Наши разные разговоры,

Наши песенки вперебой.

Нижний Новгород, Дятловы Горы,

Ночью сумрак чуть-чуть голубой.

((с) БК)

Friendly, heated long presentations,

Virtuoso guitar, endless songs.

On Dyatlov Hills Niznii Novgorod lies

Amazed by Universe in a blue sky

Axion dark matter search: The final frontier

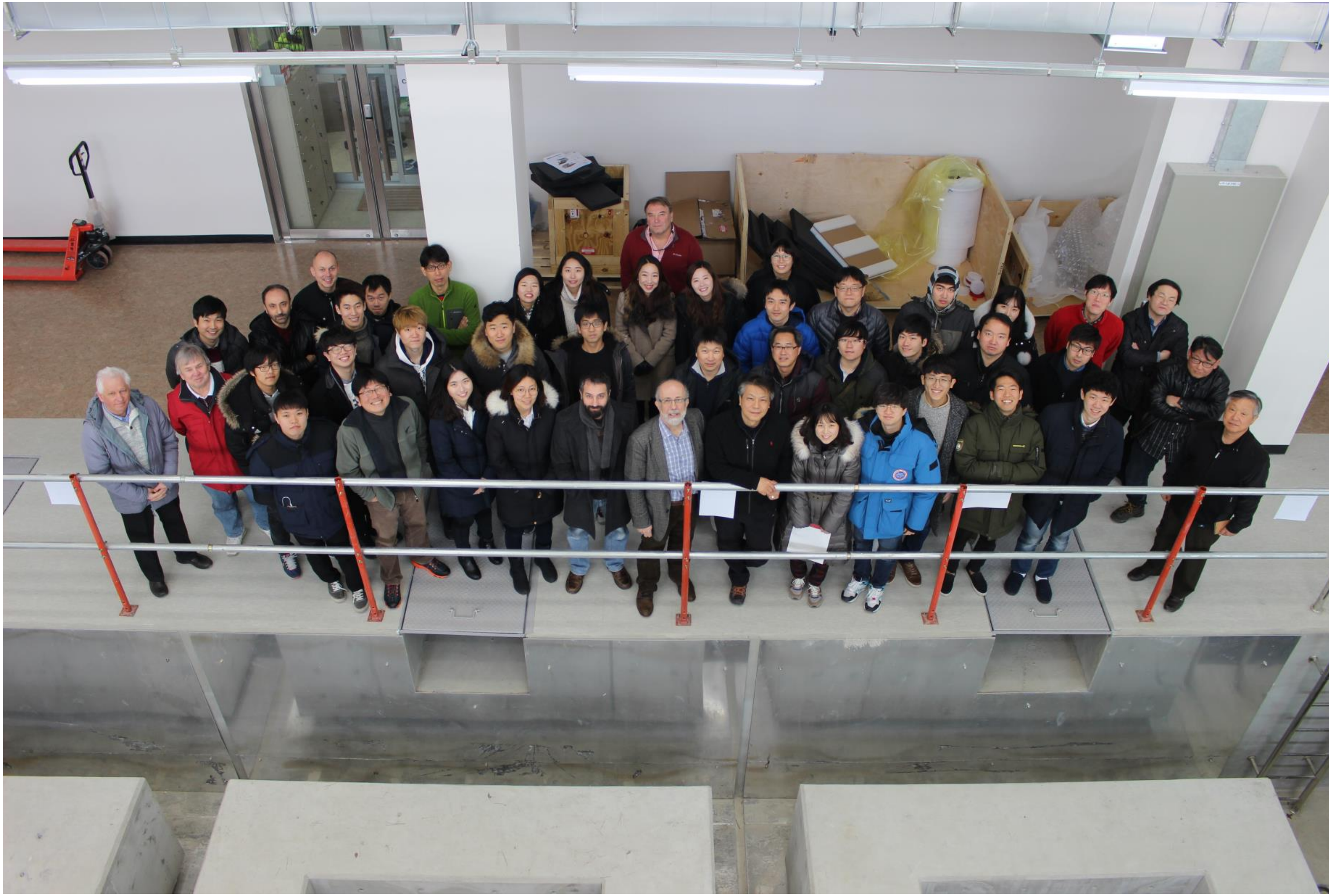
Yannis Semertzidis (CAPP)
Kolya Nikolaev (Landau Institute)

CAPP
Center for Axion and Precision Physics Research

- Weighing the vacuum using magnets and quantum-noise limited RF amplifiers!
- The technology is here to make decisive axion experiments
- Superconducting devices make the difference!
- Spin of patricles in storage rings as an axion detector
- Intimate relation to EDM & baryogenesis

LCN Workshop 13, Nizhnii Novgorod, 26 January 2019

IBS/CAPP at Munji Campus, KAIST, **January 2017**.



IBS/CAPP-Physics
(Established October 2013)

Strong CP problem (Symmetry crisis in strong forces: hadronic EDM exp. Limits too small!)

- Cosmic Frontier (Dark Matter axions): Improve in all possible fronts: B-field, Volume, Resonator Quality factor, Physical and Electronic noise.
- Storage ring proton EDM (most sensitive hadronic EDM experiment). Improve theta_QCD sensitivity by three to four orders of magnitude!
- Together with long-range monopole-dipole (axion mediated) forces probe axion Physics!

Prelude to axions: QED in gyroscopic medium

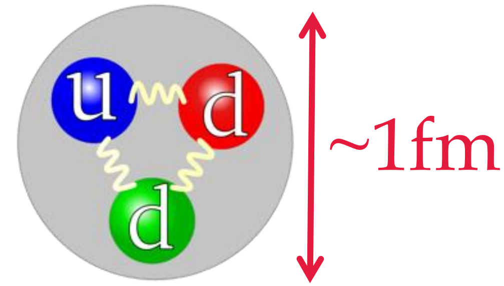
V. Mandelzweig & I. Shapiro, Sov. Phys. JETP 29 (1969) 1114 and many earlier works

- Gyrotropic medium → a nontrivial vacuum with P-violating dielectric tensor → boils down to a scalar product EB in the free field QED Lagrangian
- Familiar case of nontrivial QED vacuum: magnetoplasma
- Crucial point: P- , T-and CP-breaking mixing of the E and B fields
- **T-**reversal violation was overlooked by Mandelzweig and Shapiro
- Straightforward extension from QED to QCD

The Strong CP-problem, Axion parameters, Dark Matter

CP-breaking EB mixing in QCD and neutron EDM

$$L_{QCD,\bar\theta} = \bar\theta \frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



Dimensional analysis (naïve) estimation of the neutron EDM:

$$d_n\left(\bar\theta\right) \sim \bar\theta \frac{e}{m_n}\frac{m_*}{\Lambda_{QCD}} \sim \bar\theta \cdot \left(6\times 10^{-17}\right)\mathrm{e}\cdot\mathrm{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

$$d_n\left(\bar\theta\right) \approx -d_p\left(\bar\theta\right) \approx 3.6\times 10^{-16}\,\bar\theta\ \mathrm{e}\cdot\mathrm{cm}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

$$\text{Exp.:}\ d_n < 3\times 10^{-26} e\cdot \mathrm{cm} \rightarrow \bar\theta < 10^{-10}$$

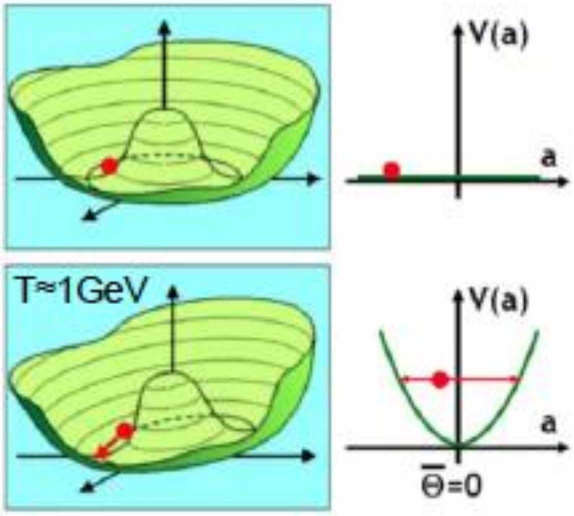
In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least ~9-10 orders of magnitude less! WHY?

Strong CP problem and axions

- Peccei-Quinn: θ_{QCD} is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally
- Wilczek and Weinberg: axion particle (1977)
- J.E. Kim: Hadronic axions (1979)
- Axions: pseudoscalars,

