Recent progress on CASPEr-gradient and New Search for High-Frequency Gravitational Waves

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IBS DMAG axion seminar
2026.03.26

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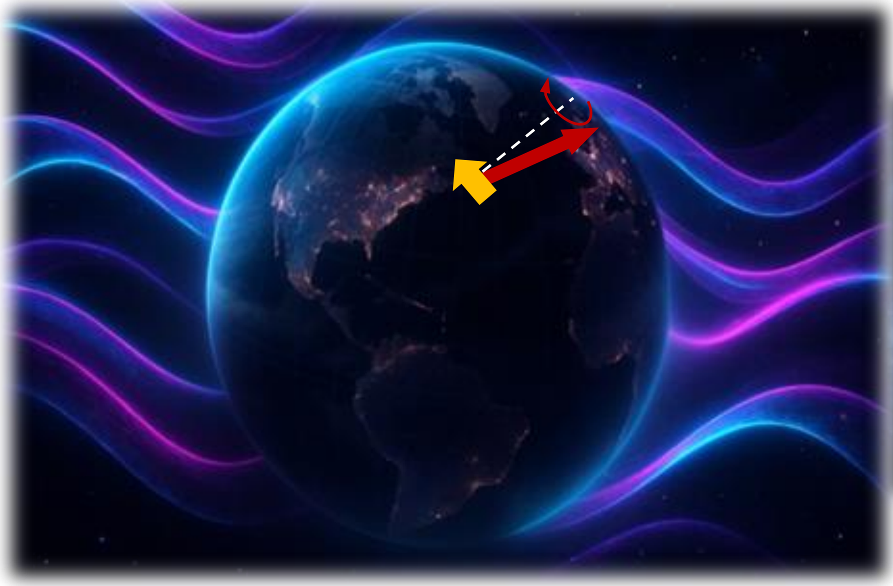
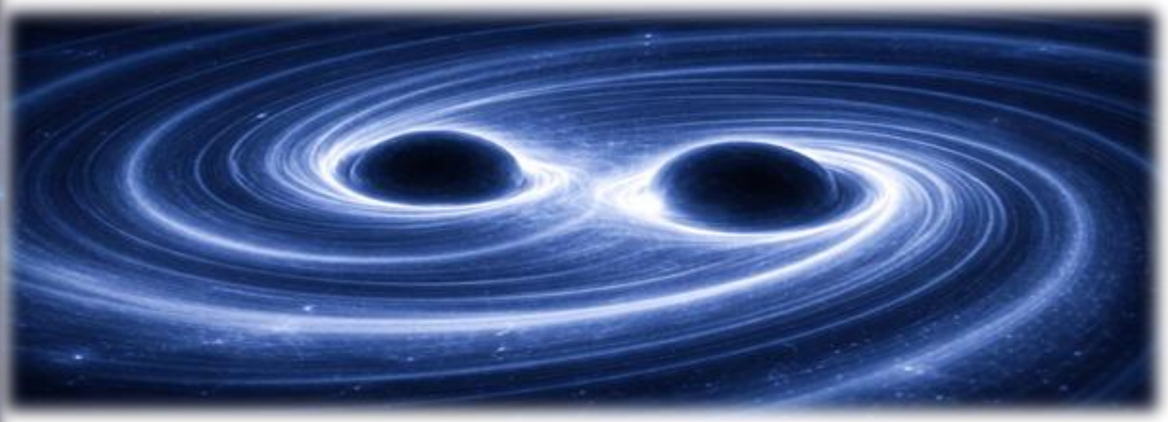
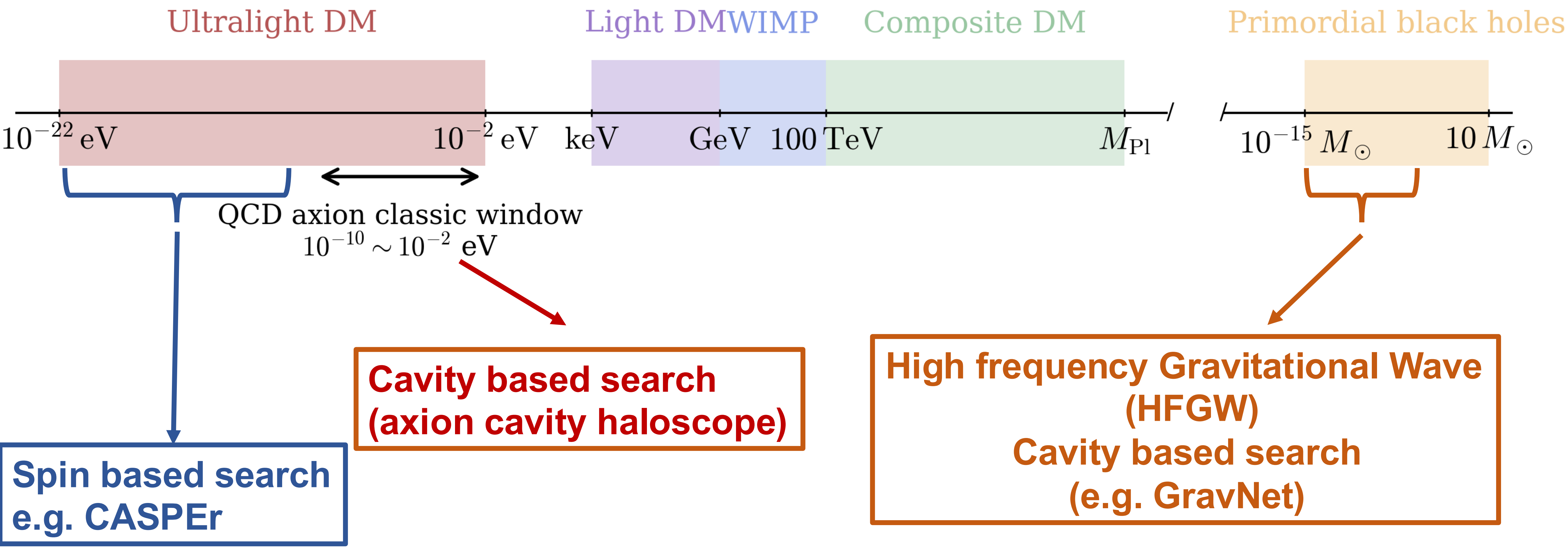
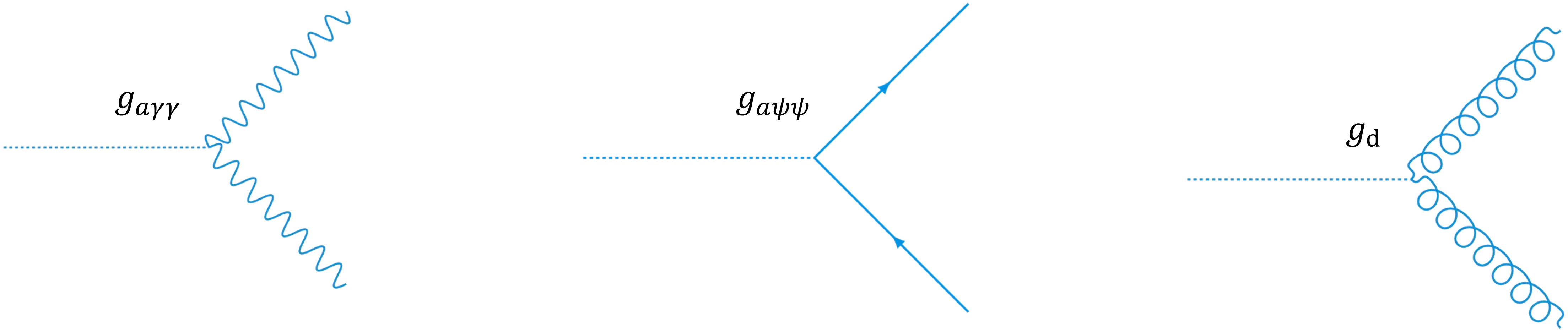




Dark matter candidates



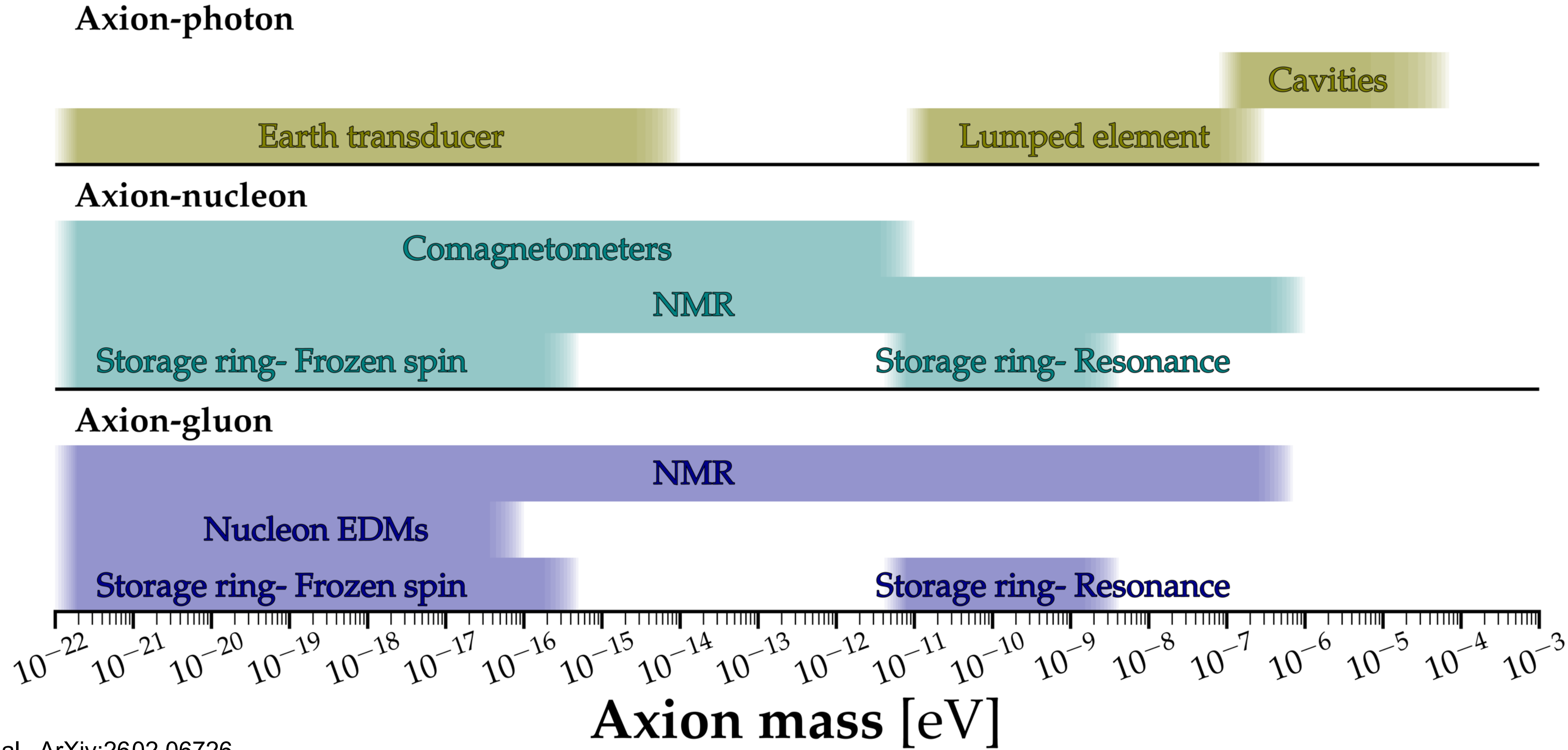
Axion detection methods-Interactions



- Axions have 3-channels to interact with SM particles:
  - $L_{int} = -\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F} + g_{a\psi\psi}\partial_\mu a\bar{\psi}\gamma^5\gamma^\mu\psi - \frac{1}{4} g_d a G\tilde{G}$
  - Photon → Generate E//B photon
  - Fermion → Torque to spin
  - Gluon → Oscillation of electric dipole moments

Y. K. Semertzidis and S. Youn, 2022.

Axion detection methods



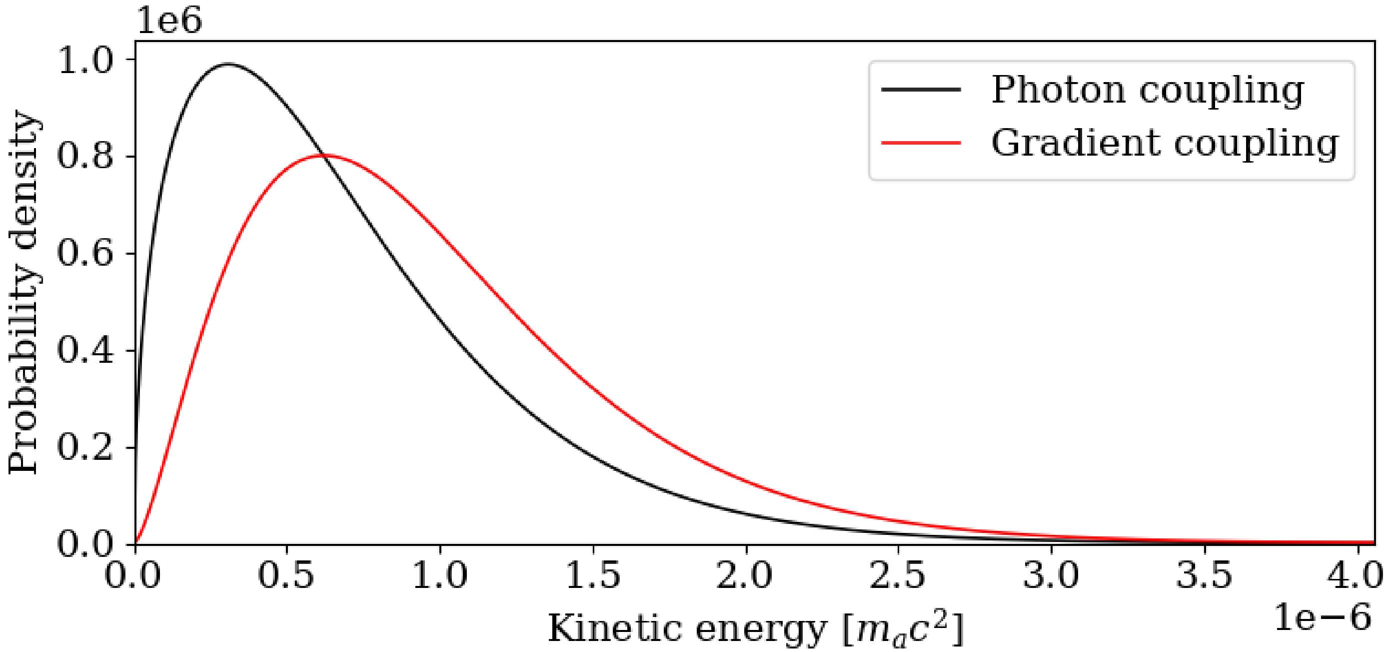
D. Aybas et al., ArXiv:2602.06726

Axion spin interaction

- Interaction Hamiltonian:
  - $H_{axion} = g_{aNN}\nabla a \cdot \vec{I}_N + g_{aee}\nabla a \cdot \vec{S} + g_d a\, \vec{I}_N \cdot \vec{E}$ → $\vec{d}_{EDM} = g_d a\, \vec{I}_N$
- Spin-magnetic field interaction:
  - $H_s = -\vec{\mu} \cdot \vec{B}$
- Axion induced effective magnetic field to spin:
  - $\vec{B}_{eff} = -\frac{2}{\gamma}(g_{aNN}\nabla a + g_{aee}\nabla a) \approx -\frac{2}{\gamma}(g_{aNN} + g_{aee})a\vec{k}$
  - Fictitious magnetic field (*Not originated from Maxwell's equation*)
- If a field oscillates with frequency ω_a, $\vec{B}_{eff}$ also oscillates with the same frequency ω_a
- Daily modulation feature → Dark matter axion

