Axion Dark Matter searches @ IAXO

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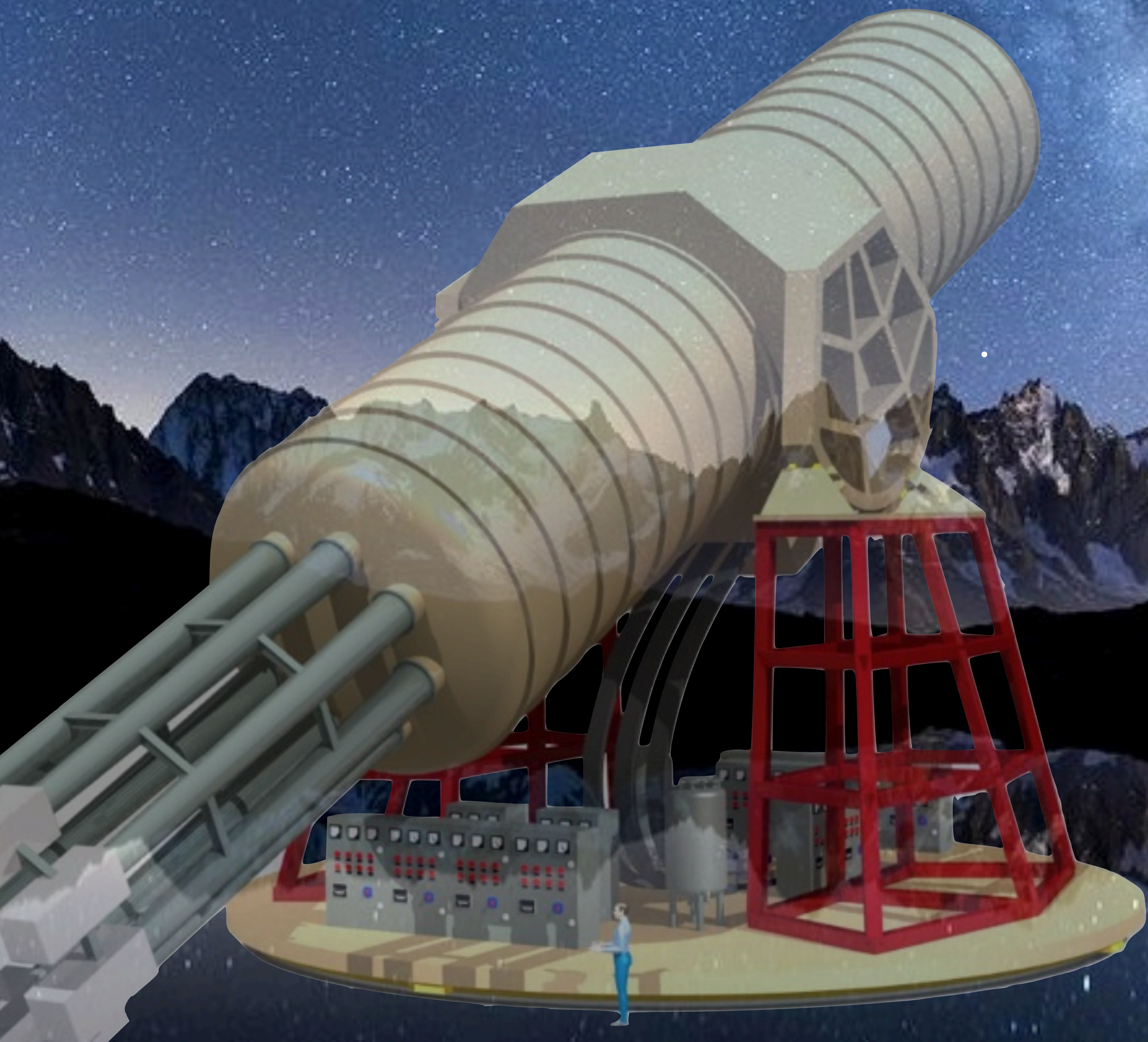


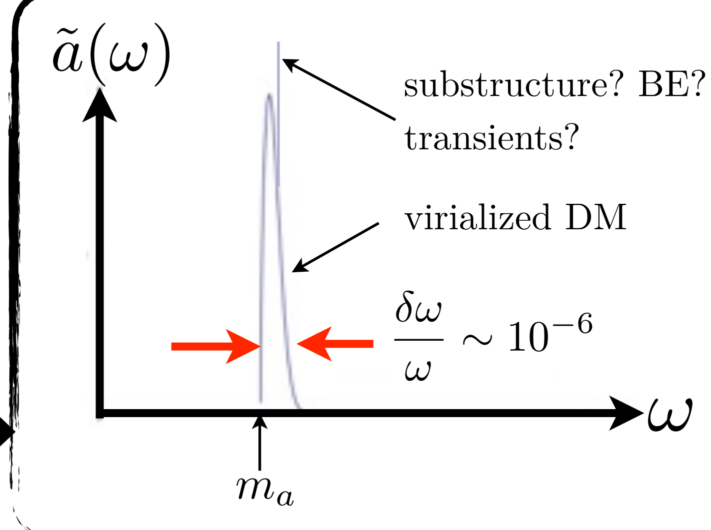
Axion Dark Matter

- Axion, $a(x)$: 0⁻ field associated with $\theta_{\rm QCD} \to a(x)/f_a$

mass, $m_a = 0.006\,\mathrm{eV}\,\dfrac{10^9\,\mathrm{GeV}}{f_a}$

couplings, $\propto \dfrac{1}{f_a}$

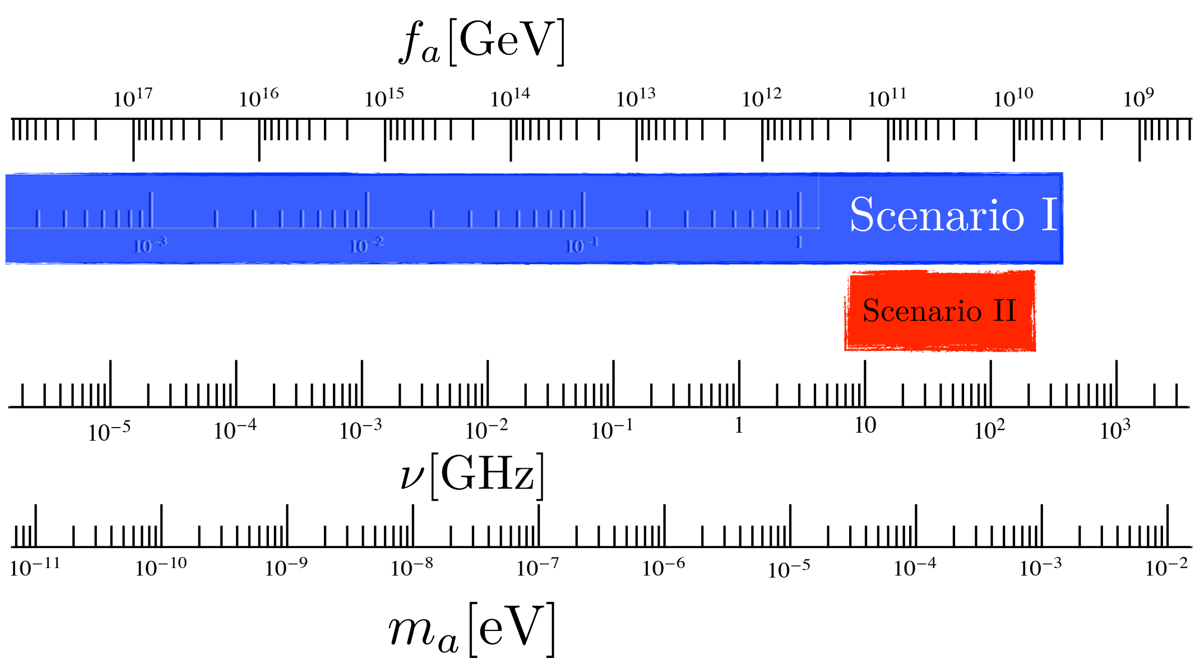
- Cold Dark Matter as a classical field $a(t) \sim a_0 \cos(m_a t)$



- Local DM density: $\rho_{\rm CDM} \equiv \frac{1}{2} m_a^2 a_0^2 \simeq 0.3 \frac{\rm GeV}{\rm cm^3} \to \theta(t) \sim \mathcal{O}(10^{-19})$

- Predictions:

Observed relic density?