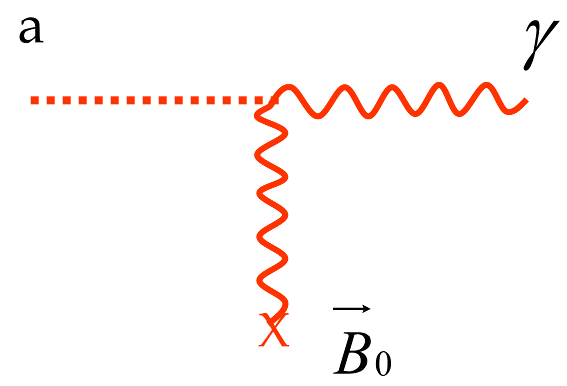
light cousins of neutral pions

$$m_a \approx 6 \times 10^{-6} \text{ eV } \frac{10^{12} \text{ GeV}}{f_a}$$

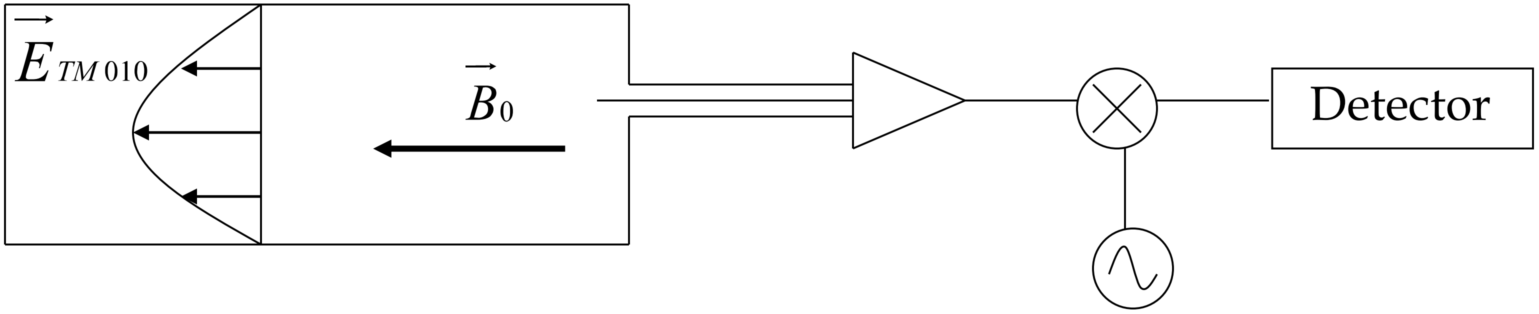


QCD induced QED signal of axions

$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



P. Sikivie: Axions convert into microwave photons in the presence of a DC magnetic field (inverse Primakov effect)

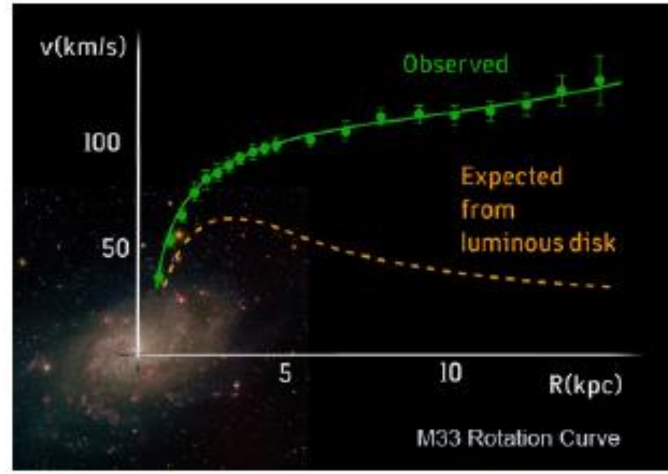


Dark Matter from Axions ?

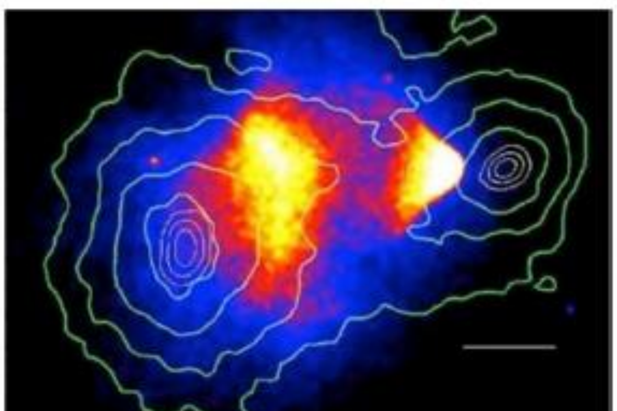
Eric Charles, Fermi-LAT collaboration

Evidence for / Salient Features of Dark Matter

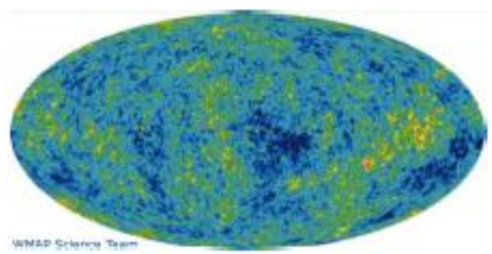
*Comprises **majority of mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)

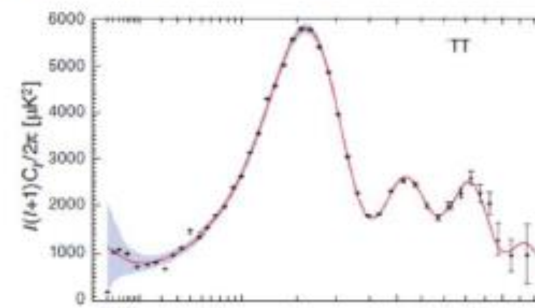


*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



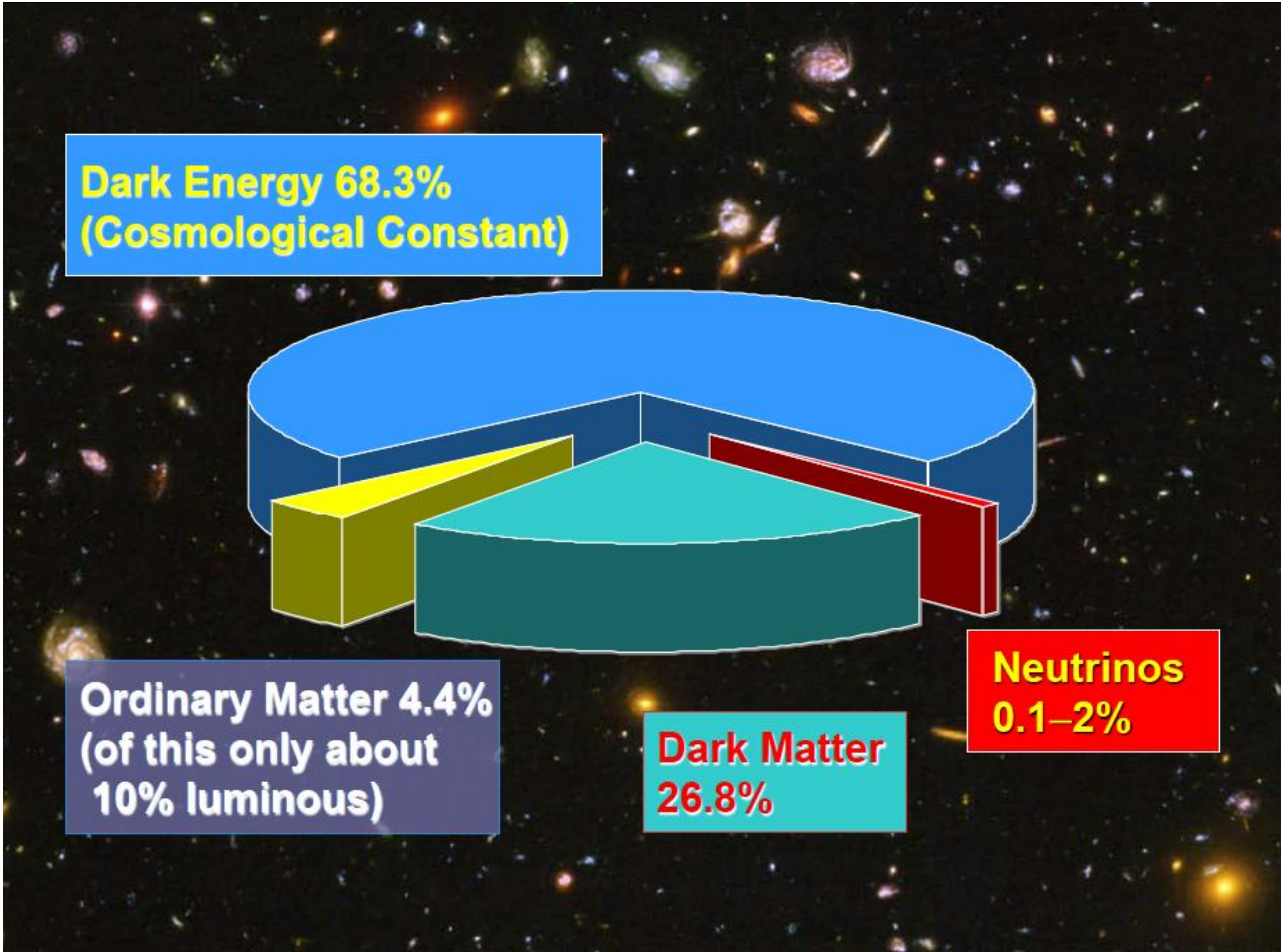
*Almost **collisionless***
Bullet Cluster
Clowe+(2006)





Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)

