Axion haloscopes with toroidal geometry at CAPP/IBS

12th PATRAS workshop @ Jeju island

2016/06/21

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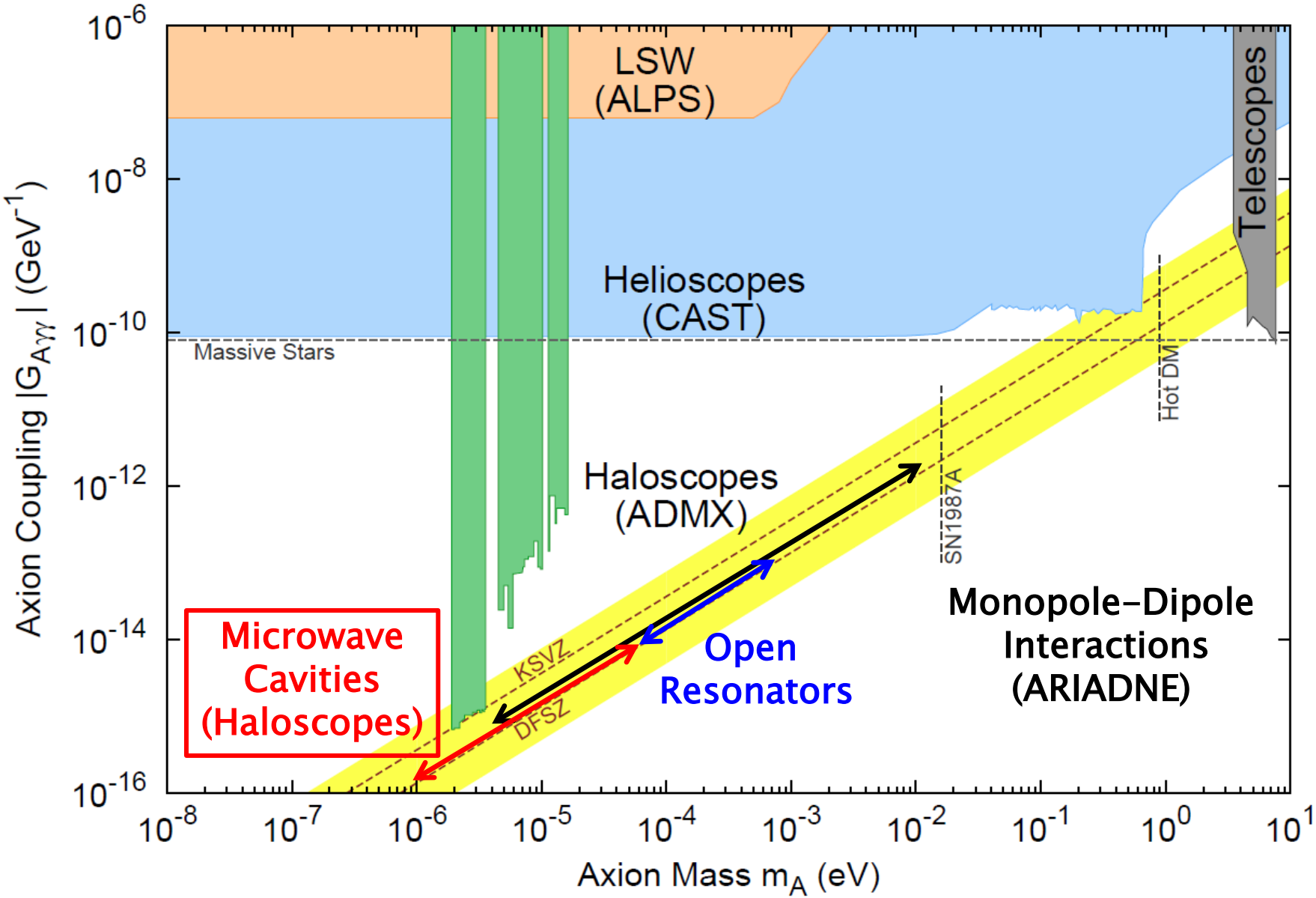
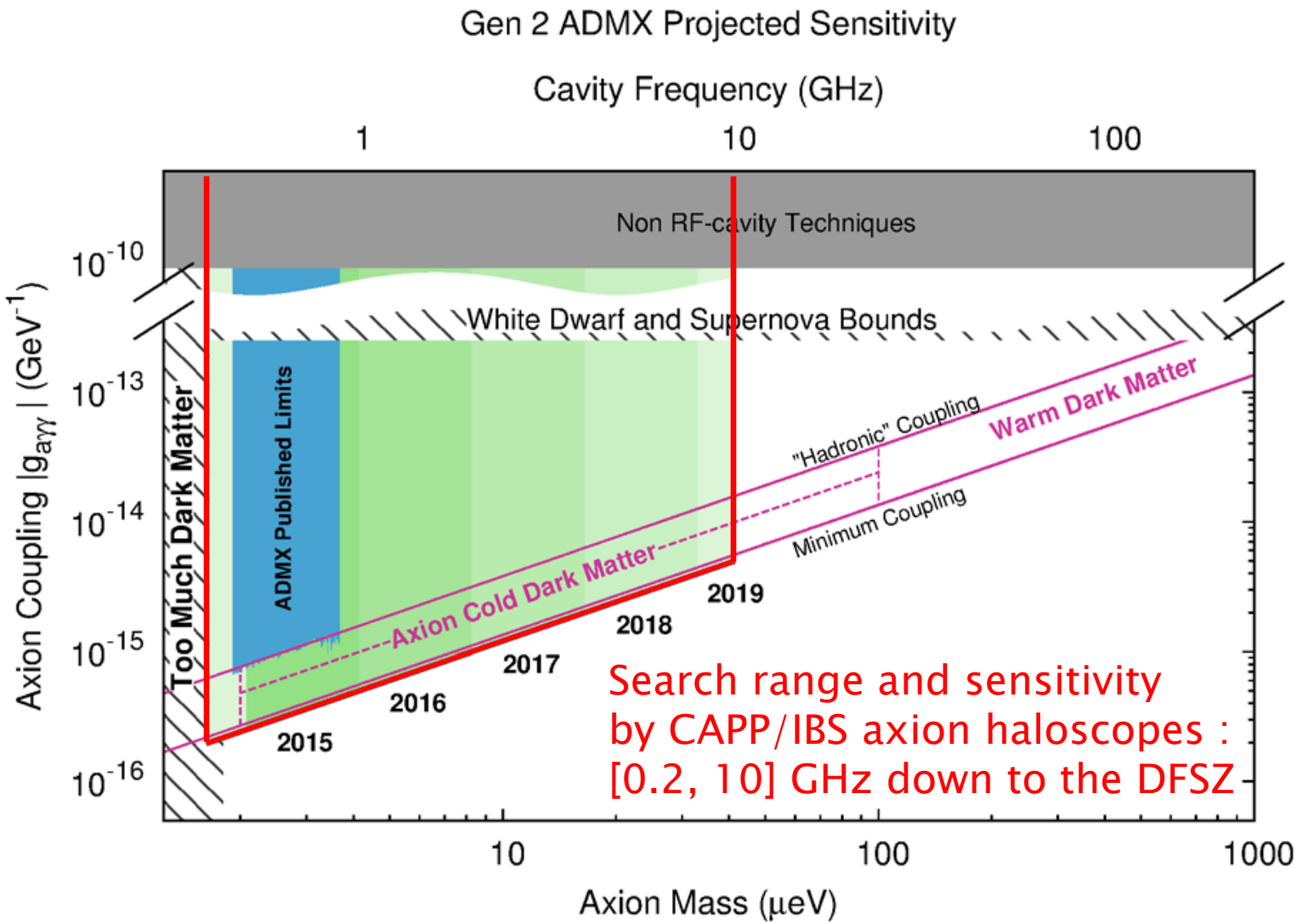
(CAPP/IBS & KAIST)

Origin of the three families,
Ko, Yang, and Bu

CAPP/IBS primary targets

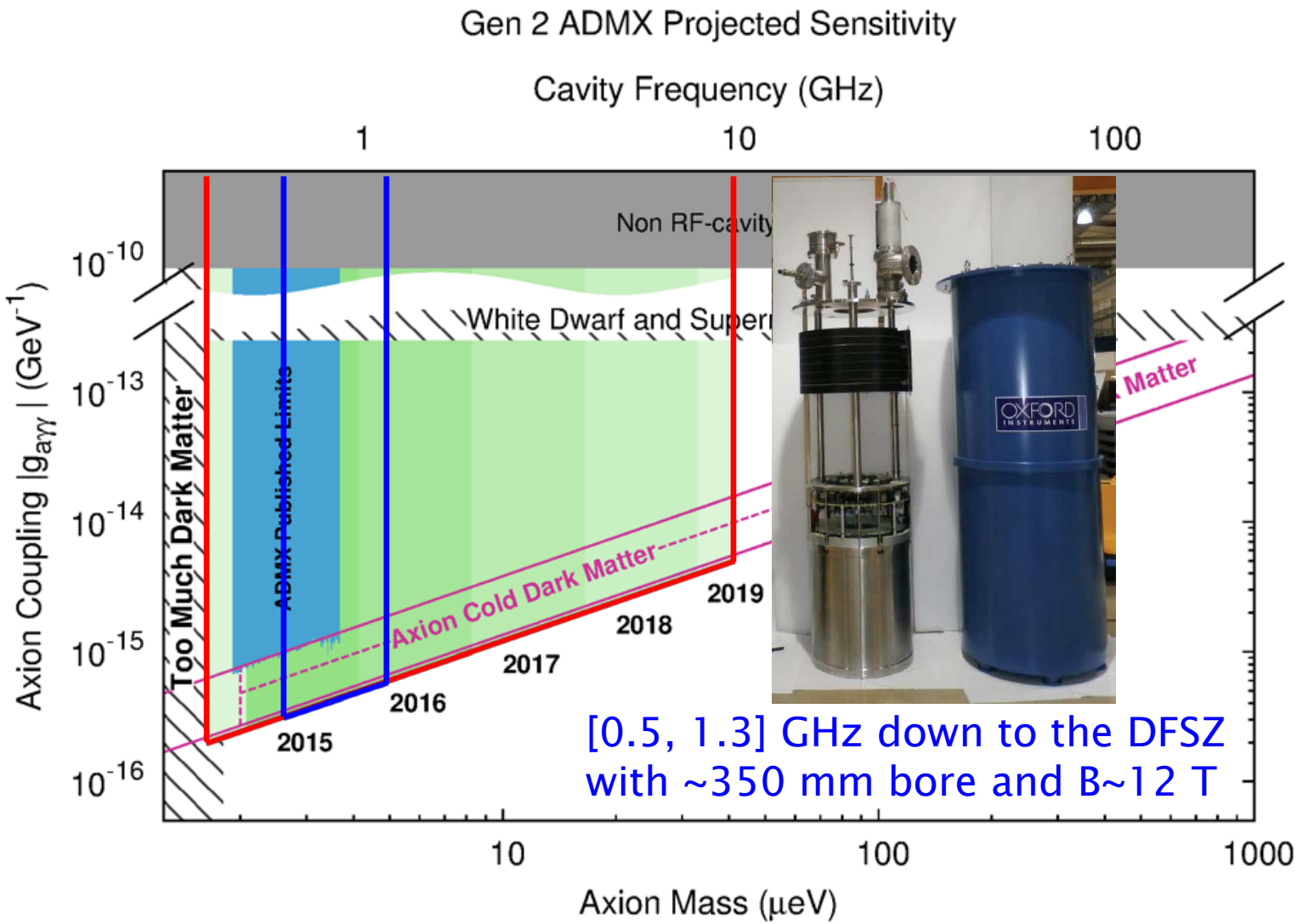


Axion Haloscopes at CAPP/IBS



Search range and sensitivity by CAPP/IBS axion haloscopes : [0.2, 10] GHz down to the DFSZ

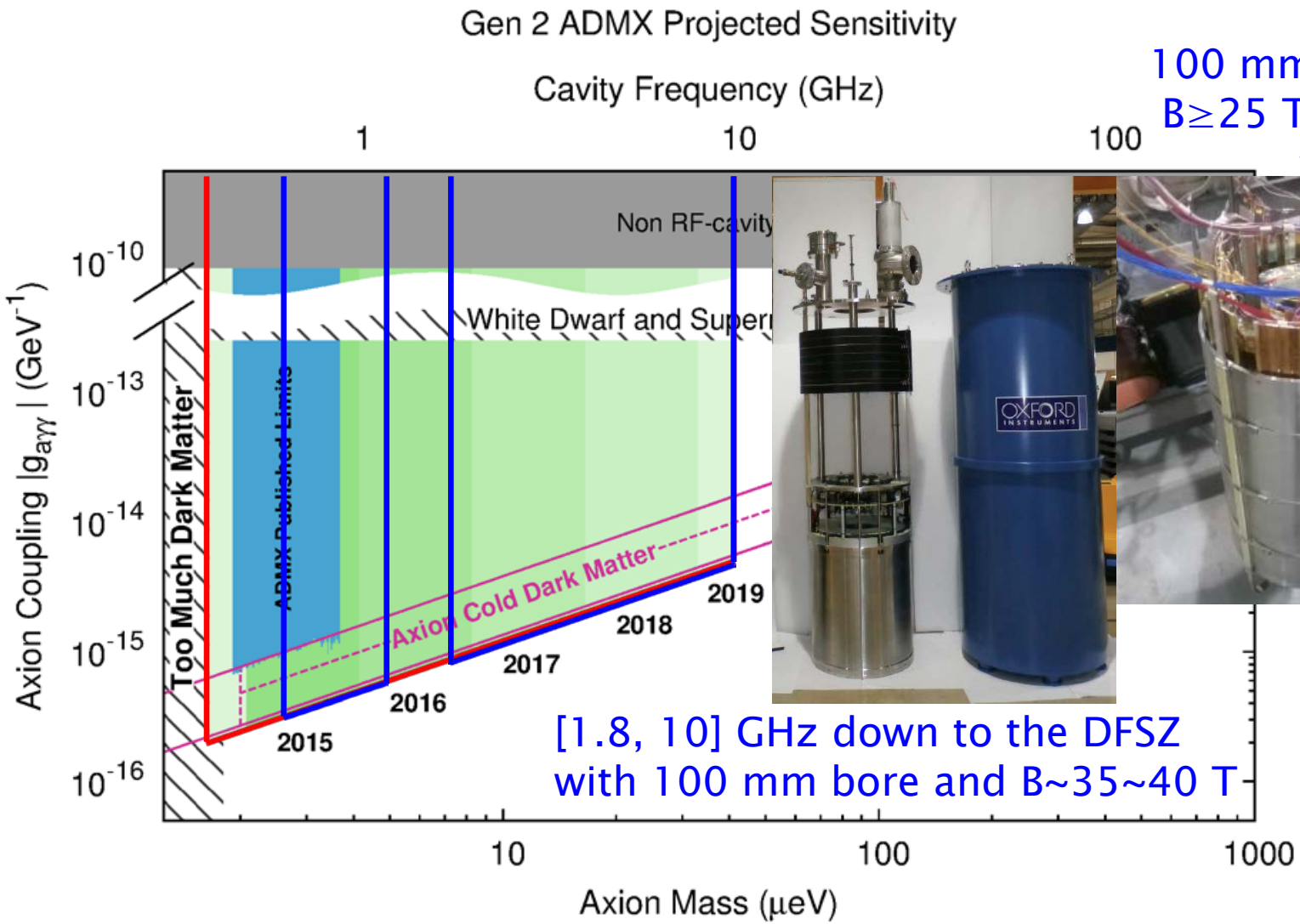
Axion Haloscopes at CAPP/IBS



[0.5, 1.3] GHz down to the DFSZ with ~350 mm bore and B~12 T

Expectation with normal conducting or hybrid SC cavities, with SQUID amps. and Dilution Fridge (DF)