Y. K. Semertzidis and S. Youn. Sci. Adv., 2022.

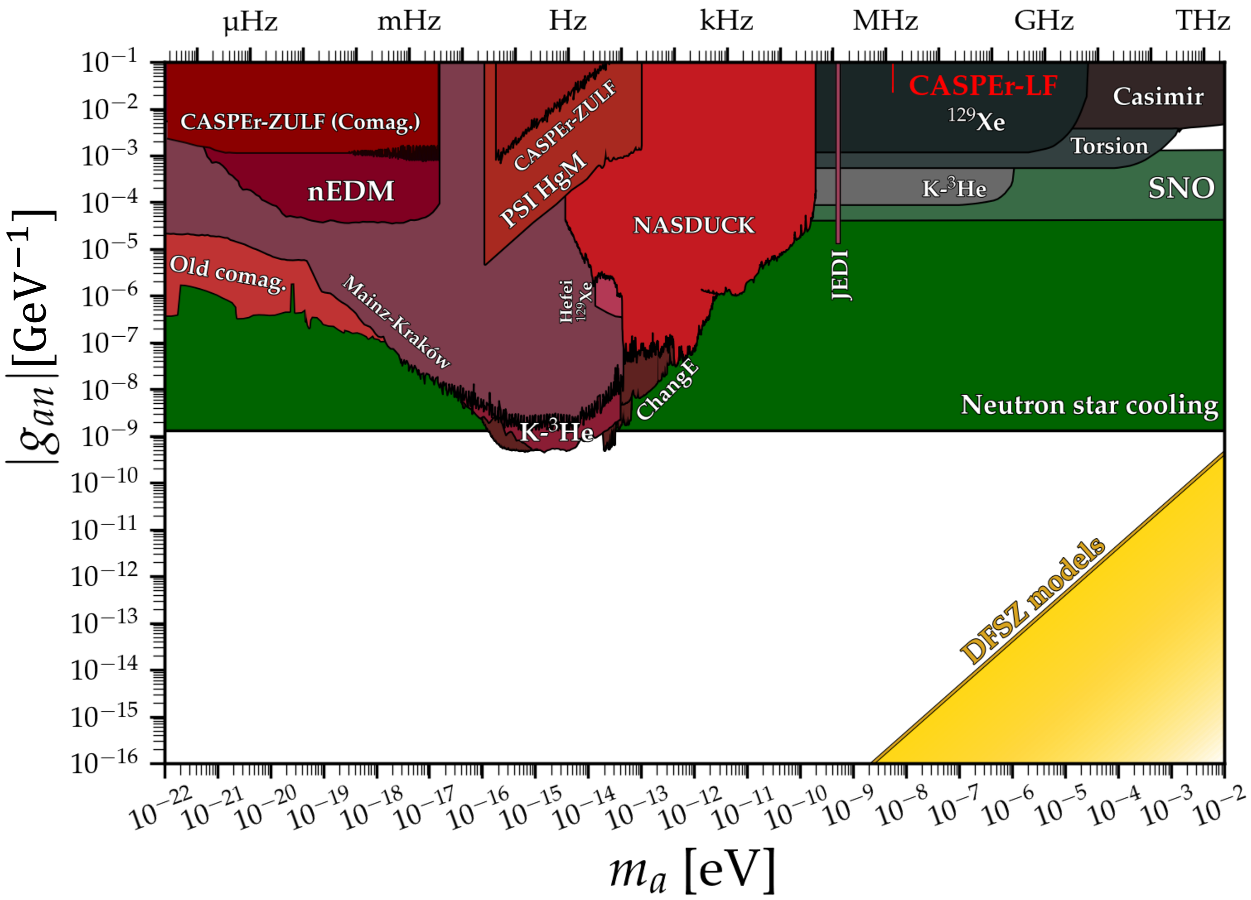
Axion spin interaction-DM

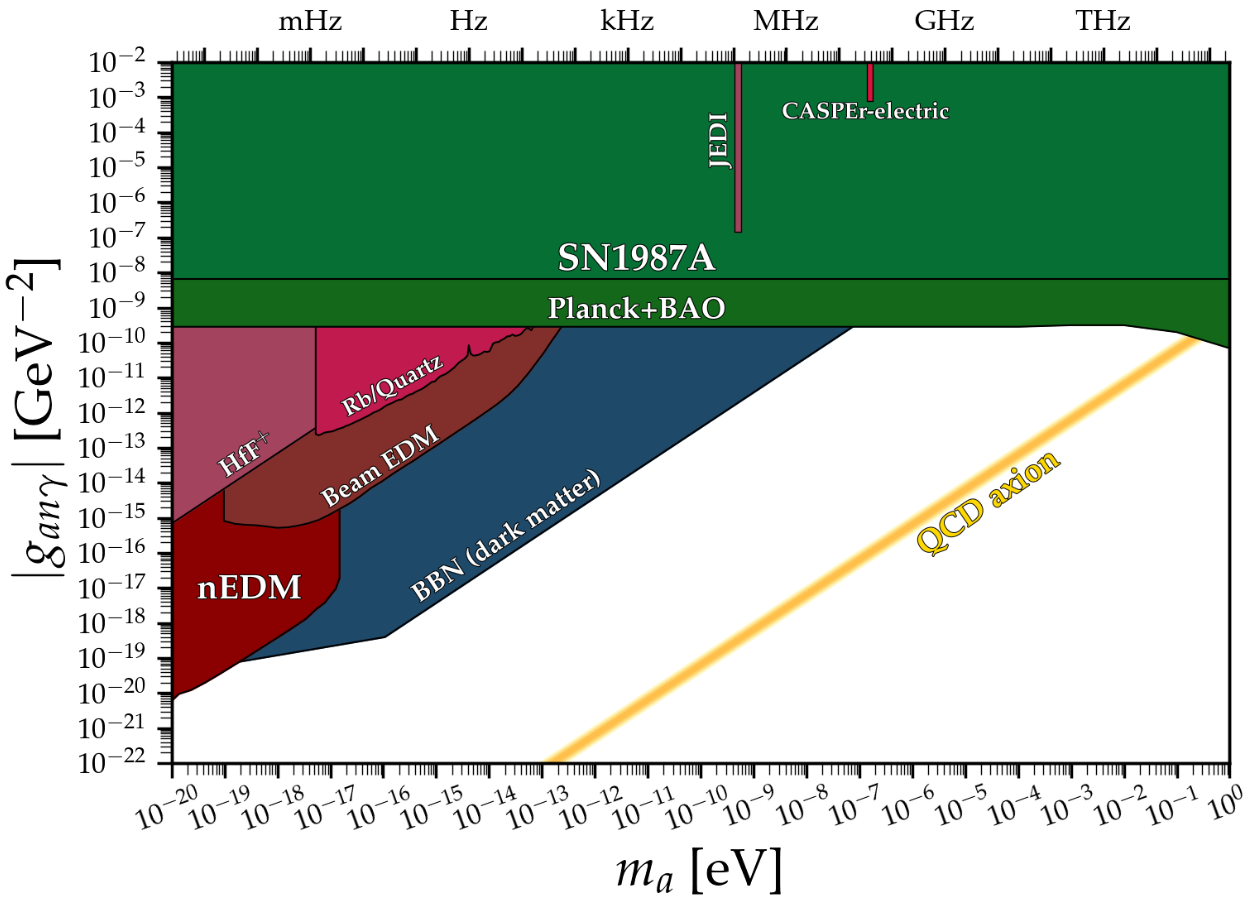


- Standard halo model, dark matter seems to have velocity due to relative motion between the Earth and DM $\vec{v} = \vec{v}_{Earth} + \vec{v}_{sun} + \vec{v}_{Galaxy} \approx 270\text{km/s}$
- Axion dark matter has wavy nature
  - $\lambda_{de\ Broglie} = \frac{h}{mv}, \lambda \approx 1km\ [\frac{1\mu eV}{m_a}]$

M. Turner, 1990
A. V. Gramolin et al., 2022

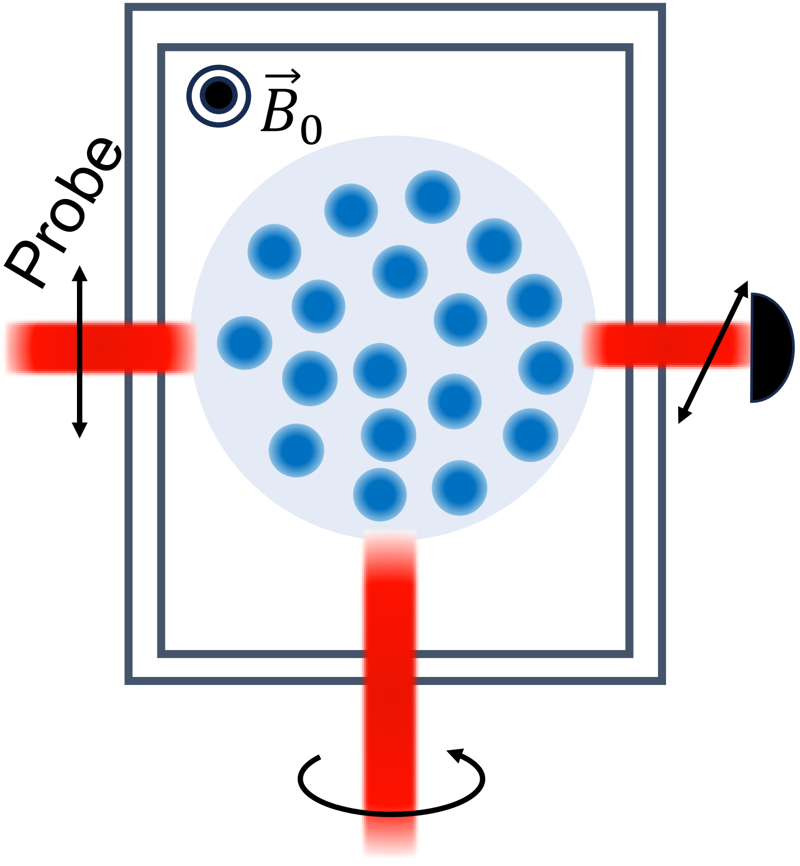
Axion spin interaction-DM

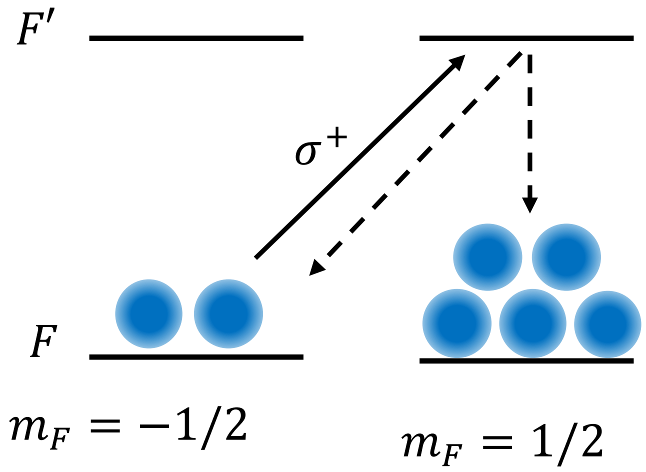


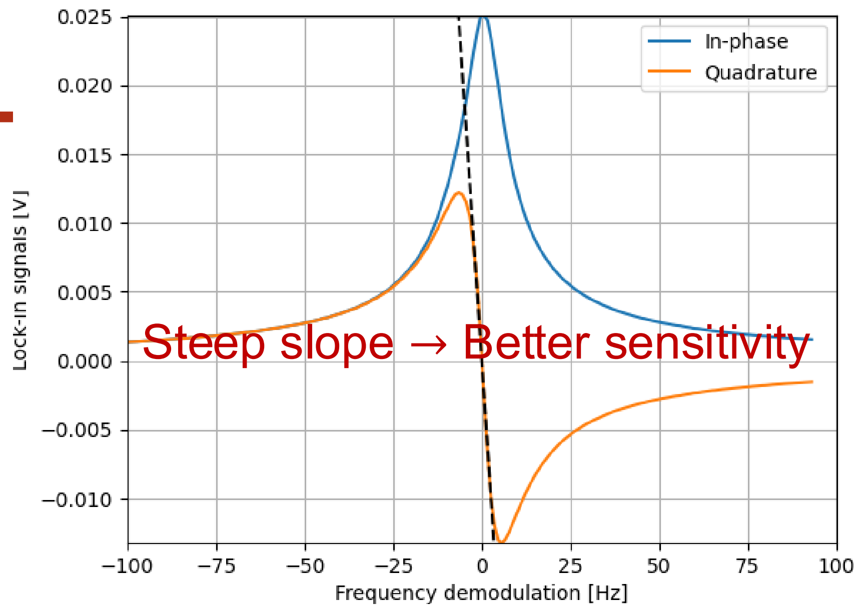


Axion limtsCiaran O'Hare

Atomic (co-)magnetometer



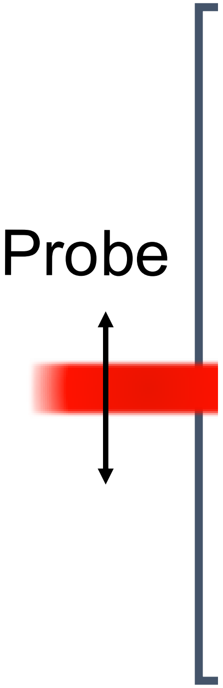


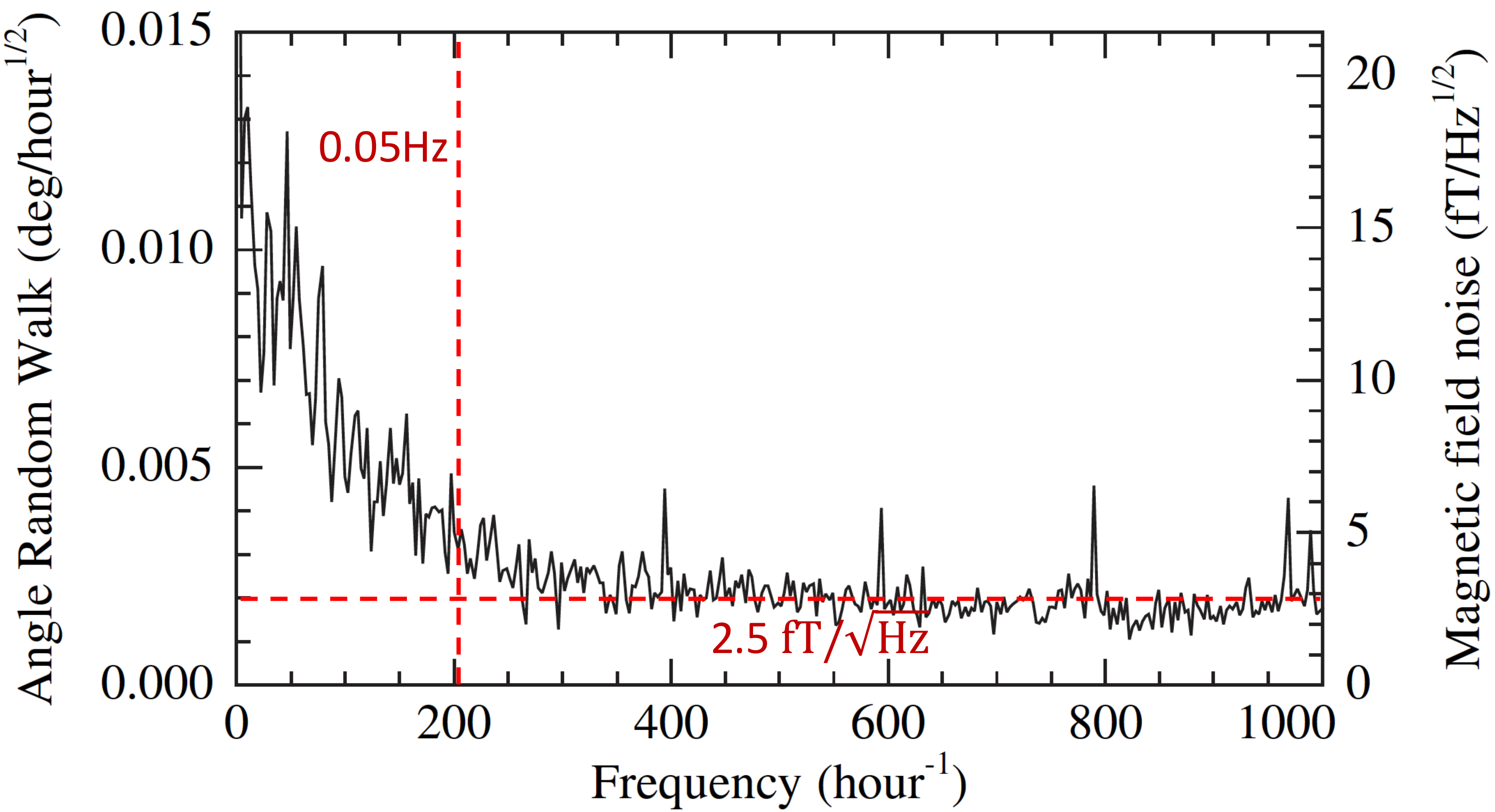


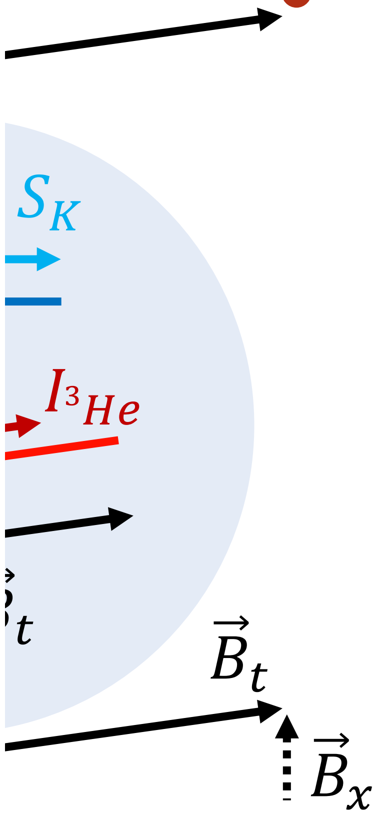
- Measure non-linear magneto optical rotation
  - $\theta_F(\omega) = \frac{\omega L}{2c}\left(n_R(\omega) - n_L(\omega)\right) \approx \alpha(\omega - \omega_0) = \alpha\gamma(B - B_0)$
- Limit: Spin-projection noise (Uncertainty of spin operator), $\delta B \propto \sqrt{\frac{\Gamma_{tot}}{Nt}}$
- Spin Exchange Relaxation Free (SERF) regime:
  - Increase *spin exchange collision rate* faster than *Larmor precession*
  - *Reduce* Γ_{tot} (mainly spin-exchange relaxation), Sensitivity: $\sim fT/\sqrt{Hz}$
  - High pressure, low magnetic field (<μT)