Cosmological inventory



Sikivie-Primakoff mechanism in a RF cavity

Axion mass is unknown - need to tune the cavity over a vast frequency range

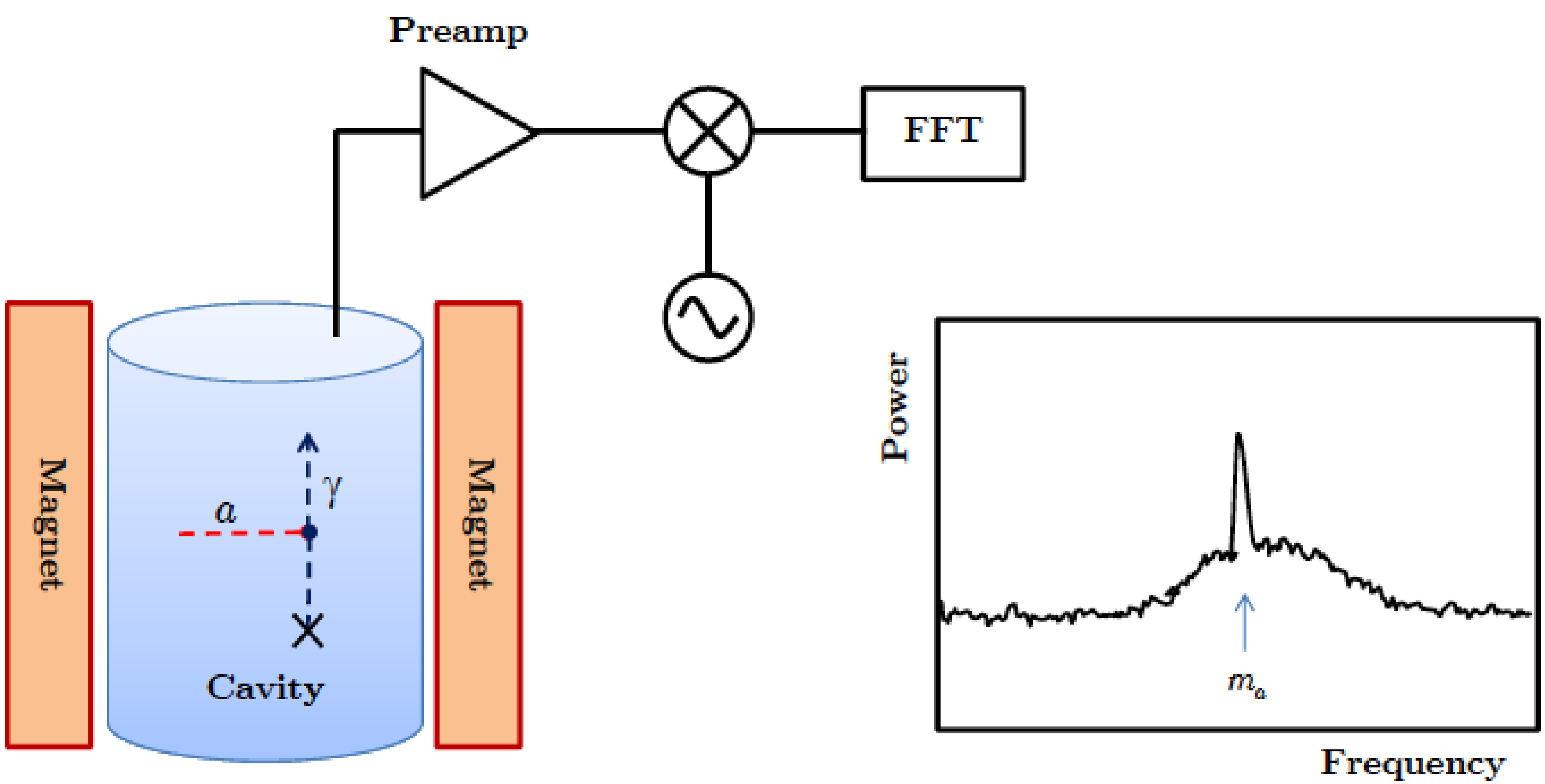


Figure 14: Conceptual arrangement of an axion haloscope. If m_a is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.

Quantum-noise limited RF-amplifiers

- Frequency of interest: 1-10 GHz first phase; 10-20 GHz second phase

- Immediate need: 2-3 GHz, 3-7 GHz

- Longer term: 1-3 GHZ, 7-10 GHz, and finally up to 20 GHz

Quantum-noise limited RF-amplifiers

- Tunable range >100MHz

- Ease of operation

- As low noise as possible

How important are the quantum noise limited amplifiers?

- Critical!
- Make or break!
- With them, we can reach theoretically interesting sensitivities. Without them, we can't.
- In other words, they mean everything!

$$a \rightarrow \gamma$$

The conversion power on resonance

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V B_0^{\,2} \rho_a C m_a^{\,-1} Q_L$$

$$= 2\cdot 10^{-22}\ \text{Watt} \left(\frac{V}{500\ \text{liter}}\right)\left(\frac{B_0}{7\ \text{Tesla}}\right)^2\left(\frac{C}{0.4}\right)$$

$$\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{5\cdot 10^{-25}\ \text{gr/cm}^3}\right)\left(\frac{m_a c^2}{h\,\text{GHz}}\right)\left(\frac{Q_L}{10^5}\right)$$

The axion to photon conversion power is very small.

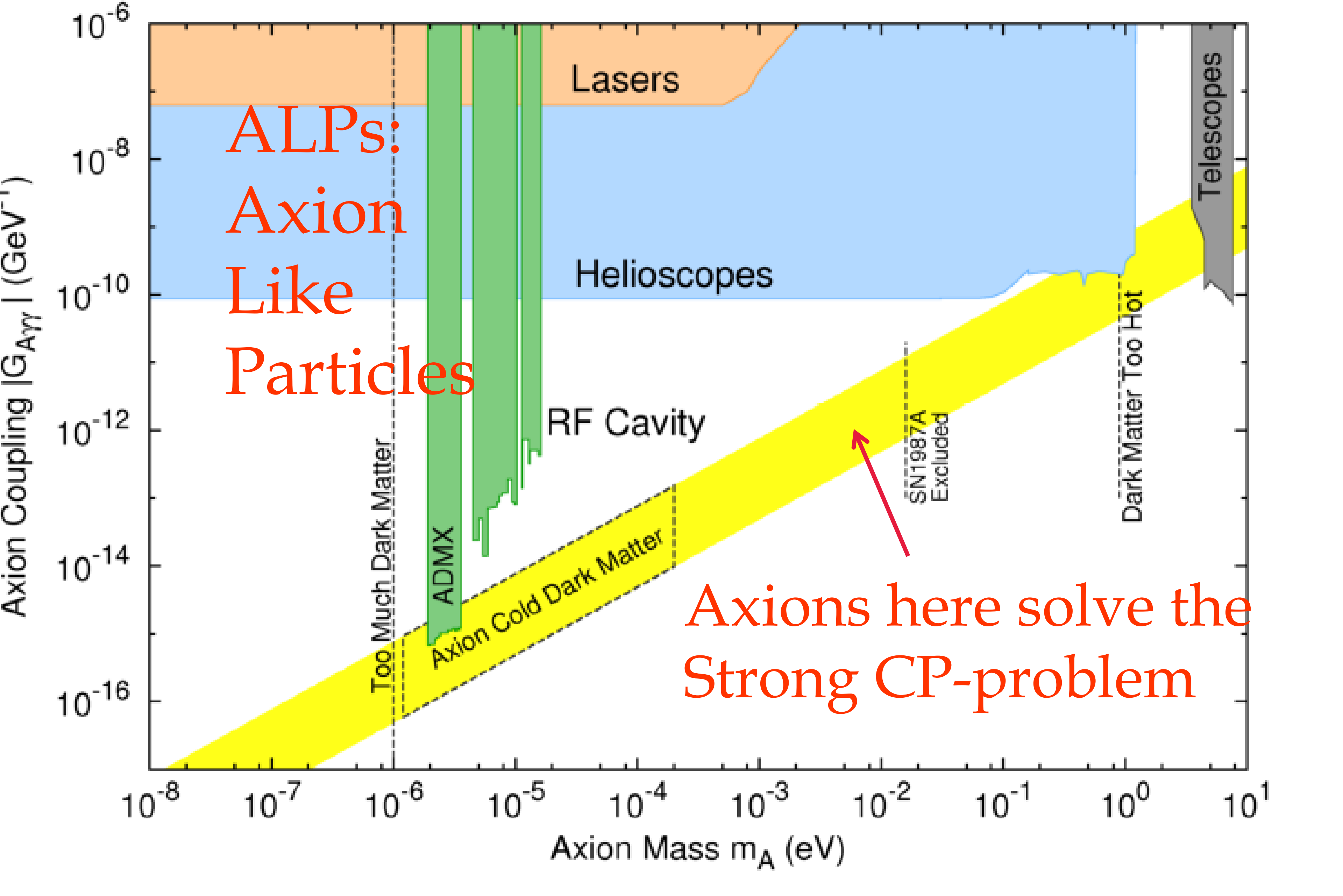
If you don't know the axion mass need to tune

Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \mathrm{GHz}}{year}\left(g_{a\gamma\gamma} 10^{15}\,\mathrm{GeV}\right)^4 \left(\frac{5\ \mathrm{GHz}}{f}\right)^2 \left(\frac{4}{SNR}\right)^2 \left(\frac{0.25\ \mathrm{K}}{T}\right)^2 \times \left(\frac{B}{25T}\right)^4 \left(\frac{c}{0.6}\right)^2 \left(\frac{V}{5l}\right)^2 \left(\frac{Q}{10^5}\right)$$

$$T = T_{\mathrm{N}} + T_{\mathrm{ph}}$$

Axion coupling vs. axion mass



How CAPP is making a difference

- Establish a facility to take immediate advantage of currently available technology
  - HTS and
  - LTS (NbTi, and Nb_3Sn) magnets

- NI-HTS, 18T, 70mm diam. Delivered Summer 2017
- NI-HTS, 25T, 100mm diam. (funding limited) delivery in 2020
- LTS (Nb_3Sn), 12T, 320mm diam. To be delivered in late 2020

CAPP's plan

- Low temperature, high quality resonators (near SC?)
- Quantum-noise limited RF-detectors (SQUIDs, JPAs)
- Single photon RF-detectors (>10GHz). (First appl. of qubits?)

CAPP's base plan

- Microwave cavities 0.7-20 GHz, using 25T/10cm and 12T/32cm magnets
- Then combine the two magnets to obtain 37T
- Phase-lock two or more axion dark matter exps.
- Open resonators R&D for higher frequency
- Wide band axion-mass network…

How CAPP is making a difference

- Establish lowest cavity temperature (<50mK)
- Develop Microstrip SQUID Amplifiers (MSAs) from KRISS, IPHT, …
- Target R&D on single photon detector (>10GHz)
- Open-resonators R&D for higher frequency (Collaboration with UW, KAIST)
- Proposal to look for transient axion to photon signals from neutron stars