Axion Haloscopes at CAPP/IBS

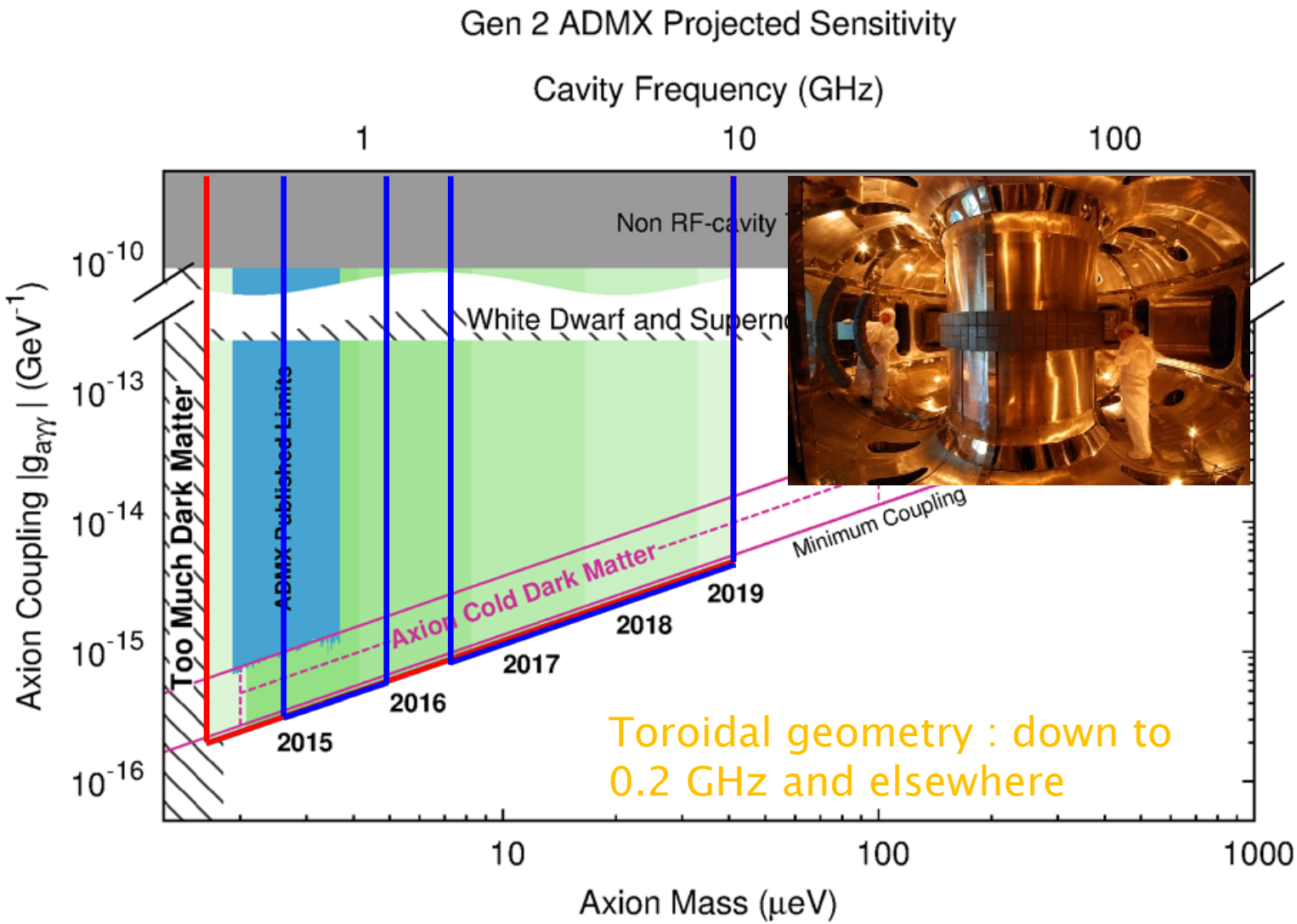


100 mm bore
B≥25 T

[1.8, 10] GHz down to the DFSZ
with 100 mm bore and B~35~40 T

Expectation with normal conducting or hybrid SC cavities, with SQUID amps. and Dilution Fridge (DF)

Axion Haloscopes at CAPP/IBS



Toroidal geometry : down to 0.2 GHz and elsewhere

Roadmap of the CAPP/IBS axion haloscopes

Contents

- Roadmap of the CAPP/IBS axion haloscopes
- Cylindrical geometry vs. Toroidal geometry
- Large toroidal system, in ~10 years
- Small toroidal system, in a few years
- Summary

Common through this talk

- halo axions, $a = a(t) = a_0 e^{-i\omega_a t} \Leftrightarrow \vec{\nabla} a = 0$

  $\rho_a = 0.3\ \mathrm{GeV}/cc$

- $B_{avg}^2 V \equiv \int dV B_{external}^2$, V is cavity volume and $B_{external}$ is always static

- Q_L : copper cavity @4 K, assuming
  Q_L@4 K ~ $\sqrt{8}Q_L$@300 K from anomalous skin effect

- require SNR=5 for a given coupling,
  taking into account
  1. signal efficiency due to the Maxwellian signal shape
  2. background parameterizations with/without signals
- scanning rate (df/dt) for SNR=5

Cylinder vs. Toroid

same or similar

- have the cavity mode $\parallel \vec{B}_{external}$,
  TM_{010} for cylinder,
  Quasi-TM (QTM) for toroid

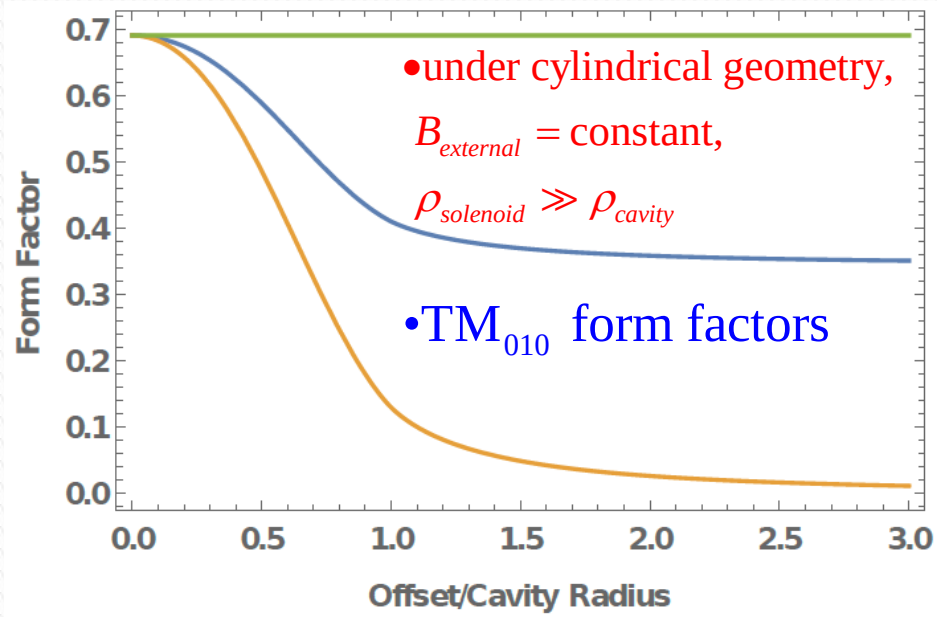
different

- $\vec{B}_{external,cylinder} \sim B_0 \hat{z}$,
  $\vec{B}_{external,toroid} \sim \frac{B_0}{\rho}\hat{\phi}$, B_0 is constant

Cylinder vs. Toroid

Form Factors

- arXiv:1512.05547 (PRL **116**,161804 (2016))



green : Electrical form factor C_E
orange : Magnetic form factor C_M
blue : EM form factor $C_{EM}=(C_E+C_M)/2$

simply speaking,

claims $C_E \neq C_M$ in general

–However,

we have a different view

$C_E = C_M$ in general

Cylinder vs. Toroid

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- $\vec{B}_{external,cylinder} \sim B_0 \hat{z}$,
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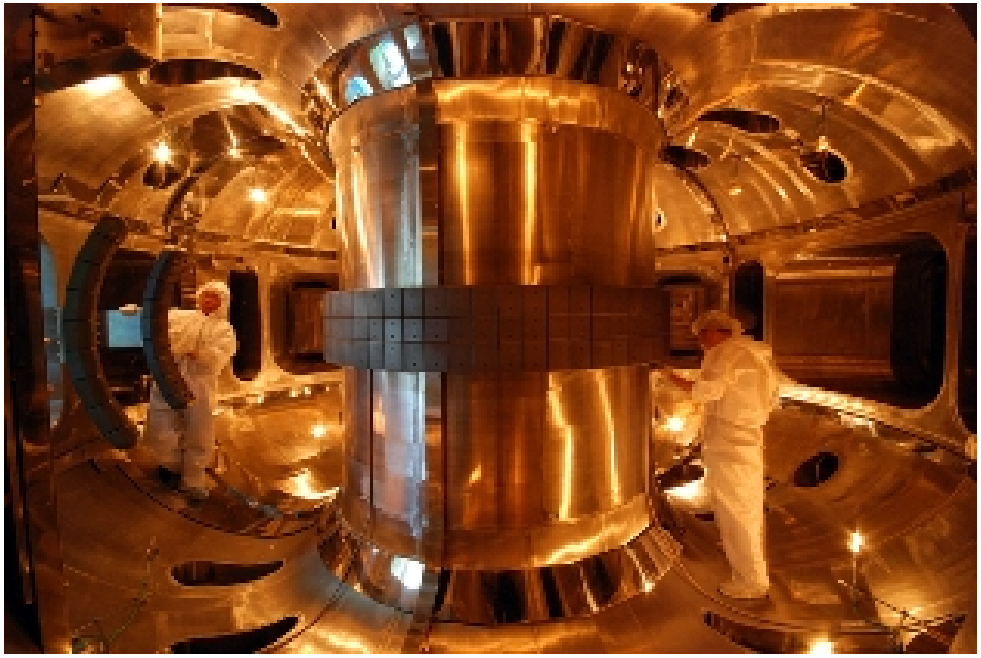
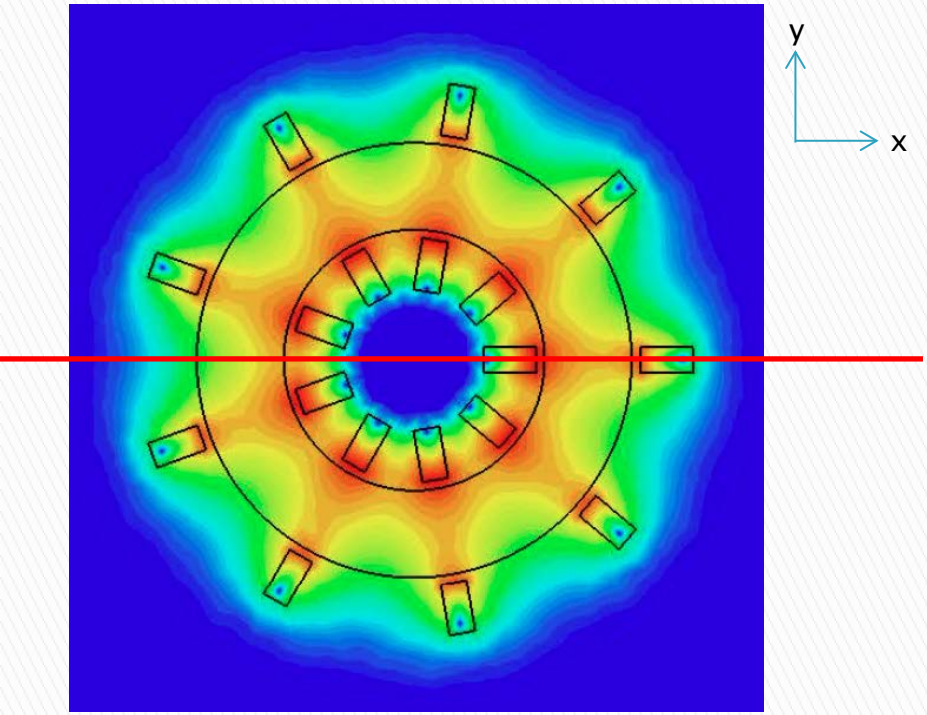
- $C_{cyinder} \propto B_{avg}^2 V = \text{constant}$
  $C_{toroid} \propto B_{avg}^2 V$ depends on the cavity location

