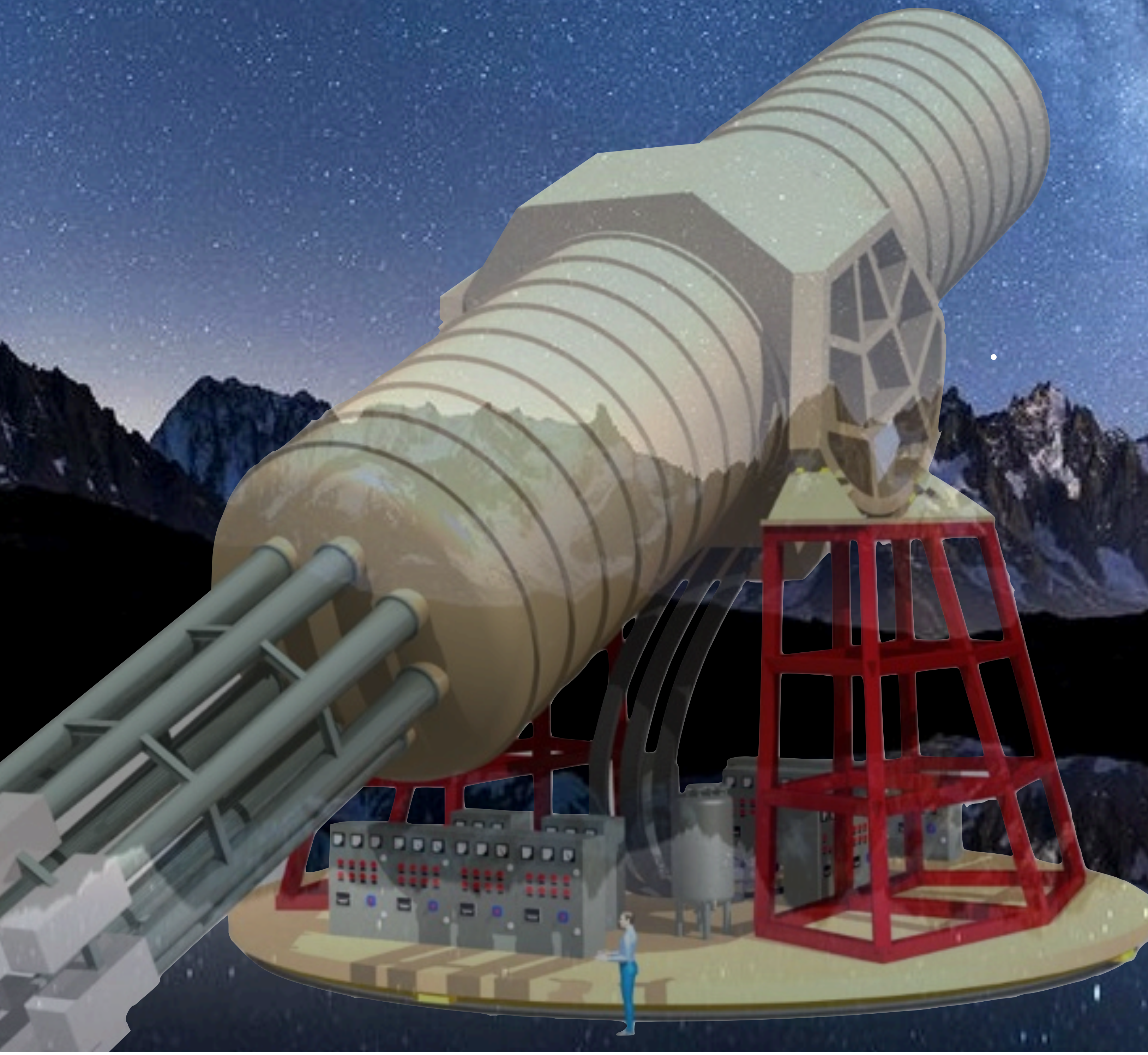
Axion Dark Matter searches @ IAXO

Javier Redondo
Ramón y Cajal fellow
University of Zaragoza (Spain)