How CAPP is making a difference

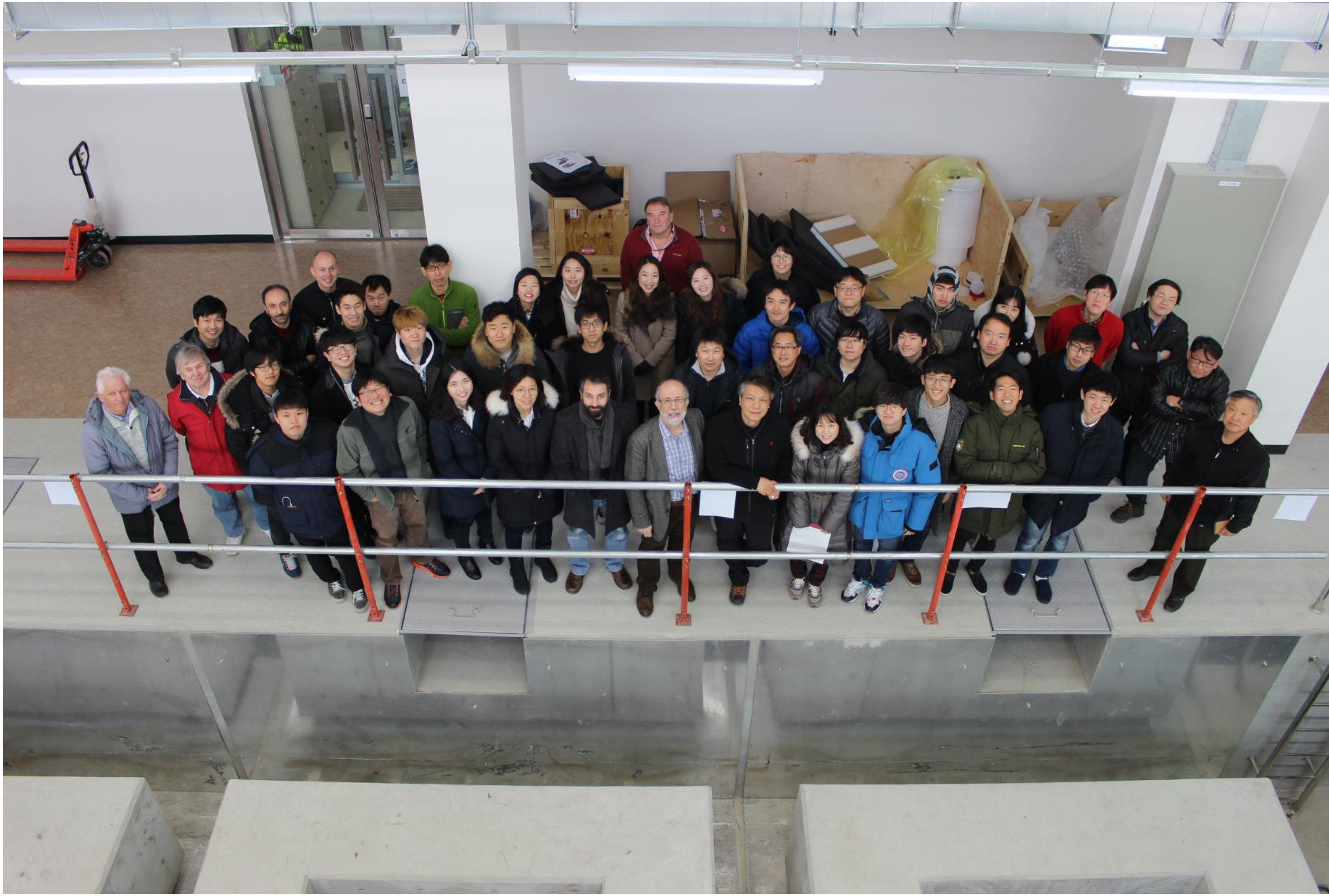
- Establish R&D to promote large BW axion scanning including:

- GNOME (axion stars, domain walls,…). CAPP is operational and reporting.

- ARIADNE (axion mediated long-range monopole-dipole interactions). Funded by NSF

Busy CAPP hall in pictures

IBS/CAPP at Munji Campus, KAIST, **January 2017**.



CAPP Experimental Hall (LVP)

Woohyun Chung's slide

CAPP experimental hall, top view

CAPP timeline

CULTASK Refrigerators and Magnets

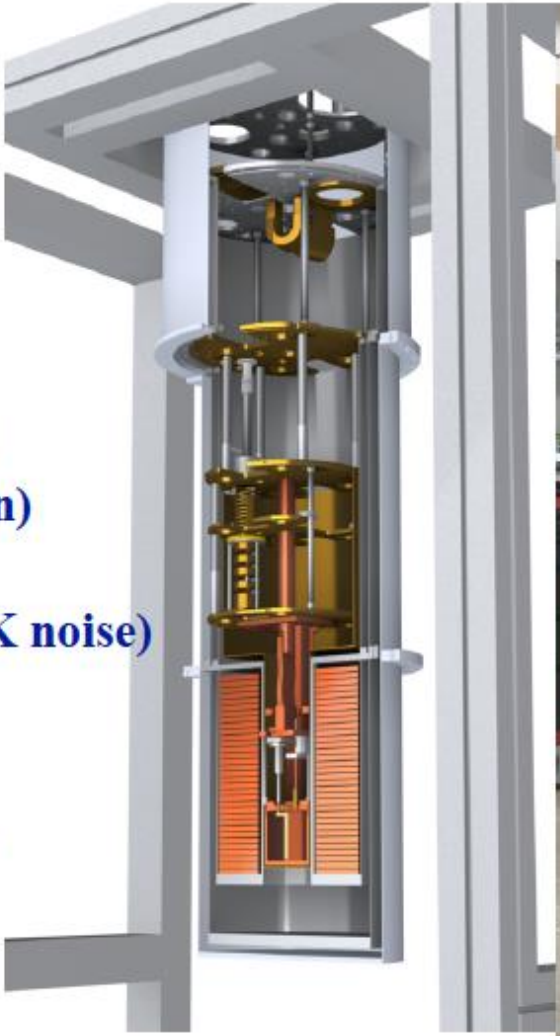
Refrigerators				
Vendor	Model	T_B (mK)	Cooling power	Installa tion
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016
BlueFors (BF4)	LD400	10	18μW@20 580μW@100	2016
Janis	HE3	300	25μW@300mK	2017
BlueFors (BF5)	**LD400**	**10**	18μW@20mK 580μW@100K	**2017**
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100K	2017
Leiden	DRS1000	100	1mW @100mK	2018
Oxford	Kelvinox	<30	400 @120mK	2017

Magnets				
B field	Bore (cm)	Material	Vendor	Delivery
26T	3.5	HTS	SUNAM	2016
18T	7	HTS	SUNAM	2017
9T	12	NbTi	Cryo-Magnetics	2017
8T	**12**	**NbTi**	**AMI**	**2016**
8T	16.5	NbTi	AMI	2017
25T	**10**	HTS	BNL/CAPP	2020
12T	**32**	Nb_3Sn	Oxford	2020

Woohyun Chung's slide

CAPP-PACE

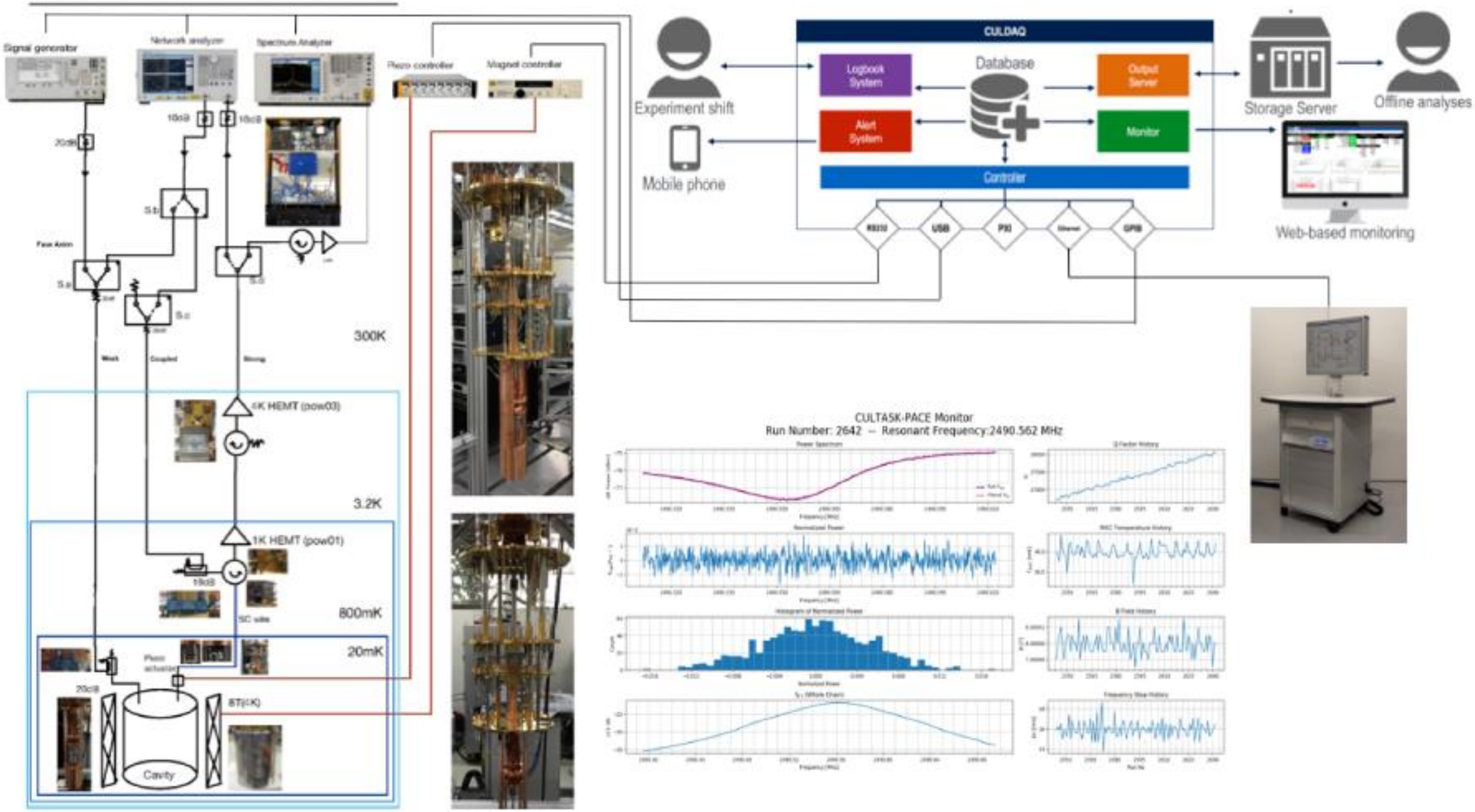
- T_{cavity} : **<40mK (WR)**
- Magnetic field: **8T**
- Bore size: 11.8cm
- Cavity volume: 0.59L
- Frequency: **2.45~2.75GHz**
  (2.45~2.50 at 1st run)
- Q unloaded: **>80,000**
- Low noise amplifier: **HEMT (1K noise)**
- C (geometrical factor) >0.55
- DAQ Efficiency:0.45
- Target sensitivity: **10*KSVZ**