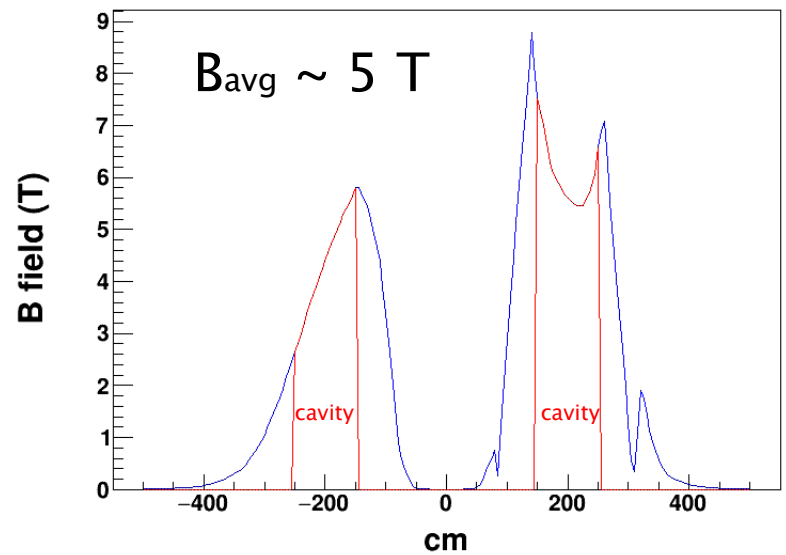
Large toroidal magnet with B_{avg}~5 T, Major R=2 m, minor r=0.6 m

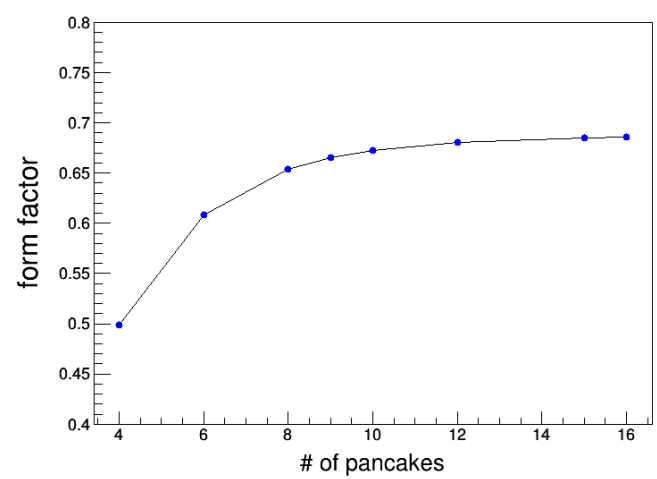


toroidal cavity with Major R=2 m, minor r=0.5 m, V~9900 liters

Initial conceptual design

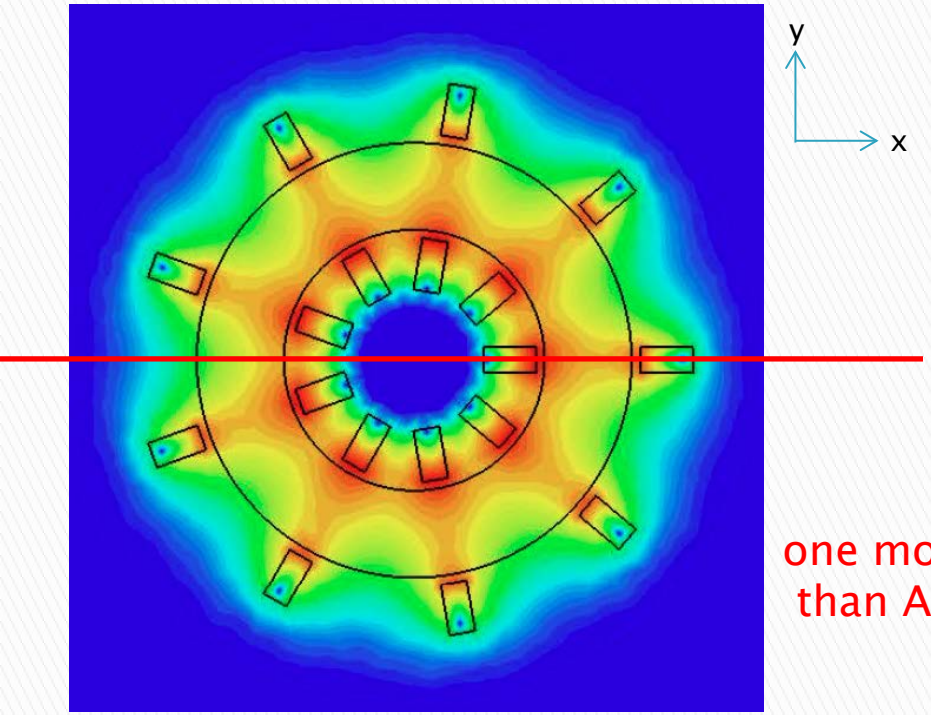




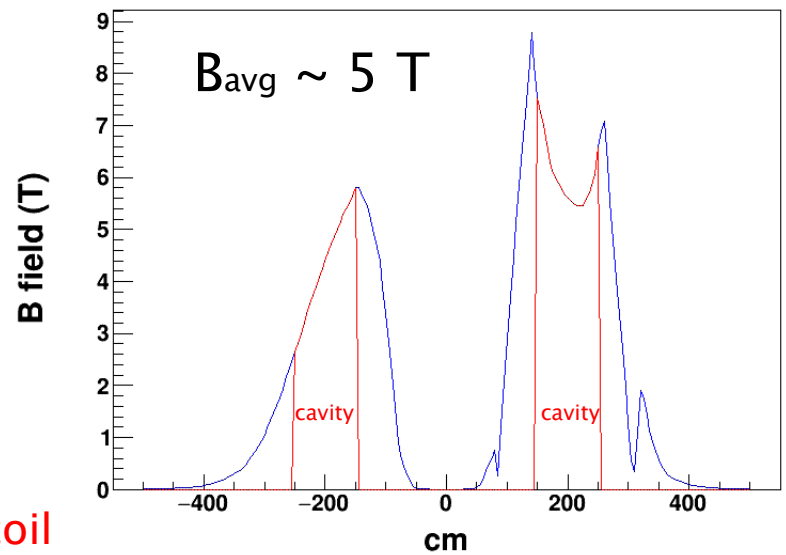


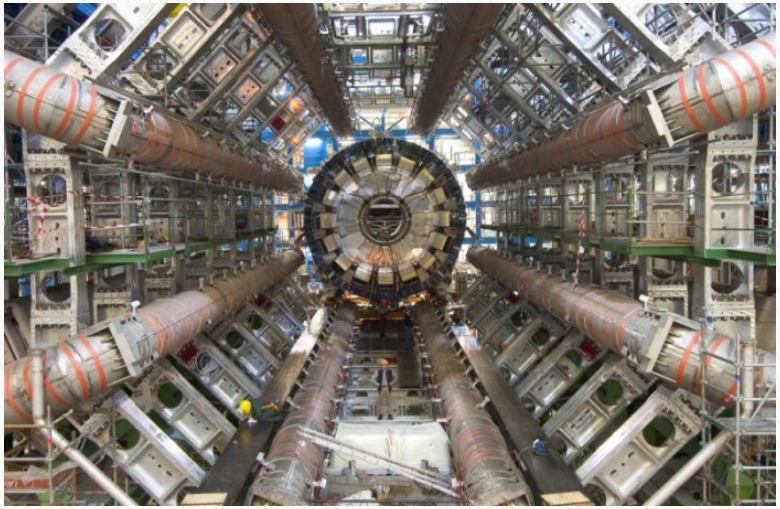
- C_{QTM} ~ 0.67 with 9 coils

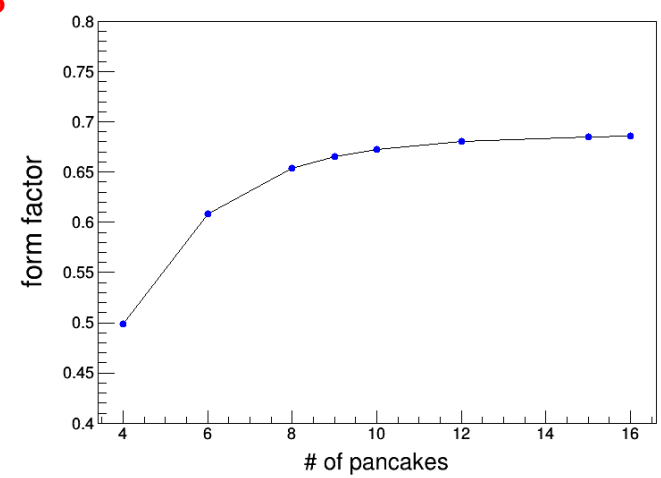
Initial conceptual design



one more coil than ATLAS

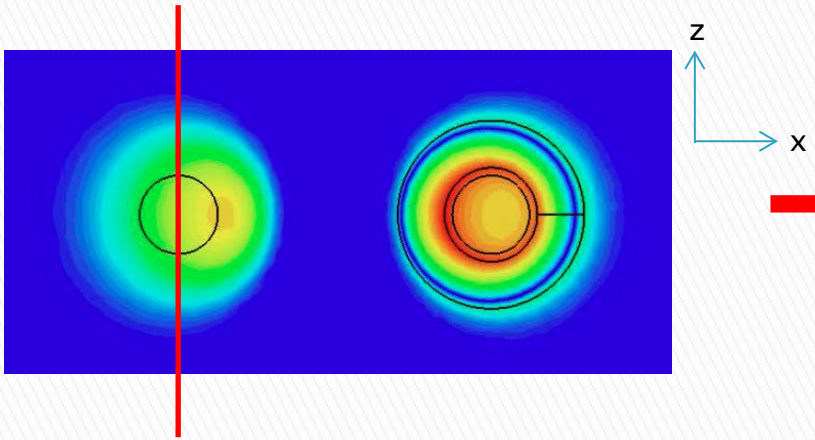


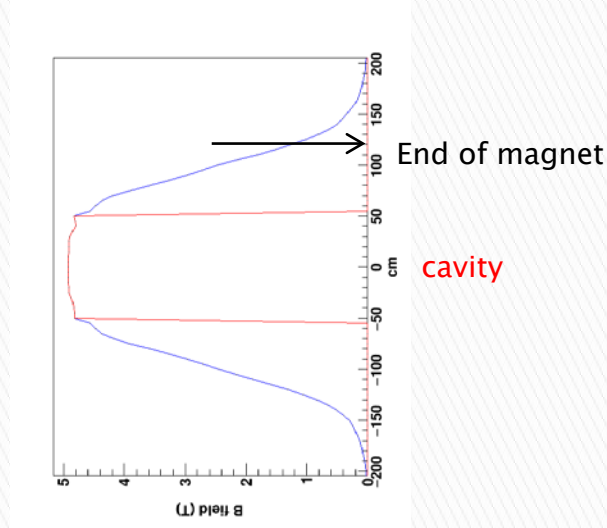


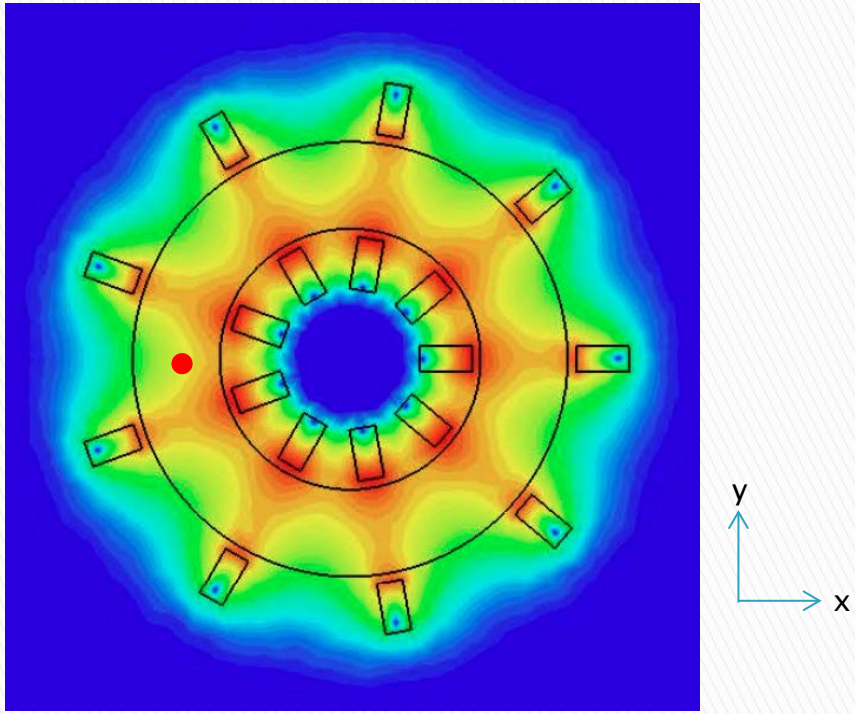


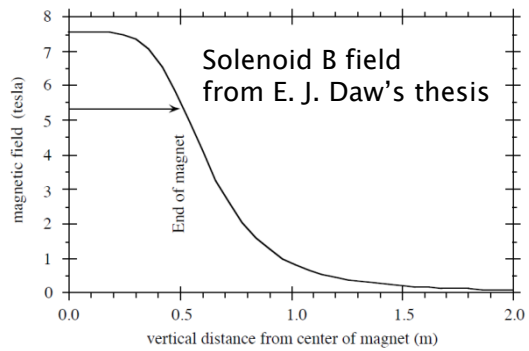
- C_{QTM} ~ 0.67 with 9 coils

Fringe B field









- toroid B_{fringe} < solenoid B_{fringe}
- toroid B_{fringe} can be reduced by increasing number of coils

→ merit with quantum devices

Cylinder vs. Toroid

same or similar

- have the cavity mode $\parallel \vec{B}_{external}$,
  TM_{010} for cylinder,
  Quasi-TM (QTM) for toroid

- $C_E = C_M$ in general

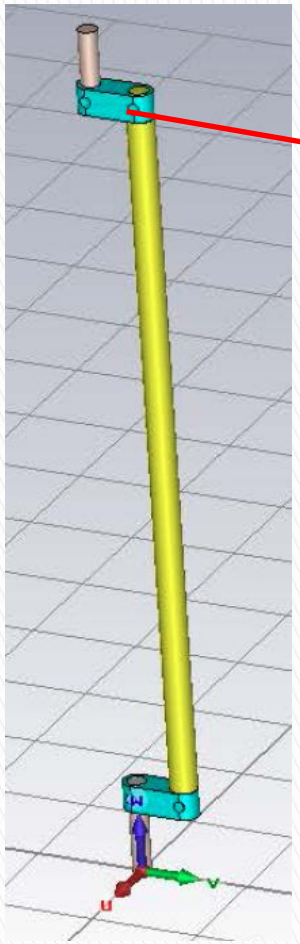
different

- $\vec{B}_{external,cylinder} \sim B_0 \hat{z}$,
  $\vec{B}_{external,toroid} \sim \frac{B_0}{\rho}\hat{\phi}$, B_0 is constant