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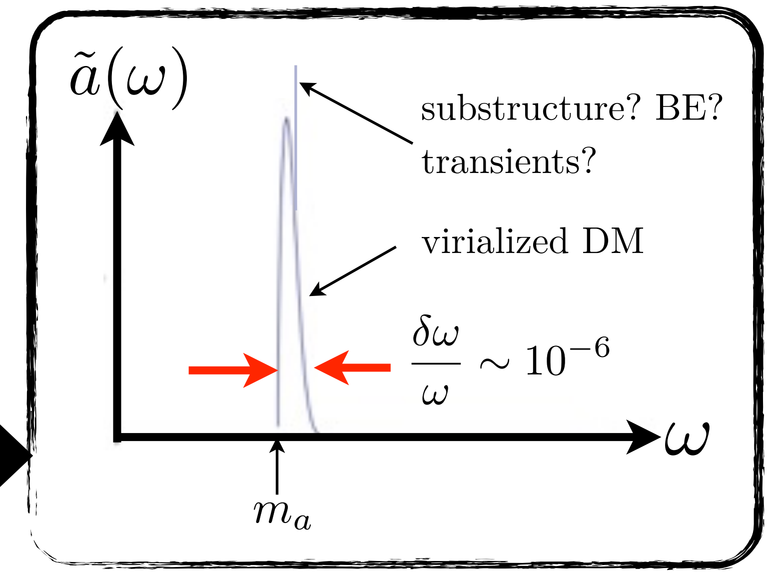

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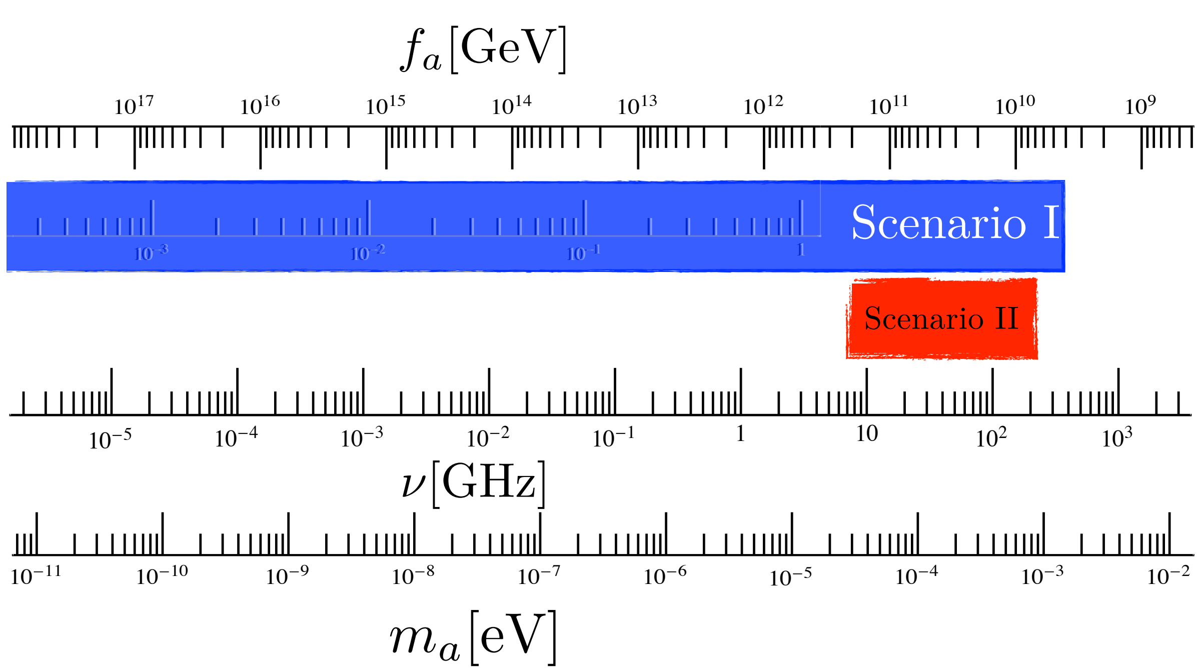
Observed relic density?