D. Budker and D. F. J. Kimball, 2013.

Atomic co-magnetometer







Opticall

Alkali a

settle along $\vec{B}_t$

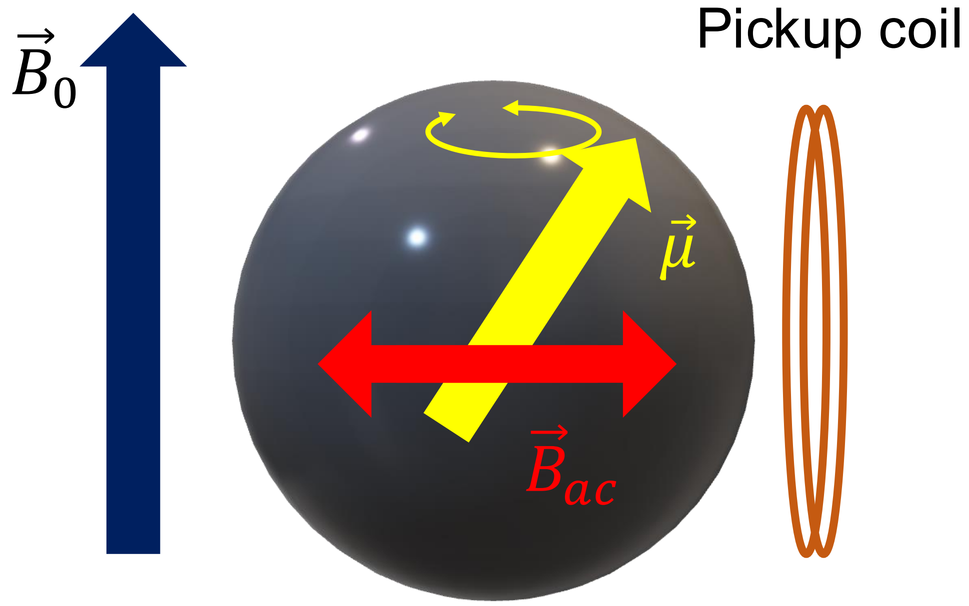
ge

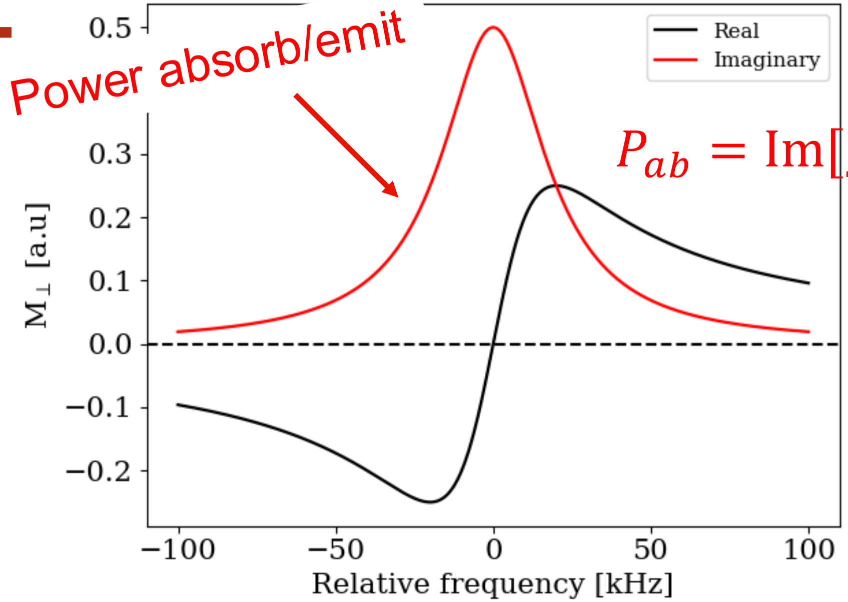
λM_0^e ~0.1nT , λM_0^n: ~100nT

D. Budker and D. F...

T. Kornack, R. Ghosh and M. Romalis, 2005

Nuclear magnetic resonance





$P_{ab} = \mathrm{Im}[\int \dot{M}_\perp \cdot B_{ac}\, dV]$

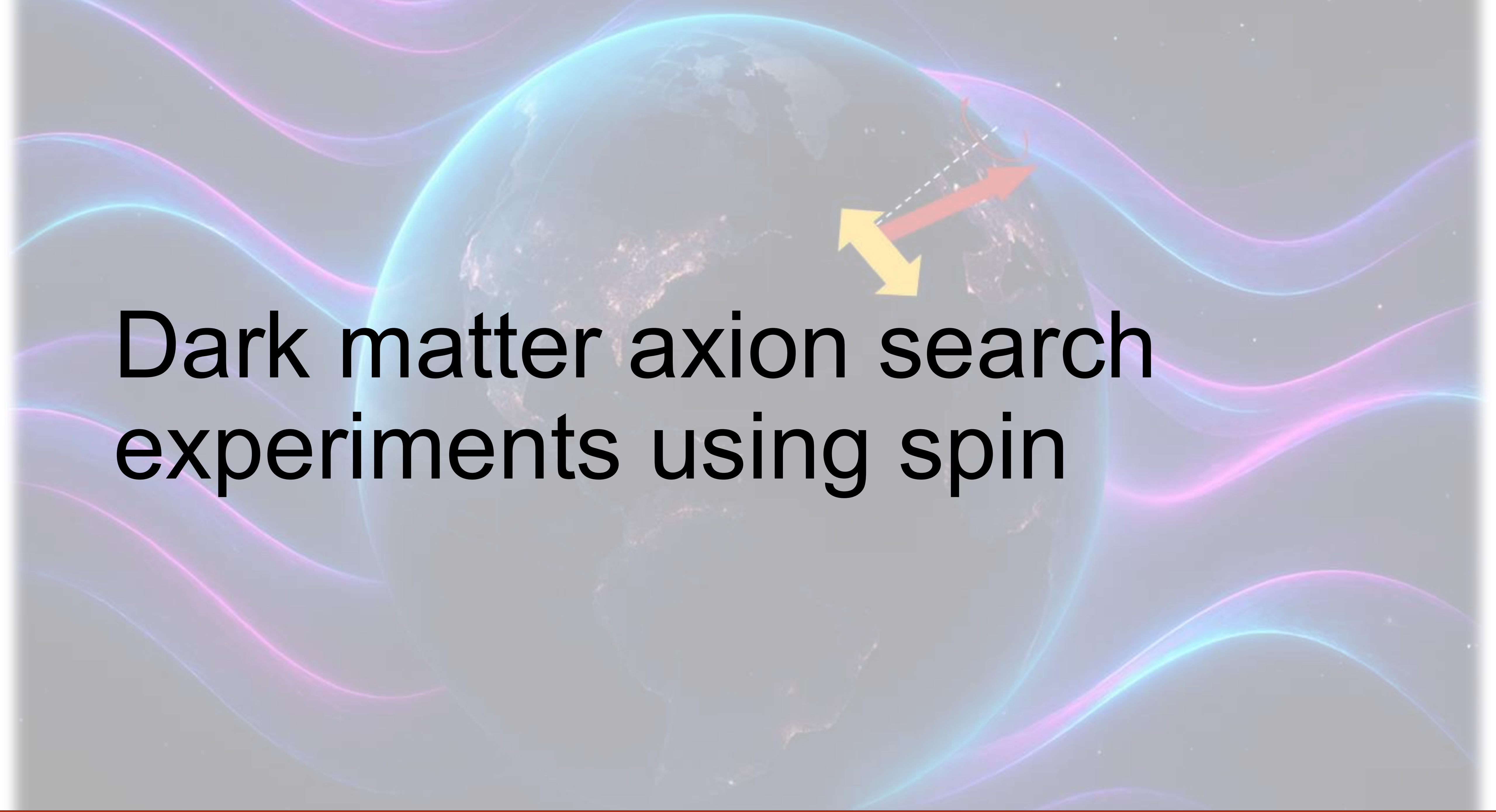
(Hyper)-polarized nuclear spin along B_0

$M_\perp$: Transverse magnetization
T_2: Transverse relaxation time

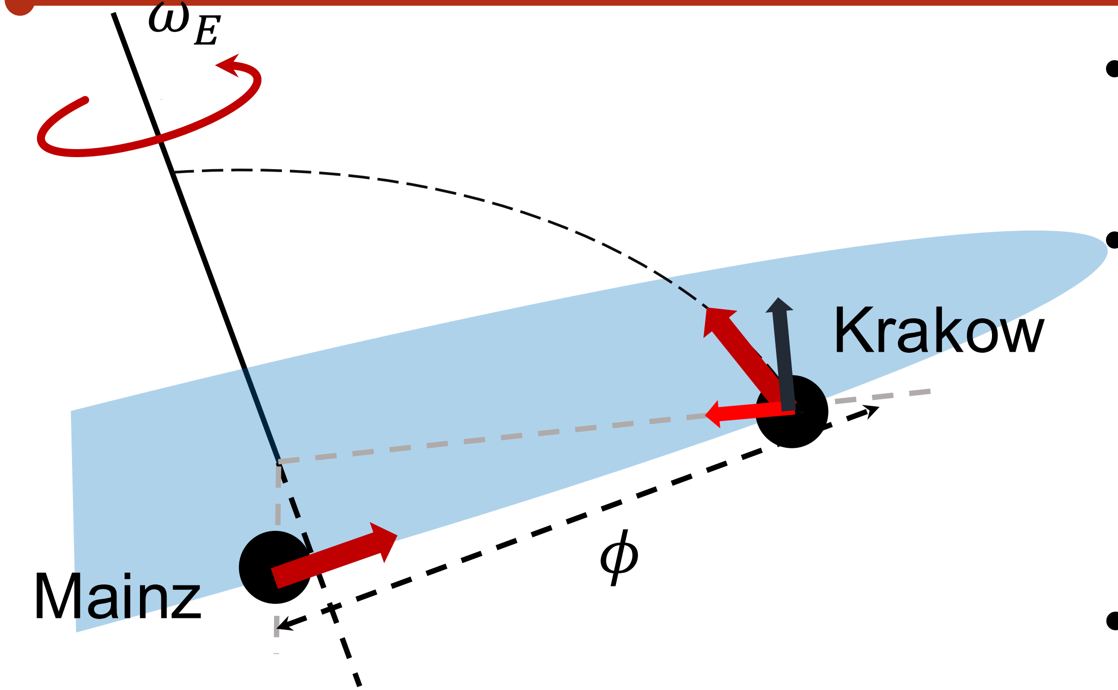
- M_0 absorb magnetization from weak continuous B_{ac}
  - Steady state $M_\perp(\omega) = \frac{\chi_0 M_0 B_{ac}}{(\omega-\omega_0)+i/T_2}$
- $M_\perp$ precess along B_0, generate oscillating E&M field
  - $f_0 \lesssim 1\mathrm{GHz}$ (e.g Proton $f_0 \approx 600$ MHz @14.1 T)
- Signal read: atomic magnetometer, SQUID, lumped element resonator with low noise amplifier

A. Garcon et al., 2017

Dark matter axion search experiments using spin



Atomic co-magnetometer



Sensitive axis of magnetometer:

$$\hat{m}(t) = \hat{x}\sin(\theta)\sin(\omega_E t + \phi_E) + \hat{y}\sin(\theta)\cos(\omega_E t + \phi_E) + \hat{z}\cos\theta,$$

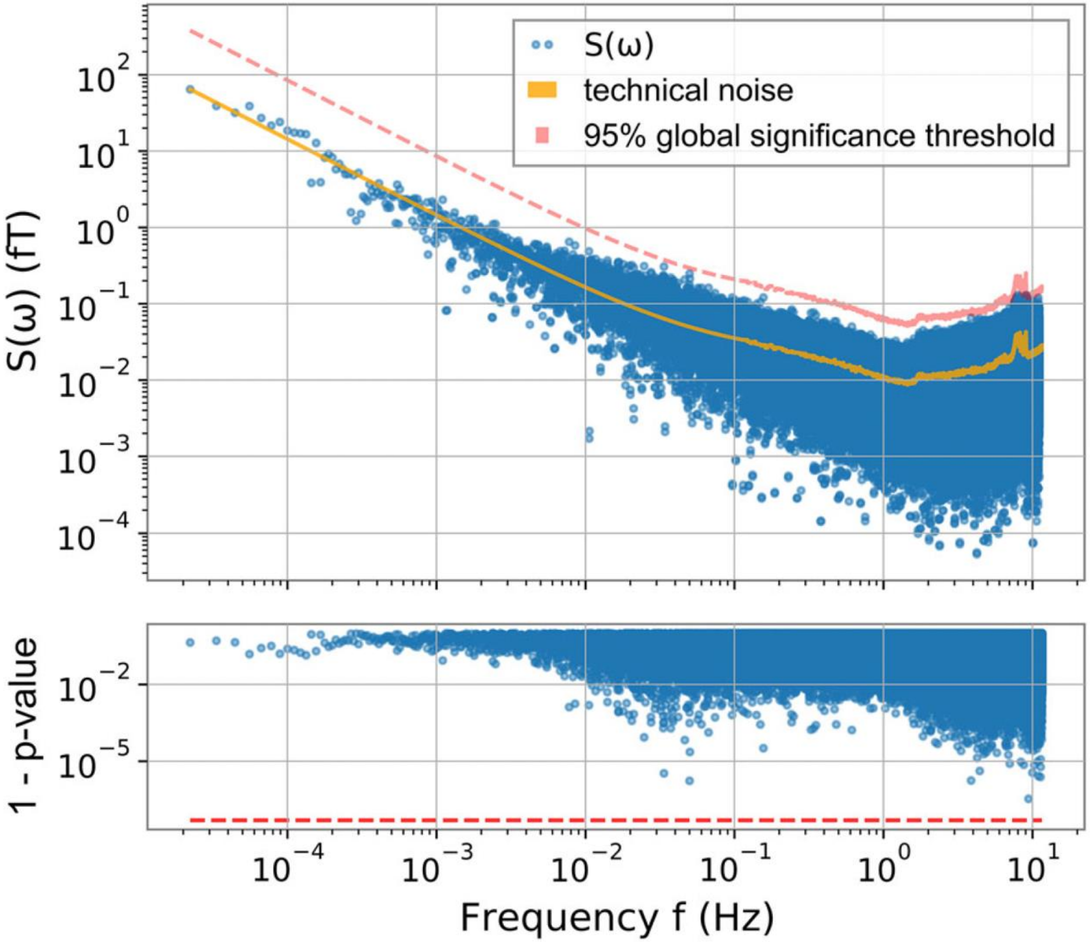
$\theta = \angle(\hat{z}, \hat{m})$, $\phi_E = \angle(\hat{x}, \hat{m})$,

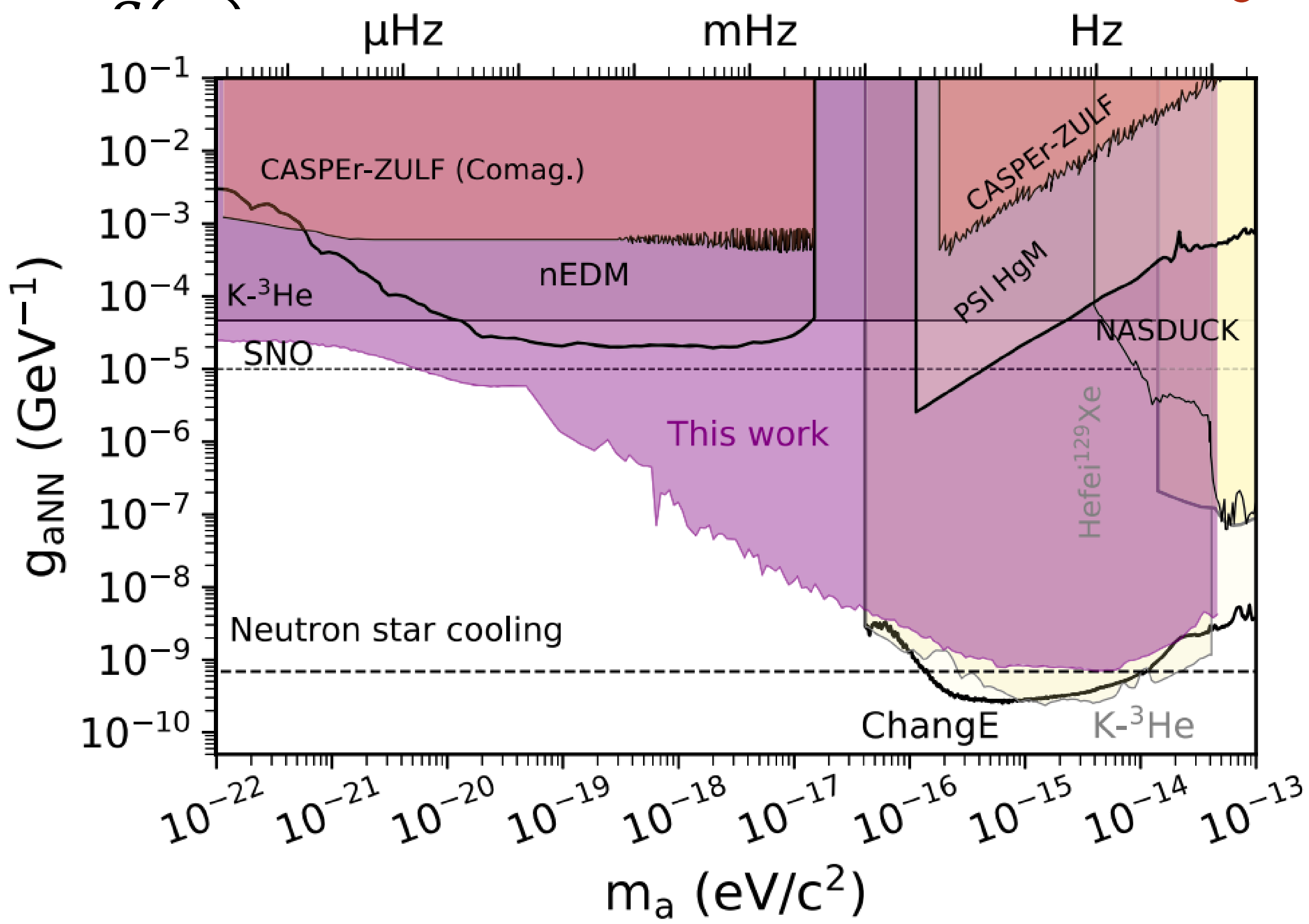
$\hat{x}$: Perpendicular to Greenwich meridian

- Target low mass axion(<11.6Hz)
  - $\lambda_{DB} > 0.2\ \mathrm{AU}, \tau_a > 0.3\ \mathrm{day}$
- Two spatially separated comagnetometer
  - $\mathrm{K-Rb-3He}$ atomic comagnetometer
  - Self compensation mode
  - Observable: ***Interference of signals from two station***
- Mainz station:
  - Laboratory horizontal, point to East
  - *Sideband oscillation contribution*
- Krakow station:
  - Laboratory horizontal, point to North
  - *Leading field/sideband oscillation*