Woohyun Chung's slide

CAPP-PACE

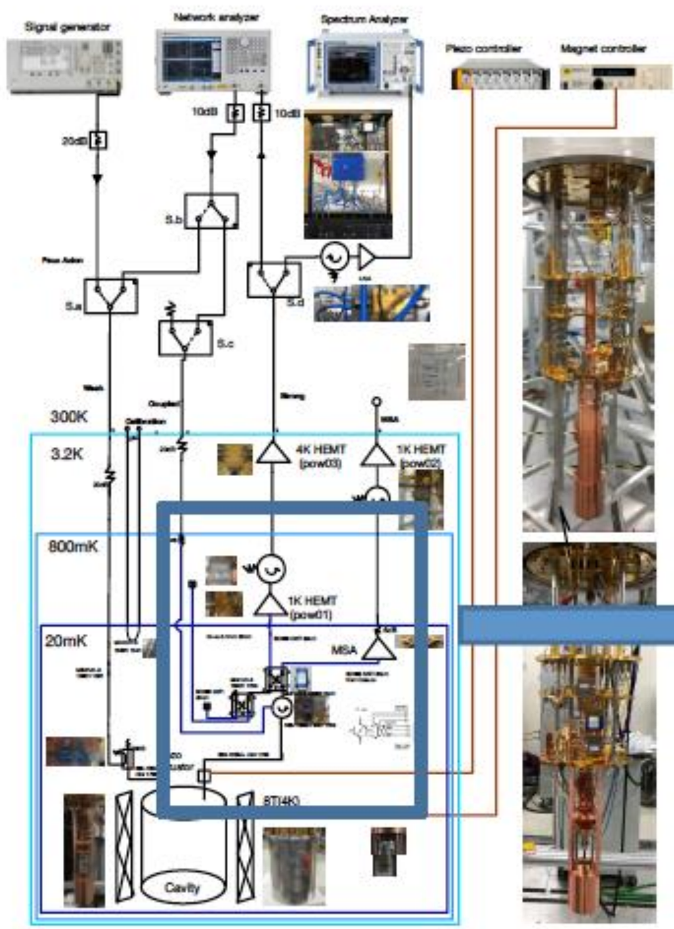
RF read-out chain & Controls



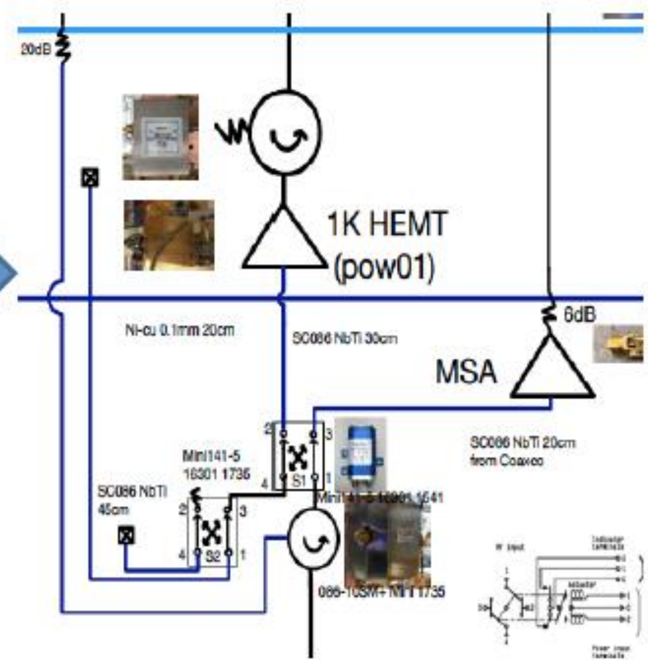
Woohyun Chung's slide

CAPP-PACE NT Measurements

- “Cold Terminator method” with cryo-switch
- “On-Off Resonance method” ADMX style
- Custom-made Y-factor method
- LHe dewar tests



05/14/2018 modified. Port 1&4 of Switch2 is interchanged. Readout line from S1 to HEMT is directly connected. Coupled line configuration is modified.



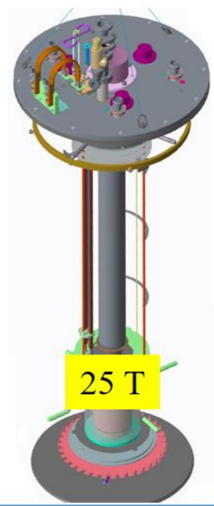
Woohyun Chung’s slide

IBS/CAPP magnet projects

- NI-HTS, 18T, 70mm diam. Delivered Summer 2017 from SuNAM. No Insulation (NI) works!
- NI-HTS, 25T, 100mm diam. (BNL) delivery in 2020.
- Insulated LTS (Nb_3Sn), 12T, 320mm diam. to be delivered in 2020 by Oxford.

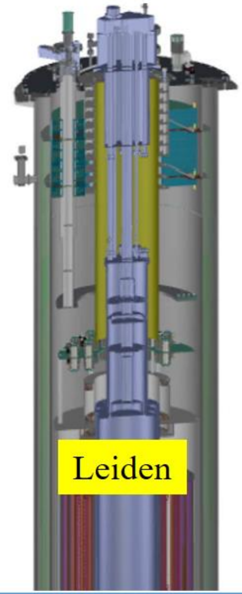
18 T HTS magnet

25 T
HTS magnet

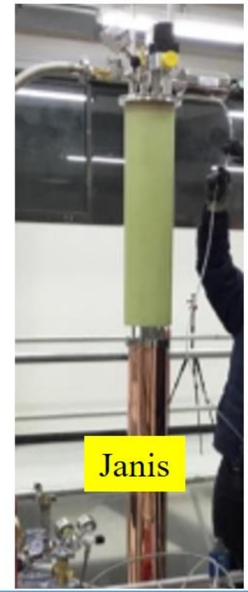


Oxford
- kelvinox

Oxford
- Leiden



9 T
LTS, Janis



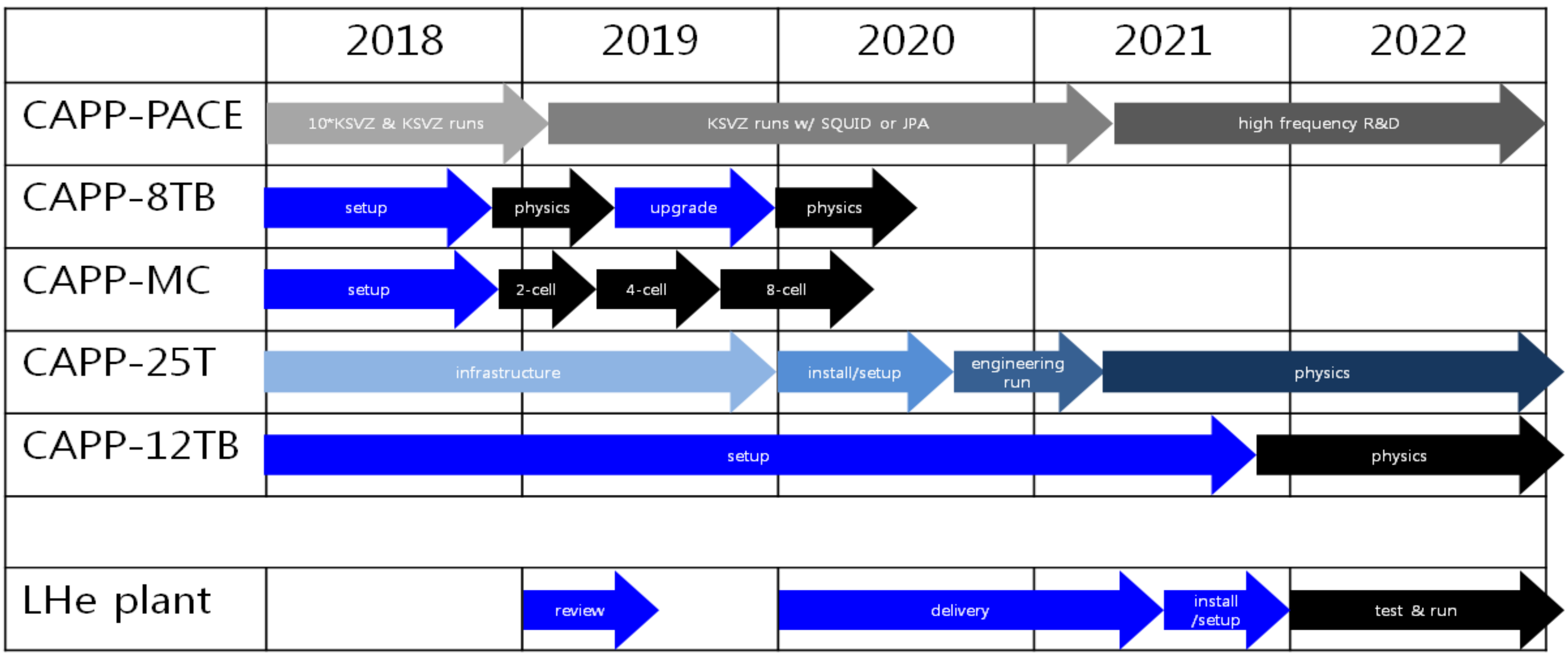
18 T	**25 T**	**9 T**	**12 T**	**9 T**
70 mm	100 mm	50 mm	320 mm	120 mm
4 K	4 K	30 mK	30 mK	300 mK
Working	2019	Testing	2018	Working