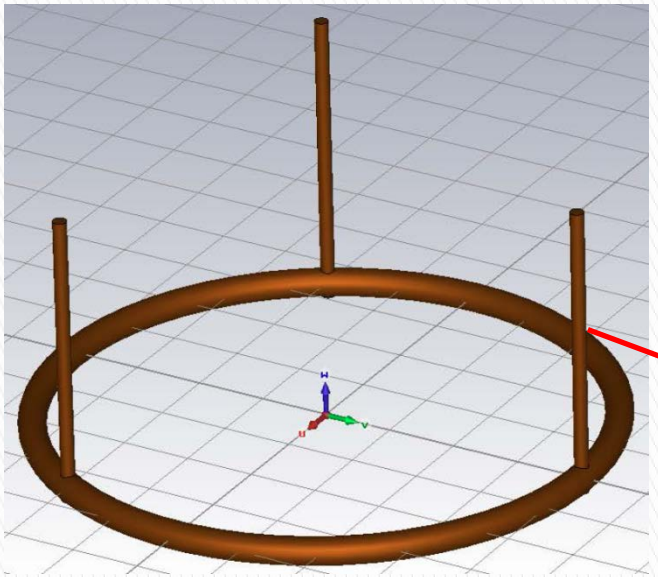
- $C_{cyinder} \propto B_{avg}^2 V = \text{constant}$
  $C_{toroid} \propto B_{avg}^2 V$ depends on the cavity location

- toroid $B_{\text{fringe}} <$ solenoid B_{fringe}, furthermore toroid B_{fringe} can be reduced with additional coils, but solenoid B_{fringe} can't be

tuning mechanism



gaps between cranks and endcaps of a cavity is important! affect the cavity modes a lot

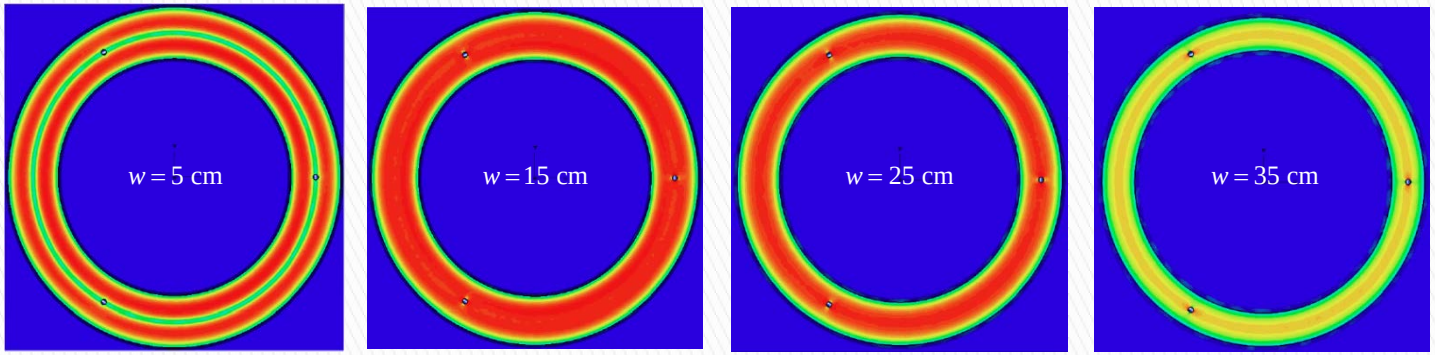


•for toroid :

up and down

along the w axis

no such gaps exist, but three posts



•for cylinder :

rotate

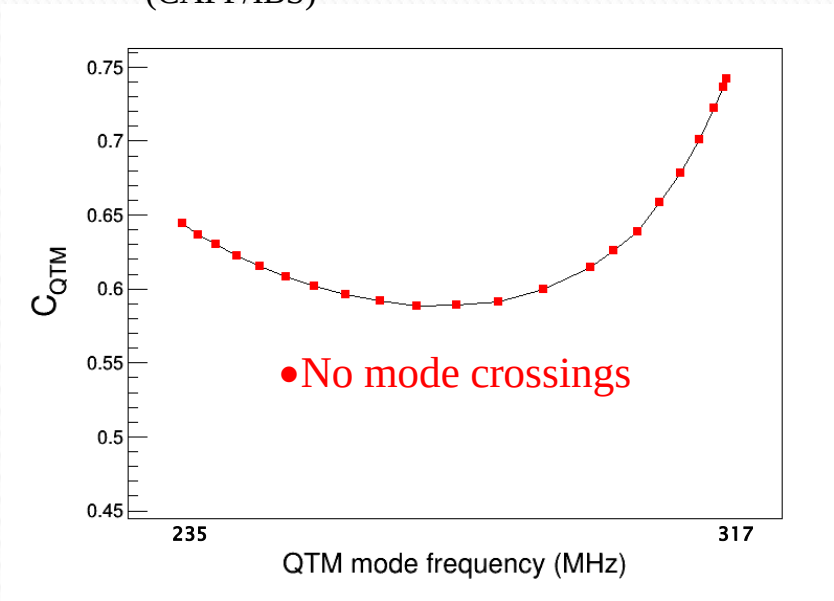
w.r.t. the w axis

•the cavity mode as a function of *w* when conducting tuning hoop at the center of the cavity together with the three conducting posts

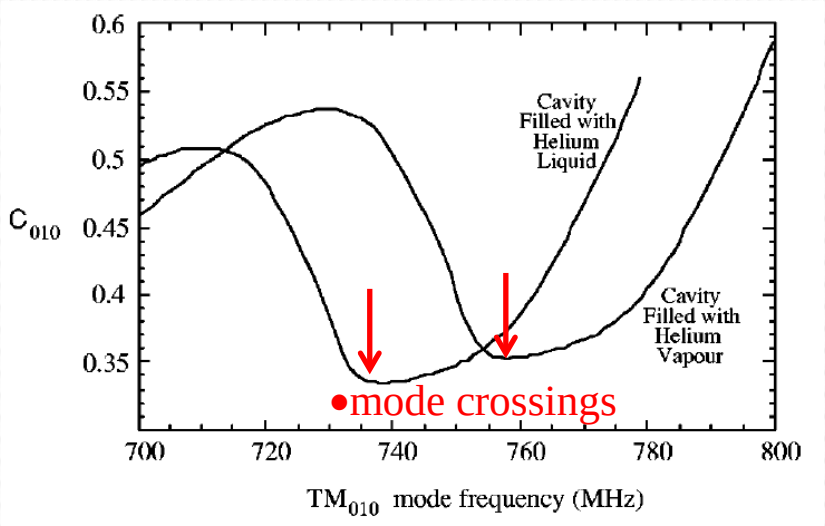
→ the cavity mode little affected by the three posts

tuning mechanism : mode crossing

–toroidal geometry
(CAPP/IBS)



–cylindrical geometry
(PRD 64, 092003 (2001))



•toroidal geometry :
resonant frequencies
depend only on the minor radius
→~ free from the mode crossing

•cylindrical geometry :
resonant frequencies
depend on the radius and length
→ higher degeneration probability

Cylinder vs. Toroid

same or similar

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different

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- toroid $B_{\text{fringe}} <$ solenoid B_{fringe}, furthermore
  toroid B_{fringe} can be reduced with additional coils,
  but solenoid B_{fringe} can't be

- No mode crossing in toroidal geometry

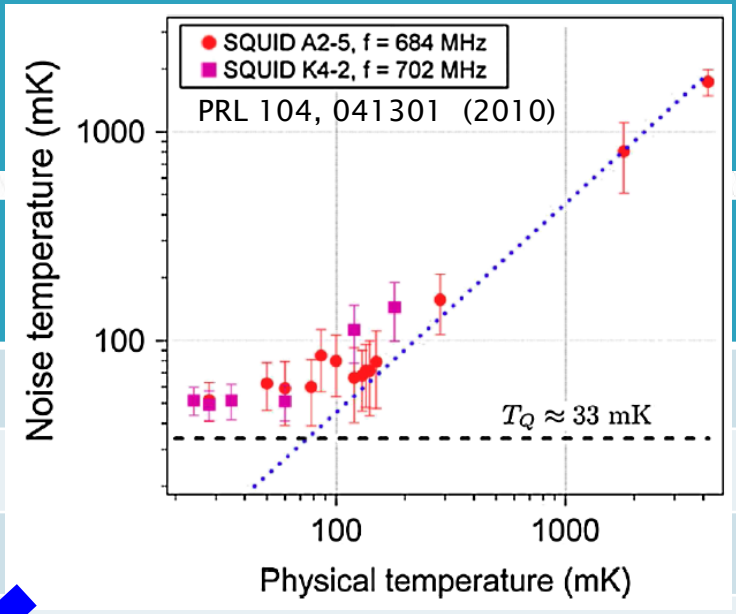
Large toroid : sensitivity down below 200 MHz

- toroidal cavity with Major R=2 m and minor r=0.5 m

→QTM frequency of the empty cavity ~ 230 MHz

- 10 cm OD alumina rod (ϵ_r=9.9)

→ can go down to ~190 MHz



Search range	[190, 230] MHz → 40 MHz	
average B	5 T	
Q_L	~180,000	
volume	~9,900 liters	
C_{QTM}	~0.4 with dielectric	
T_N	T_P~100 mK with DF, T_{amp}~T_{QN}~100 mK with SQUID	T_P~4 K with LHe, T_{amp}~ 2 K with HEMT
DFSZ df/dt	224 GHz/year	140 MHz/year

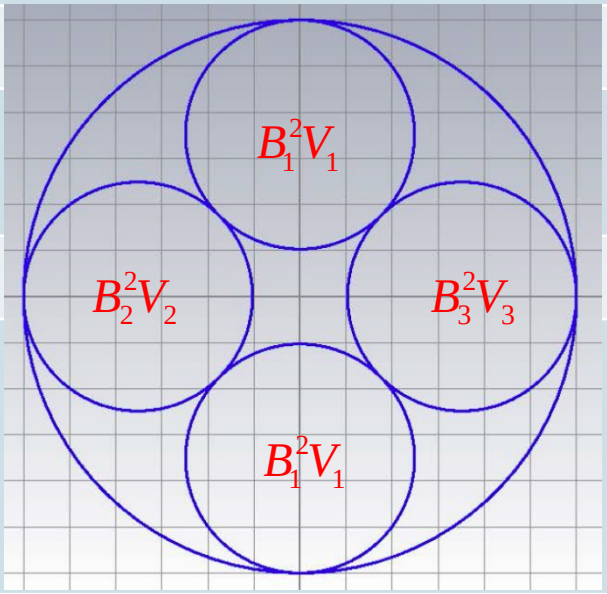
certainly feasible

Large toroid : sensitivity up to 850 MHz

- toroidal cavity with Major R=2 m and minor r=0.2 m
- 6 cm OD copper rod

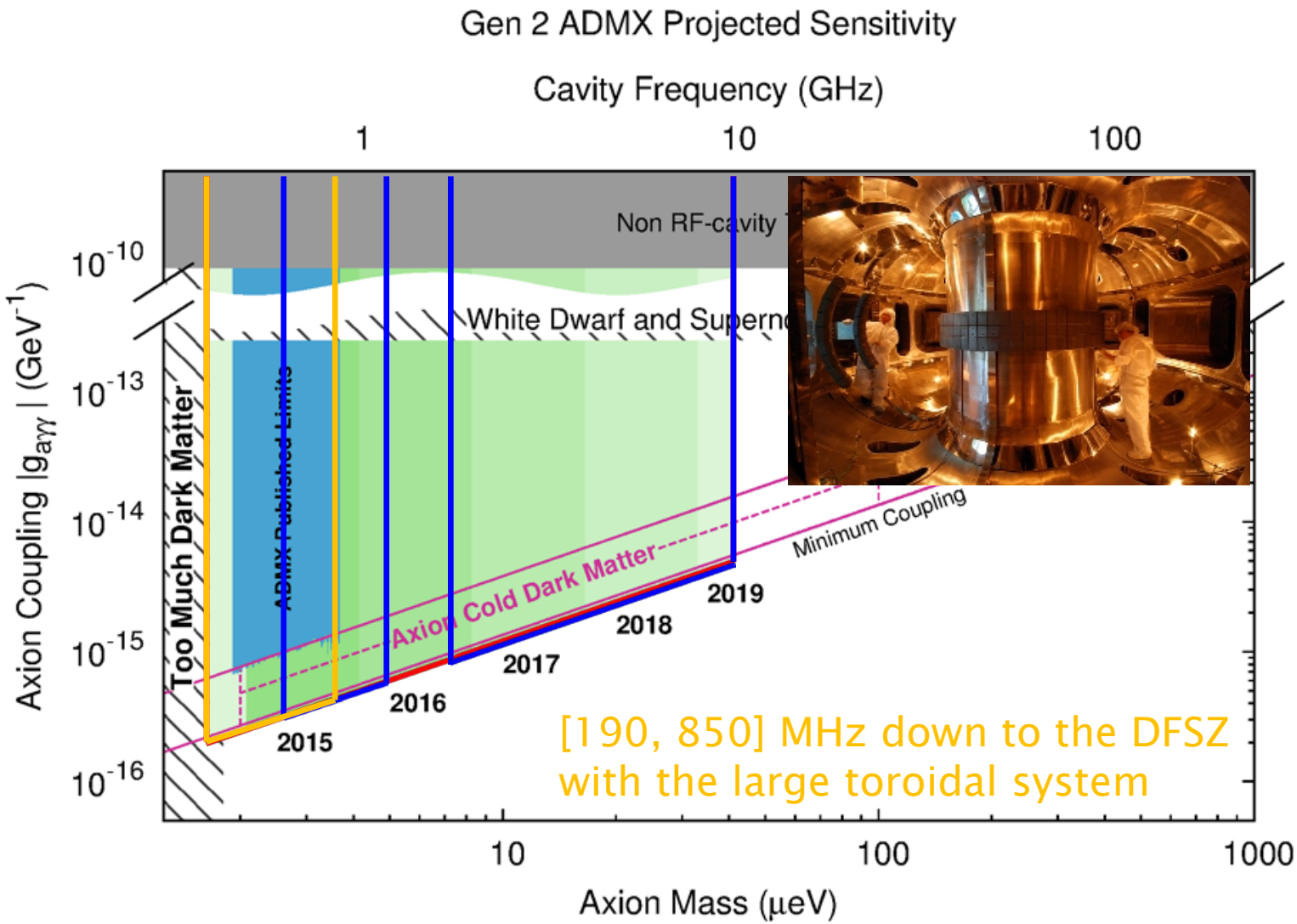
→ can go up to ~850 MHz

search range	[600, 850] MHz → 250 MHz	
average B	5 T	
Q_L	~70,000	
volume	1,579 liters (single-cavity)	1,579x4 liters (4-cavity)
C_{QTM}	~0.6	~0.6
T_N	T_P~100 mK with DF, T_{amp}~ 2 K with HEMT	T_P~4 K with LHe, T_{amp}~ 2 K with HEMT
DFSZ df/dt	560 MHz/year	620 MHz/year