D.G.Martin, G.Lukasiewicz et al., 2025

Atomic co-magnetometer





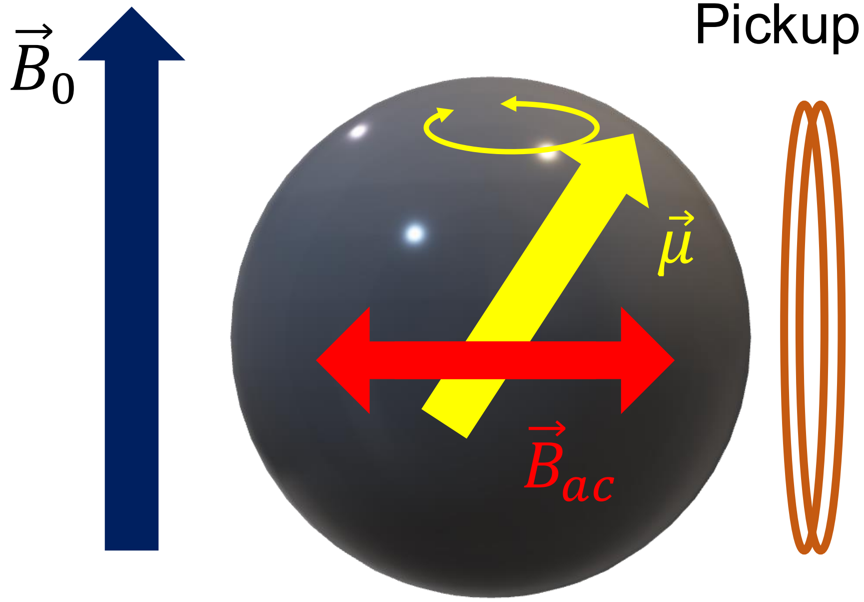
D.G.Martin, G.Lukasiewicz et al., 2025

Cosmic Axion Spin Precession Experiment

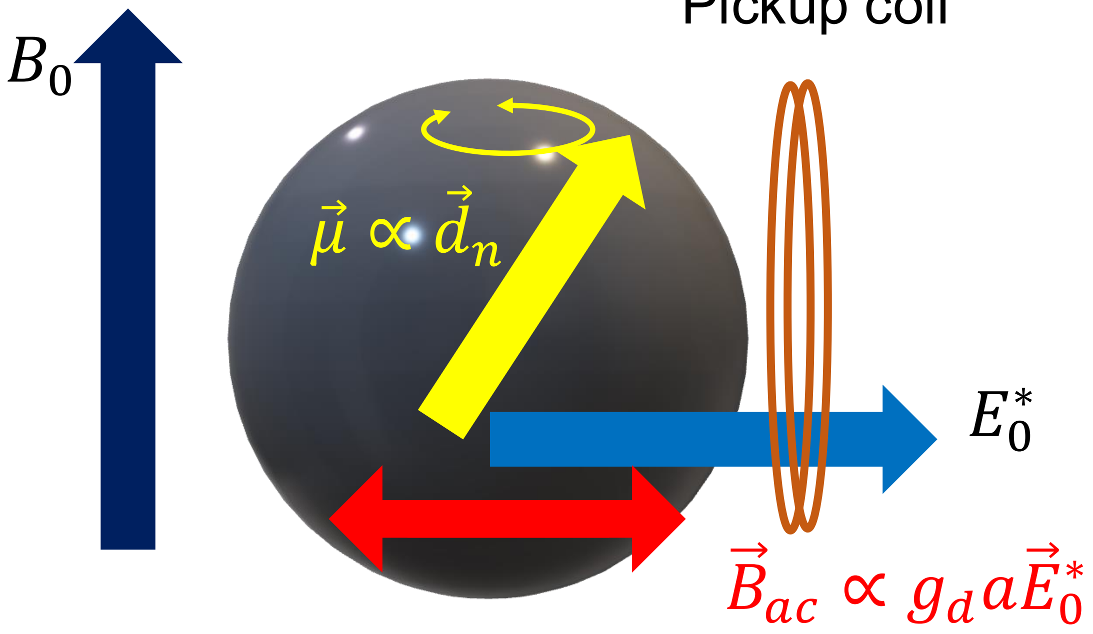
Cosmic Axion Spin Precession Experiment

$$L_{spin} = g_{aNN}\partial_\mu a\bar{\psi}\gamma_5\gamma^\mu\psi$$

$$L_{EDM} = -\frac{i}{2}g_d a\,\bar{\psi}\sigma_{\mu\nu}\,\psi F^{\mu\nu}$$



CASEPEr- Gradient

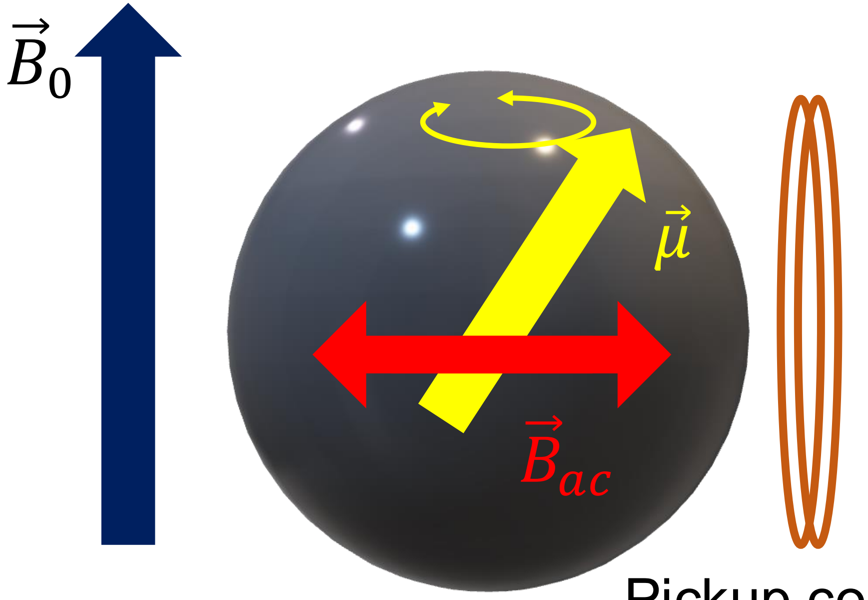


CASEPEr- Electric

D. Budker et al., 2014

CASPEr-Gradient

$L_{spin} = g_{aNN}\partial_\mu a\bar{\psi}\gamma_5\gamma^\mu\psi$

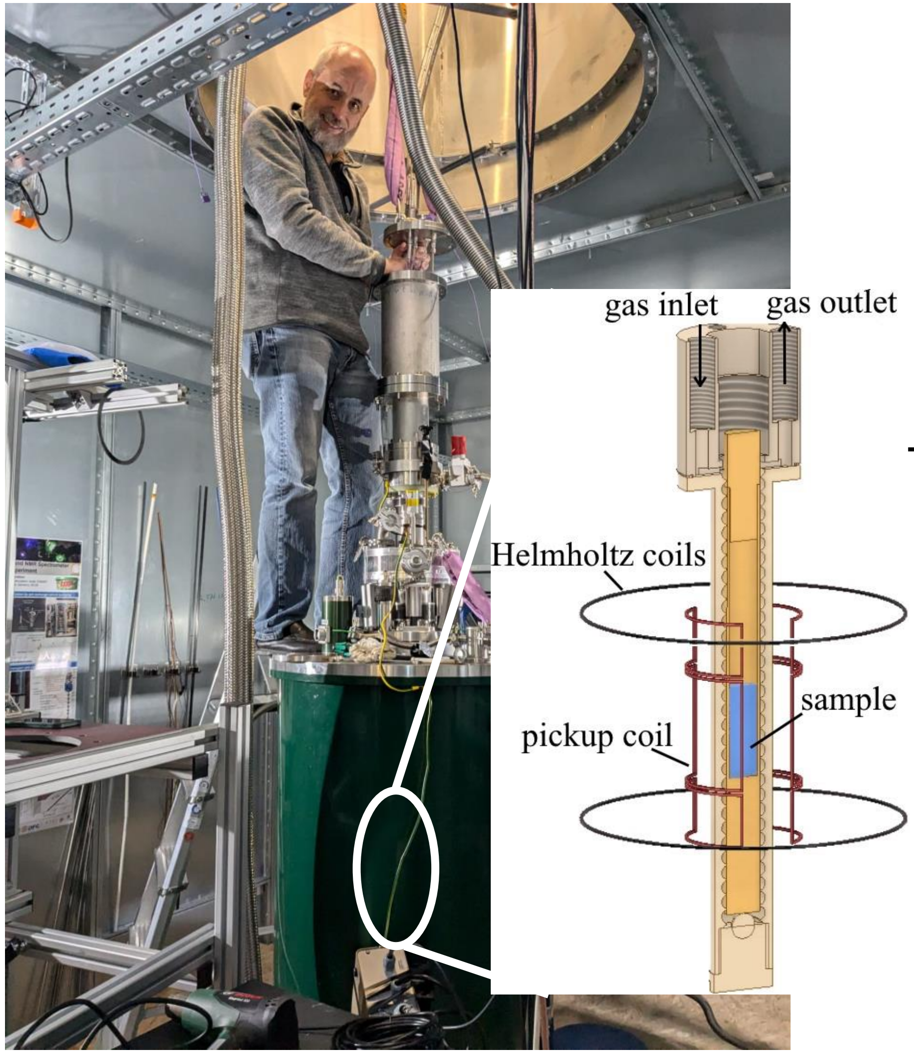


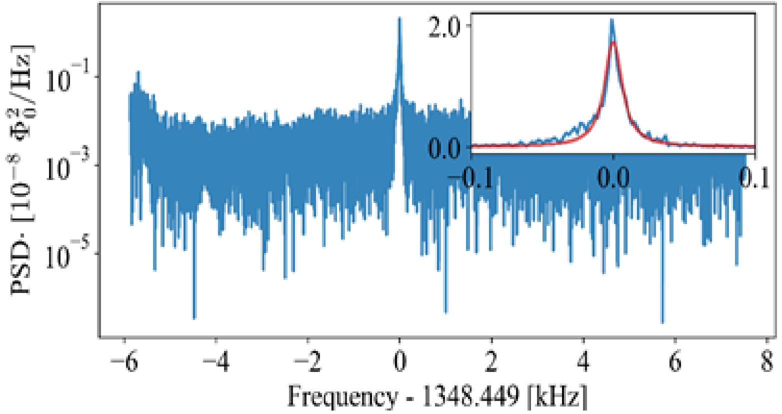
- Initially, spin($\vec{M}_0 = n_s\vec{\mu}$) ∥ external magnetic field $\vec{B}_0$
- Weak AC field ($\vec{B}_{ac}$) ⊥ $\vec{B}_0$,
  - Spin system tilts to transverse plane,
  - Starts to precess along $\vec{B}_0$ with $\omega_L = \gamma B_0$
- Transverse magnetization:
  - Weak coupling (Pickup coil does not affect to spin)
  - $\langle M_\perp^2(t)\rangle \propto M_0^2 B_{ac}^2 T_2 \tau_a \left(1 - e^{-\frac{2t}{T_2}}\right)$
- Detect magnetic field induced by $M_\perp$
  - Atomic magnetometer
  - SQUID, LC circuit
  - …

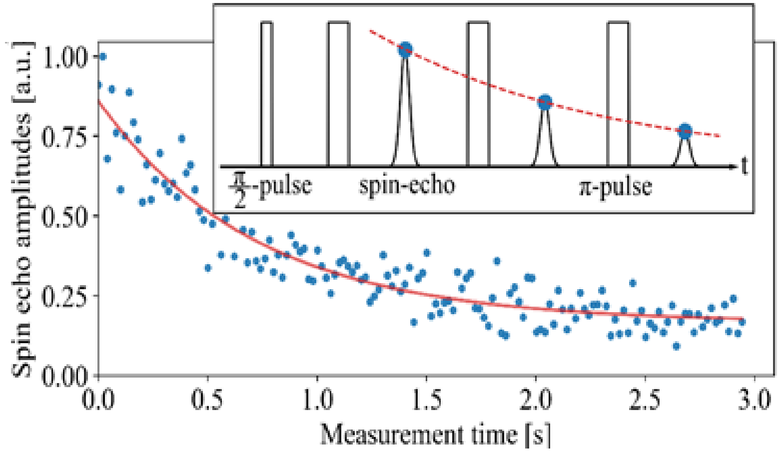
$M_\perp$: Transverse magnetization
τ_a: Axion coherence time
T_2: Transverse relaxation time
α: Arbitrary phase of AC field

D. Budker et al., 2014

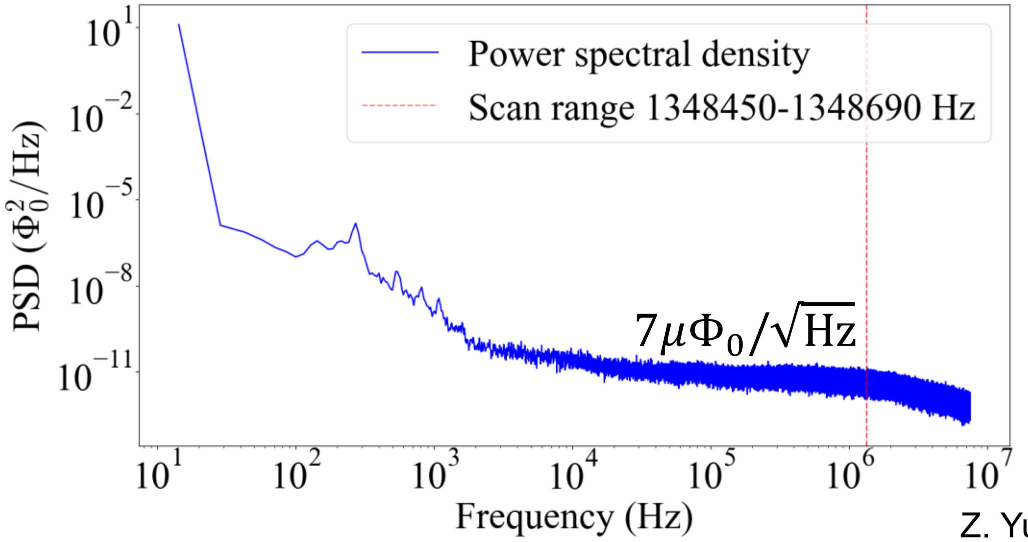
CASPEr-Low field (LF)





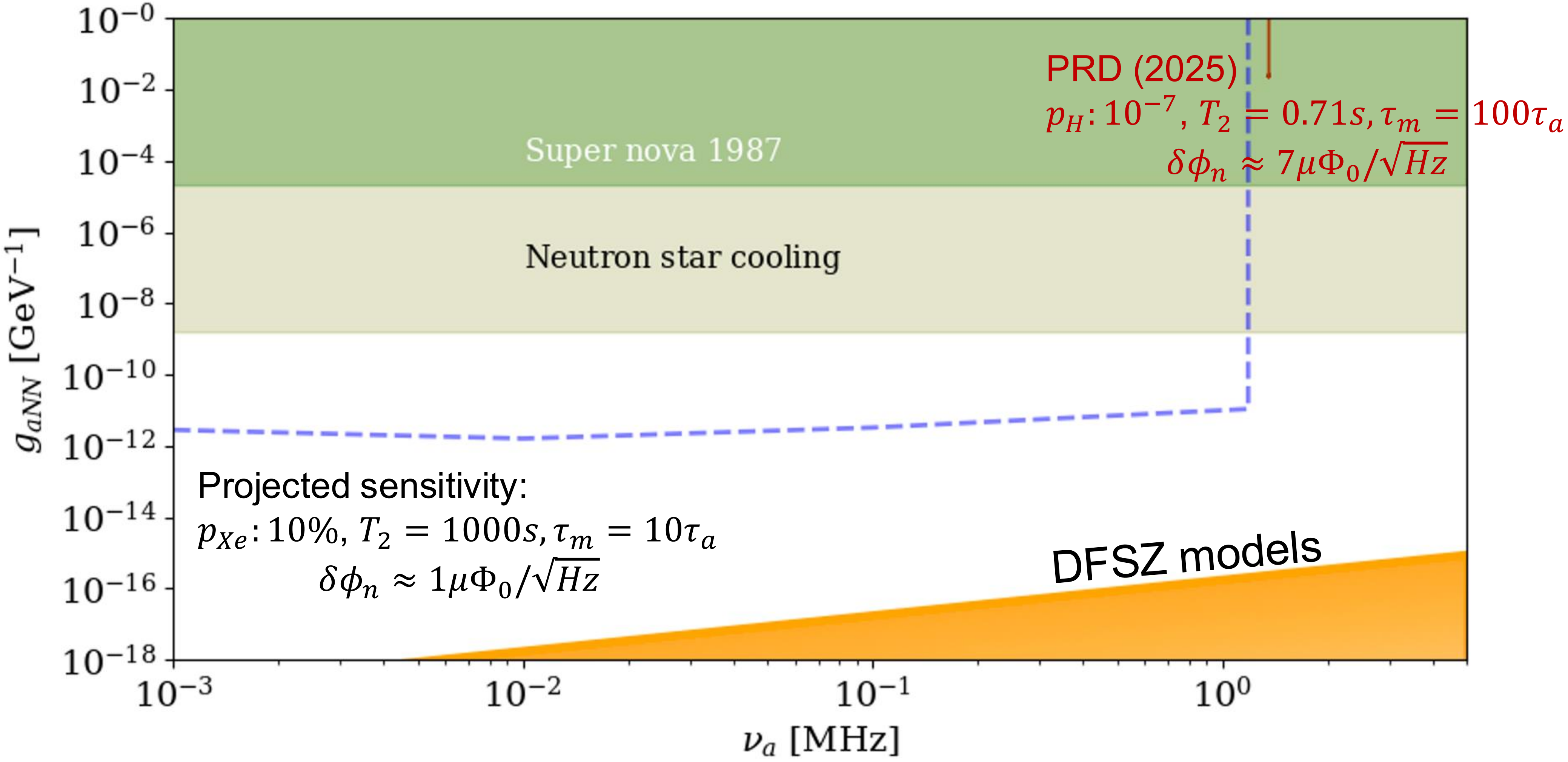


Thermal polarized Methanol(proton), $p \approx 10^{-7}$ $T_2^* = 0.02\ s, T_2 = 0.71\ s$

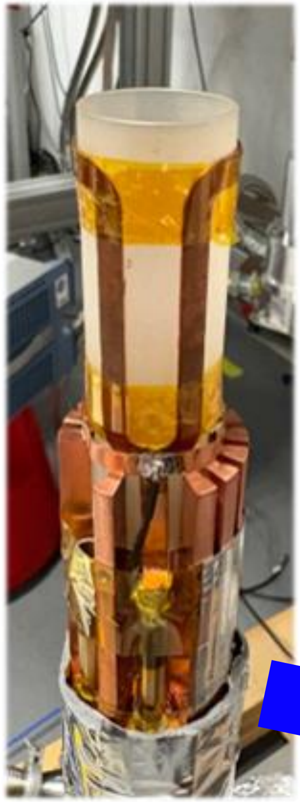


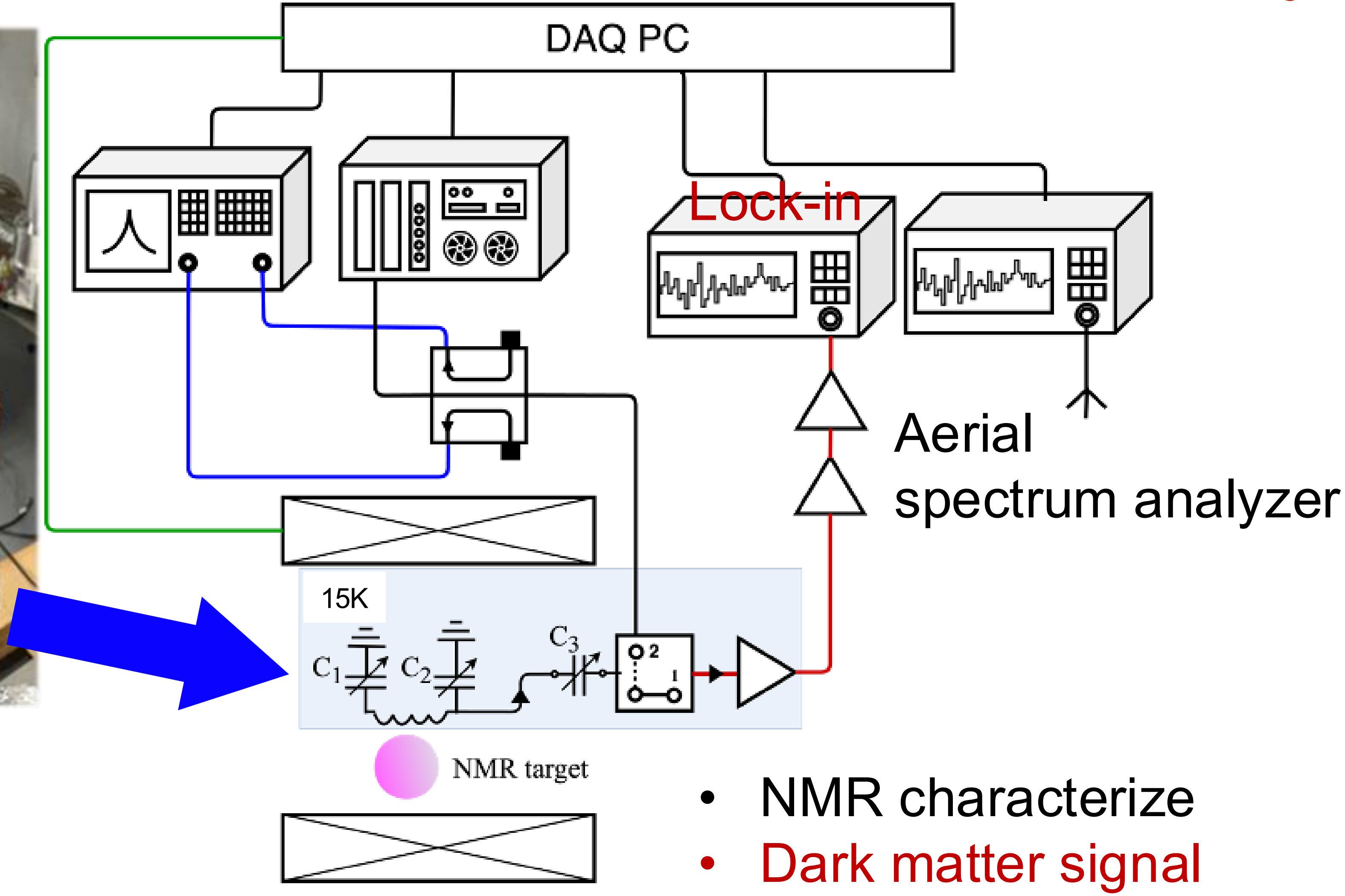
Z. Yuzhe et al, 2025

CASPEr-LF: Projected sensitivity



CASPEr-High field (HF)