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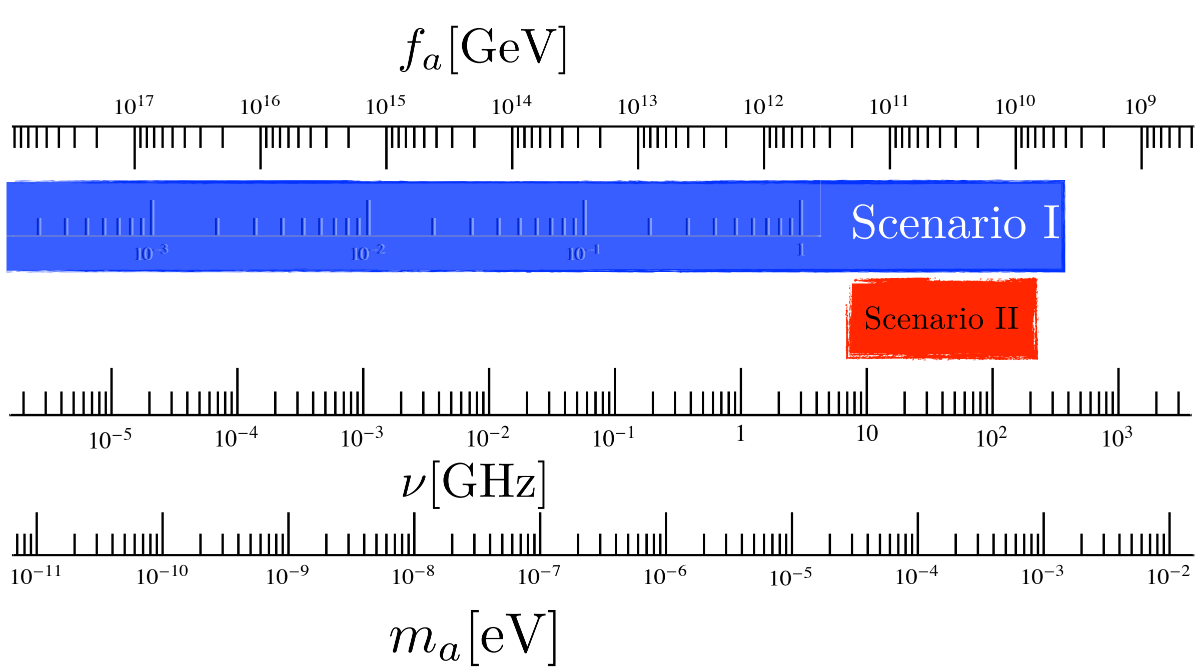

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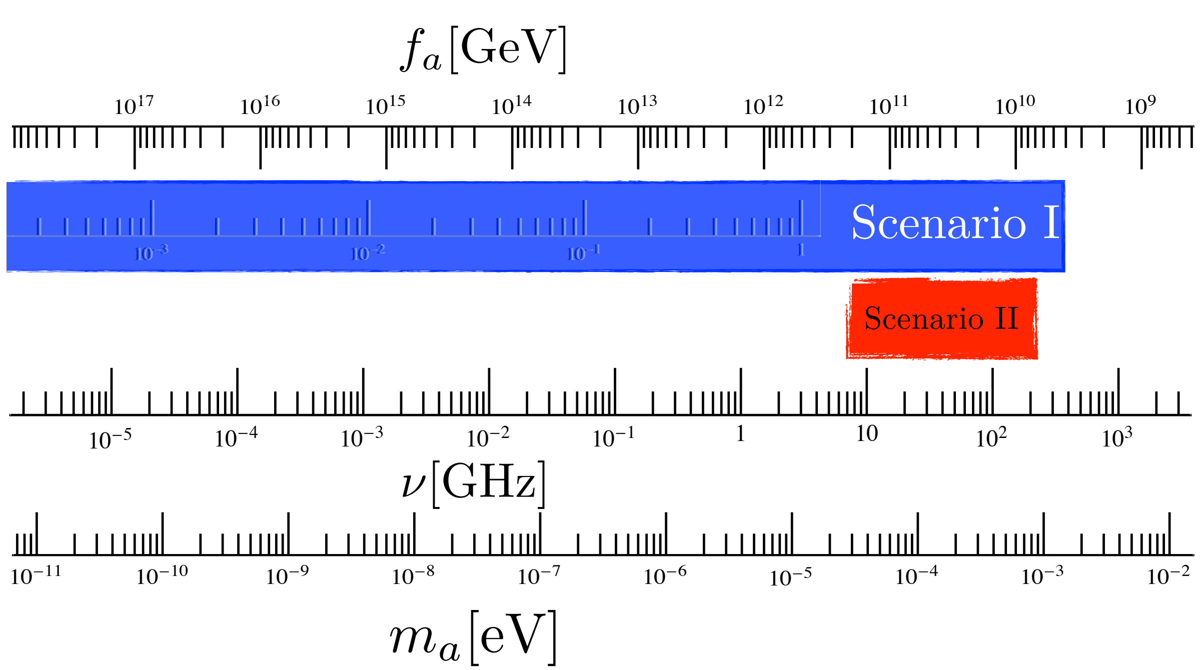