Liquid helium type superconducting magnet system at CAPP

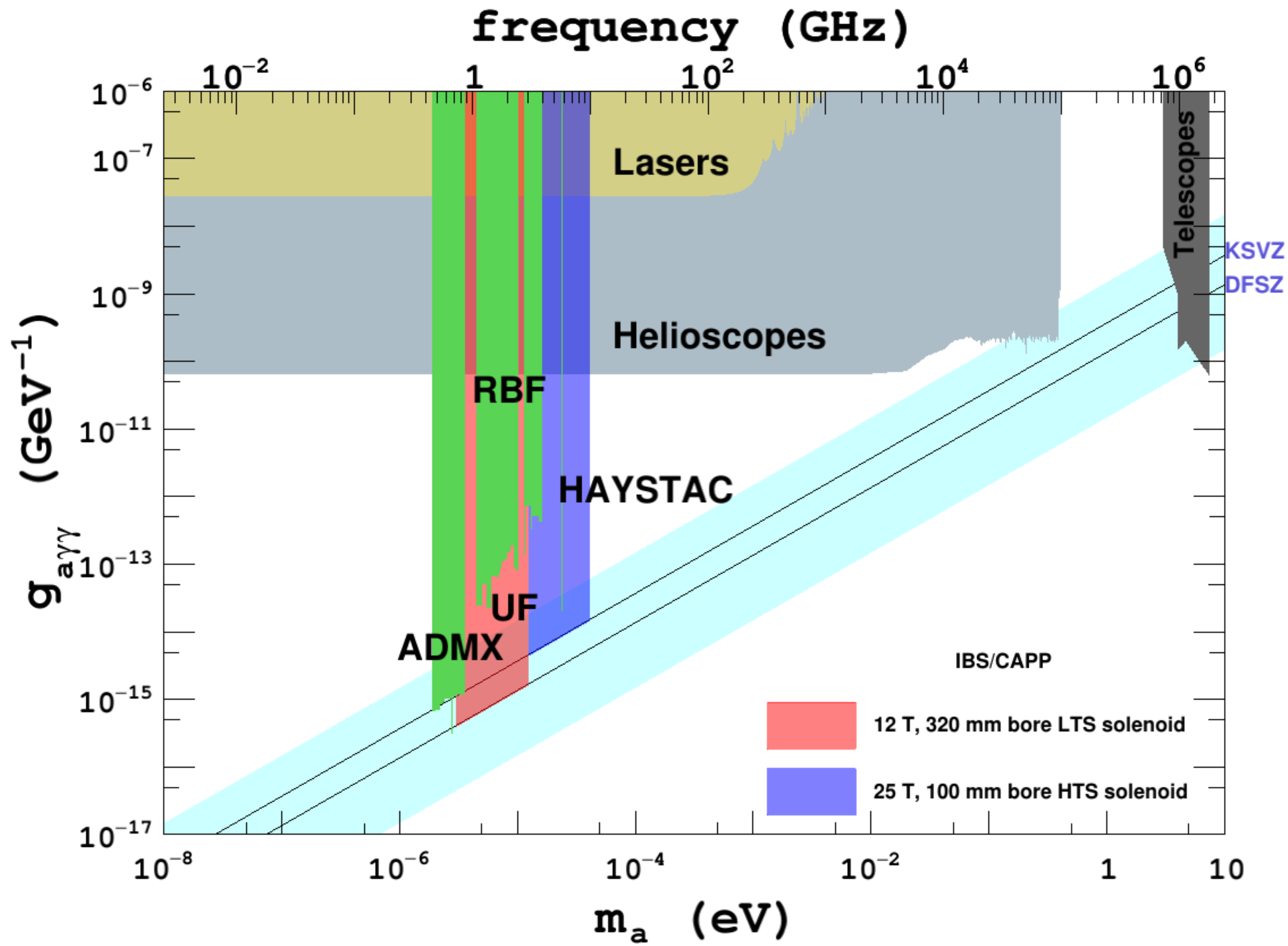
CAPP Physics Targets

IBS/CAPP Timeline, 1st phase

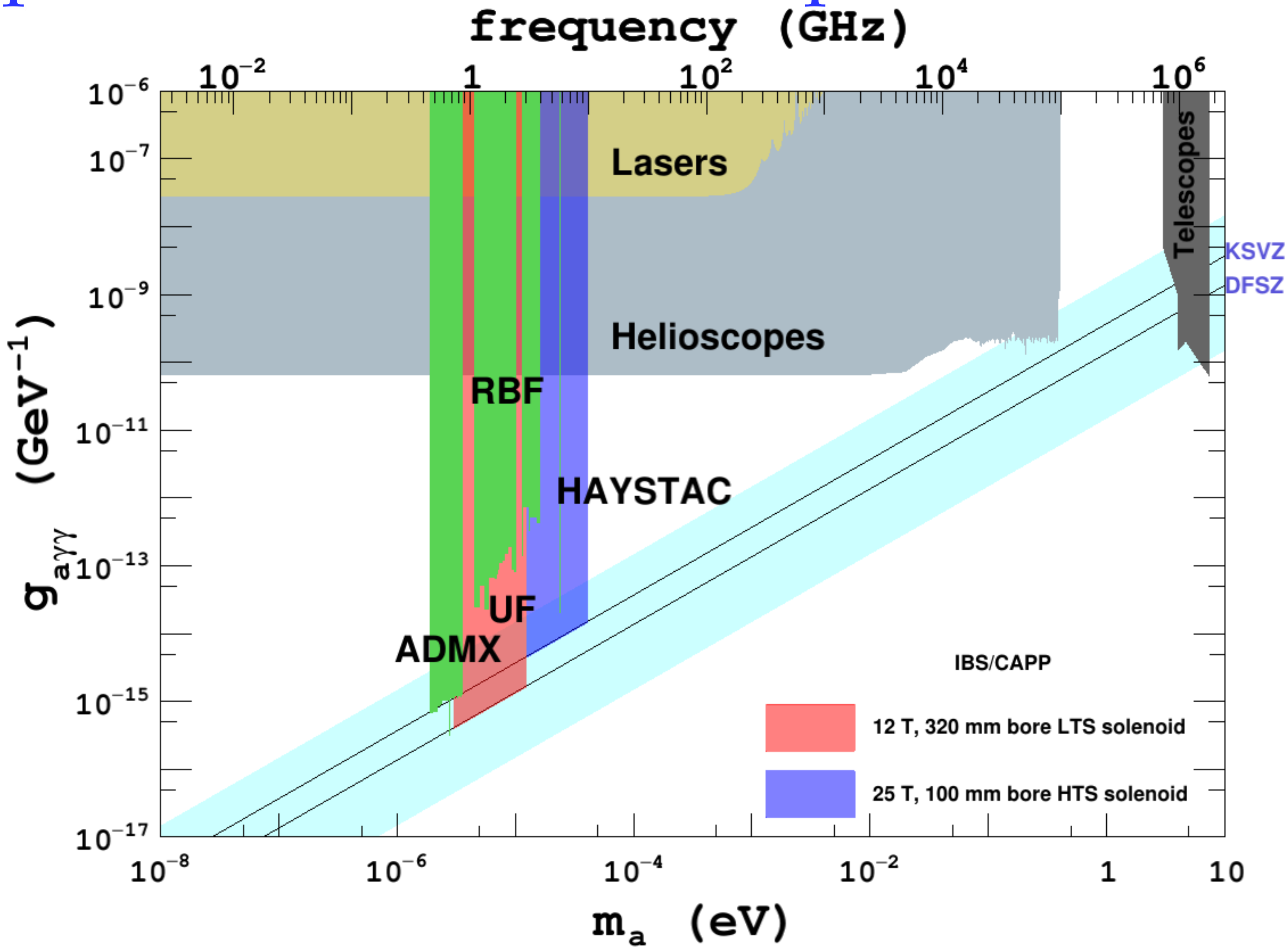
CAPP Axion Dark Matter Search Timeline



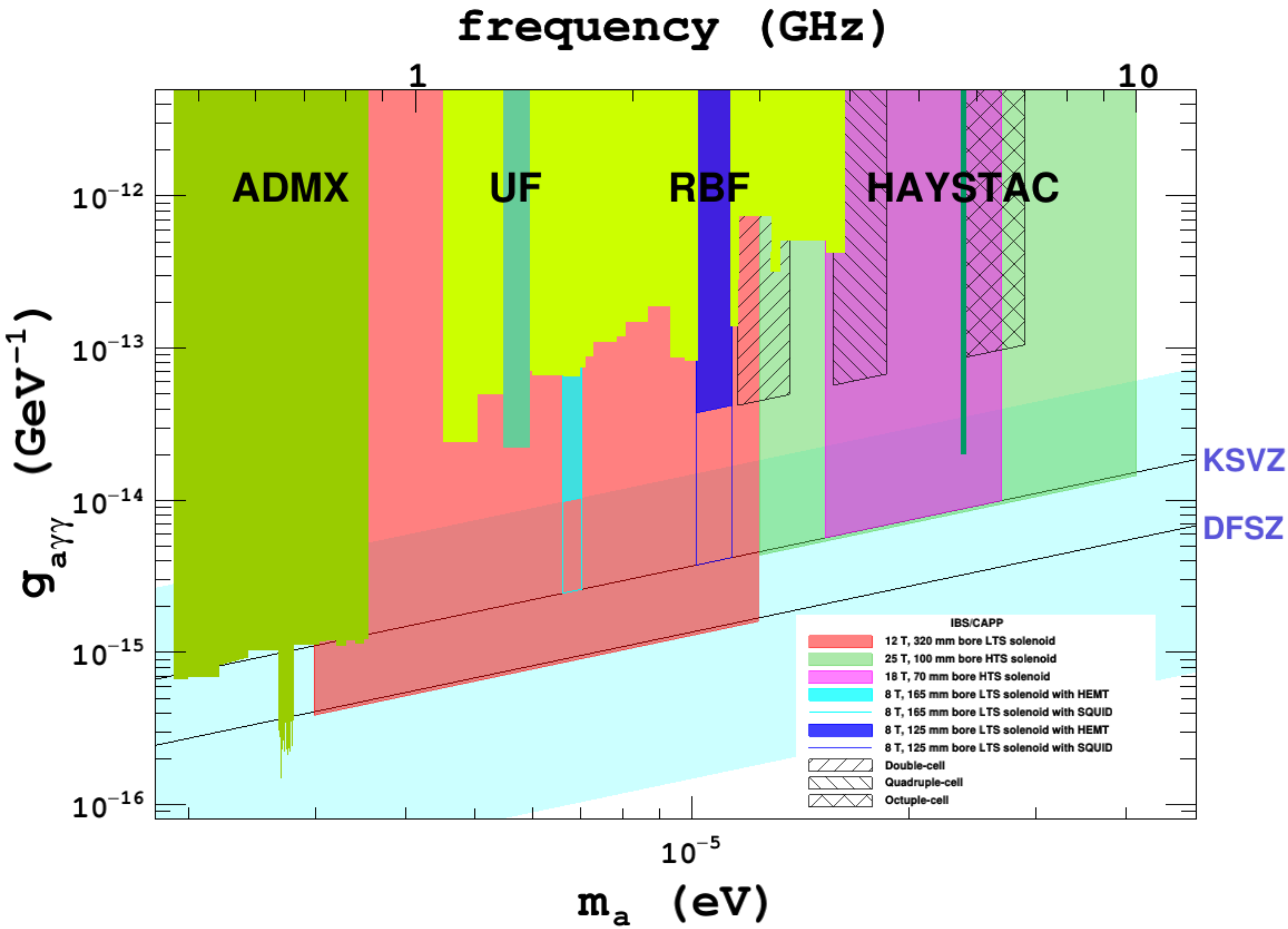
Potential shown based on single cavities (existing technology only)
1st phase: 0.7-10 GHz, 2nd phase: 10-20 GHz