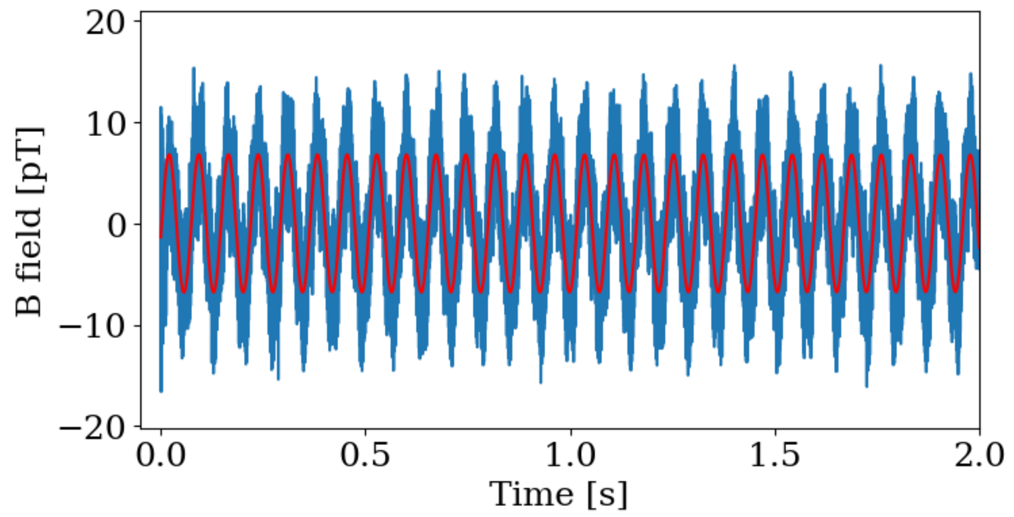


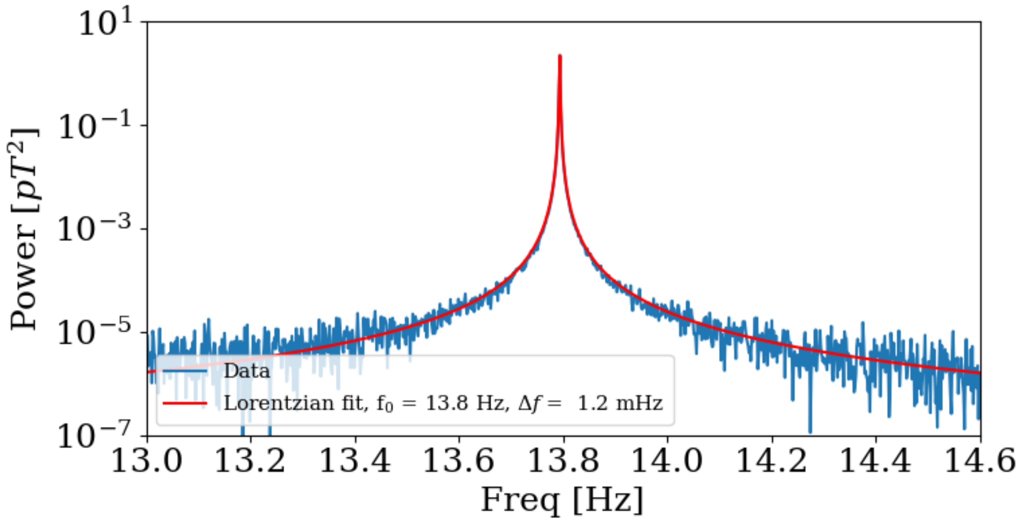


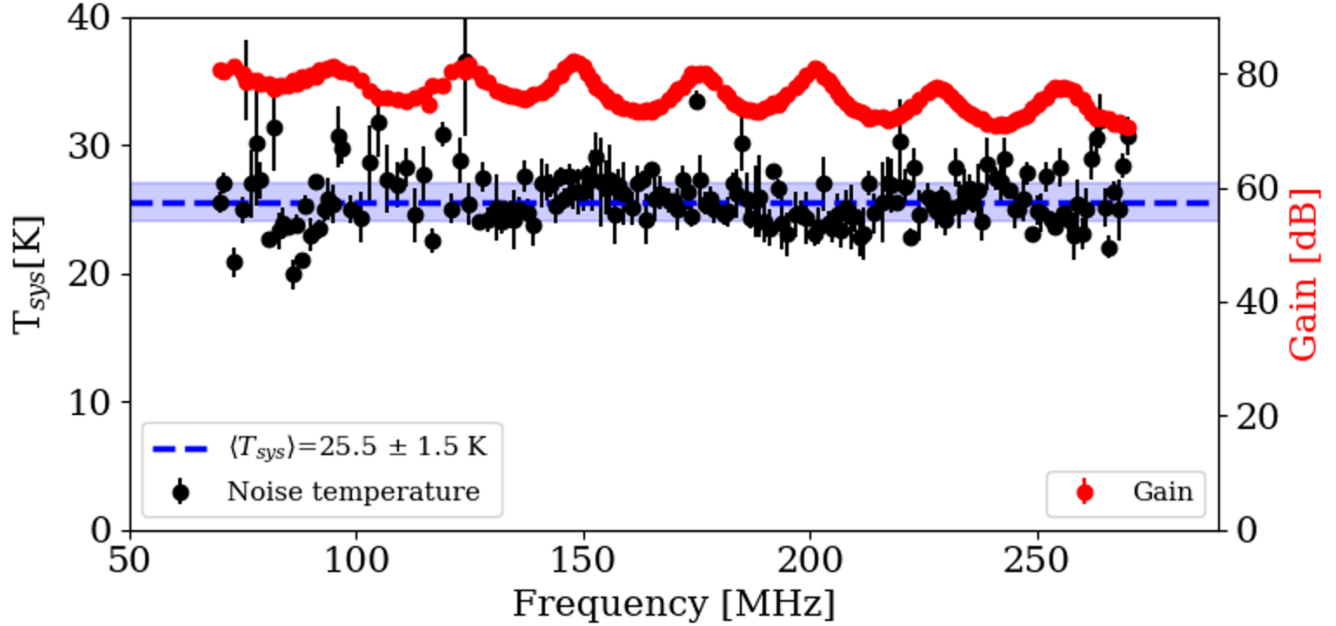
- Pickup loop tune/matching
- Solenoid magnetic control

- NMR characterize
- Dark matter signal

CASPEr-HF: NMR Target and Noise

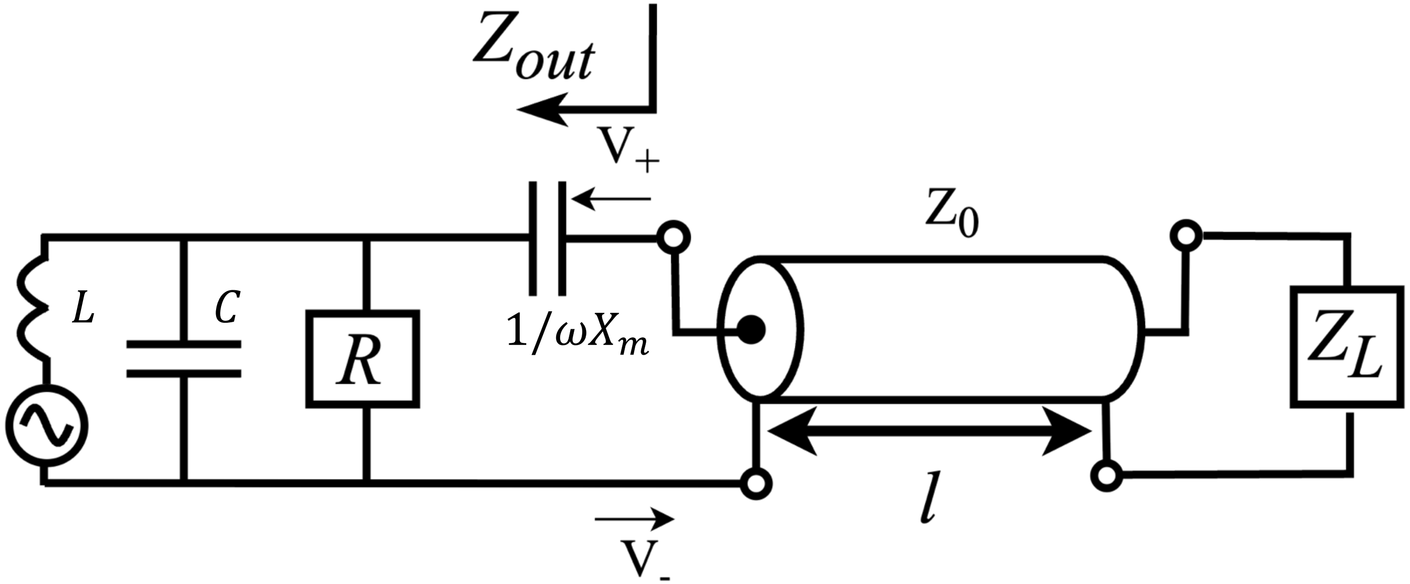






- Polarized NMR target:
  - Hyper polarized Xe
    - (Spin Exchange Optical Pumping)
  - $p \sim 10\%,\ T_2 \approx 300\ s$
- RF chain characterization by Y-factor method
  - T_{sys}: 25.5K, Gain: 78-80 dB

CASPEr-HF: Readout Signal Estimation



$$P_{out} = |V_s|^2 \frac{Z_L}{|Z_{out} + Z_L|^2} \approx \frac{|V_s|^2}{4Z_0}$$

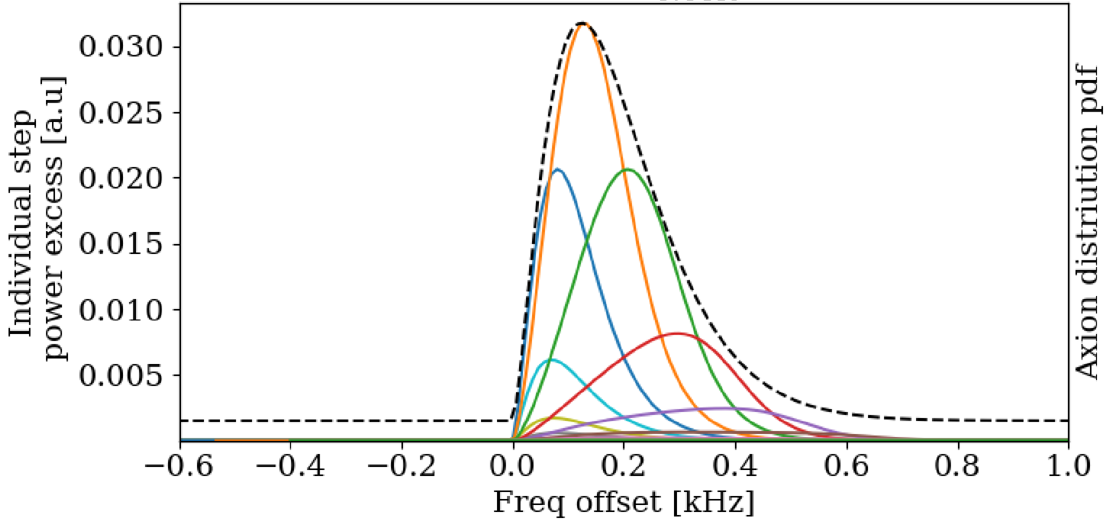
- $P_{out} = N^2 \omega_0 \phi^2 \frac{Q}{4L}$
- ϕ: Flux at pickup loop
- $N = 2, Q \approx 100, \omega_0/2\pi \approx 0.1GHz$
- $L = 210nH$

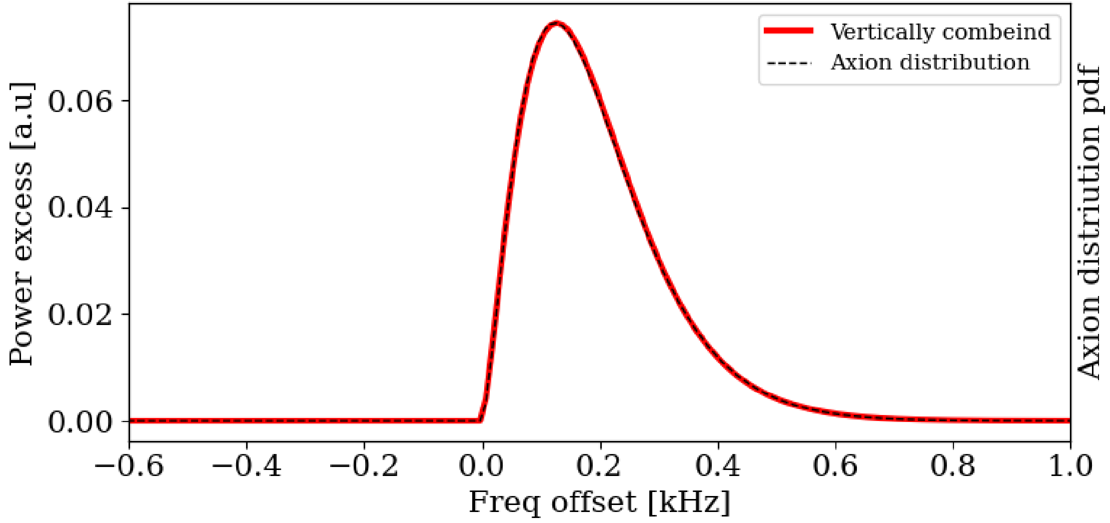
- Tune/match circuit: $Z_{out}(\omega_0) = Z_0$
- $V_s = V_+ - V_- = iN\omega_0\phi \frac{\left(\frac{1}{R}+i\omega C\right)^{-1}}{i\omega L+\left(\frac{1}{R}+i\omega C\right)^{-1}} \approx iN\omega_0\phi\sqrt{\frac{QZ_0}{\omega_0 L}},$
- N: turn number, Q: circuit Q factor

J Miller et al., 2000

CASPEr-HF: Expected Signal

$\Delta\nu_{NMR}$: 2ppm ($Q = 5 \times 10^5$)





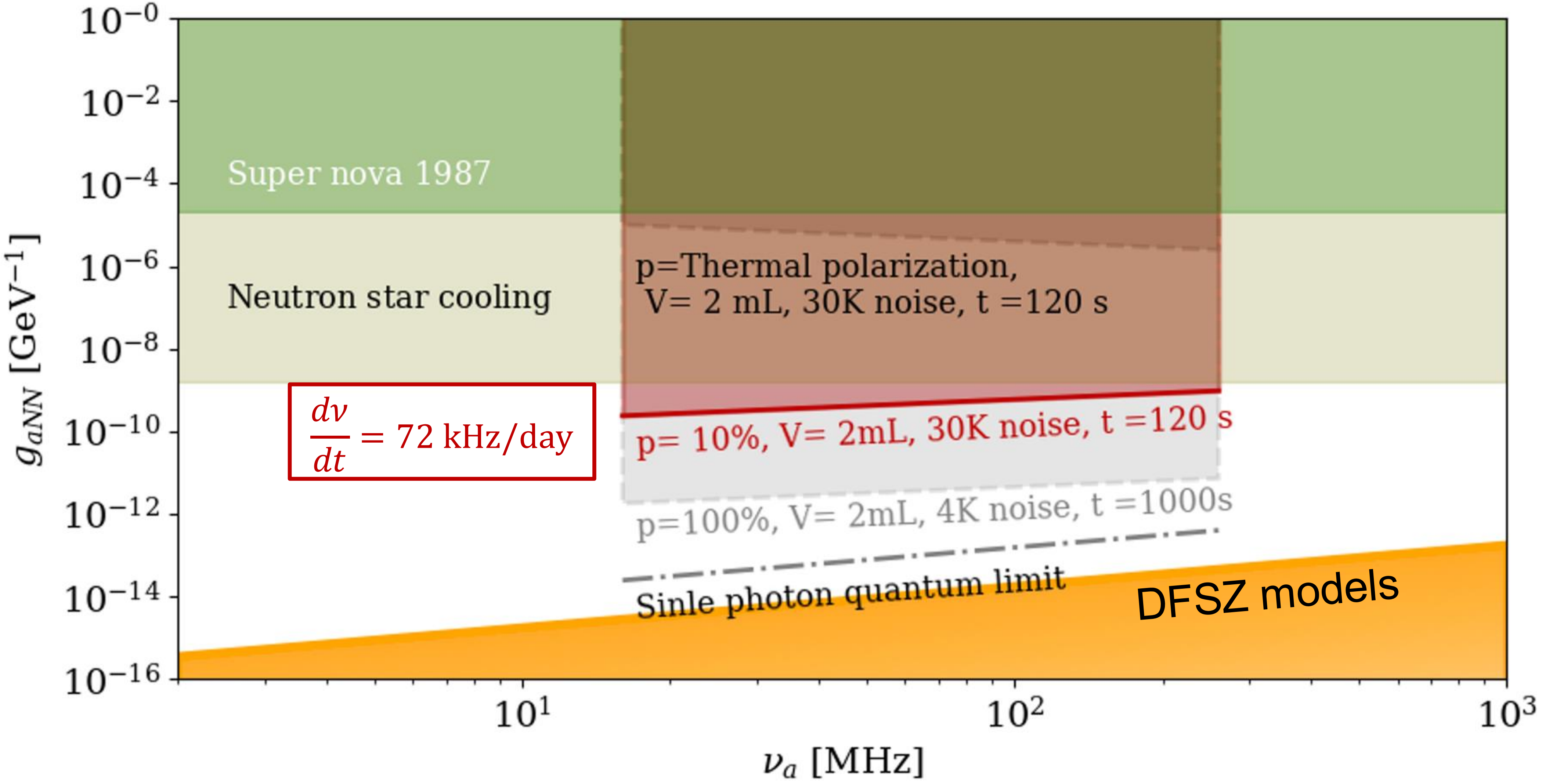
Axion rest mass: Freq offset =0
Each color: Different Larmor(tuning) frequency
(different bias field)

