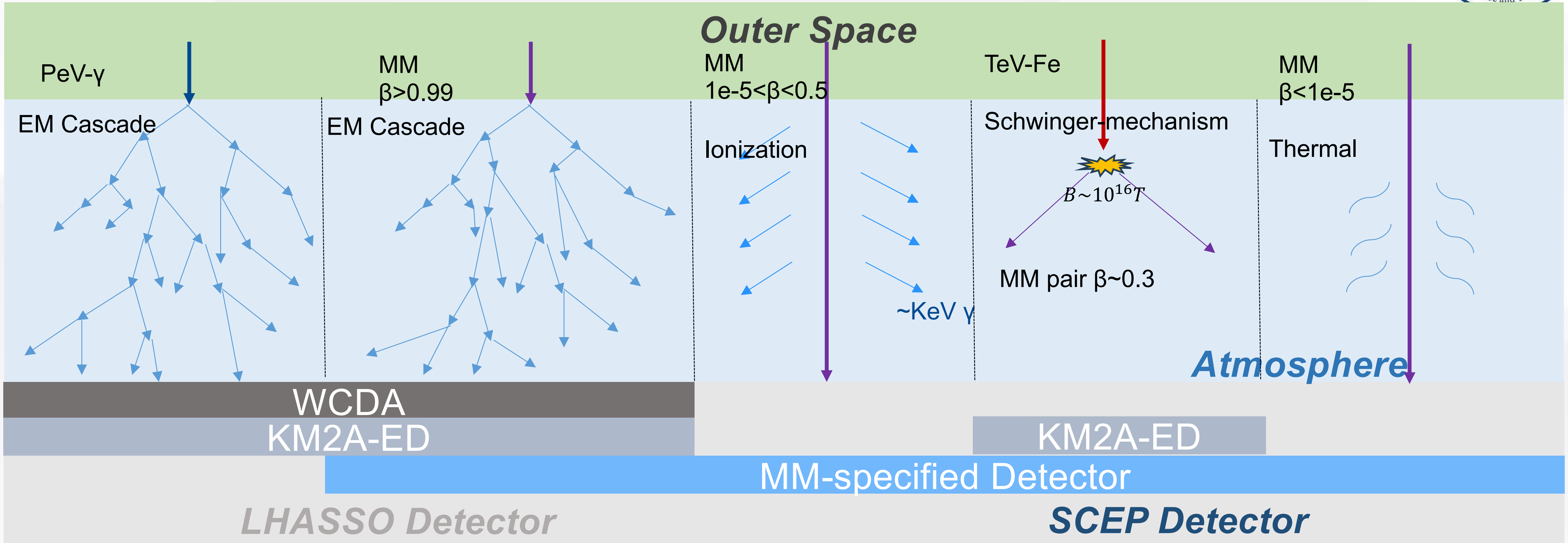




	Abs. Length [m]	Refle-ctivity	Light yield [ph/MeV]
PS+PMT	2.11+-0.01	0.970+-0.001	13.6+-0.3
PS+WLS+SiPM	2.15+-0.04	0.847+-0.004	13.0+-0.4

- Abs. lengths and light yields from two types of samples are consistent;
- Reflectivities are different due to the lights trapped inside WLS fibers;
- Light collection of PS+PMT is better;

LHAASO + SCEP?



- Relativistic MM: Can cause EM shower, detected by WCDA and KM2A; High bkg from PeV-γ;
- Medium speed MM (1e-5<β<0.9): Cause ionization; can be detected when directly passing KM2A-ED;
- Low speed MM (β<1e-5): Deposit energy is converted into thermal, undetectable; Only detectable when passing through induction detectors;
- Relativistic heavy ions can produce pair of MMs with speed ~0.3c through Schwinger mechanism;