Effects depend on couplings

$$\frac{\alpha_s}{8\pi} G\widetilde{G}\theta(t) \Rightarrow$$

oscillating neutron EDM

$$d_n \sim \mathcal{O}(10^{-34}\,\mathrm{e\,cm}) \times \cos(m_a t)$$

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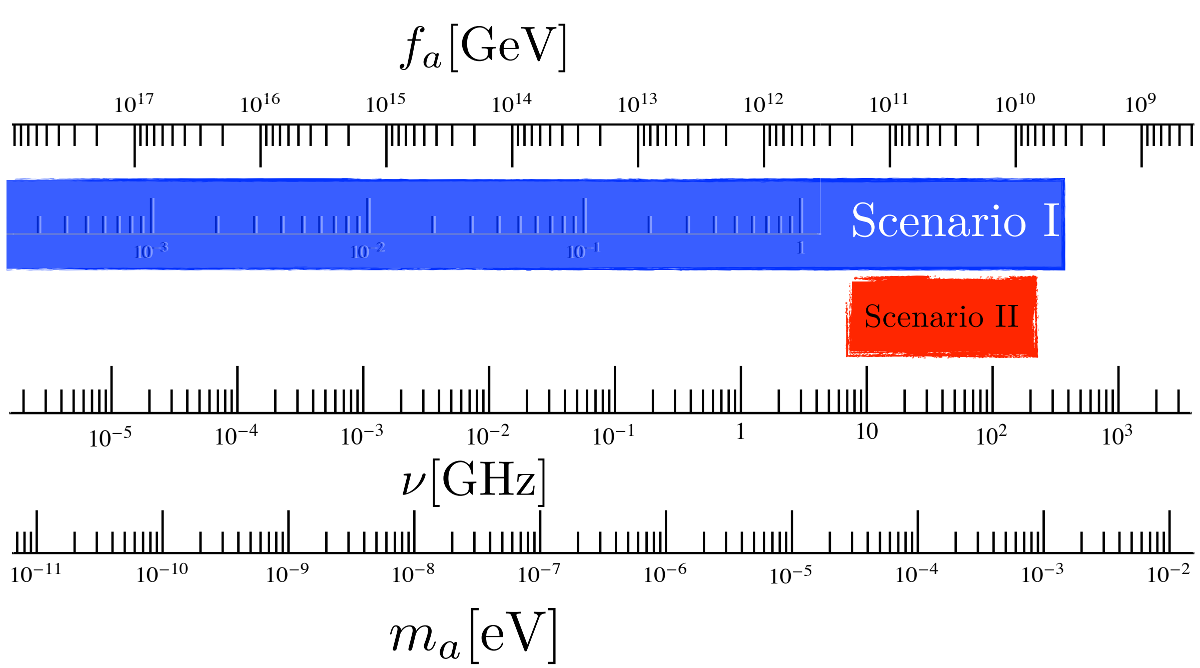

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$\frac{\alpha_s}{8\pi} G\widetilde{G}\theta(t)$ ➡ oscillating neutron EDM

$d_n \sim \mathcal{O}(10^{-34}\text{e cm}) \times \cos(m_a t)$

$c_\gamma \frac{\alpha}{2\pi} \mathbf{E} \cdot \mathbf{B}_{\text{ext}}\, \theta(t)$ ➡ Electric (magnetic) fields

$E \sim \mathcal{O}(10^{-12}\text{V/m}) \frac{|\text{B}_{\text{ext}}|}{10\,\text{T}} c_\gamma \times \cos(m_a t)$