After combined each response in different tuning step(red)
Exactly followed axion own distribution

$$P_{sig} = 5 \times 10^{-23} W \left(\frac{g_{aNN}}{1\times10^{-9} GeV^{-1}}\right)^2 \left(\frac{n_s}{10^{22} cm^{-3}}\right)^2 \left(\frac{p}{0.05}\right)^2 \left(\frac{Q_a}{10^6}\right) \left(\frac{Q_{pickup}}{100}\right) \left(\frac{L}{210nH}\right) \left(\frac{T}{120[s]}\right)$$

Spectral factor(Max[$n^2(\omega)$]) :≈ 0.56

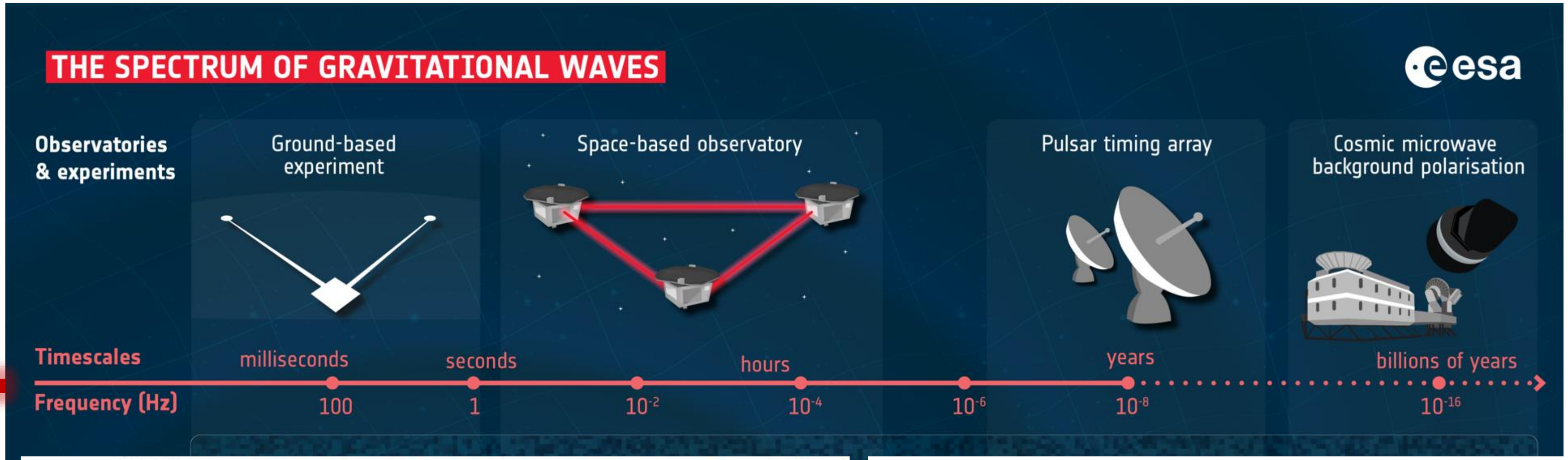
CASPEr-HF: Projected Sensitivity

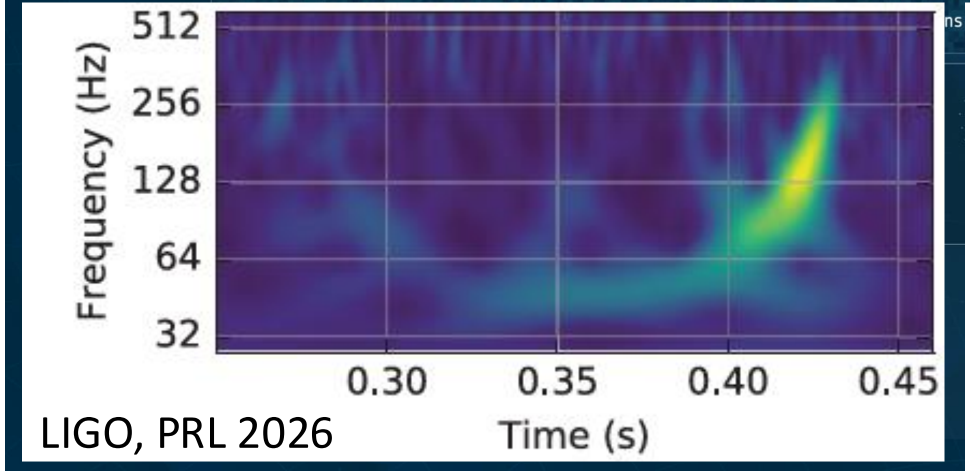


High Frequency Gravitational Waves search using RF cavity

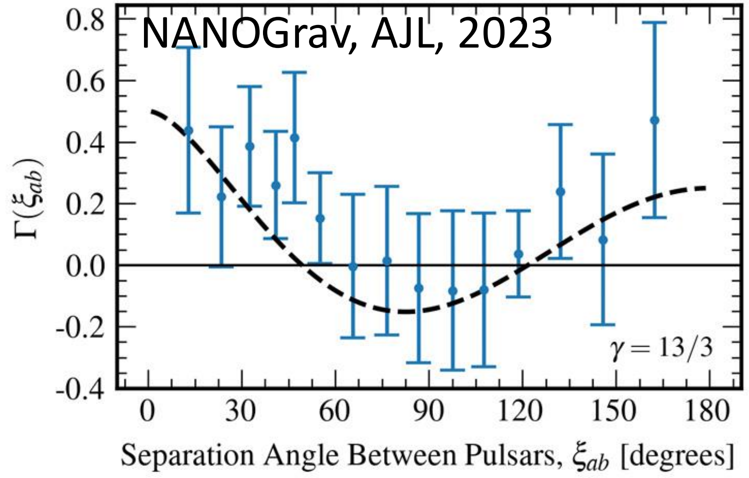
Motivation on HFGW

?





LIGO, PRL 2026



NANOGrav, AJL, 2023

- Largely unexplored GW band
- Access to early-Universe and dark sector physics

HFGW Sources & Detection

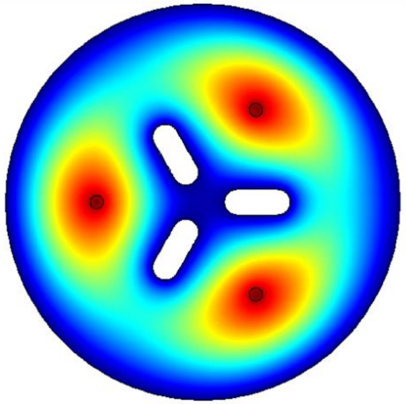
- HFGW sources:
  - Primary blackhole merger
  - Black hole superradiance (w. axion cloud)
  - Cosmic string radiation
  - …
- Detection:
  - Inverse Gerhenstein effect
  - Resonant cavity+ SC magnet + Quantum readout
  - Synchronize data by network

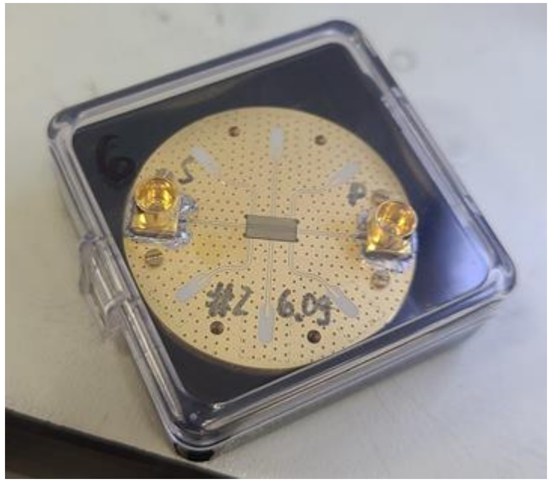
Re-analysis of existing data

- Consider monochromatic GW signal
- Main source of consideration:
  - Blackhole superradiance
- Physical feature of Blackhole superradiance signal ($a + a \to h$):
  - Monochromatic
  - $f_{GW} = 2f_a$
  - Coherent until duration time τ_c
- Signal power:
  - $P_{sig}(\beta) = \frac{b}{1+b} \frac{\omega_g h_0^2}{2\mu_0} \langle B_0^2 \rangle Q_l C_{GW}(\beta) V$

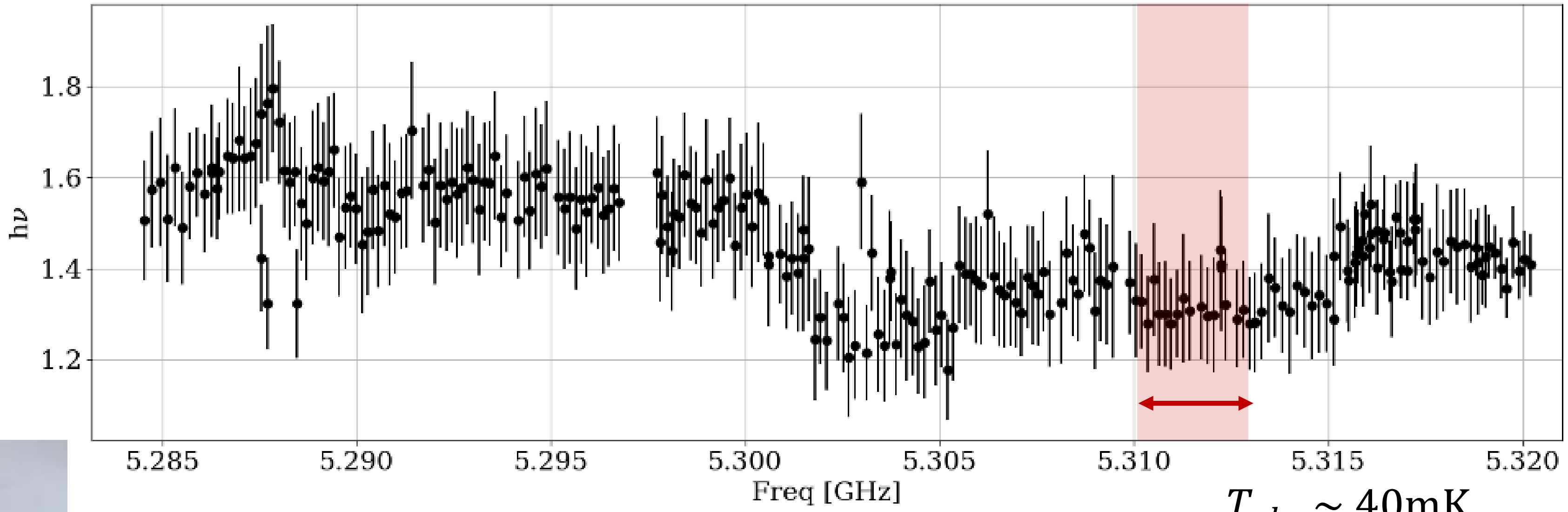
Y. Kim et al., ArXiv:2511.17817

Re-analysis Axion Data





GW analysis region



$T_{phy} \sim 40\text{mK}$

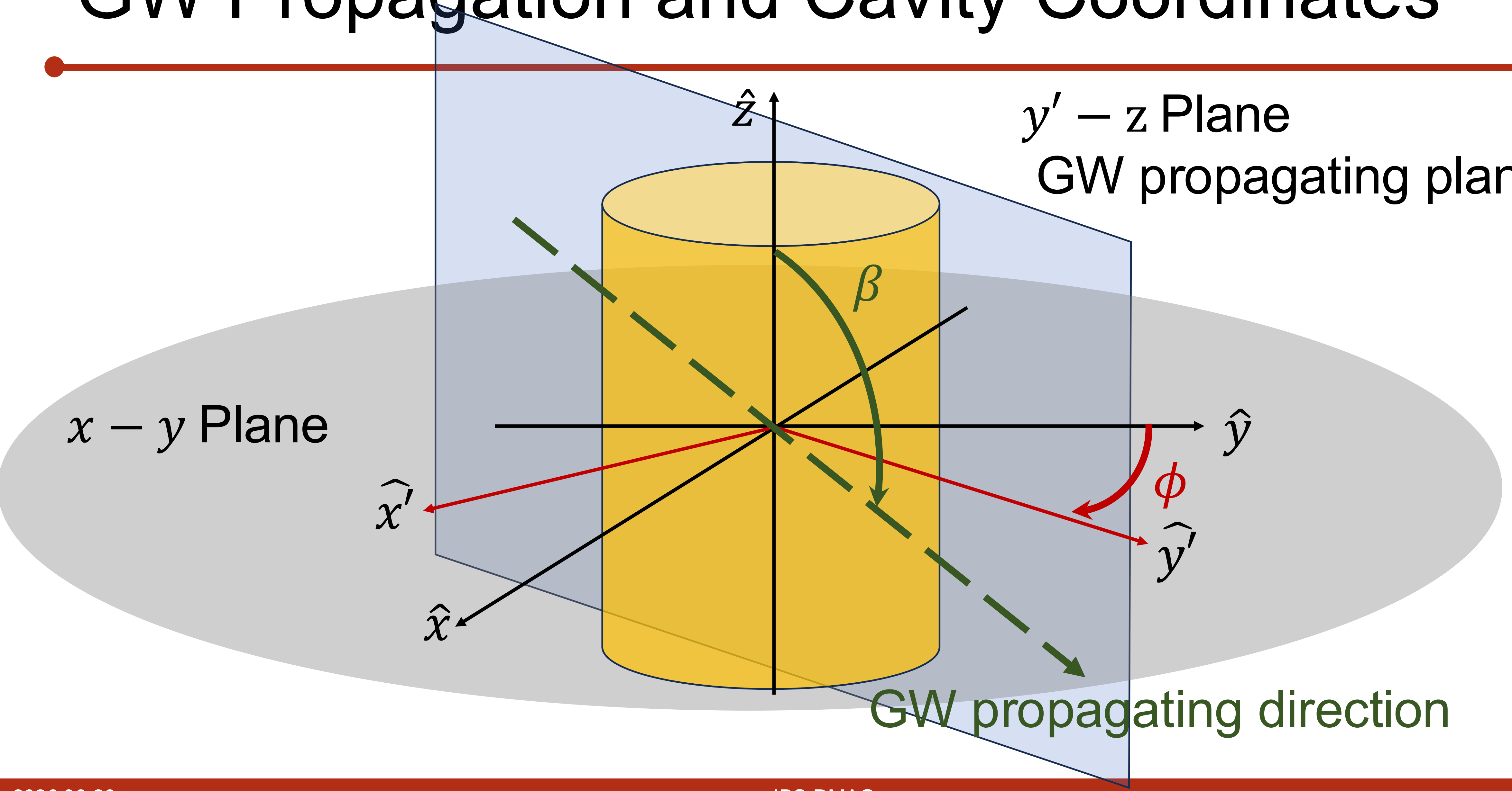
Original data: CAPP-12T MC [Y. Kim, J. Jeong et al., 2024]

Sensitivity: ~0.9KSVZ (5.3 GHz)

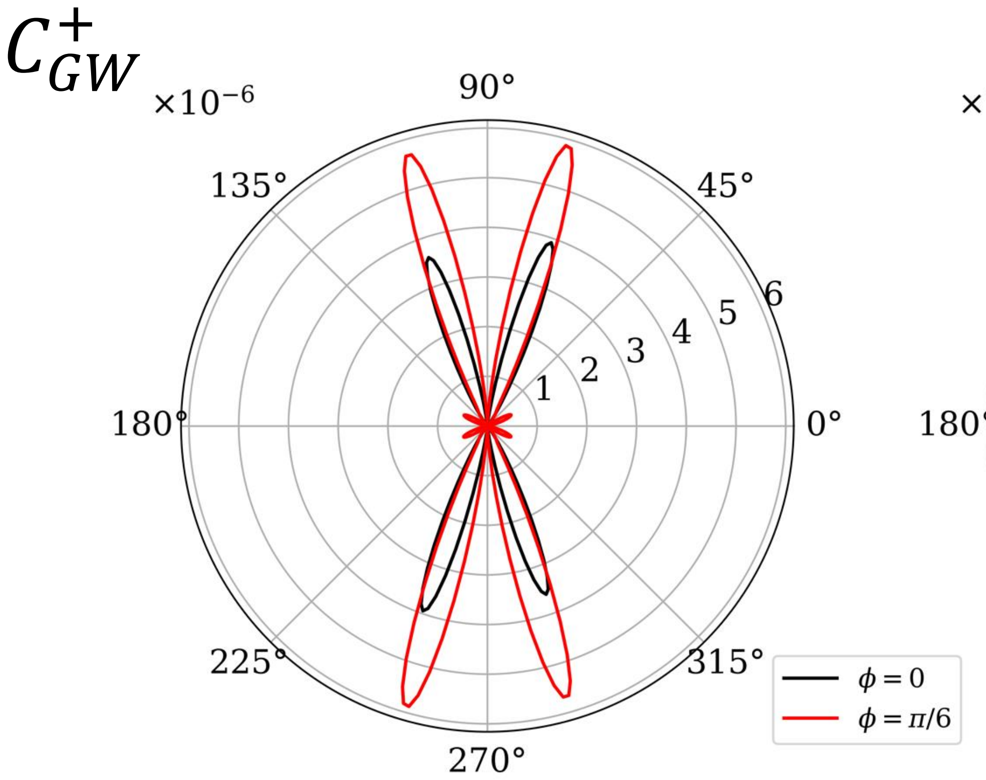
Readout: Flux driven JPA

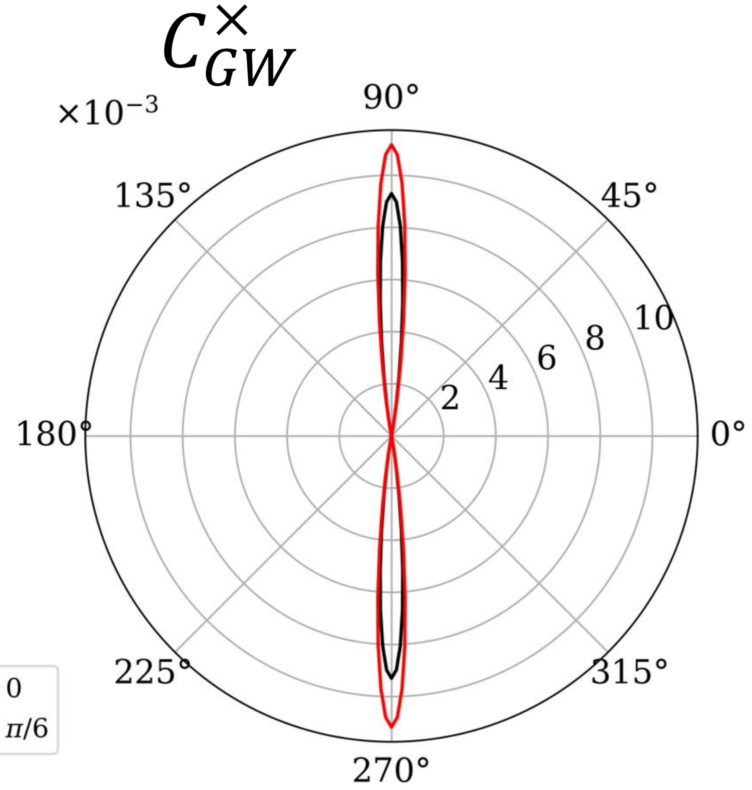
Freq: 5.31—5.32GHz → $T_{sys} \sim 1.3 \times h\nu = 350\,mK$