Proposed Placement

Image credit: LHAASO

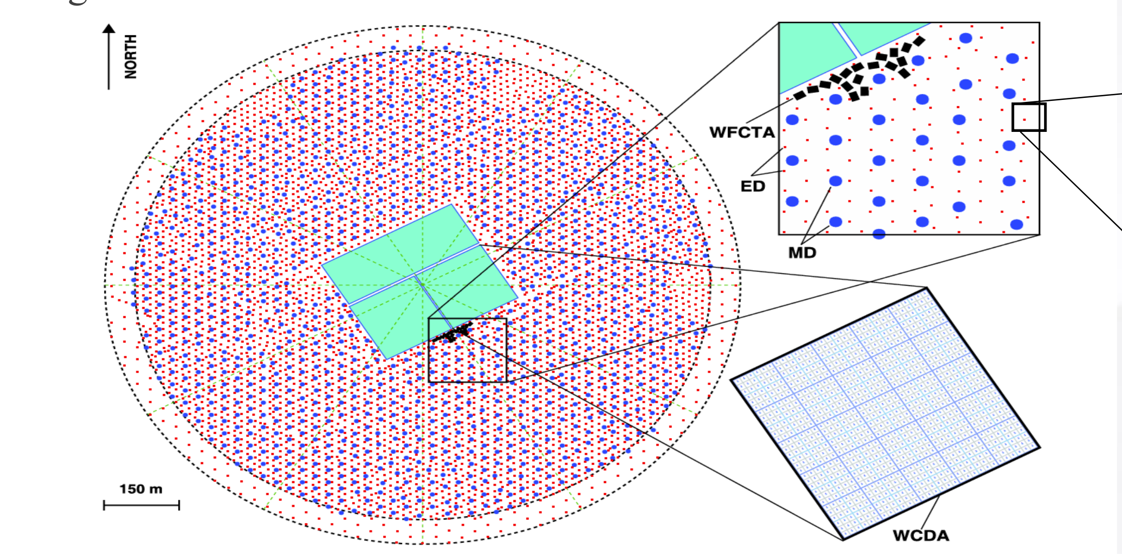
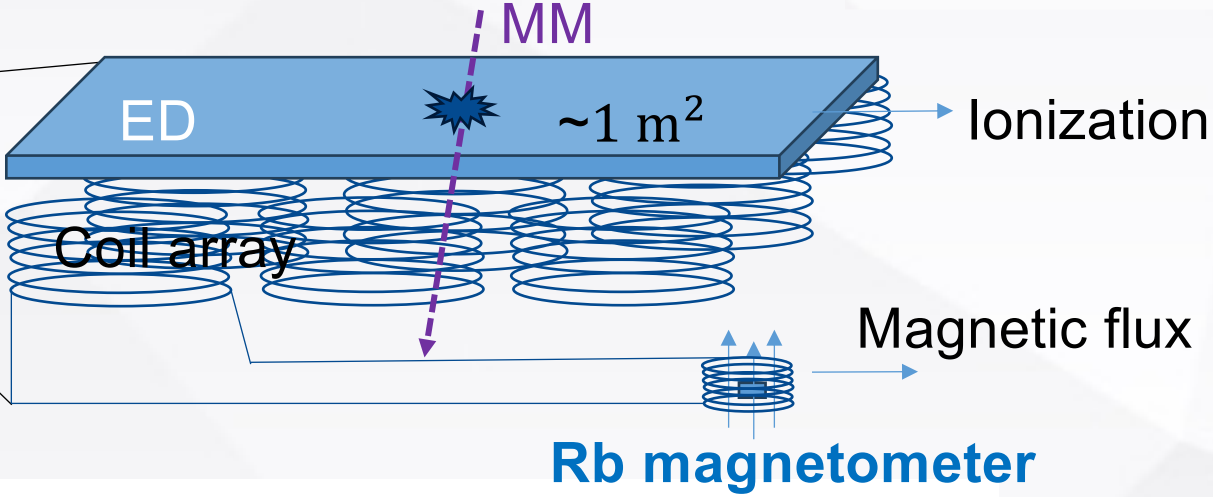


Fig. 1. (color online) Layout of LHAASO.



- Induction module can be placed under KM2A-ED;
- Coincidence measurements of MM's ionization and induction;
- Total Exposure area ~ 5000 m^2
- Synergy with MANDATE to cover low-speed regions;

Summary

- SCEP aims at searching for cosmic magnetic monopoles beyond current constraints with large area under room-temperature condition;
- We estimated the ionization background for terrestrial and lunar detectors; The SNR is required to be larger than 4.5.
- Three methods of induction collection to cover large speed parameter space;
- We consider the best place for implementation is to collaborate with LHAASO;
- First step: Meter-square detector

Backup