assume $B_1^2V_1 \simeq B_2^2V_2 \simeq B_3^2V_3$

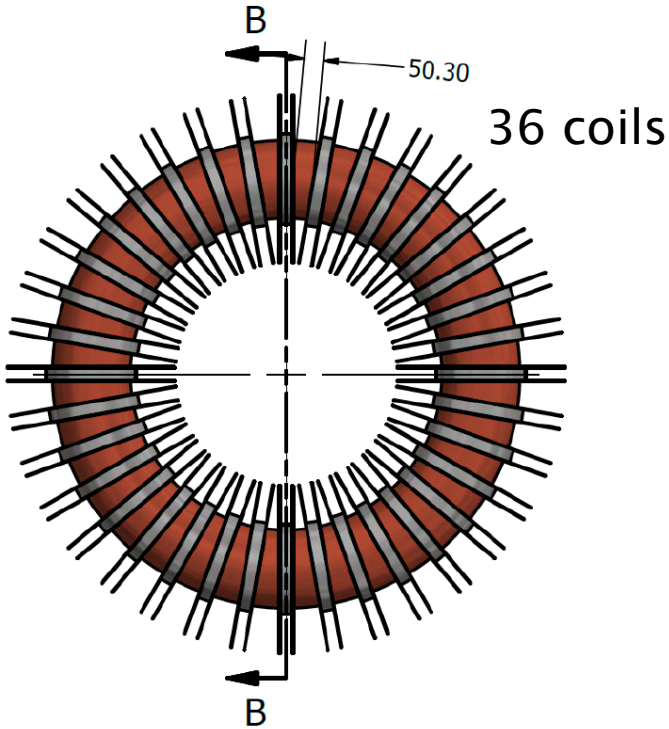
Axion Haloscopes at CAPP/IBS



[190, 850] MHz down to the DFSZ with the large toroidal system

Roadmap of the CAPP/IBS axion haloscopes

Small toroidal magnet with B_{avg}~12 T, Major R=50 cm, minor r=11 cm

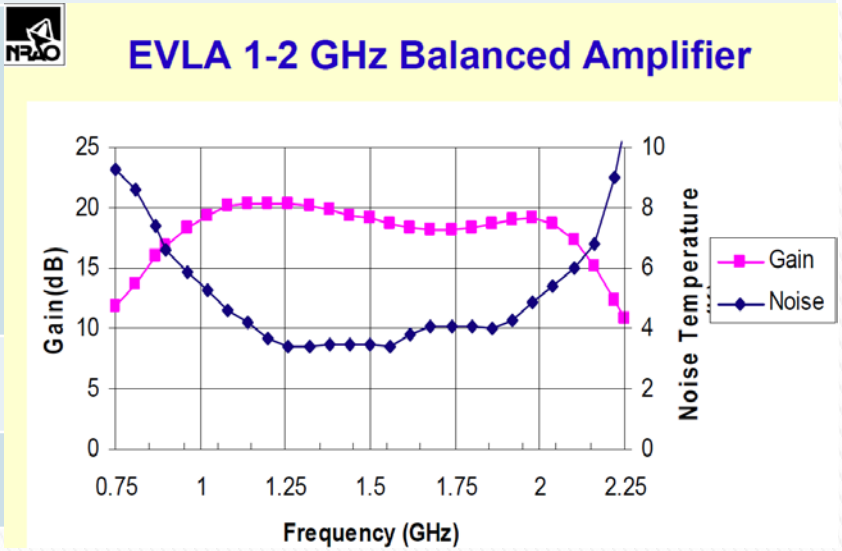


toroidal cavity with Major R=50 cm, minor r=9 cm, V~80 liters

Small toroid : sensitivity

- toroidal cavity with Major R=50 cm and minor r=9 cm
- 1.8 cm OD copper rod

search range	[1300, 1800] MHz ; ~ 600 MHz
average B	12 T
Q_L	~50,000
volume	80 liters
C_{QTM}	~0.6
T_N	T_P~100 mK with DF, T_{amp}~ 4 K with HEMT
KSVZ df/dt	455 MHz/year
DFSZ df/dt	< 10 MHz/year



Small toroid : sensitivity

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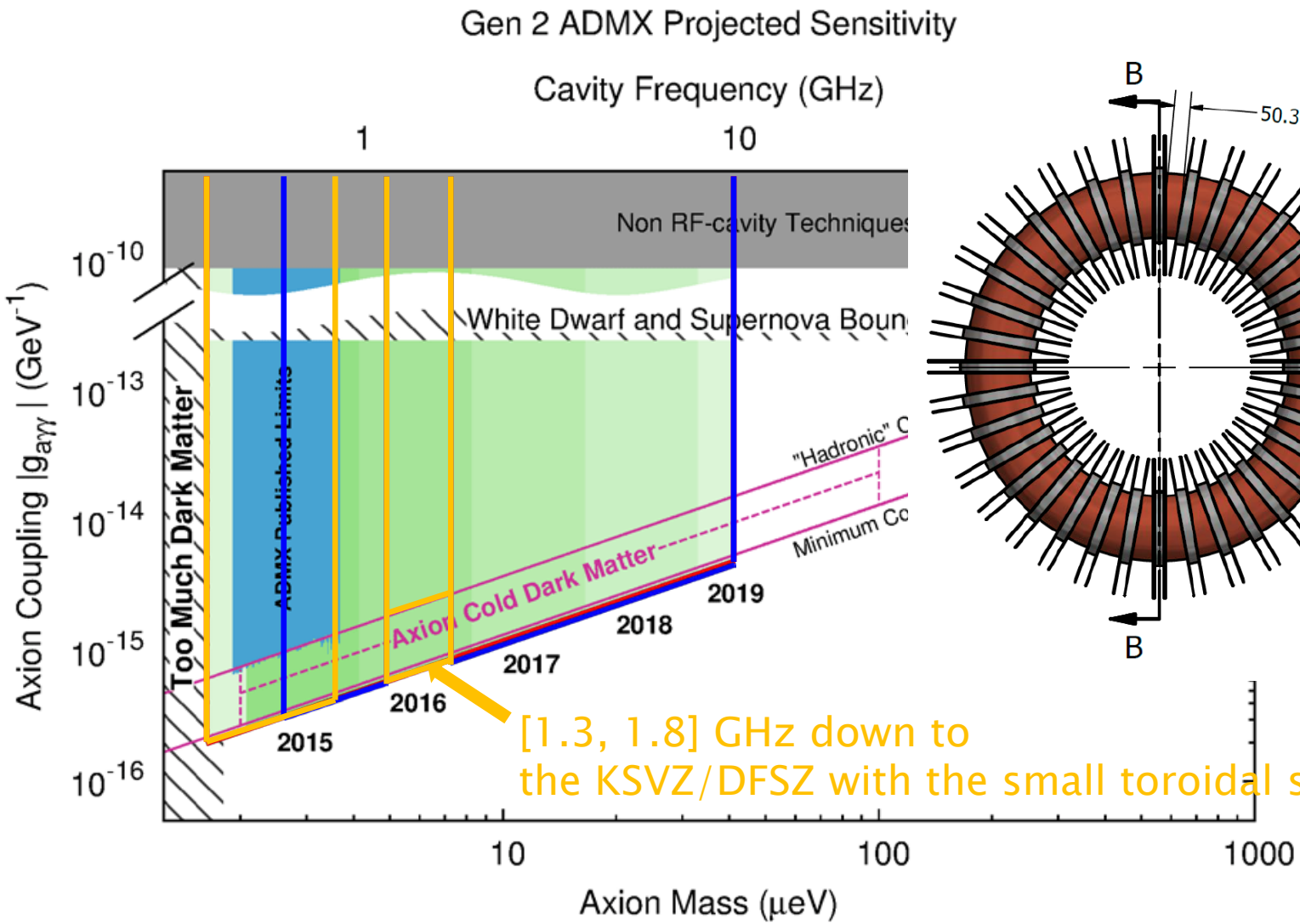
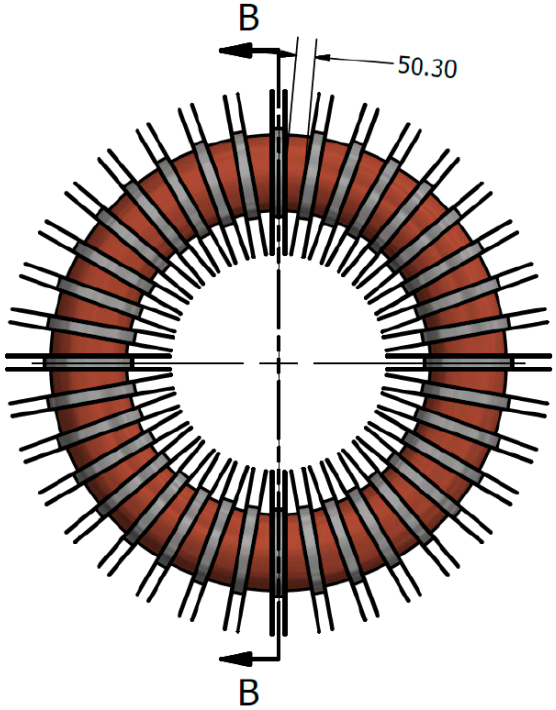
average B	12 T	
Q_L	~50,000	
volume	80 liters	
C_{QTM}	~0.6	
T_N	T_P~100 mK with DF, T_{amp}~ 4 K with HEMT	T_P~100 mK with DF, T_{amp}~T_{QN}~100 mK with SQUID
KSVZ df/dt	455 MHz/year	> 300 GHz/year
DFSZ df/dt	< 10 MHz/year	6296 MHz/year