Effects depend on couplings

$\frac{\alpha_s}{8\pi} G\widetilde{G}\theta(t)$ → oscillating neutron EDM
$d_n \sim \mathcal{O}(10^{-34}\,\mathrm{e\,cm}) \times \cos(m_a t)$

$c_\gamma \frac{\alpha}{2\pi} \mathbf{E}\cdot\mathbf{B}_{\rm ext}\,\theta(t)$ → Electric (magnetic) fields
$E \sim \mathcal{O}(10^{-12}\,\mathrm{V/m}) \frac{|\mathrm{B_{ext}}|}{10\,\mathrm{T}} c_\gamma \times \cos(m_a t)$
$B \sim \mathcal{O}(10^{-20}\,\mathrm{T}) \frac{|\mathrm{B_{ext}}|}{10\,\mathrm{T}} c_\gamma \times \cos(m_a t)$

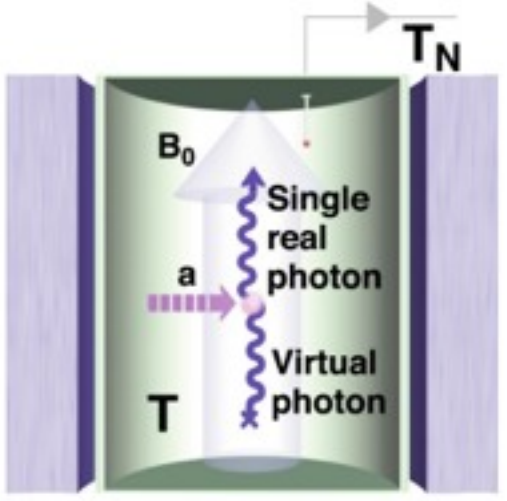
$c_\gamma \frac{\alpha}{2\pi} \mathbf{E}\cdot\mathbf{B}\,\theta(t)$ → pol. & freq. changes
cosmic rays

$\bar{\psi}\gamma_5\gamma_\nu\psi\,\partial^\mu\theta(t)$ → Spin precession
freq. dep. forces

Detecting EM fields from Axion Dark Matter

- Haloscope (Sikivie 83)

"Amplify resonantly the EM fields created by axionDM in a B-field in a cavity"



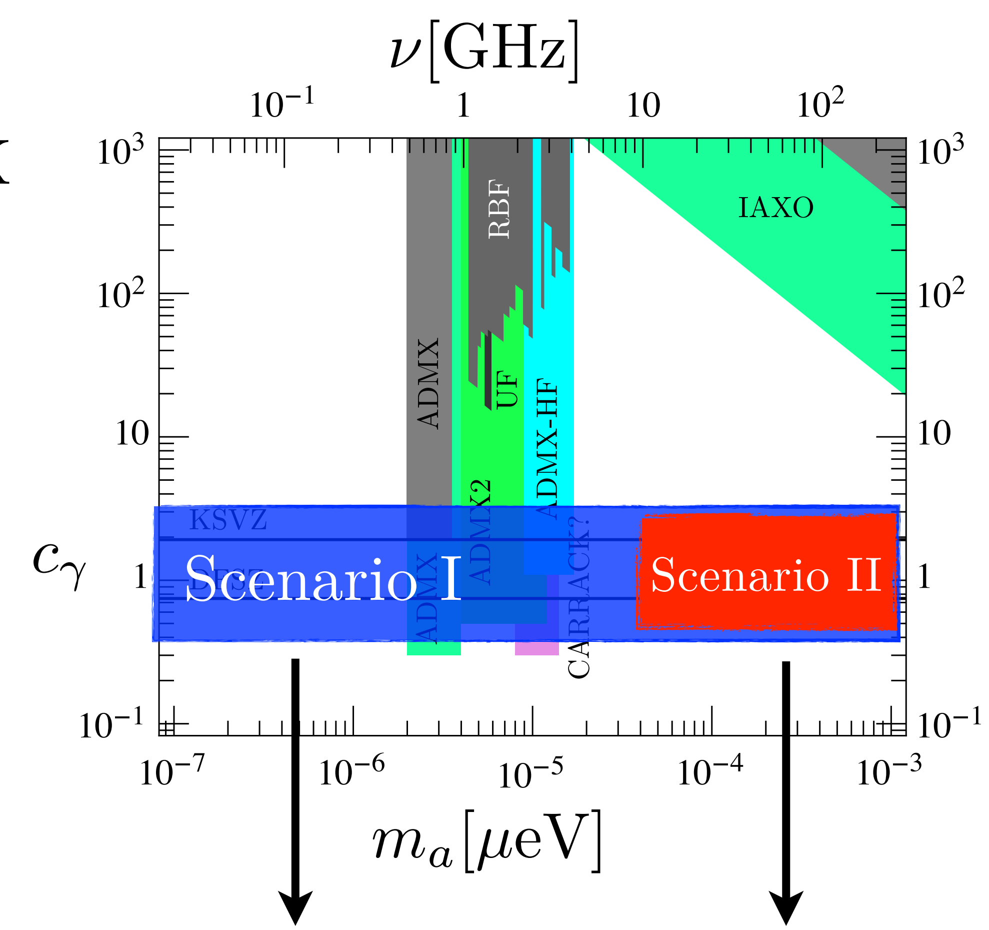
$$P_{\rm out} = \kappa\, \rho_{\rm CDM} \left(\frac{c_\gamma \alpha |\mathbf{B}|}{2\pi f_a m_a}\right)^2 [V\, m_a]\, \mathcal{G}\, Q \qquad \text{(on resonance)}$$

$$|E_a|^2 \propto c_\gamma^2 B^2$$

- Past experiments Florida U., RBF, ADMX, CARRACK
- Future endeavors: ADMX, ADMX-HF, YMCE, CAPP
- Parameters unexplored at low and high masses: WHY?

Cylindrical cavity $(h/r{=}b)$ like ADMX but scaled

- Signal $\quad (V \propto m_a^{-3}) \quad P_{\rm out} \propto V m_a \sim \frac{1}{m_a^2}$
- Noise $\quad P_{\rm noise} = T_{\rm sys} \Delta\nu_a \propto m_a^2$
- Signal/noise in $\Delta\nu_a$ of time, t, $\frac{S}{N} = \frac{P_{\rm out}}{P_{\rm noise}} \sqrt{\Delta\nu_a t}$
- Scanning rate $\frac{1}{m_a}\frac{d\Delta m_a}{dt} \propto \frac{c_\gamma^4}{m_a^9}$