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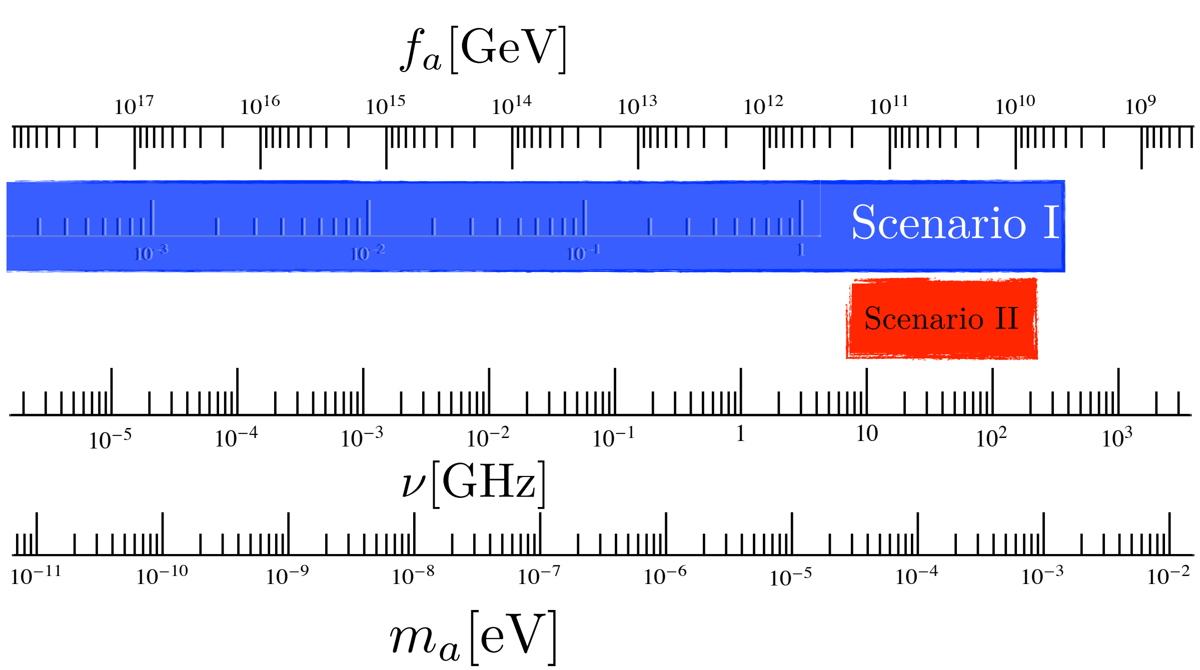

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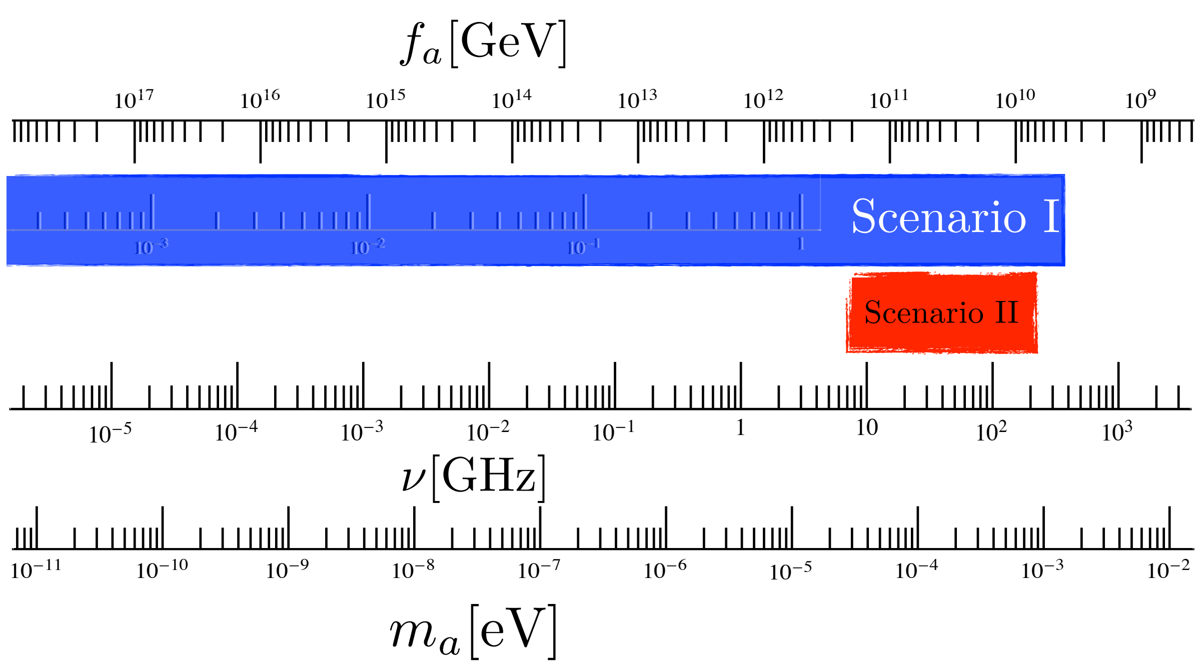