Axion Haloscopes at CAPP/IBS

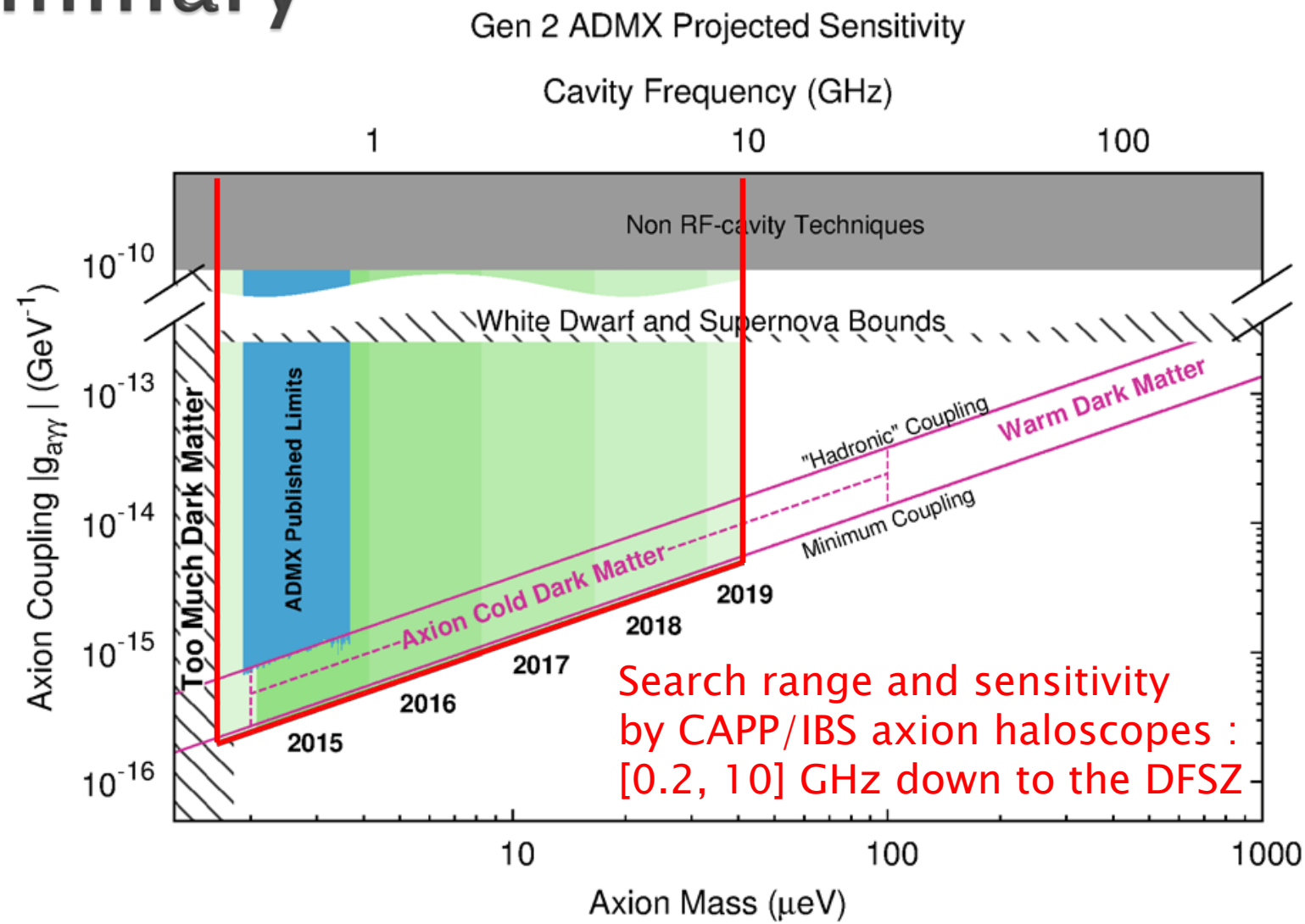




[1.3, 1.8] GHz down to
the KSVZ/DFSZ with the small toroidal system

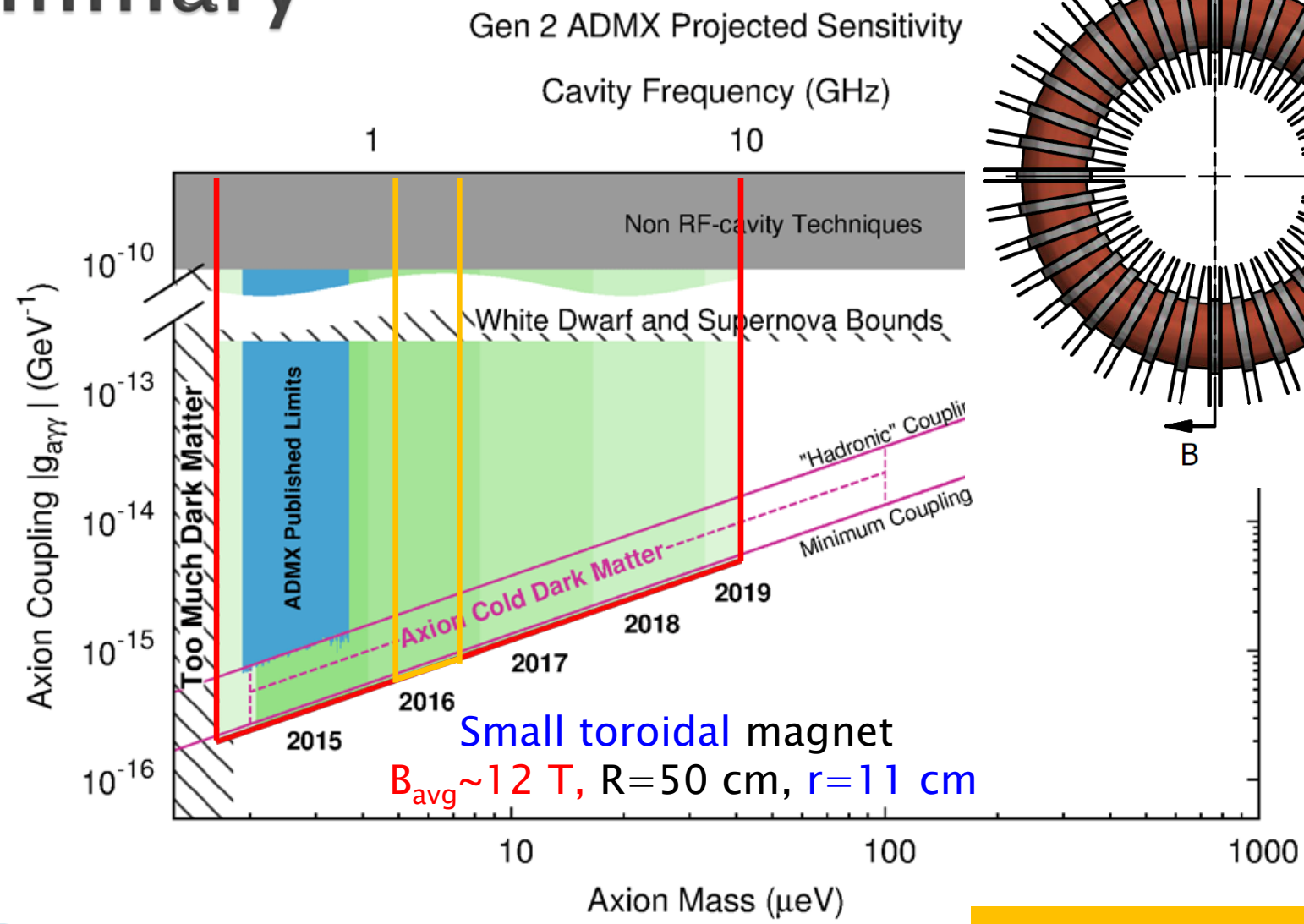
Roadmap of the CAPP/IBS axion haloscopes

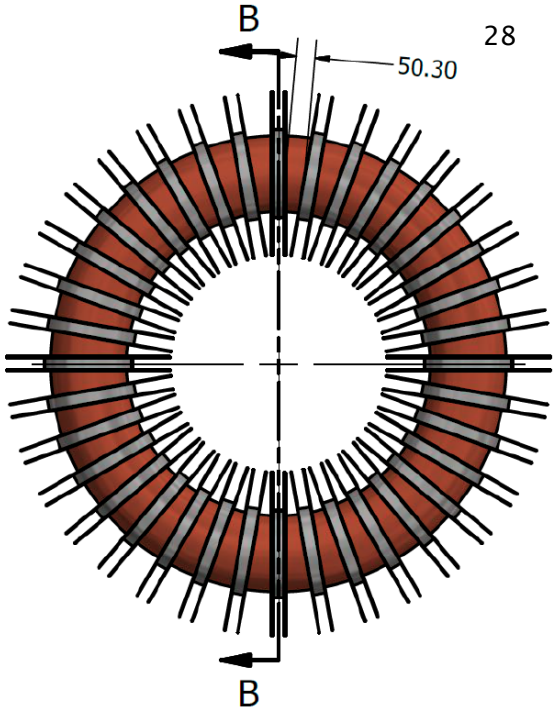
Summary



Search range and sensitivity by CAPP/IBS axion haloscopes : [0.2, 10] GHz down to the DFSZ

Summary



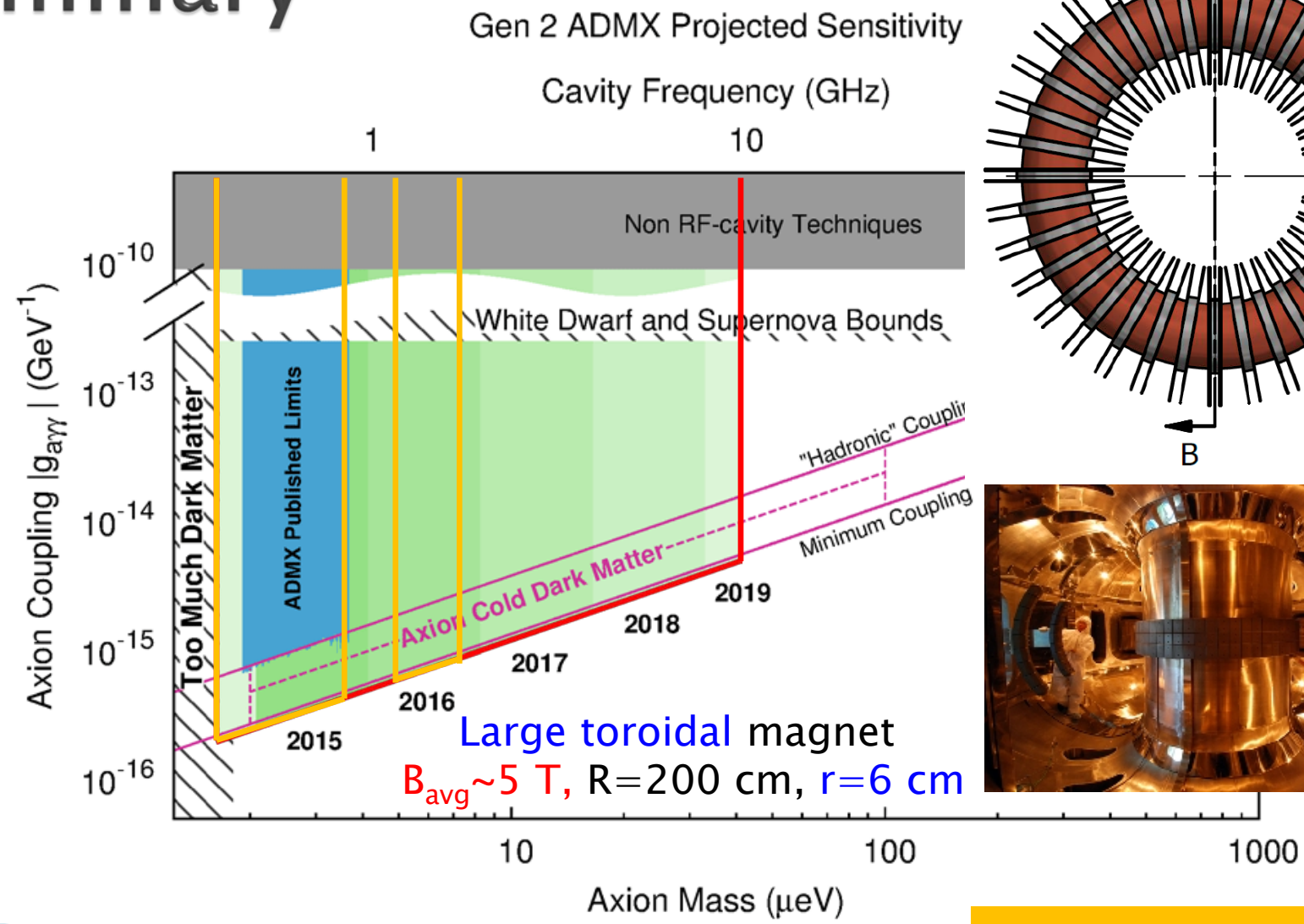


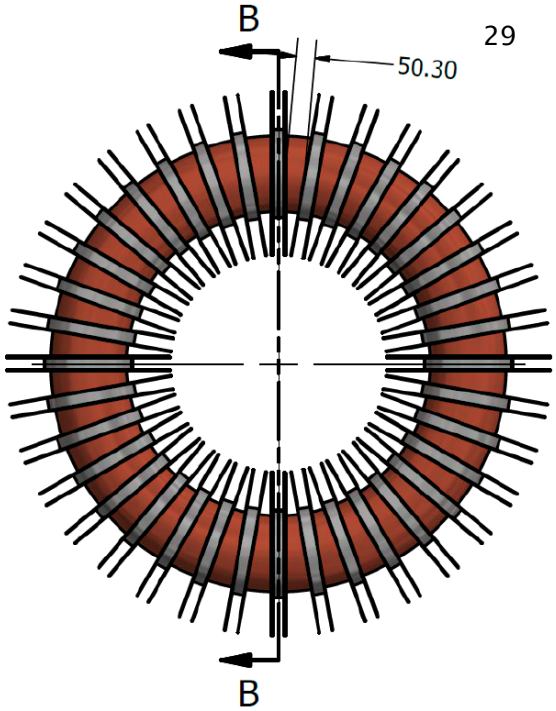
Small toroidal magnet

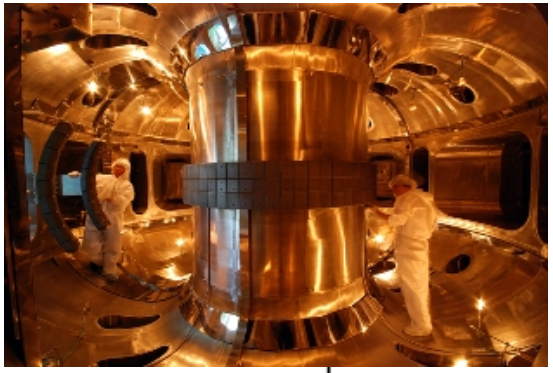
B_{avg}~12 T, R=50 cm, r=11 cm

Coming soon !

Summary





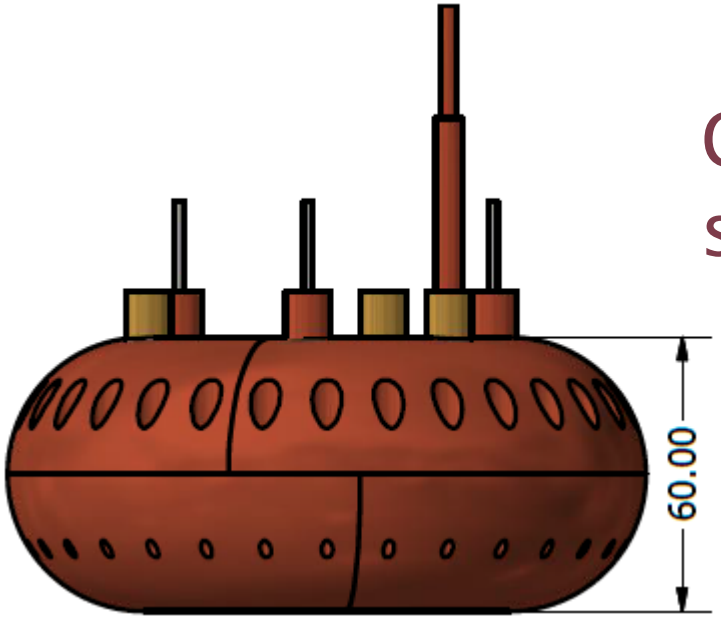


Large toroidal magnet

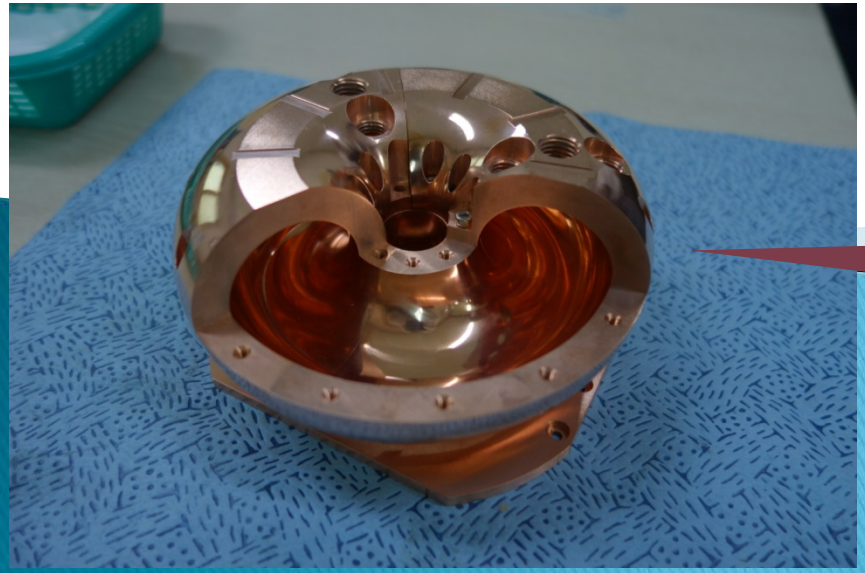
B_{avg}~5 T, R=200 cm, r=6 cm

Stay tuned !