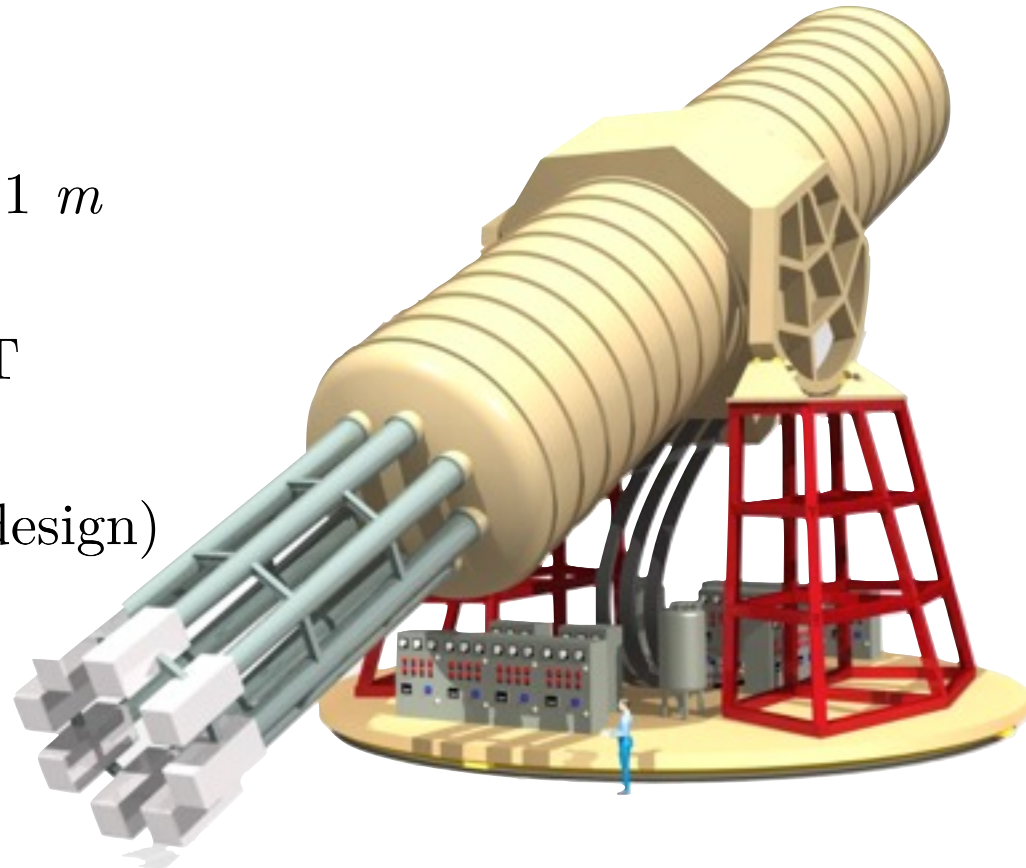
Very easy, but needs large magnet volume! IAXO!!!!!!!!!!!!!!!!!!!!!

Very complicated, needs new ideas...

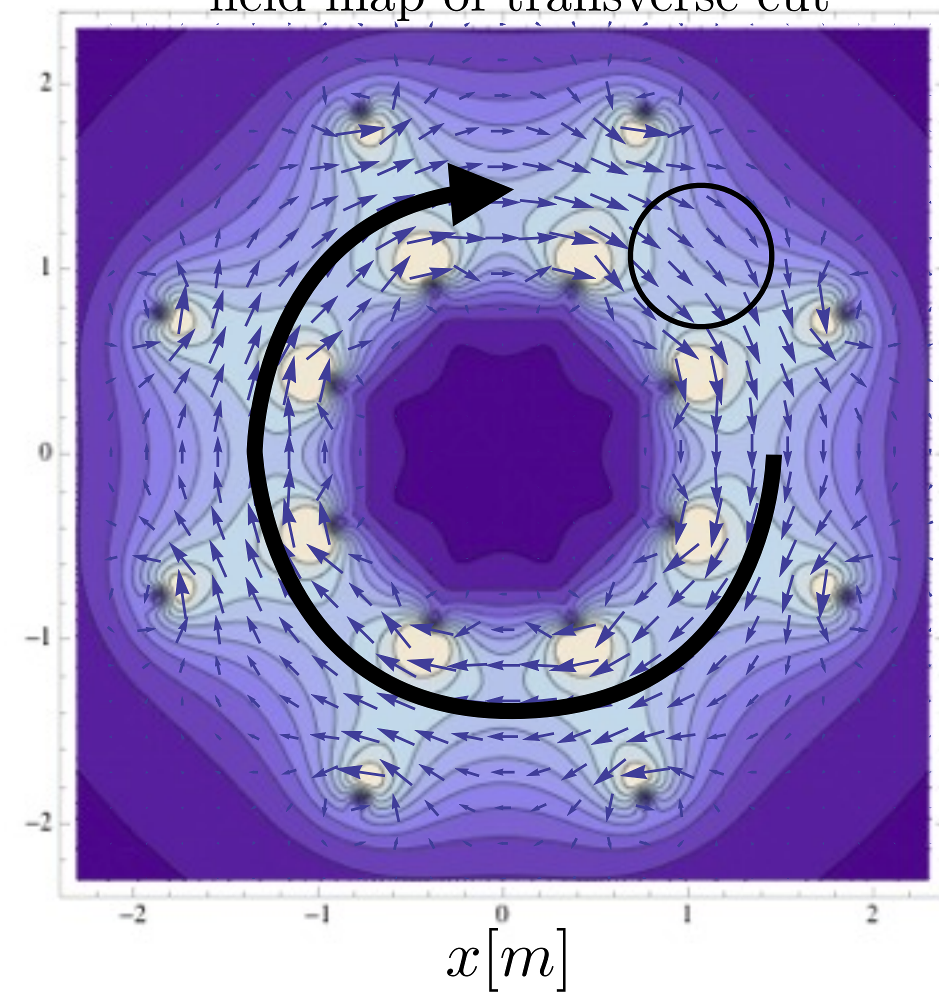
IAXO magnet

(Shilon *et al JINST 9 (2014) T05002*

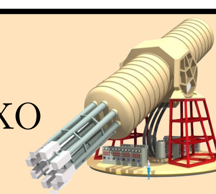
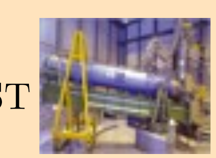
- Length $= 20\ m$
- Magnetised radius $\sim 1\ m$
- Peak value ~ 5.4 T
- Average in bore 2.5 T
- Available T ~ 4.5 K
  (but warm bores in design)



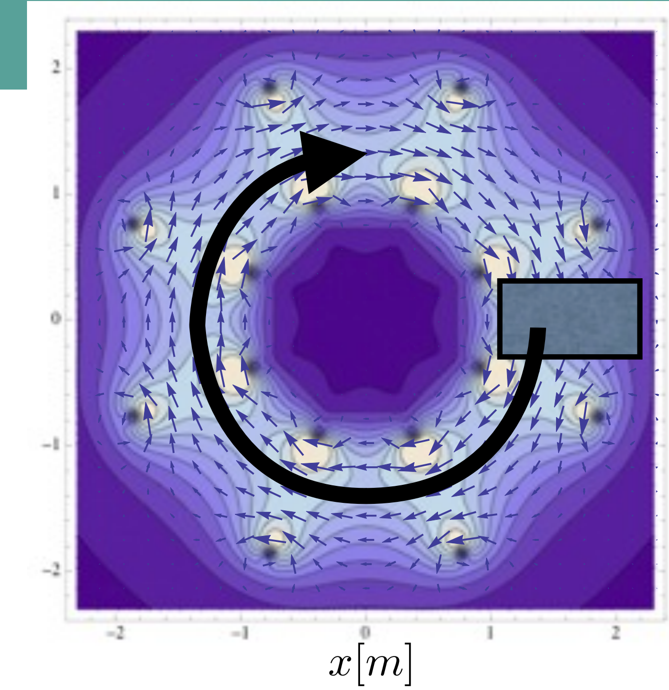
field map of transverse cut



- Comparison B^2V with other haloscope magnets is promising

	ADMX 	ADMX-HF 	IAXO 	CAST 
B [T]	8	9	2.5 *	9
Dimensions [cm]	h,R=100,21	h,R=25,5	h,R^*=2000,30	h,R=920,2.2
V [L]	140	2	8 x 1700	2 x 14
$P_{\rm out} \propto \lvert\mathbf{B}\rvert^2 V$ [T^{2}L]	9000	160	8 x 35000	2 x 1100