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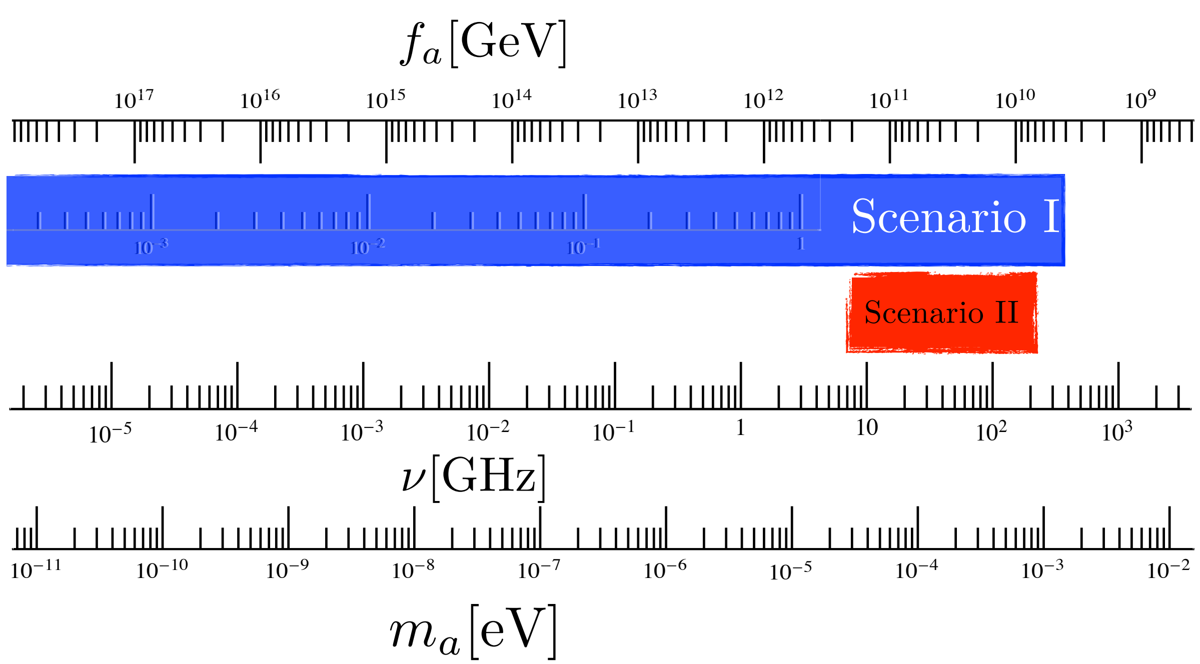

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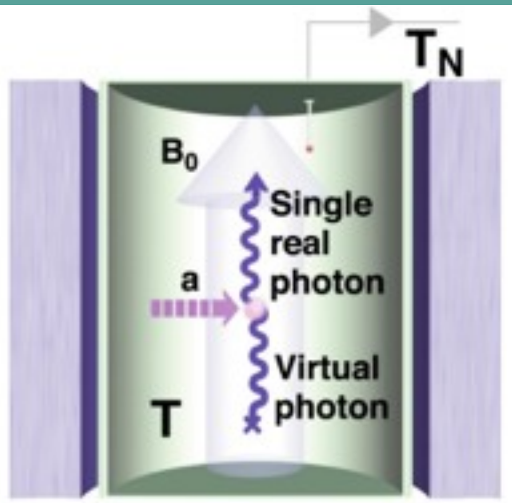
"Amplify resonantly the EM fields created by axionDM in a B-field in a cavity"