Potential shown based on single cavities
1st phase: 0.8-10 GHz. 2nd phase: 10-20 GHz



Potential shown based on single cavities: <10 GHz
Technology developed at CAPP for 10-20 GHz



Spinning particles in storage rings as high-Q axion detectors

Axion dark matter and spins in storage rings

Seung Pyo Chang, Selcuk Haciomeroglu, On Kim, Soohyung Lee, Seongtae Park & Yannis K. Semertzidis, arXiv:1710.05271 **[hep-ex]**

- Axions dark matter makes a nontrivial QCD vacuum with oscillating pseudoscalar field
- Hadrons in this vacuum acquire oscillating EDM
- Infer axion field amplitude from the dark matter density
- If the axion mass matches a frequency of the spin precession in a storage ring the in-plane polarization will rotate into the upright one --- the EDM signal
- Scan frequency from 10^{-9} Hz to 100 MHz varying a combination of E & B confining fields in a storage ring and testing axion coupling in the range
- $10^{13} < f_a < 10^{30}$ GeV.

Are spins good enough as an axion detector?

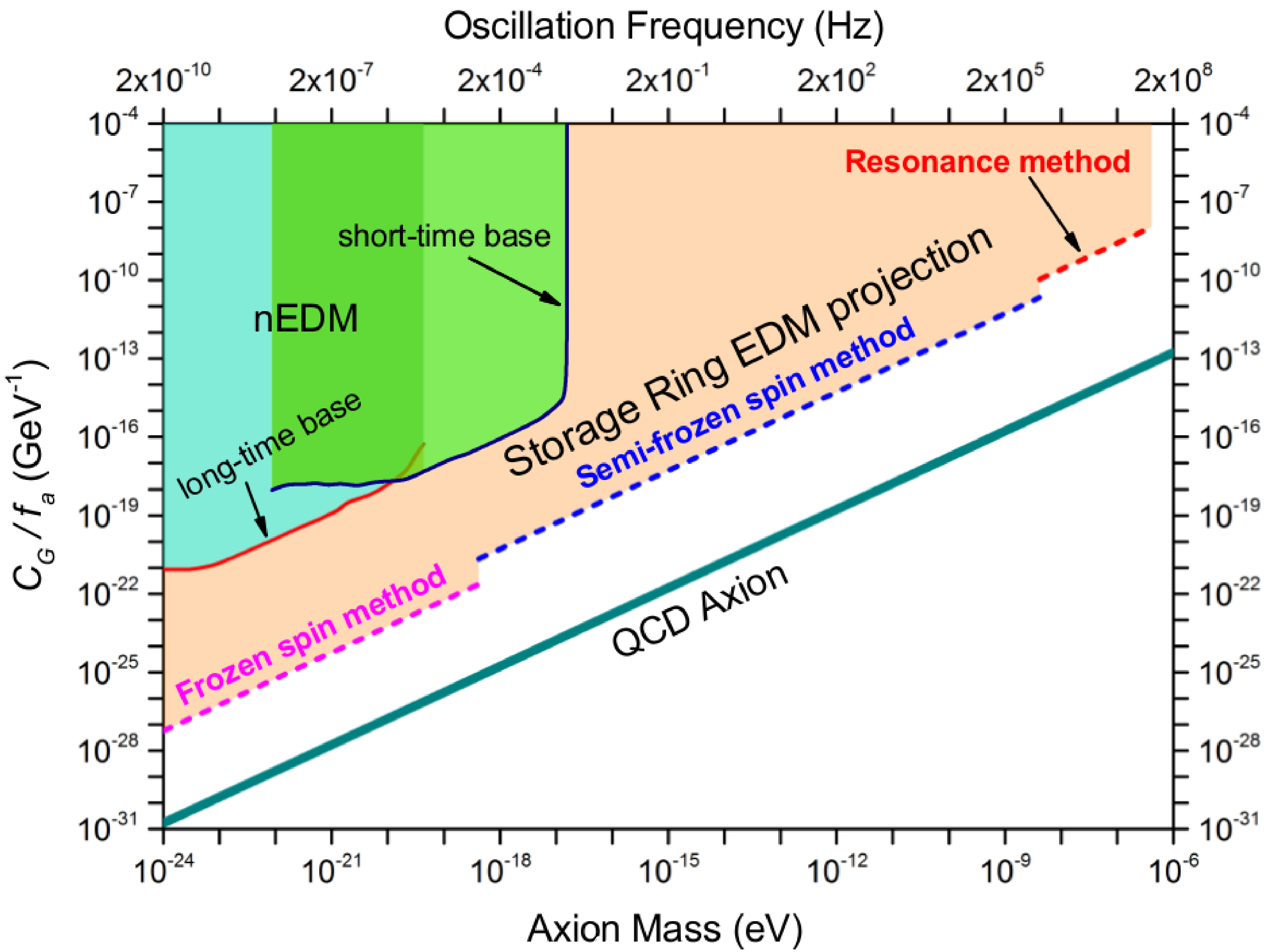
Encouraging message from the JEDI collaboration at COSY@Juelich

- **JEDI@COSY**: an ensemble of 10^9 polarized 1 GeV deuterons idly precessing in-plane at 120 KHz preserves polarization for longer than 1500 s.

- **JEDI@COSY achievements for maintaining axion resonance condition**: the idle in-plane precession of spin as a comagnetometer, routine 10^{-10} precision in the spin tune, 0.15 rad stability of the spin phase during whole spin coherence time

- **JEDI@COSY ---** a pilot search for axions with spin as a detector is in the pipeline

Sensitivity for a 2-year run at a known axion mass



More and EDM and baryogenesis and JEDI @ COSY

EDM vs. MDM (learnt from Lev Okun in 60's)

- MDM: allowed by all symmetries, a scale is set by a nuclear magneton μ_N
- Trust CPT theorem: EDM is P and T/CP forbidden
- Price for the P-violation: 10^{-7}, for CP-violation extra 10^{-3} from K-decays
- **Natural scale $d_N = \mu_N \times 10^{-7} \times 10^{-3} \sim 10^{-24} e \cdot cm$**
- The SM: CPV linked to the flavor change. Pay 10^{-7} more to neutralize the flavor change

$$d_{N,SM} \sim \mu_N \times 10^{-7} \times 10^{-3} \times 10^{-7} \sim 10^{-31} e \cdot cm$$

Why: EDM and baryogenesis

- Sakharov (1967): CP violation is imperative for baryogenesis in the Big Bang Cosmology

	observed	*SM prediction*
$\frac{n_B - n_{\overline{B}}}{n_\gamma}$	$(6.1 \pm 0.3) \times 10^{-10}$	10^{-18}
neutron EDM limit $(e \cdot cm)$	3×10^{-26}	10^{-31}

- EDM as a high-precision window at physics Beyond Standard Model
- nEDM: plans to increase sensitivity by 1 order in magnitude
- pEDM: statistical accuracy of 10^{-29} is aimed at dedicated all-electric storage rings
- dEDM and pEDM in precursor experiment at COSY: dEDM $\sim 10^{-20}$ is within reach?
- Sequel to JEDI: CPEDM & prototype pure electric ring (at CERN? at COSY?...) --- big international effort, CDR under preparation for the fall 2020

A principle of EDM measurement: spin rotation by EDM-interaction with E-fields

- FT-BMT eqn :

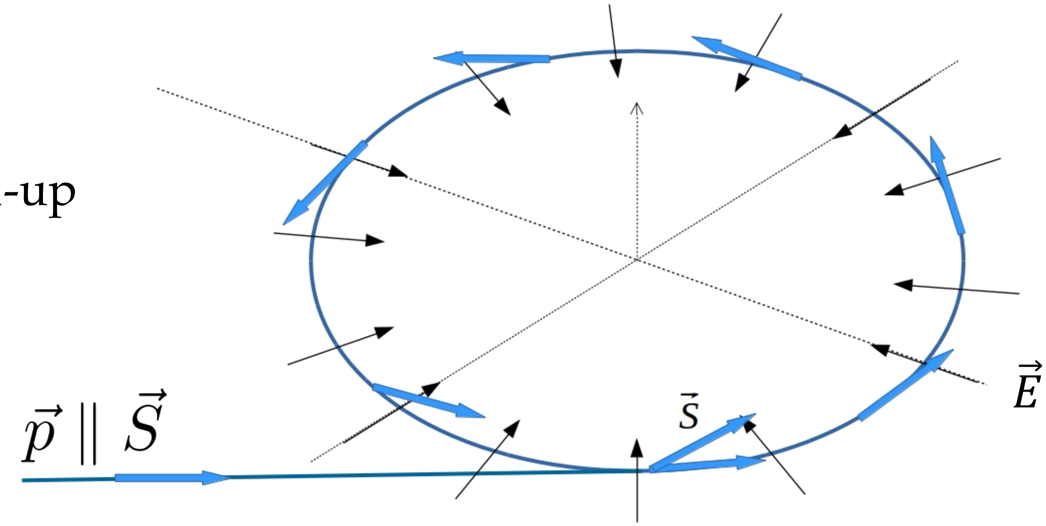
- $$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}(t) = -\frac{q}{m}\left(G\vec{B} + \left(\frac{1}{\gamma^2-1} - G\right)\vec{\beta} \times \vec{E} + \frac{1}{2}\eta(\vec{E} + \vec{\beta} \times \vec{B})\right) \times \vec{S}(t)$$