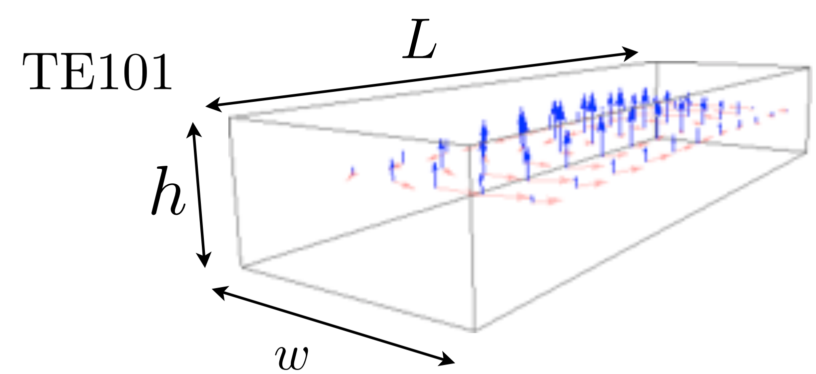
Low mass axion DM search in IAXO



- Geometry is not optimal for cylindrical cavity
- Use a big rectangular cavity (Baker *et al*, PRD D85 035018)

$$\omega^2_{nml} = \left(\frac{n\pi}{w}\right)^2 + \left(\frac{m\pi}{h}\right)^2 + \left(\frac{l\pi}{L}\right)^2$$

- w =1 m, h =0.5 m, L = 20 m



- Searching in the fundamental mode TE101

$$\omega_{101} \sim \frac{\pi}{w} \sim 0.6\,\mu\mathrm{eV}\frac{1\,\mathrm{m}}{\mathrm{w}}$$

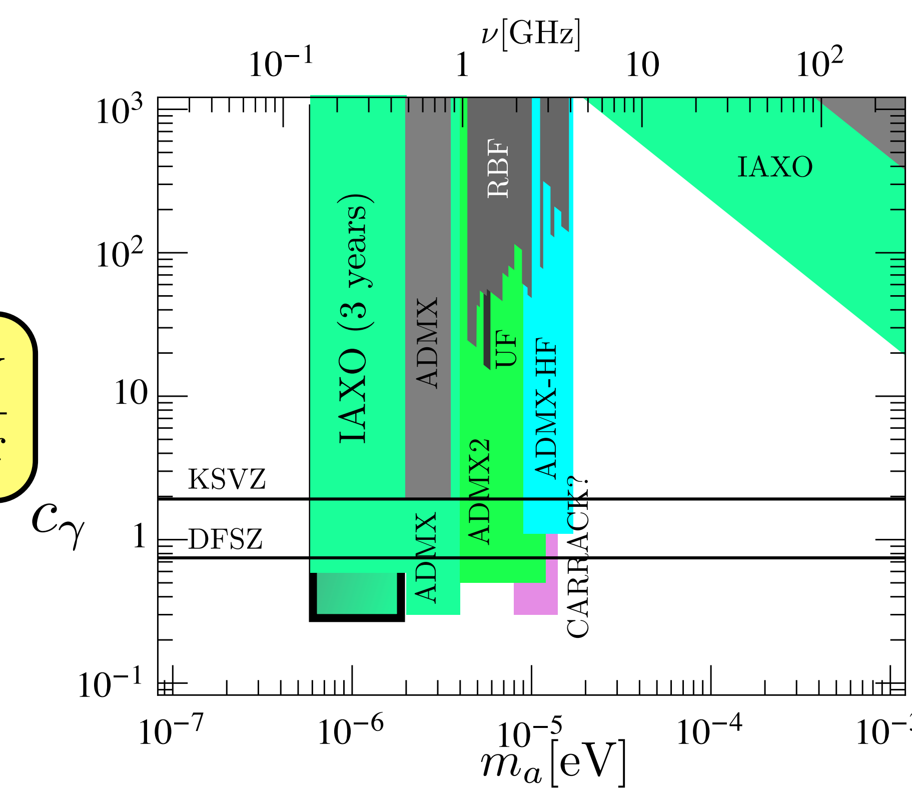
$$\mathcal{G} = \frac{64}{\pi^4} = 0.66$$

$$Q(w, h \ll L) \sim \frac{2\pi}{\omega_{101}\delta}\frac{h}{2w+4h}$$

- Very preliminary/rough and conservative estimates

$$\frac{S}{N} = 2\,c_\gamma^2\left(\frac{B}{2.5\mathrm{T}}\right)^2\left(\frac{5.5\,\mathrm{K}}{T_{\rm sys}}\right)\frac{\mathcal{G}}{0.65}\left(\frac{Q}{3.5\times10^5/\sqrt{m_6}}\right)\sqrt{\frac{t}{1\mathrm{min}}}$$

$$\left.\frac{dm_a}{dt}\right|_{S/N=3} \sim 4\,c_\gamma^4\,\frac{\mu\mathrm{eV}}{\mathrm{year}}$$

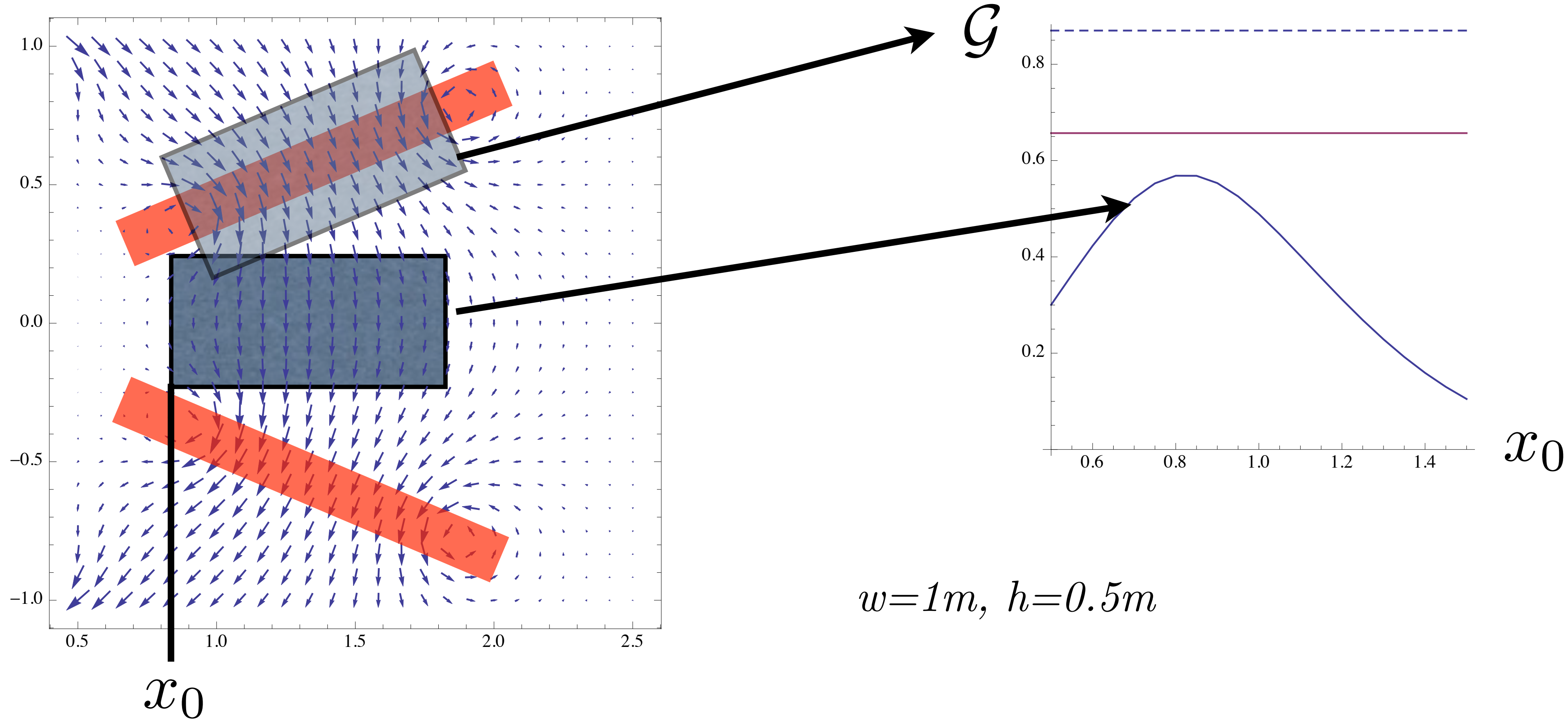


- Possible (cryo. to 1+ K, best magnet position)

more...