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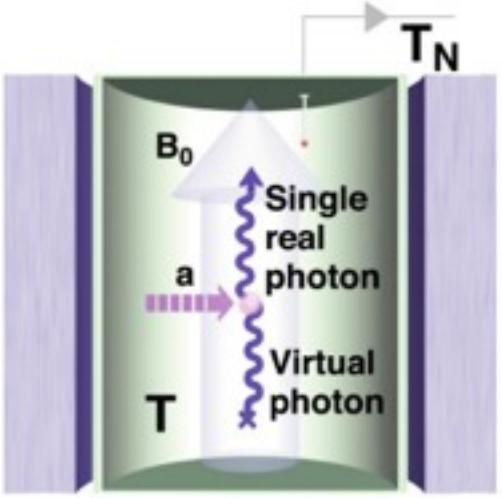

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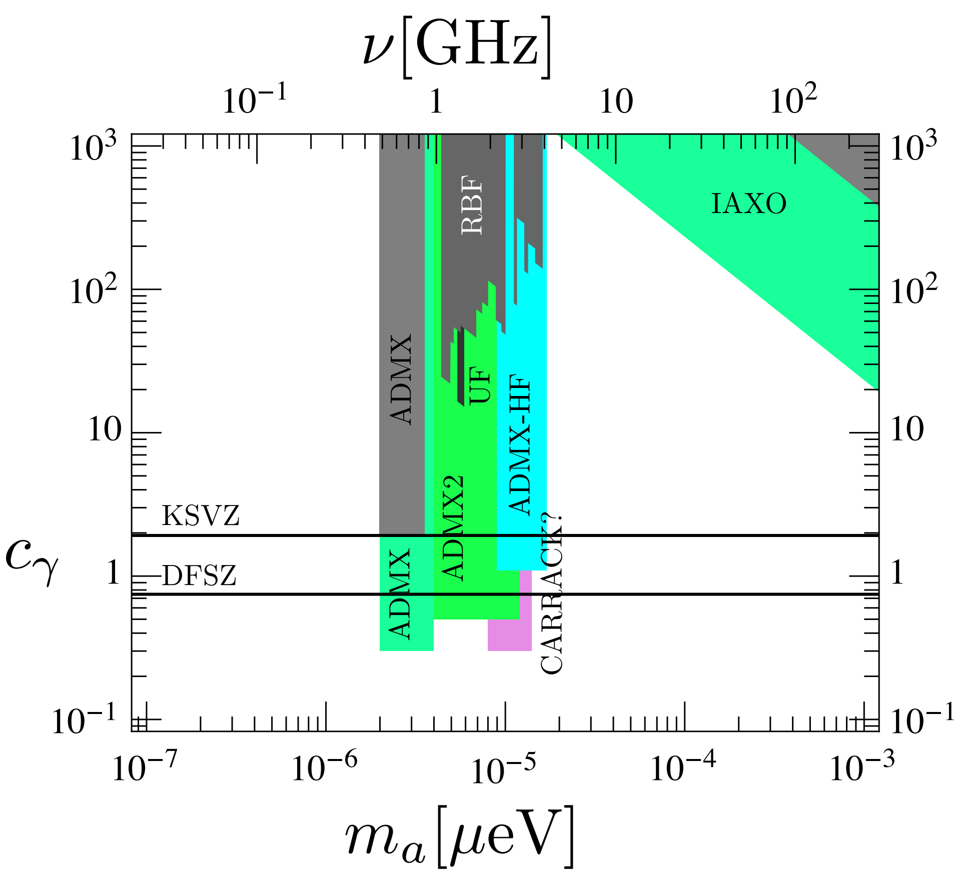