GW Propagation and Cavity Coordinates



GW Couplings

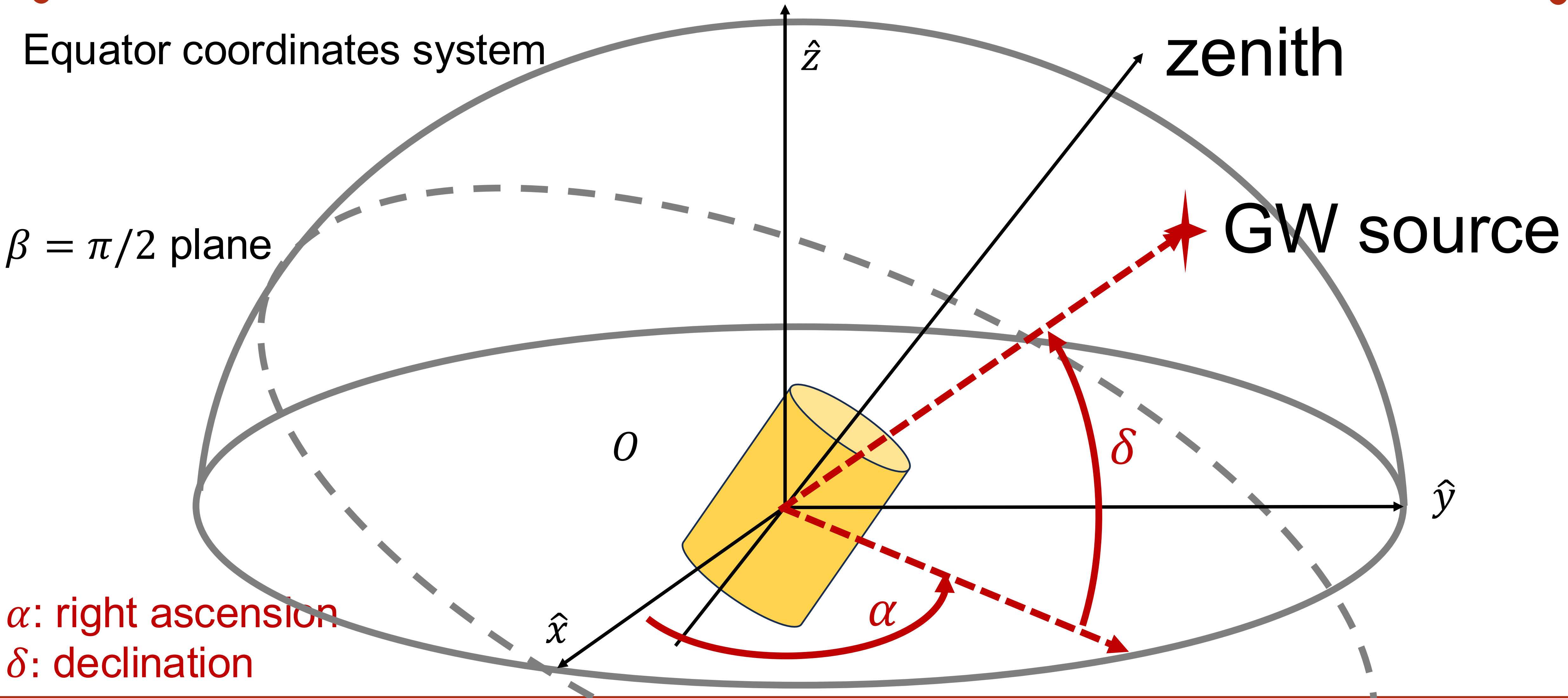




- More sensitive to cross polarization
- Weak coupling: Big aspect ratio (contrast to axion haloscope)

Sky-map Coordinates

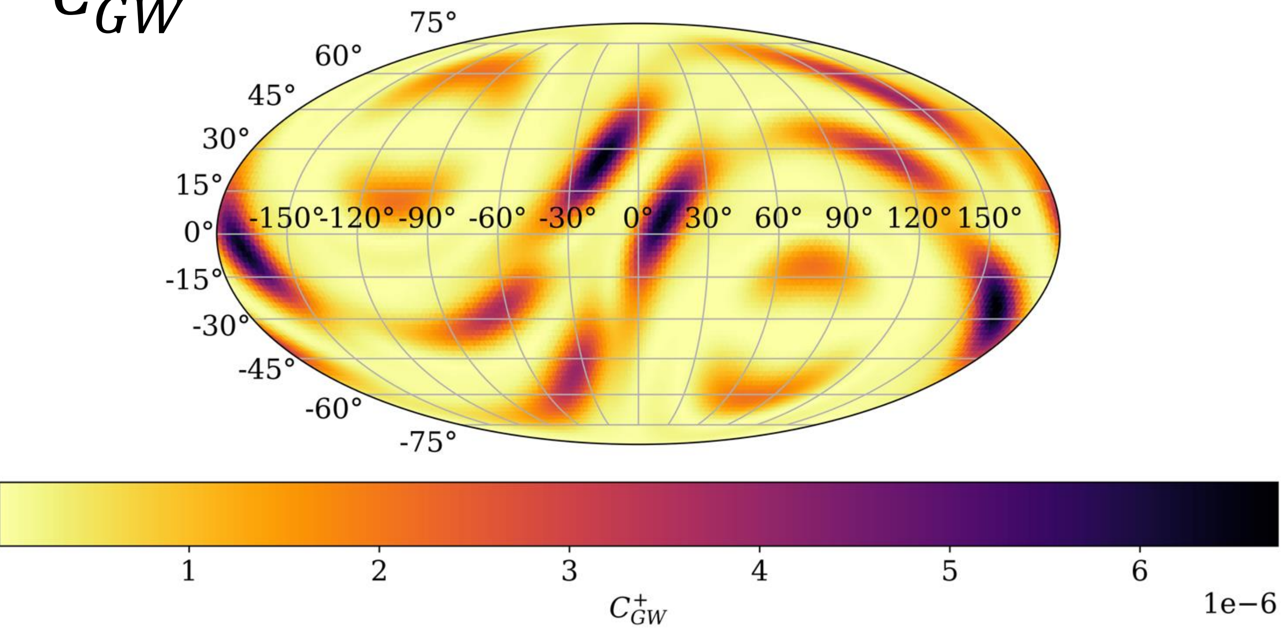
Equator coordinates system



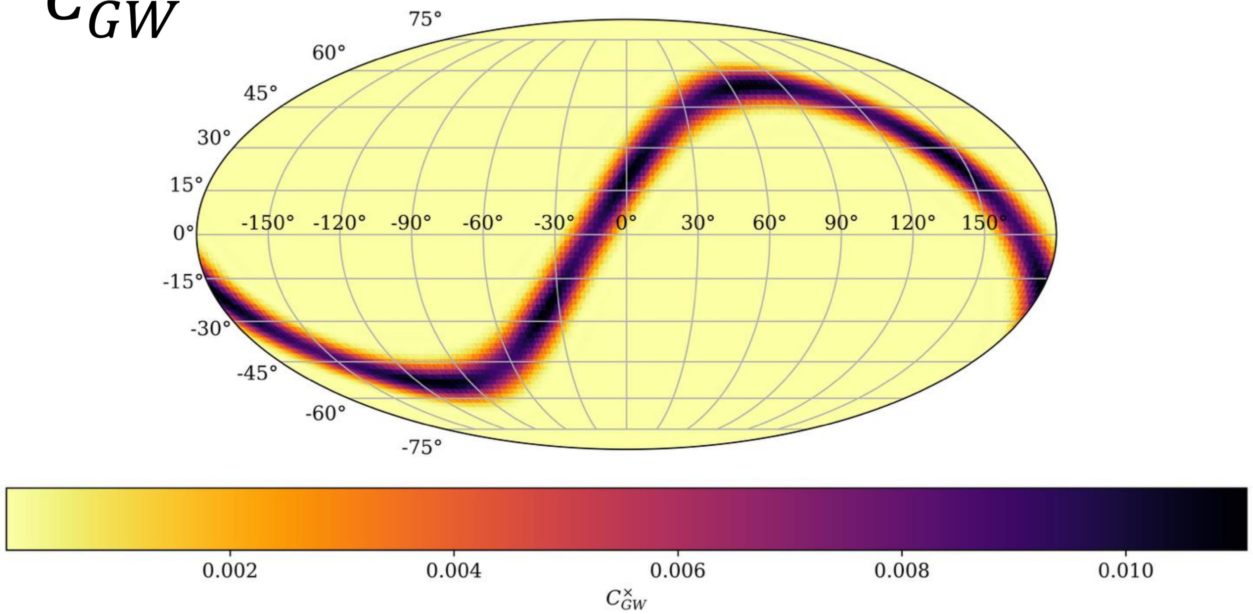
α: right ascension
δ: declination

GW Couplings

C_{GW}^{+}



$C_{GW}^{\times}$

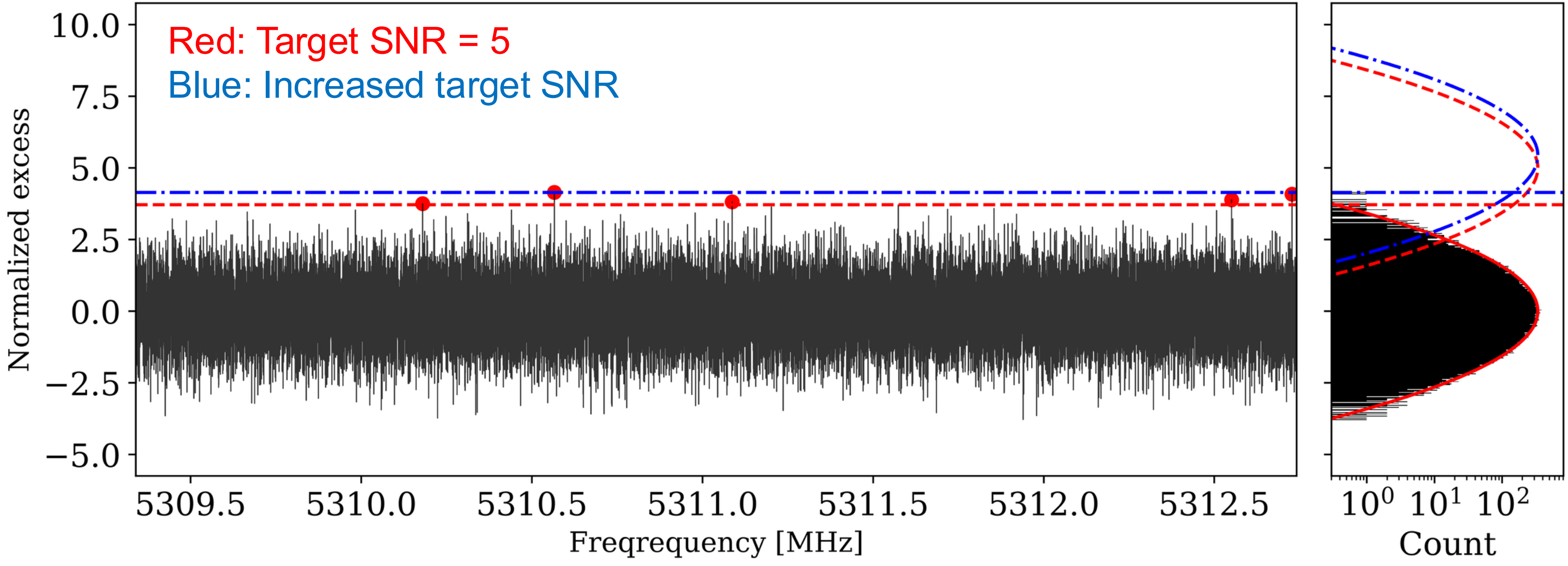


Y. Kim et al., ArXiv:2511.17817

Location: Daejeon
Time: 9:00AM

Sensitivity

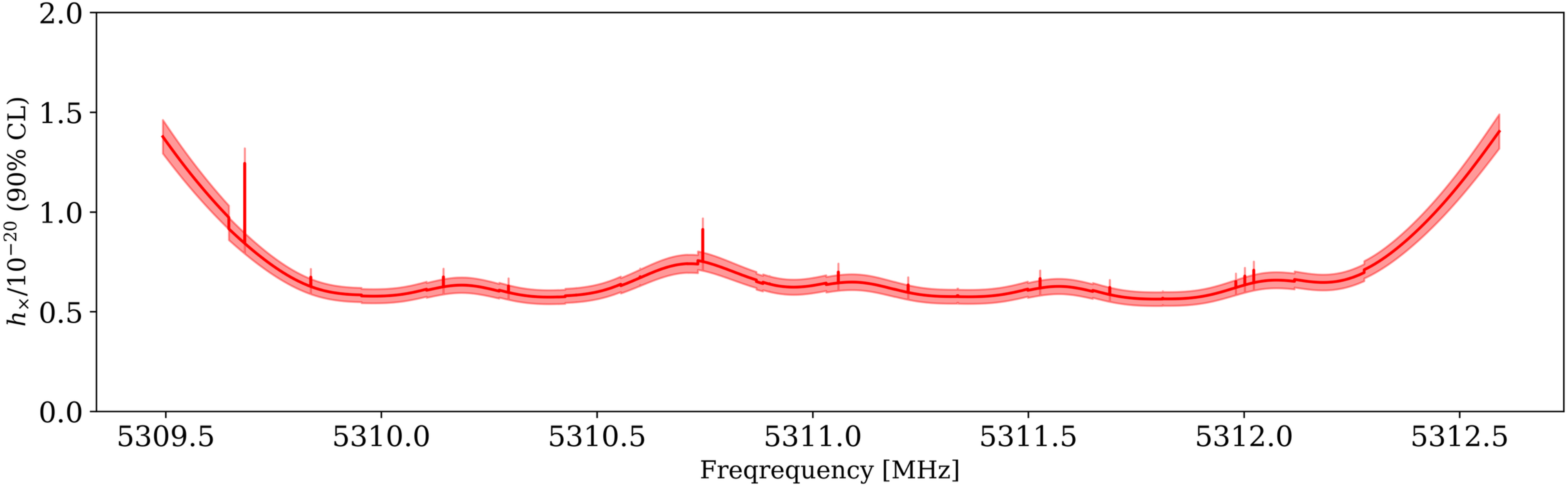
GW source direction: $(\alpha, \delta) = (0, 0)$ in equatorial coordinates



Y. Kim et al., ArXiv:2511.17817

Sensitivity

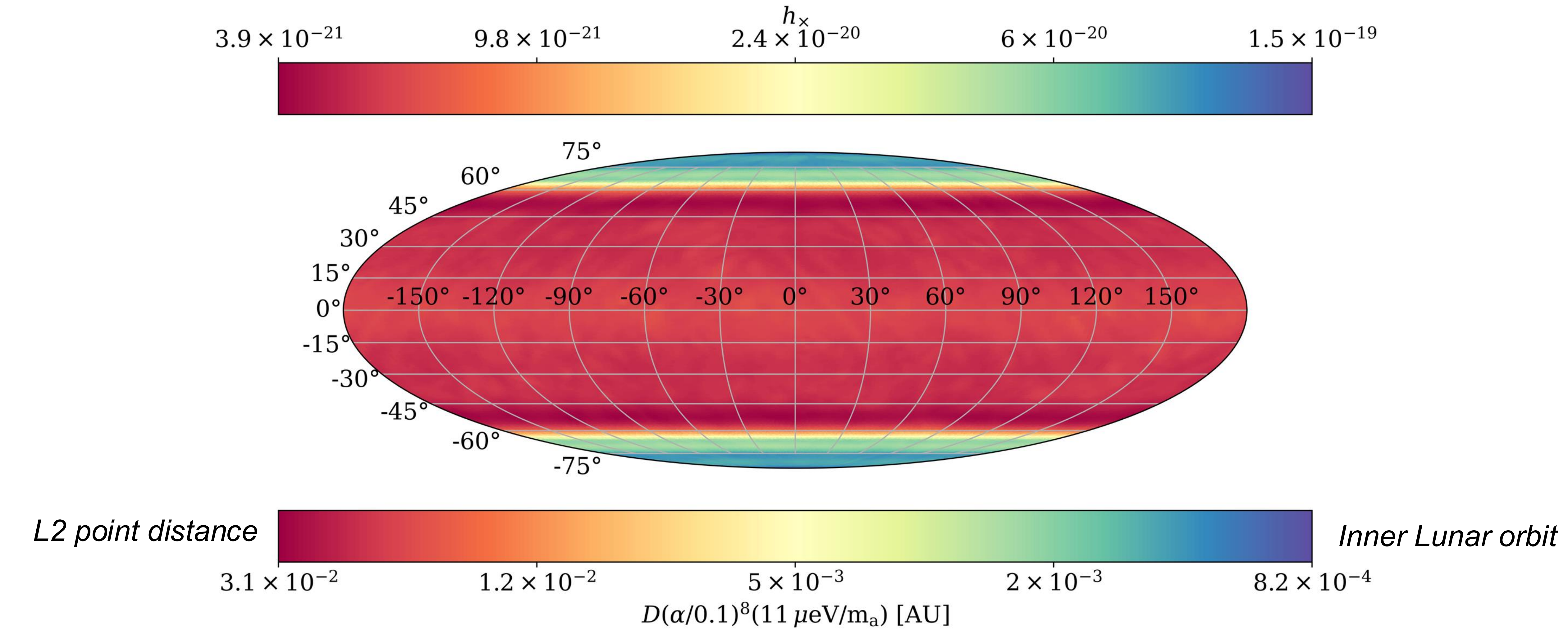
GW source direction: $(\alpha, \delta) = (0, 0)$ in equatorial coordinates



Error budget: $\delta T_{sys} = 8.8\%, \delta C = 7.6\%, \delta b = 1.6\%\ \delta Q = 0.7\% \rightarrow 6.0\%$