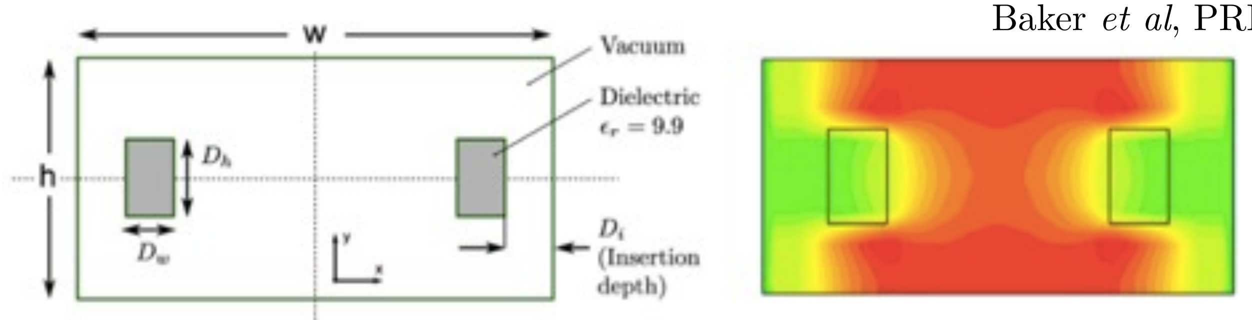
- High Q cavity requires good stability of temperature, mechanical vibrations, etc...
- Not compatible with solar tracking (?)
- After IAXO solar run
- Up to 8 cavities!

- Optimise the location and compare with in-coil configuration



- Tunning; dielectric rods, other ideas

Baker *et al*, PRD D85 035018



high mass axion DM searches ... ideas

- Boost all ADMX-like parameters (with ADMX-HF), CAPP
  - develop Q-limited amplifies beyond 10 GHz (SQUIDs, JPAs: Shokair *et al* 1405.3685)
  - bolometers (CARRACK, Lamoreaux 1306.3591)
  - superconducting films to boost Q (Shokair *et al* 1405.3685)
  - multirod cavities
  + combine cavities (Kinion, UMI-30-19020)

+ Rectangular cavities (Baker *et al*, PRD D85 035018)

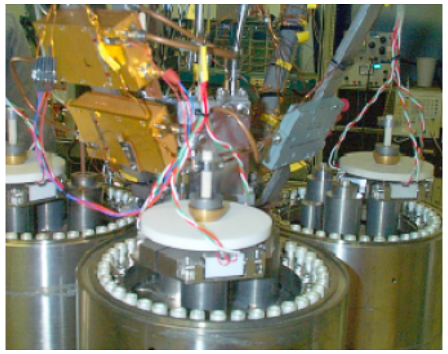
+ Dish antenna (Horns *et al* JCAP04(2013)016)

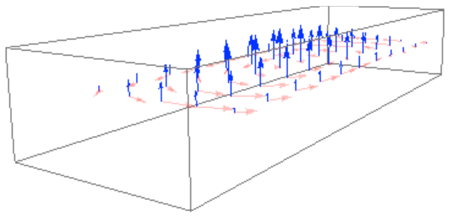
+ Dielectric mirrors (Jaeckel PRD 88 (2013))

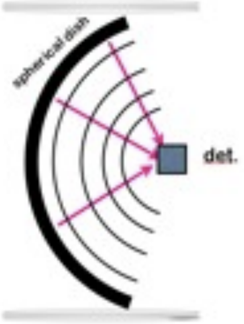
- Open resonators (Hong *et al*, 1403.1576)

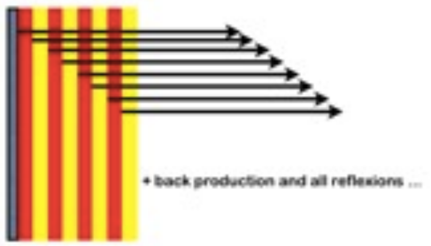
- Fabry-Perot resonators (Rybka, 1403.3121)

- Dielectric resonators (Jaeckel Ringwald, PLB659 509)





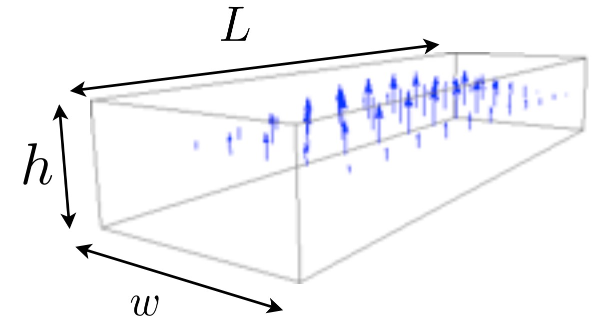




Rectangular cavities

- fixed m_a, maximise power?

TE101



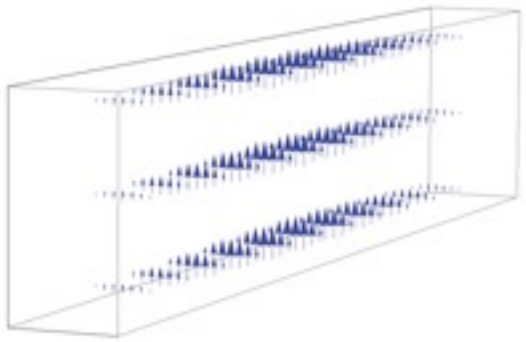
$$P \propto [V m_a]\mathcal{G}Q \sim [whLm_a]\frac{64}{\pi^4 n^2}\frac{1}{\omega\delta}\frac{h}{4h+2w} \to hL\frac{1}{m_a}$$

tune $m_a = \omega_{n01} \sim \dfrac{n\pi}{w}$

(independent of n...)

maximise transverse area!

TE101



not the fundamental!