Thank you very much for your attention



CAPPuccino submarine



See you 2017

Cylinder vs. Toroid

Modified Maxwell's equations
$B_{external}$ only, and T=0

$$\left(\begin{array}{ll} \vec{\nabla}\cdot\vec{E}_a = 0, & \vec{\nabla}\cdot\vec{B}_a = 0 \\ \vec{\nabla}\times\vec{E}_a = -\dfrac{\partial\vec{B}_a}{\partial t}, & \vec{\nabla}\times\vec{B}_a = \dfrac{1}{c^2}\dfrac{\partial\vec{E}_a}{\partial t} \end{array} \right)$$

← taking the first order in $g_{a\gamma\gamma}a$ $\because g_{a\gamma\gamma}^2 a^2 \sim O(10^{-43})$,

and using $\vec{\nabla}\times\vec{B}_{external} \sim 0$ in the both geometry

$\vec{E}_a$ and $\vec{B}_a$ induced from axions and $\vec{B}_{external}$

$$\left(\begin{array}{ll} \vec{\nabla}\cdot\vec{E} = 0, & \vec{\nabla}\cdot\vec{B} = 0 \\ \vec{\nabla}\times\vec{E} = -\dfrac{\partial\vec{B}}{\partial t}, & \vec{\nabla}\times\vec{B} = \dfrac{1}{c^2}\dfrac{\partial\vec{E}}{\partial t} \end{array} \right)$$

$\vec{E}$ and $\vec{B}$ from radiation

Cylinder vs. Toroid

Modified Maxwell's equations with the cavity boundary conditions

$B_{external}$ only, and T=0

$$\left(\begin{array}{ll} \vec{\nabla}\cdot\vec{E}_{a,c}=0, & \vec{\nabla}\cdot\vec{B}_{a,c}=0 \\ \vec{\nabla}\times\vec{E}_{a,c}=-\dfrac{\partial\vec{B}_{a,c}}{\partial t}, & \vec{\nabla}\times\vec{B}_{a,c}=\dfrac{1}{c^2}\dfrac{\partial\vec{E}_{a,c}}{\partial t} \end{array}\right)$$

• $\vec{E}_{a,c}$ and $\vec{B}_{a,c}$: known cavity modes, but MUST be induced from axions and $\vec{B}_{external}$

$$=\left(\begin{array}{ll} \vec{\nabla}\cdot\vec{E}_{a,c}=0, & \vec{\nabla}\cdot\vec{B}_{a,c}=0 \\ \vec{\nabla}\times\vec{E}_{a,c}=i\omega_a\vec{B}_{a,c}, & \vec{\nabla}\times\vec{B}_{a,c}=-\dfrac{i\omega_a}{c^2}\vec{E}_{a,c} \end{array}\right)$$

$\leftarrow E_{a,c}(t)\propto e^{-i\omega_a t}$ and $B_{a,c}(t)\propto e^{-i\omega_a t}$

$$\bullet\,\vec{E}_{a,c}\cdot\vec{E}^*_{a,c}=c^2\vec{B}_{a,c}\cdot\vec{B}^*_{a,c}-\cancel{\frac{ic^2}{\omega_a}\vec{\nabla}\cdot\left(\vec{E}^*_{a,c}\times\vec{B}_{a,c}\right)}$$

surface integral

$$\bullet\,U_{c,E}=U_{c,M}$$

• relation between electric and magnetic energy densities

taking the boundary conditions at the cavity surface, the 2nd term in right side goes to zero

Always true regardless of 1) the cavity location inside the magnet 2) solenoid or toroidal magnet

Cylinder vs. Toroid

Form Factors

- CAPP/IBS claims $U_{c,E} = U_{c,M}$ in general

$\Leftrightarrow U_{a,E} = U_{a,M}$ in general

$\Leftrightarrow C_E = C_M$ in general

if $\vec{\nabla} \times \vec{B}_{external} \sim 0$, solenoid and toroidal magnet

- $U_{a,E} = \frac{1}{2} c^2 \varepsilon_0 g_{a\gamma\gamma}^2 a_{rms}^2 B_{avg}^2 V C_E$
- $U_{a,M} = \frac{1}{2} c^2 \varepsilon_0 g_{a\gamma\gamma}^2 a_{rms}^2 B_{avg}^2 V C_M$

- under cylindrical geometry, $B_{external} \propto B_0$

– C_E : independent of the cavity location inside the solenoid

– C_M : independent of the cavity location inside the solenoid

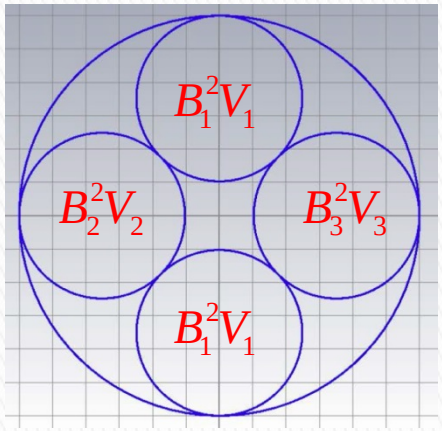
$C_E = C_M$ = constant, inside the solenoid

- $C_E = C_M$ also true for toroidal geometry

– however, under toroidal geometry, $B_{external} \propto 1/\rho$ and the $V \propto$ Major R

C_E and C_M depend on the cavity location inside the magnet

$\because C_E \leftarrow U_{a,E} \propto B_{avg}^2 V$, which depends on the cavity location



- $U_{a,E} = -\frac{1}{4}\varepsilon_0 \int_V dV \vec{E}_a \cdot \vec{E}_{a,c}$,

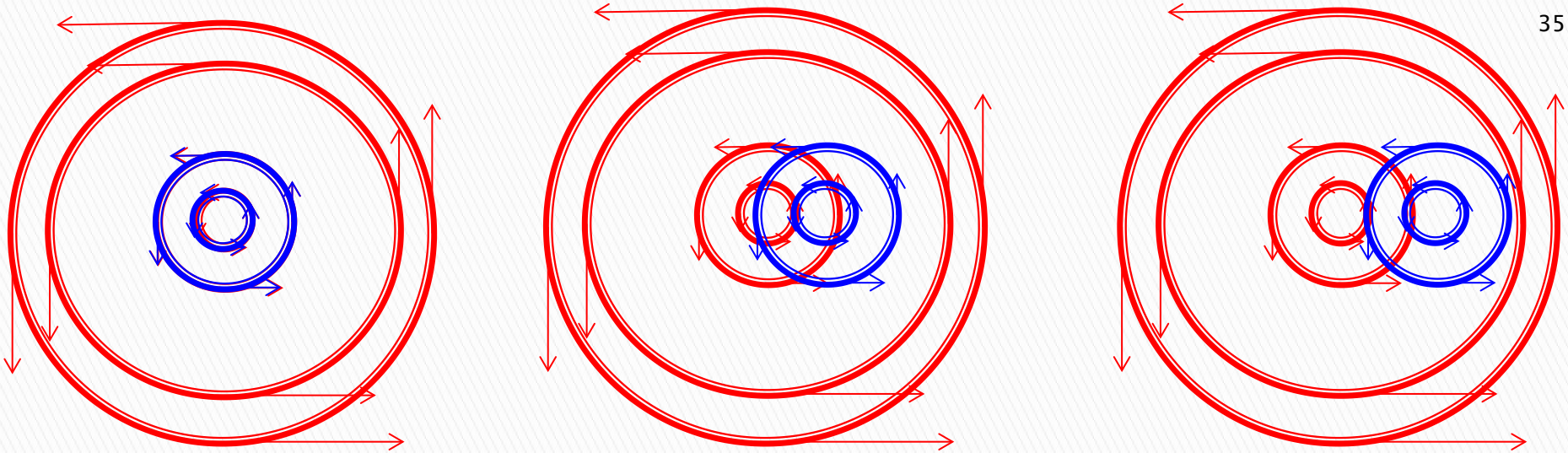
$$U_{a,M} = -\frac{1}{4\mu_0}\int_V dV \vec{B}_a \cdot \vec{B}_{a,c}$$

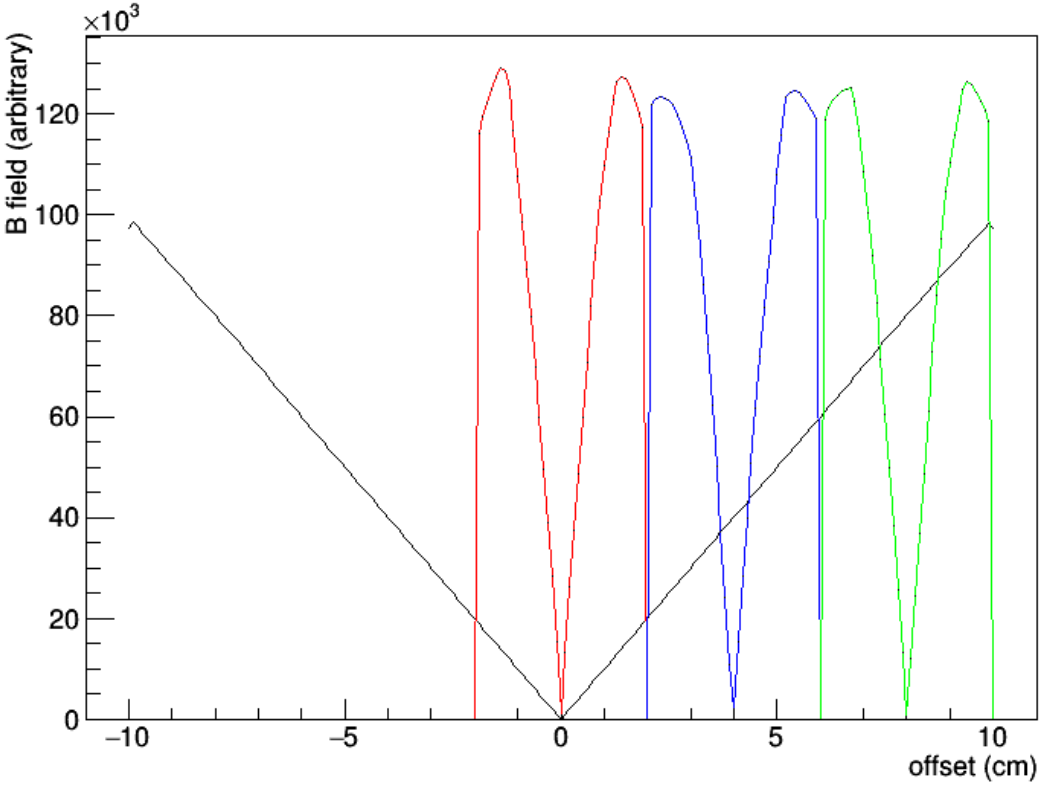
- if $\vec{B} = B_0 \hat{z}$ (cylindrical geometry),

$$\vec{E}_a = -g_{a\gamma\gamma} a c B_0 \hat{z},$$

$$\vec{B}_a = -\frac{g_{a\gamma\gamma}}{c}\frac{r}{2} B_0 \frac{\partial a}{\partial t}\hat{\phi} \text{ inside the solenoid}$$

$$\propto \frac{1}{r} \text{ outside the solenoid}$$





- $\vec{B}_{a,c} \cdot \vec{B}_a = B_{a,c} B_a \cos\phi$,

$\cos\phi$ decreasing,

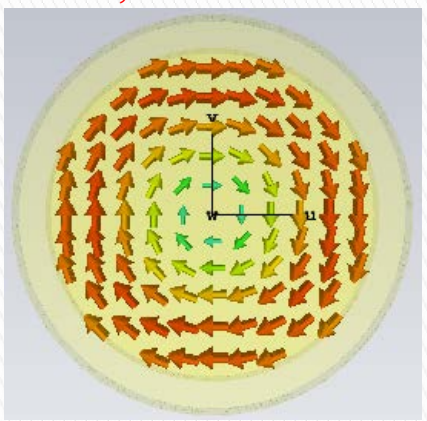
but B_a increasing

w.r.t. the offset

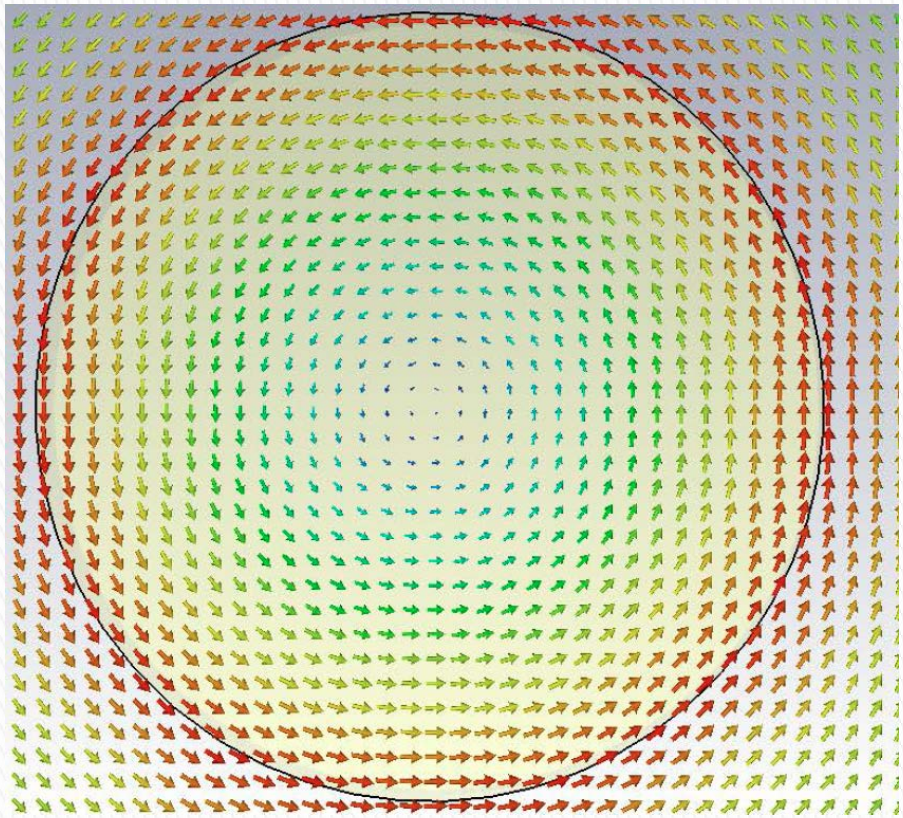
black : B_a
red : $B_{a,c}$ (no offset)
blue : $B_{a,c}$ (4 cm offset)
green : $B_{a,c}$ (8 cm offset)

–ran simulation

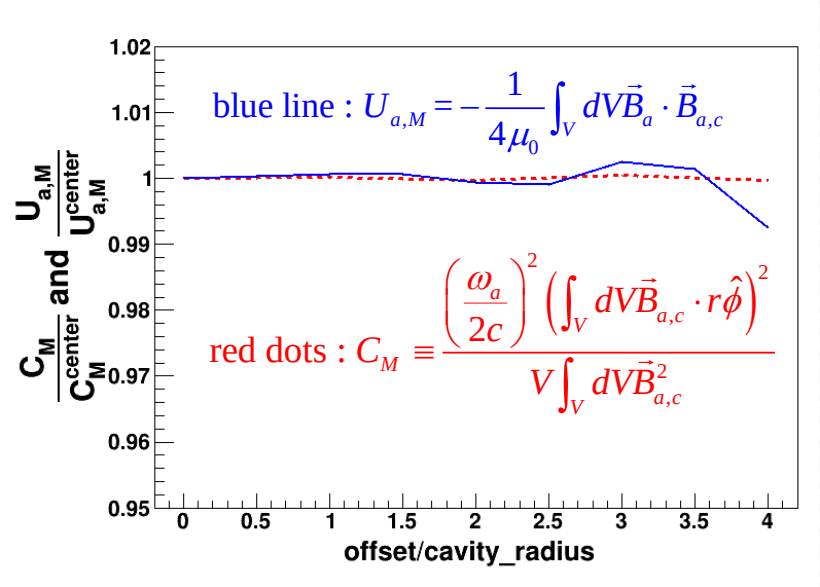
• $\vec{B}_{a,c}$: TM_{010}



• $\vec{B}_a$: put a position dependence



• calculate $U_{a,M}$ as a function of offset/cavity_radius



• $U_{a,M} \Rightarrow C_M$: shows NO cavity position dependence

Can a cavity measure solenoid position ?