MDM EDM $d = \frac{\eta \hbar q}{2mc}$

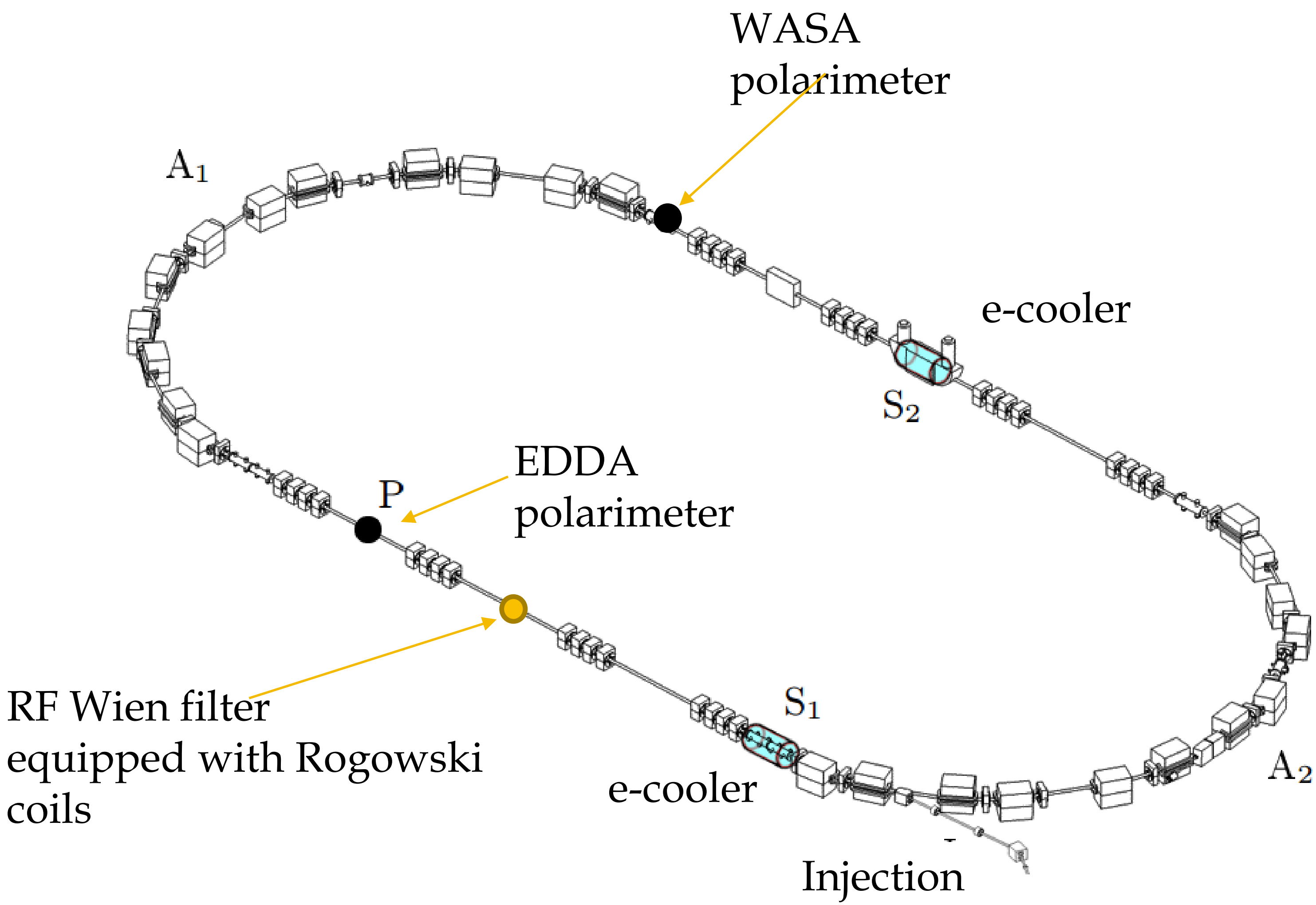
All-electric ring is ideal for protons (Yu. Orlov, Y. Semetrtzidis et al, srEDM at BNL)

- MDM-term → 0 - "frozen spin" at p =700.74 MeV/c
- Longitudinal initial spin
- EDM signal: vertical spin build-up

  per turn → $\pi\eta$



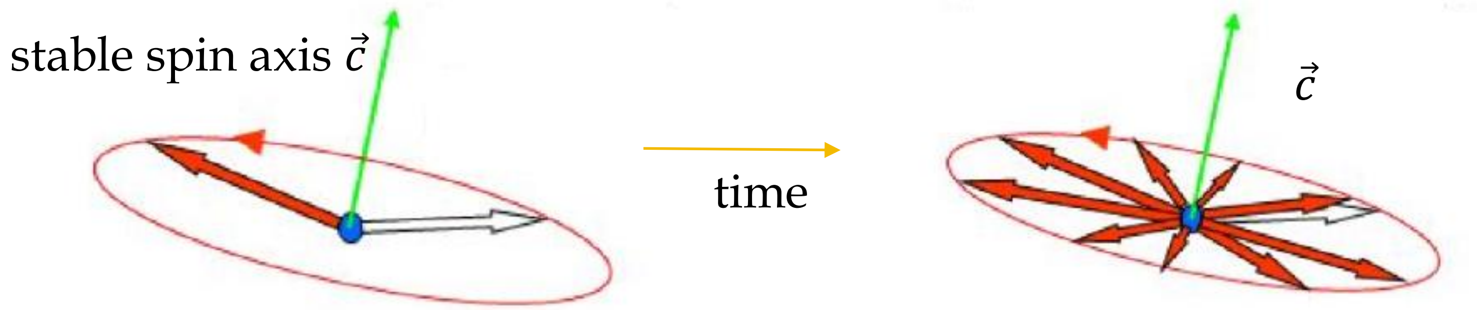
Meanwhile COSY as a Testing Ground



2.9 GeV **CO**oler **SY**nchtoron in Juelich, Germany

Spin coherence time

- **Long spin coherence is crucial for high sensitivity to EDM signal**



Inititally all spins aligned

Spins decohered - polarization vanishes

Prerequisite for long SCT: fight a spread of spin frequencies

- use bunched beam
- decrease beam emittance via electron-cooling
- Betatron oscillations: fine-tune sextupole families to suppress chromaticity (old idea by Ivan Koop and Yuri Shatunov (1988))

- ***JEDI is routinely running at COSY with SCT of 1500 s***

- **In plane polarization rotation frequency serves as a comagnetometer**

Ideal experimental setup

- Ideal storage ring (alignment, stability, field homogeneity, no systematics)
- high intensity beams ($N = 4 \times 10^{10}$ per fill)
- polarized hadron beams ($P = 0.8$)
- large electric fields ($E = 10$ MV/m)
- long spin coherence time ($\tau = 1000$ s)
- polarimetry (analyzing power A = 0.6, f = 0.005)

$$\sigma_{\text{stat}} \approx \frac{1}{\sqrt{Nf\tau}PAE} \quad \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 10^{-29}\ e\cdot\text{cm}$$

challenge: get σ_{sys} to the same level

JEDI: EDM searches at COSY

- COSY is all-magnetic storage ring, unique for studying spin dynamics but still needs upgrades for EDM searches
- Statistical accuracy for $d_d = 10^{-24} e \cdot cm$ is reachable at COSY
- Systematic effects: **horizontal imperfection magnetic fields are evil** because MDM >> EDM and MDM rotations give false EDM signal
- **JEDI** experimental studies of imperfections at **COSY** : based on a novel ***in situ*** determination of the spin orientation the MDM background can be suppressed to 10^{-6} level. Further suppression of systematics is possible
- COSY as is: EDM $\leq 10^{-6}$MDM $\cong 10^{-20}\ e \cdot cm$

CERN jumping a boat

- Record setting JEDI results are well taken by community and new CPEDM collaboration with participation of CERN has been formed in 2018
- Conceptual Design Report for the prototype all electric 30 MeV proton storage ring is under preparation
- Good chances to reach a sensitivity to the proton EDM of the order of $10^{-24} e \cdot cm$
- A future: **EDM may become part of CERN Physics Beyond LHC**
- Executive summary of the CPEDM proposal is presented in

Feasibility Study for an EDM Storage Ring,
arXiv:1812.08535 [physics.acc-ph], *Submitted on 20 Dec 2018*

CERN Concil Review of European Strategy for Particle Physics Update 2018 - 2020

Summary

- Axion-dark-matter efforts are becoming very exciting: Cryogenics, High field magnets, High volume-high frequency, detectors, …
- A discovery can be announced at any moment (depending on the frequency number!)
- Within the next five to ten years we may very well know whether axions are 100% of the dark matter…
- The RF, Quantum-noise limited amplifiers play a major role!
- Complementary EDM and Axion searches with polarized particles in storage rings
- Future with storage rings: CPEDM and more?

Thank you for your attention !

Extra Slides

Axion plans at IBS/CAPP

- Establish lowest cavity temperature (<50mK)
- Develop Microstrip SQUID Amplifiers (MSAs) from KRISS, IPHT, …; JPAs
- R&D on SC cavity w/ B-field
- Single photon detector (>10GHz), based on qubits?
- Open-resonators R&D for higher frequency (Collaboration with UW, KAIST)
- Neutron stars for signals (and transients?), check it with conventional experiment
- srEDM for axion-EDM: spin of particles in a storage ring as a substitute for RF cavity

How important are the quantum noise limited amplifiers?

Dil. Refr. installed

The experimental hall is getting very busy

Several high power dilution refrigerators have been procured, installed and are running at mK temps.