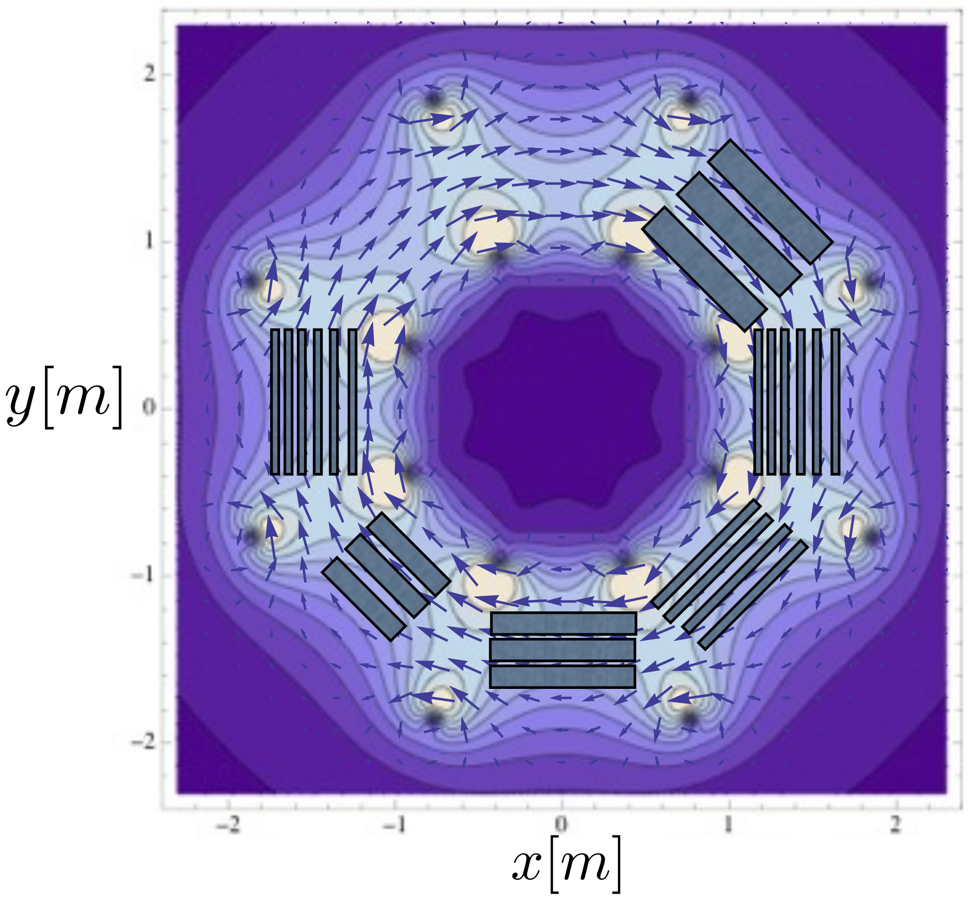
Crossings with TE0ml (avoided?, coupling?)

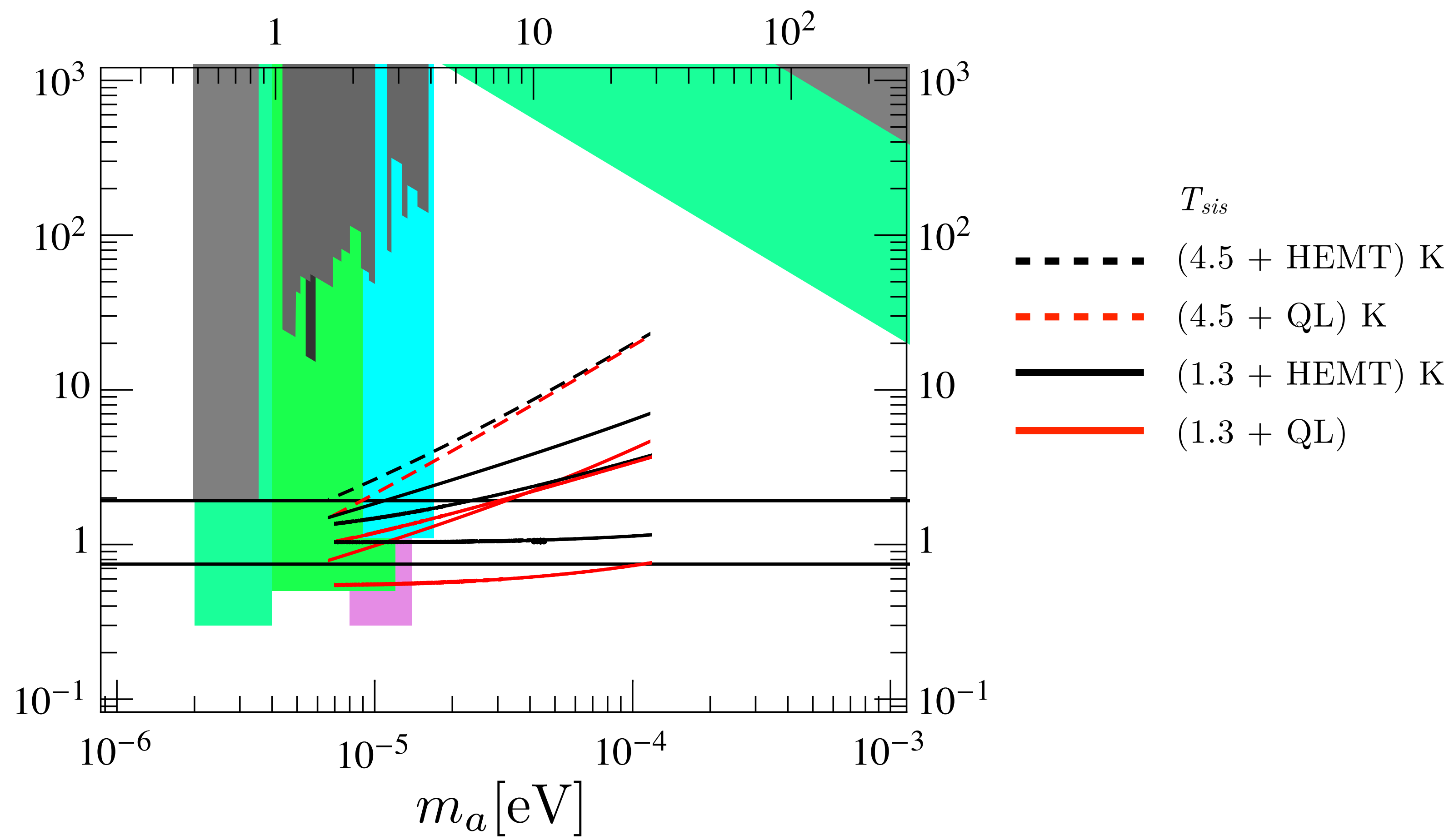
R+D in progress (B. Gimeno Valencia U., J.D. Gallego, Yebes O.)

- cavity(s) to reach SCENARIO-II ?

Flat rectangular cavities

- h=1 m, L=20 m, w tuned to m_a, ~40 cavities (15% tuning), 1 year



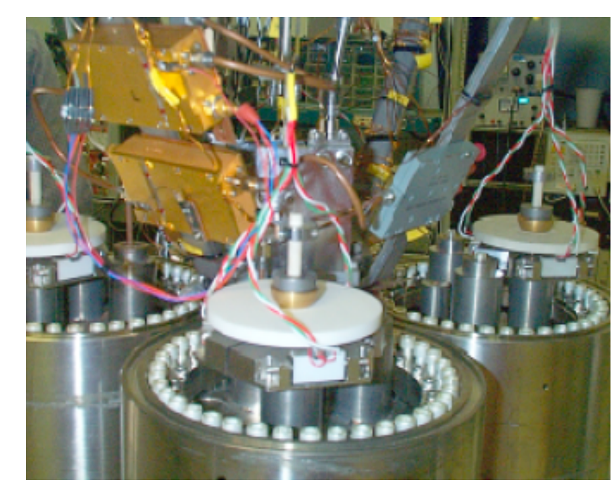


- Boost the power even more by combining N equal cavities <u>coherently</u> (high Q?)

$$\frac{1}{m_a}\frac{dm_a}{dt} \propto \frac{1}{Q}\left(\frac{P_{\rm out}}{T_{\rm sis}}\right)^2 \propto c_\gamma^4\, Q\, V^2 \times N^2$$

trade part of the Q for a large number

prospects ranging 1-100 (# with increasing mass), (Q=3000 to 500)