Y. Kim et al., ArXiv:2511.17817

Sensitivity for all direction



Y. Kim et al., ArXiv:2511.17817

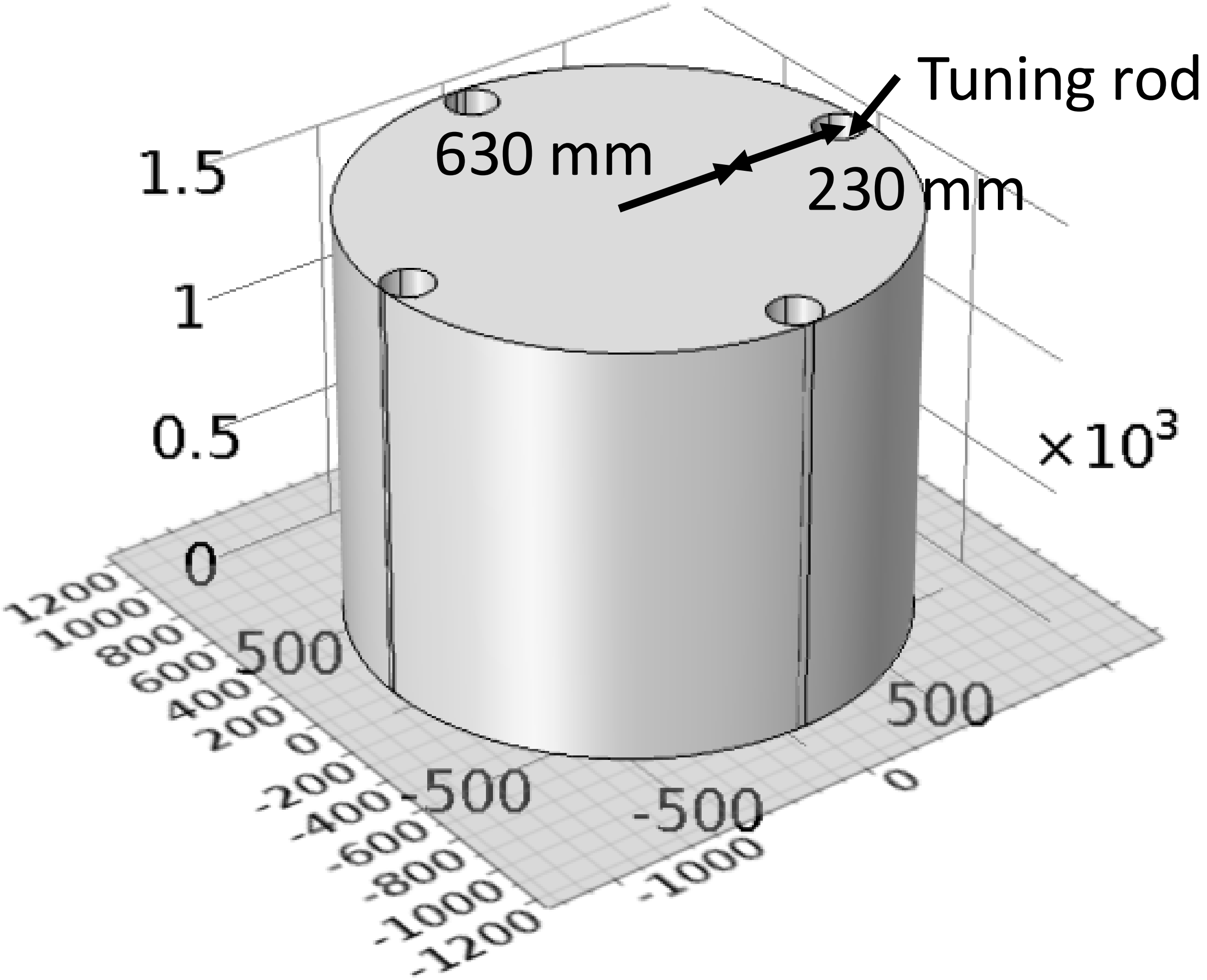
Status on GravNet

GravNet

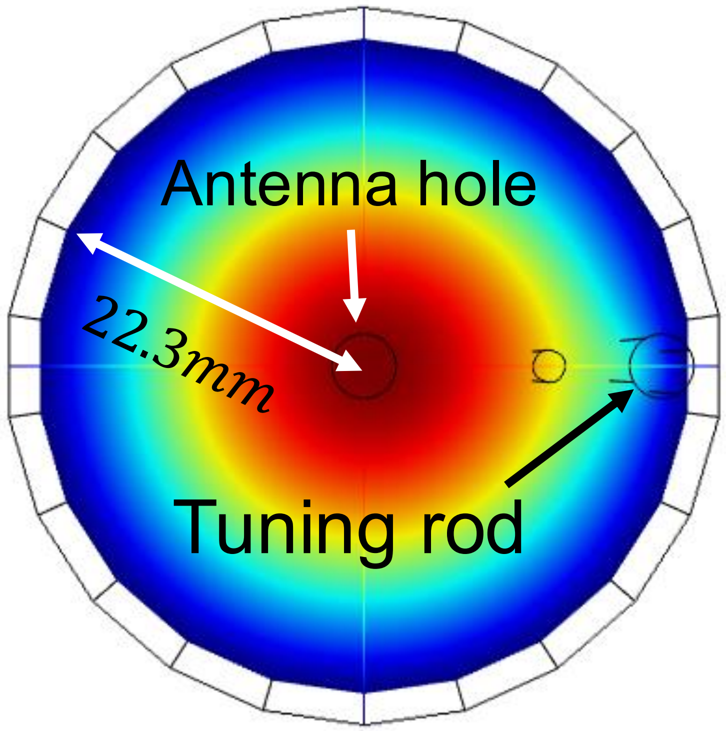
- Global detector network to search high-frequency gravitational waves
  - Extend GW observation range > kHz
- Physics target:
  - Characteristic strain: $h_0 < 10^{-21}$ ($P_{sig} < 1.5 \times 10^{-24}$ W)
  - Blackhole superradiance
  - PBH merger ($M_{PBH} < 10^{-12} M_{\odot}$) within solar system scale ($d < 1$ AU)
- Detectors:
  - Mainz ($49.99°$N, $8.25°$E): 5GHz, B_0=12T, $T_{sys} \sim 340\ mK$
  - Bonn ($50.74°$N, $7.10°$E): 5 GHz, B_0=12T, $T_{sys} \sim 340\ mK$
  - Frascati ($41.81°$N, $12.68°$E): 9 GHz, B_0=9 T, $T_{sys} \sim 740\ mK$ / 120 MHz (FLASH), $B_0 = 1.1$ T, $T_{sys} = 2$ K
- Network operation: $\mathrm{SNR} \propto \sqrt{N_{station}}$

Status on RF cavity development

Low frequency cavity (~ 100MHz) / FLASH



High frequency cavity (>GHz)



Radius: 22.3 mm, Height: 178 mm

Status on RF cavity development

Mode	Freq[MHz]	Q-factor	FOM1 $(Max(C_\times)Q)$	FOM1 $(Max(C_+)Q)$	FOM2 $(Q\langle C_\times\rangle)$	FOM2 $(Q\langle C_+\rangle)$
TM010	129	2.49×10^5	6.10×10^4	7.08×10^{-4}	$\mathbf{3.07\times10^4}$	2.43×10^{-4}
TE211	190.1	2.02×10^5	3.15×10^3	3.64×10^4	7.45×10^2	$\mathbf{1.01\times10^4}$
TM110	203.9	3.18×10^5	1.01×10^5	4.45×10^{-3}	$\mathbf{1.84\times10^4}$	7.76×10^{-4}
TE011	218.3	4.36×10^5	1.75×10^1	4.99×10^4	3.84	$\mathbf{2.37\times10^4}$

Mode	Freq[GHz]	Q-factor	FOM1 $(Max(C_\times)Q)$	FOM1 $(Max(C_+)Q)$	FOM2 $(Q\langle C_\times\rangle)$	FOM2 $(Q\langle C_+\rangle)$
TE111	4.0190	44790	3.814	**17267.212**	0.634	**2476.452**
TE112	4.2716	48938	11.032	10178.607	1.844	**2108.351**
TM010	5.1190	57183	**15677.098**	0.042	**1554.747**	0.007
TM011	5.1864	52277	7298.92	292.605	1095.541	18.694

Conclusion

- Spin-based dark matter axion detection provides a complementary approach beyond cavity haloscopes
- **CASPEr-gradient** targets spin-based axion detection below 600 MHz
  - High field at ~O(100) MHz is under development
  - Target sensitivity: *Exceeding current astrophysical limit* (neutron star)
- Cavity haloscope techniques can be also extended to search for HFGWs
- We carried out the *first cavity haloscope reanalysis* targeting monochromatic HFGWs from BH superradiance
- **GravNet, a** networked HFGW detection platform, is under development

Thank you!

Deutsche Forschungsgemeinschaft

COSMIC WISPERS CA21106

Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

National Science Foundation

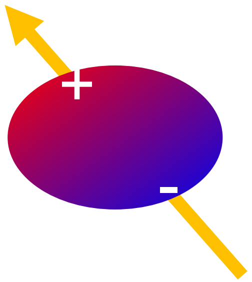
UNTERSTÜTZT VON / SUPPORTED BY Alexander von HUMBOLDT STIFTUNG

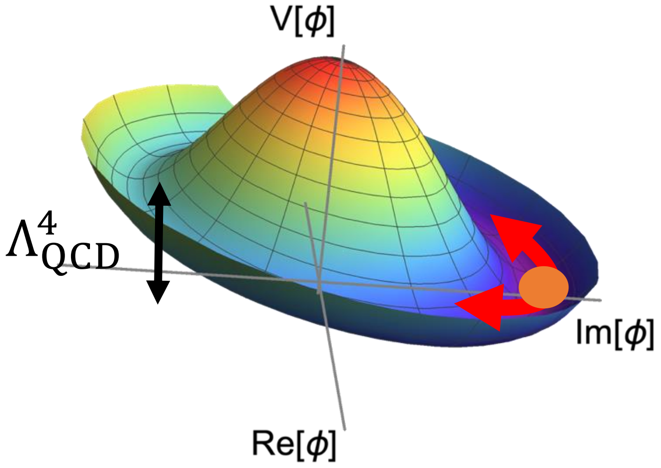
European Research Council Established by the European Commission

Strong CP problem and axion

- Neutron Electric Dipole Moment (nEDM):
  - Standard Model calculation: $d_n = 3 \times 10^{-16}\ \bar{\theta}_{QCD}\ [e \cdot cm]$
  - Expect: $\bar{\theta}_{QCD} \approx O(1)$
  - $d_n < 1.8 \times 10^{-26}\ \mathrm{e \cdot cm}:\ \ \bar{\theta}_{QCD} < 10^{-10}$ [1]
  - Unnatural small $\bar{\theta}_{QCD}$: Strong CP problem
- Peccei-Quinn proposed global $U(1)_{PQ}$ symmetry to solve the Strong CP problem [2],
  - Minimizing solution is $\theta_{eff} \equiv \bar{\theta}_{QCD} + \frac{\langle a \rangle}{f_a} = 0$
- QCD axion as Cold dark matter candidate:
  - Astrophysical observations and cosmological scenario

  $\rightarrow 1\ \mu\mathrm{eV} < m_a < 10\ \mathrm{meV}$ [3]

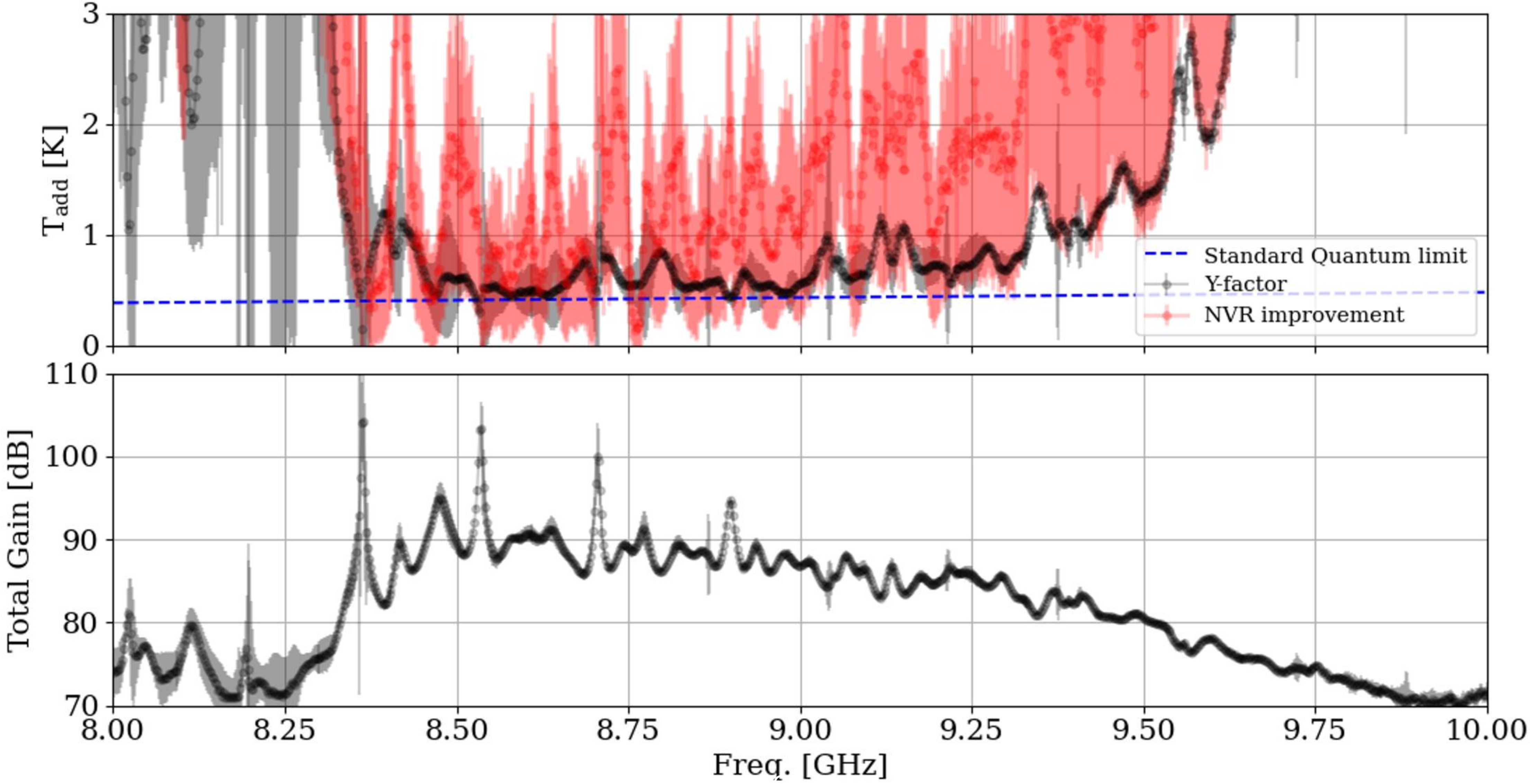




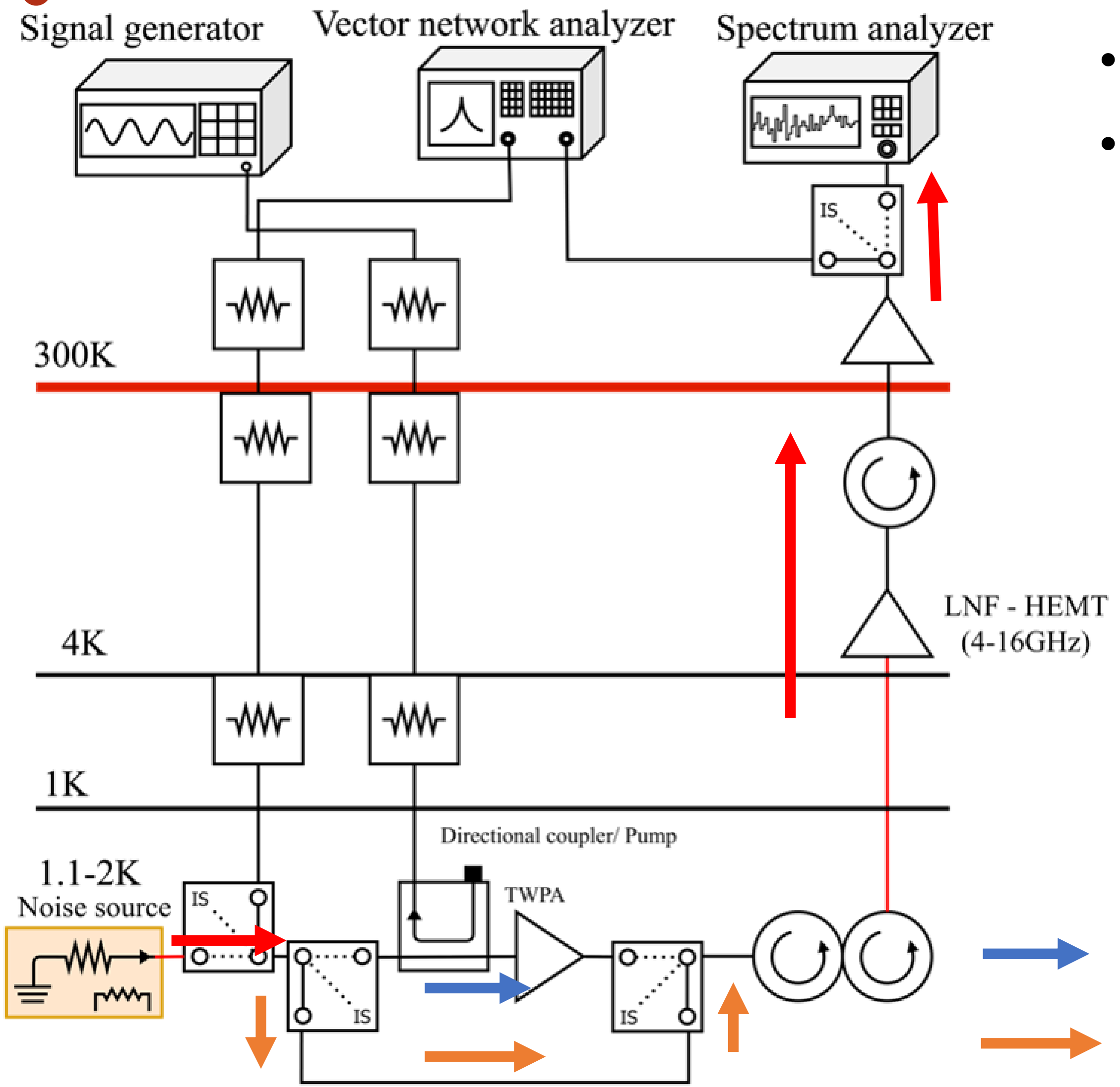
$\bar{\theta}_{QCD} \equiv \theta_{QCD} + \mathrm{Det}(\mathrm{Arg}\ M_q)$

[1] C. Abel et al., 2020.
[2] R. D. Peccei and H. R. Quinn, 1977.
[3] P. Sikivie, 1983

Broadband amplifier (TWPA)



TWPA noise measurement



- Using SNR improvement method & Y- factor method
- SNR improvement method:
  - Estimate noise temperature of amplifier by measuring spectrum enhance on/off the amplifier
  - Noise visibility ratio (NVR):

$$NVR = \frac{Spectrum_{on}}{Spectrum_{off}} = G_{TWPA}\frac{T_{eff} + T_{add}}{T_{eff} + T'_{add}}$$

$$T_{eff} = \frac{h\nu}{k_B}\left(\frac{1}{2} + \frac{1}{\exp(\frac{h\nu}{k_B T} - 1)}\right),$$

T_{add}: Added noise with TWPA

T'_{add}: Added noise without TWPA (by pass line)

TWPA line

By pass line (off)