Harry Themann

The Peccei-Quinn mechanism was proposed to explain the strong CP problem. It was quickly realized that this implied a new particle that was dubbed the "axion" since it "cleaned up" the strong CP problem. Consistent with the failure of early experimental searches, the constraints of existing theoretical framework and other observations, the axion is postulated to have a very weak coupling to the electromagnetic force.

In the presence of a magnetic field axions will begin to oscillate along the field lines with a frequency proportional to their mass (and momentum which is postulated to be one millionth of the mass). The present non-excluded mass range includes oscillation in the microwave region. Assuming a roughly uniform distribution of axions one can then efficiently collect this energy in a resonant cavity as long as the size is less than the deBroglie wavelength of the axion (coherent detection). The simplest configuration for a strong magnetic field in the lab is a solenoid, from this follows a cylindrical resonant cavity. This is now our frame of reference for further discussion.

Let us imagine a solenoidal magnet with a bore of radius R and that has a uniform magnetic field over this radius and length L. These dimensions are much smaller than the deBroglie wavelength. The magnet is turned on and the axions begin to oscillate parallel to the axis of the solenoid. We know from Maxwell's equations that a current in a wire has a circular magnetic field around it. We can imagine the oscillating axions as a current in a wire with a magnetic field oscillating around them.

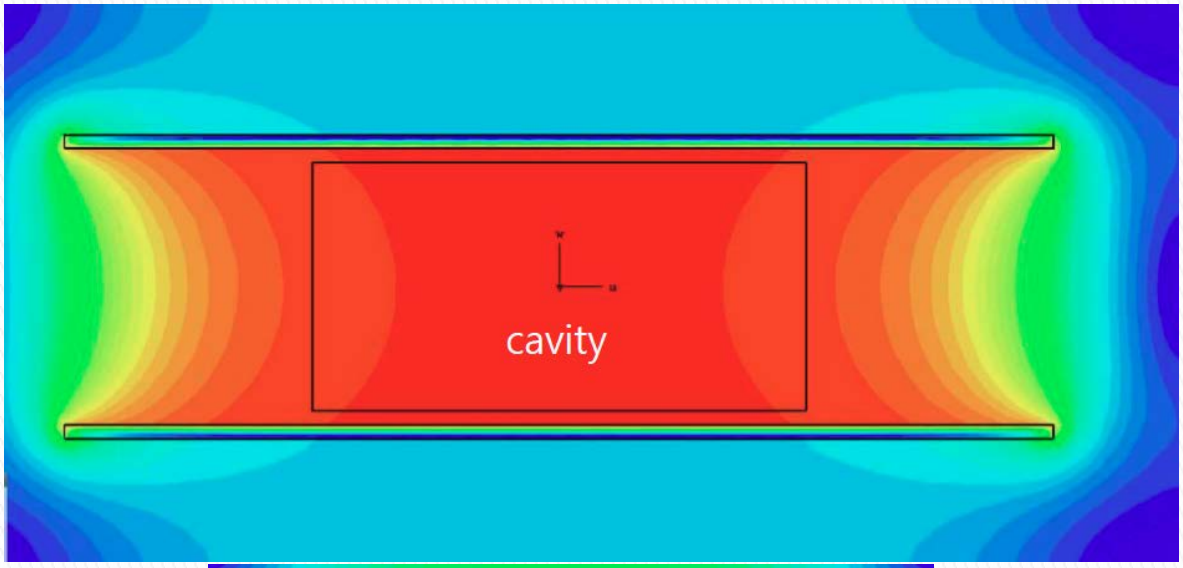
Let us imagine an Ampere's law path centered on the solenoidal axis. If we calculate the B field for increasing loop radius we will see a linear increase in the B field from the axions as long as the loop radius is less than the radius of the solenoid. We exploit this by using the TM010 mode of the cylindrical cavity in which the E field is parallel to the axis and the B field is circular about the axis going from zero in the center to a maximum at cavity perimeter. With the cavity centered in the solenoid the dot product of the axion E field to the cavity E field as well as axion B field to cavity B field is trivial as the angle between them is always zero.

Now let's imagine that we have a resonant cavity with infinitely thin walls and a radius of 1/2R and length L. This cavity can now be placed at the center of the solenoid and once again all of the fields will line up with zero degrees between them. What happens if we place the cavity at 1/2R away from the center of the solenoid? Now the angle between the two B fields goes from 0 to 360, parallel to anti-parallel and back again. But, since the B field of the axion is linearly increasing with r of the solenoid, there is no net effect on the integral of the dot product.

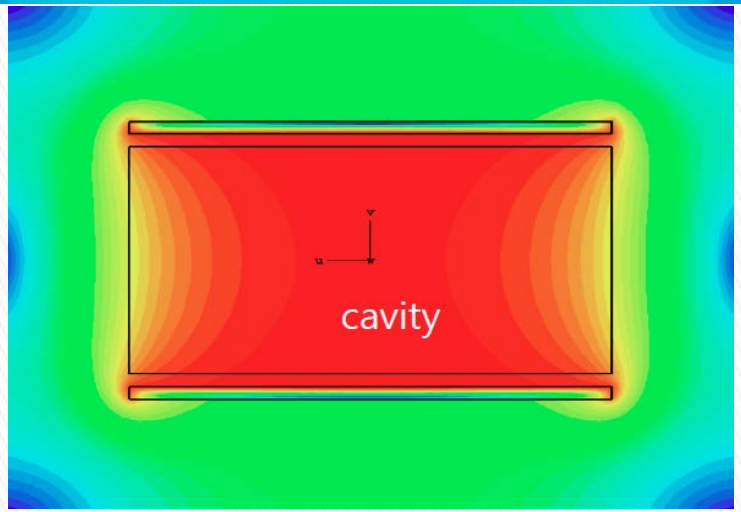
Up until this point we have been neglecting the boundary conditions imposed by the resonant cavity. We generally idealize these boundary conditions, that is we assume that only axions that oscillate within the boundaries of the cavity contribute to the power collected in the cavity. We try to make the conductivity of the walls as high as possible. Our ampere's law loop of earlier is always centered about the axis of the cavity NOT the solenoid.

Therefore, if a microwave resonant cavity is our viewing lens into our solenoid and the light passing through this lens is the collected power measured in the cavity then there is no way of knowing where the cavity is placed within the solenoid. Even if the oscillating field of the axions outside of the cavity were to influence the inside, the linearity of the field would insure that we still would not be able to know where the cavity is.

Effective volume



- $C_{TM_{010}} \sim 0.69$



- $C_{TM_{010}} \sim 0.63$

- $V_{eff,toroid} \sim 0.69 V_{magnet}$

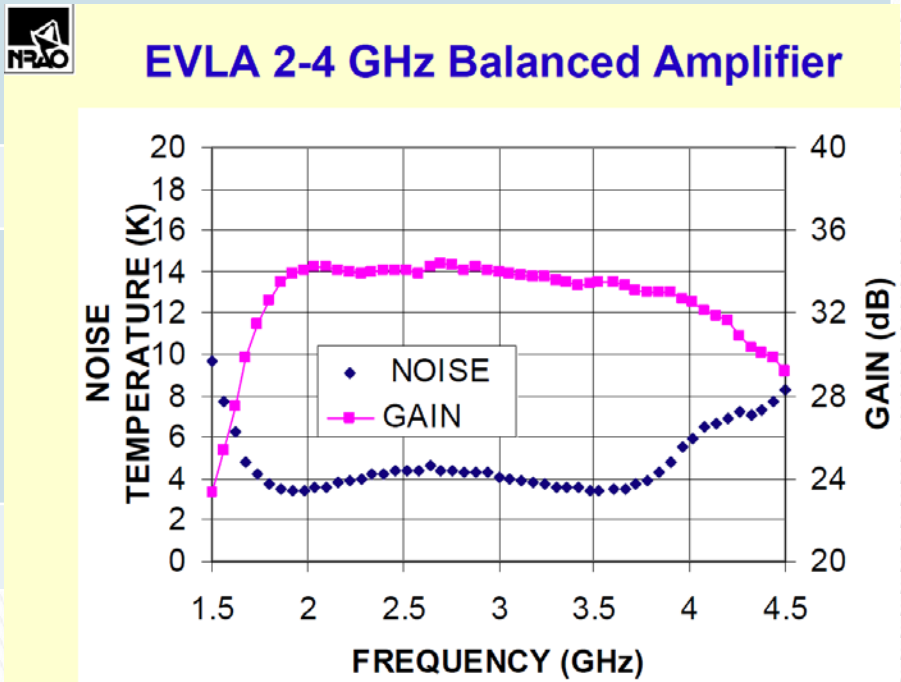
$V_{eff,cylinder} \sim 0.63 V_{magnet}$

Toroidal geometry : Ongoing

- toroidal cavity with Major R=50 cm and minor r=4 cm
- 0.8 cm OD copper rod

search range	[2.93, 3.96] GHz ~ 1 GHz
average B	12 T
Q_L	~31,000
volume	15.79 liters (single-cavity)
C_{QTM}	~0.6
T_N	T_P~100 mK with DF, T_{amp}~ 4 K with HEMT
KSVZ df/dt	0.06 GHz/year

→ not enough !



Toroidal geometry : Ongoing

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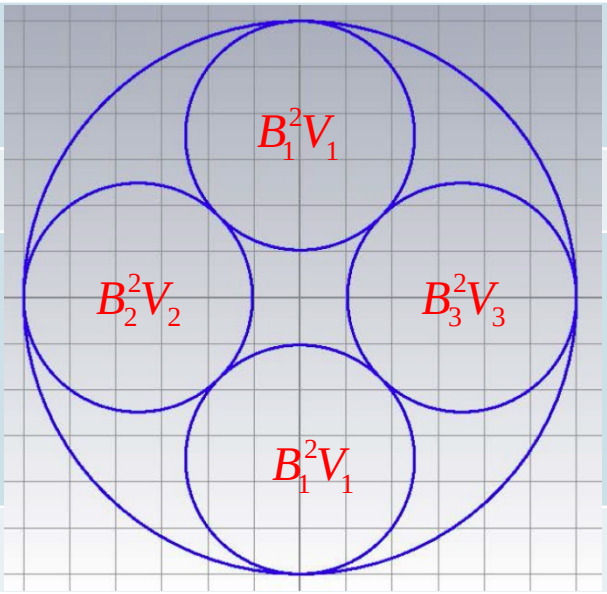
search range	[2.93, 3.96] GHz ~ 1 GHz	
average B	12 T	
Q_L	~31,000	
volume	15.79 liters (single-cavity)	15.79x4 liters (4-cavity)
C_{QTM}	~0.6	~0.6
T_N	T_P~100 mK with DF, T_{amp}~ 4 K with HEMT	T_P~100 mK with DF, T_{amp}~ 4 K with HEMT
KSVZ df/dt	0.06 GHz/year	0.98 GHz/year

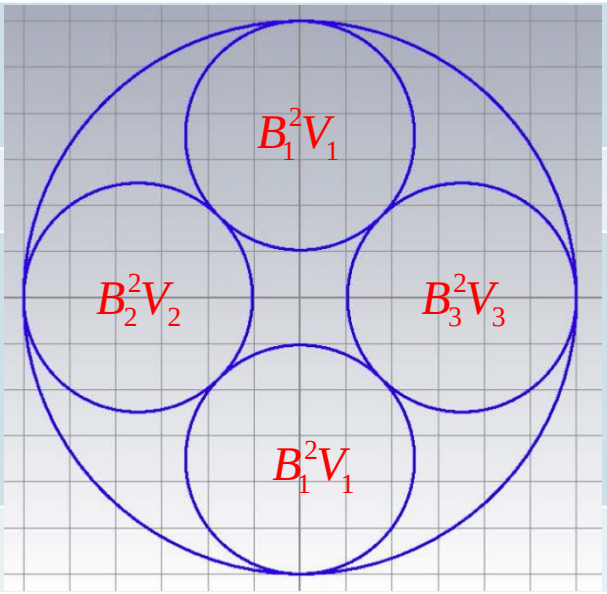


→ not enough ! → ok to go ! assume $B_1^2V_1 \simeq B_2^2V_2 \simeq B_3^2V_3$

Toroidal geometry : Ongoing

- toroidal cavity with Major R=50 cm and minor r=4 cm
- 0.8 cm OD copper rod

search range	[2.93, 3.96] GHz ~ 1 GHz	
average B	12 T	
Q_L	~31,000	
volume	15.79 liters (single-cavity)	15.79x4 liters (4-cavity)
C_{QTM}	~0.6	~0.6
T_N	T_P~100 mK with DF, T_{amp}~ 200 mK with SQUID	T_P~100 mK with DF, T_{amp}~ 200 mK with SQUID
DFSZ df/dt	0.21 GHz/year	3.34 GHz/year



assume $B_1^2V_1 \simeq B_2^2V_2 \simeq B_3^2V_3$