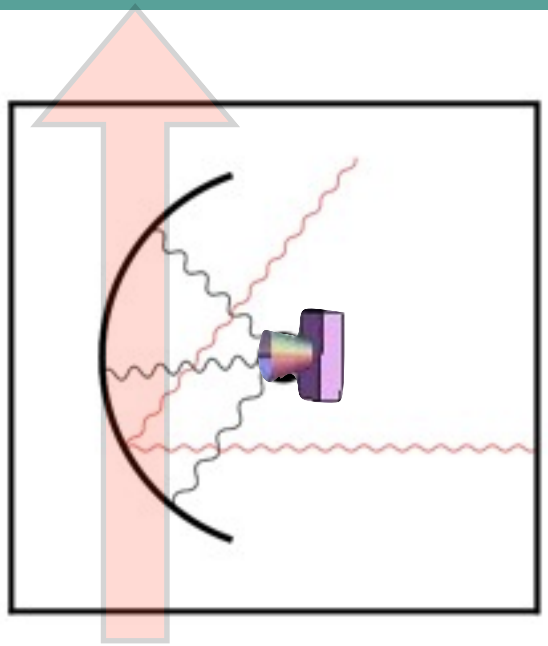
Kinion, UMI-30-19020

Dish Antenna

(Horns *et al* JCAP1304016, Jaeckel & JR JCAP1311016, PRD 88, 2013)

- Trade cavity's Q for volume (well... area...) $[Vm_a]\mathcal{G}Q \leftrightarrow A$

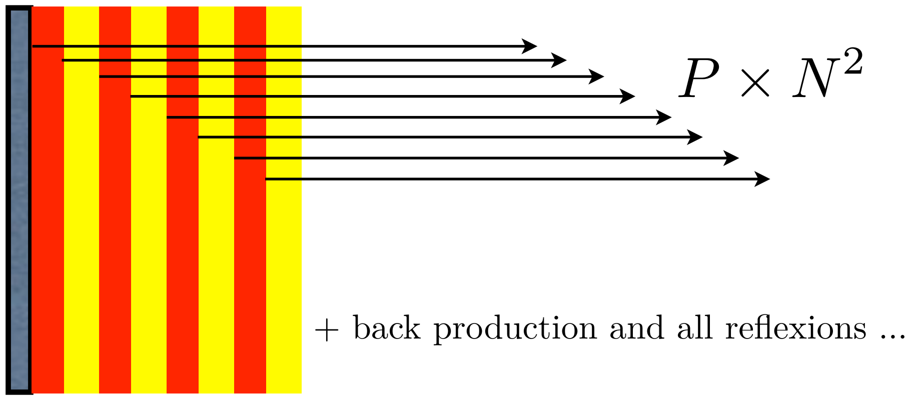
$$P_{\rm out} \simeq \rho_{\rm CDM}\left(\frac{c_\gamma \alpha |\mathbf{B}|}{2\pi f_a m_a}\right)^2 A$$



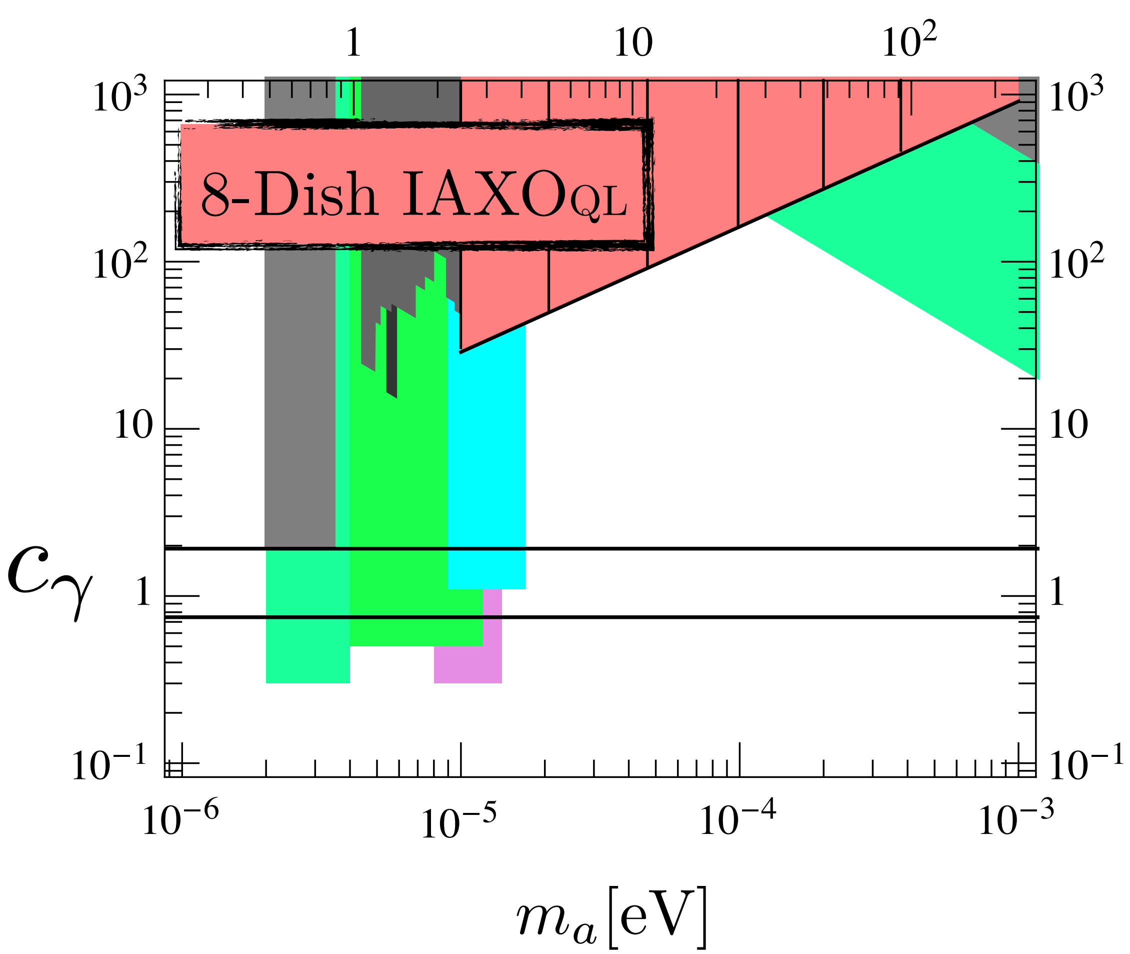
- **Broadband** (cavity has to tuned to get Q),
here the band is limited by amplifier noise and gain (1 octave)

- IAXO (B~ 2.5 T, A ~ 1 m^2, t=$year$, T_{sis}=QL)
is NOT enough for $\rho_{\rm CDM} = 0.3{\rm GeV/cm^3}$

- Dielectric layers enhance the emission (in phase)



Alternating N layers of low/high, $\lambda/2$
turn your "dielectric mirror" into a resonator, (+narrows the band)
Enhancements Q~ N^2 are feasible in small bands $\Delta m_a \sim m_a/N^2$



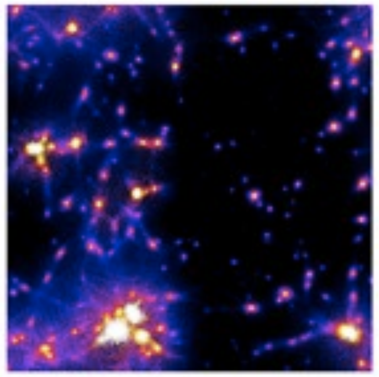
Dish Antenna

(Horns *et al* JCAP1304016, Jaeckel & JR JCAP1311016, PRD 88, 2013)

- IAXO (B~ 2.5 T, $A \sim 1\ m^2$, t=*year*, T_{sis}=QL)
  is NOT enough for $\rho_{\rm CDM} = 0.3{\rm GeV/cm^3}$

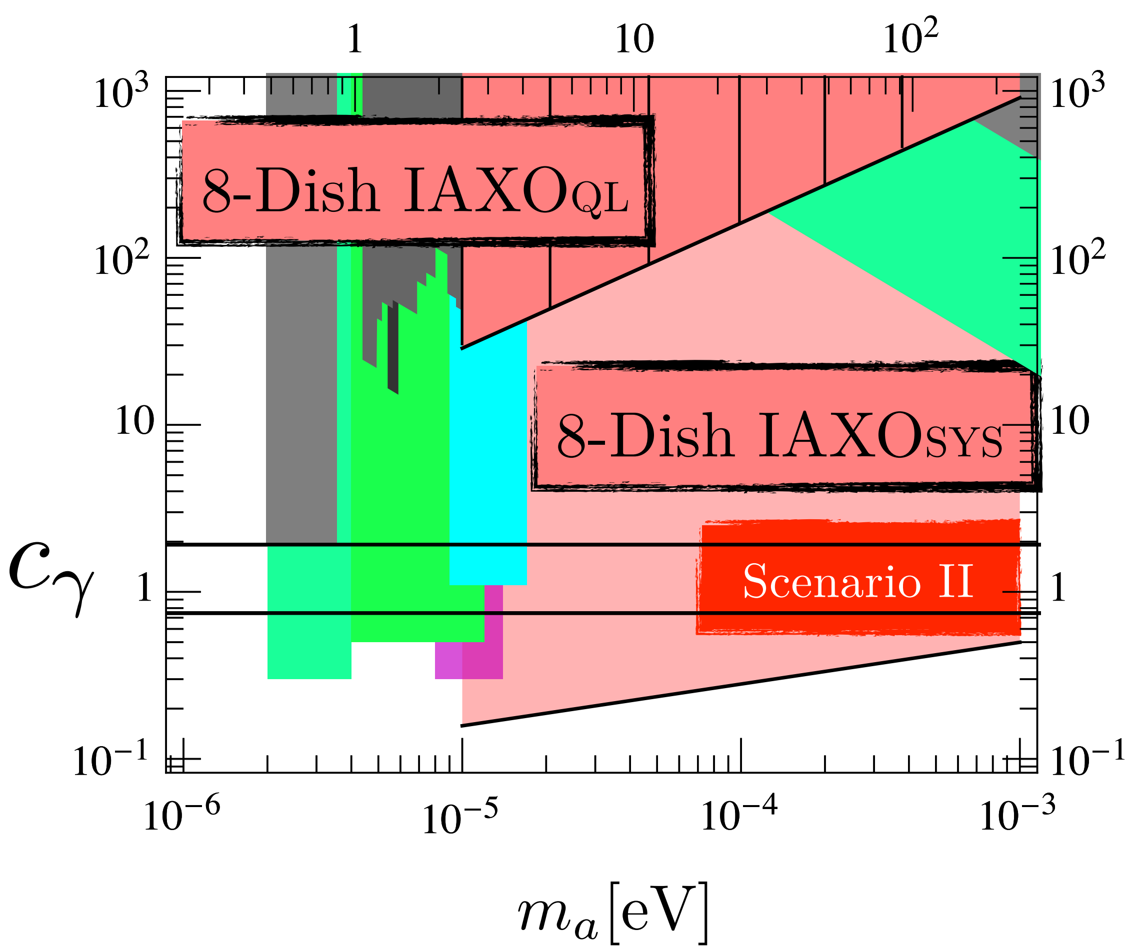
- 0.1-1 meV range is most interesting in **Scenario-II**

- S-II predicts miniclusters of axion CDM



$$M_{\rm mc} \sim 10^{-12} M_\odot$$
$$\Omega_{mc}/\Omega_{a{\rm CDM}} \sim O(1)$$

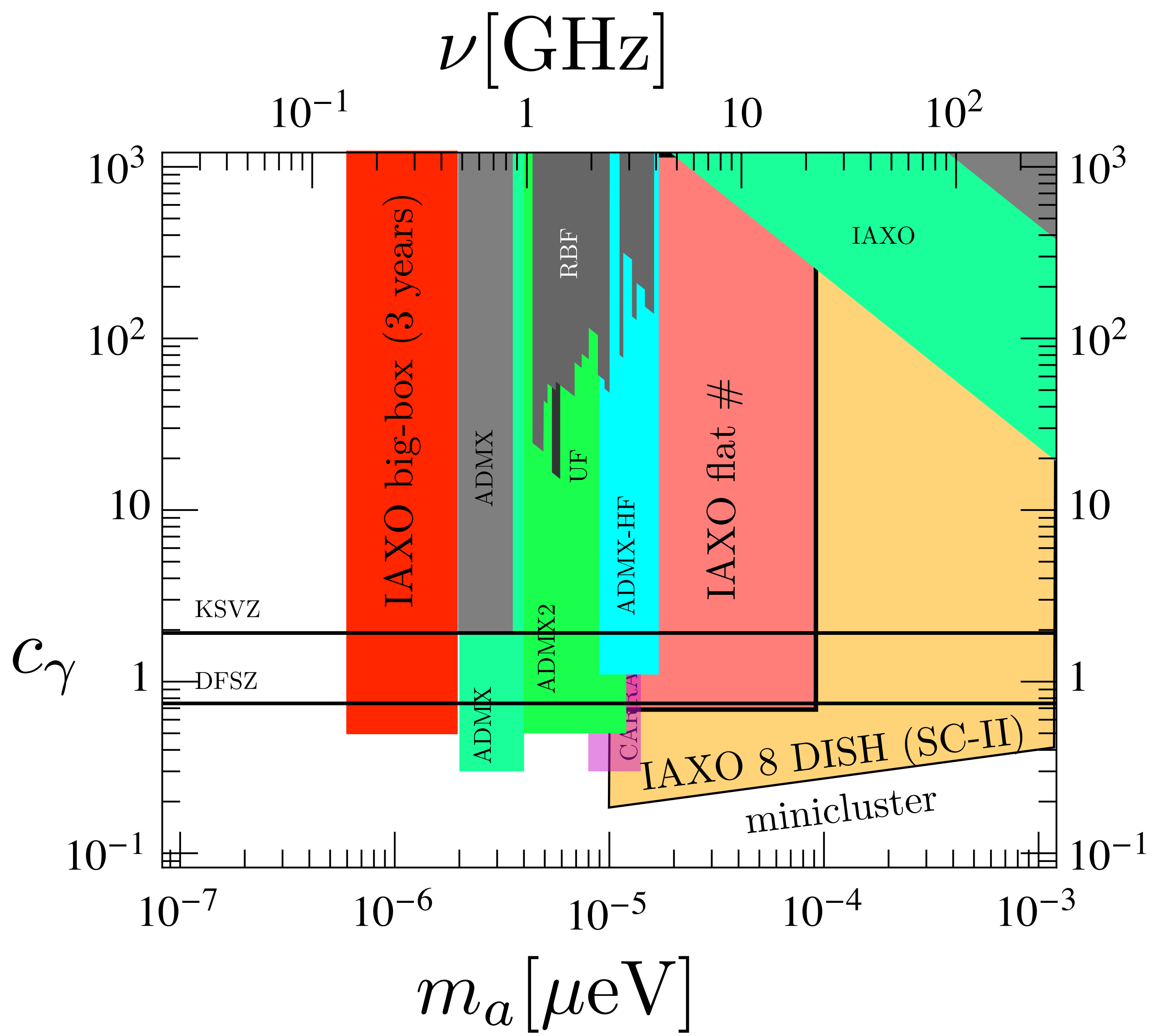
Zurek et al 07, See also Kolb & Tkachev 94



- Encounter with the Earth (every 10^4 years)
  $\rho_{\rm CDM} \times 10^6, Q_a \sim 10^9, t \sim 3{\rm days}$
- IAXO would see a huge signal, even with a realistic detector!!!!

Conclusions

- IAXO huge magnetic volume can have extraordinary applications in Axion Dark Matter



- Low mass, rectangular cavities plum

- Intermediate mass, combine flat rectangular cavities (R+D needed!) and QL detectors up to 20 GHz (JPAs?)

- High mass is difficult
  But mostly interesting for SC-II which implies miniclusters
  8 Dish in IAXO can cover the 0.01-1 meV range continuously (1 encounter/10^4 years...?)

- Other possibilities under scrutiny!

Thanks!