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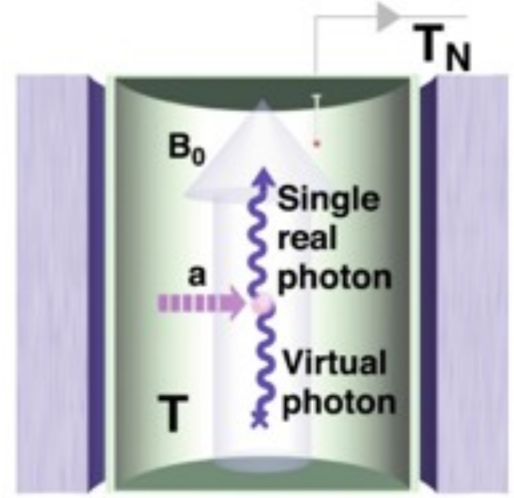

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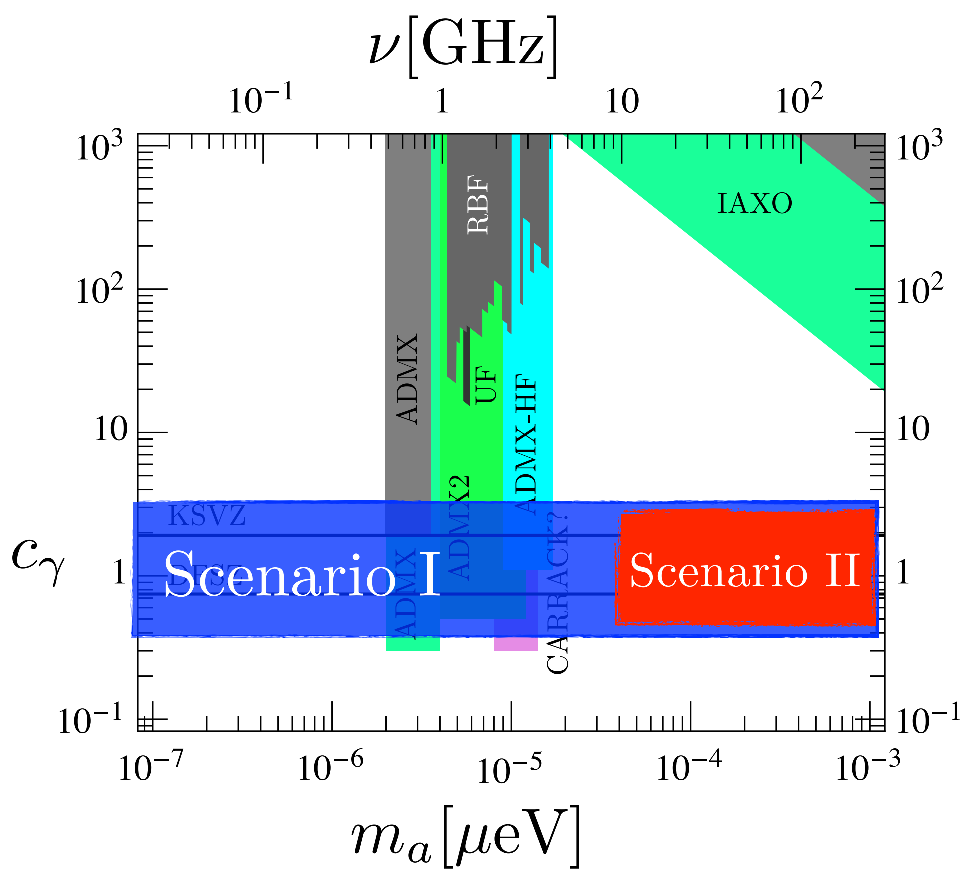

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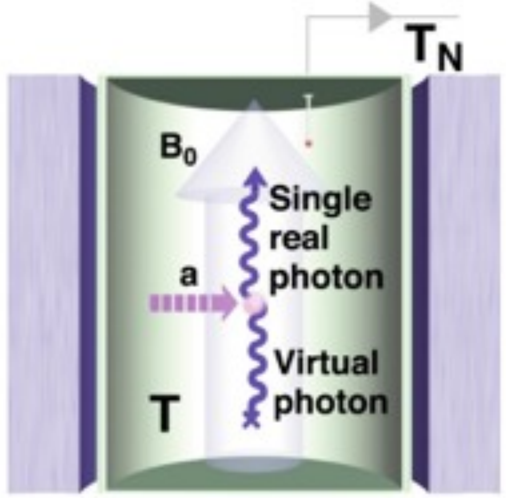

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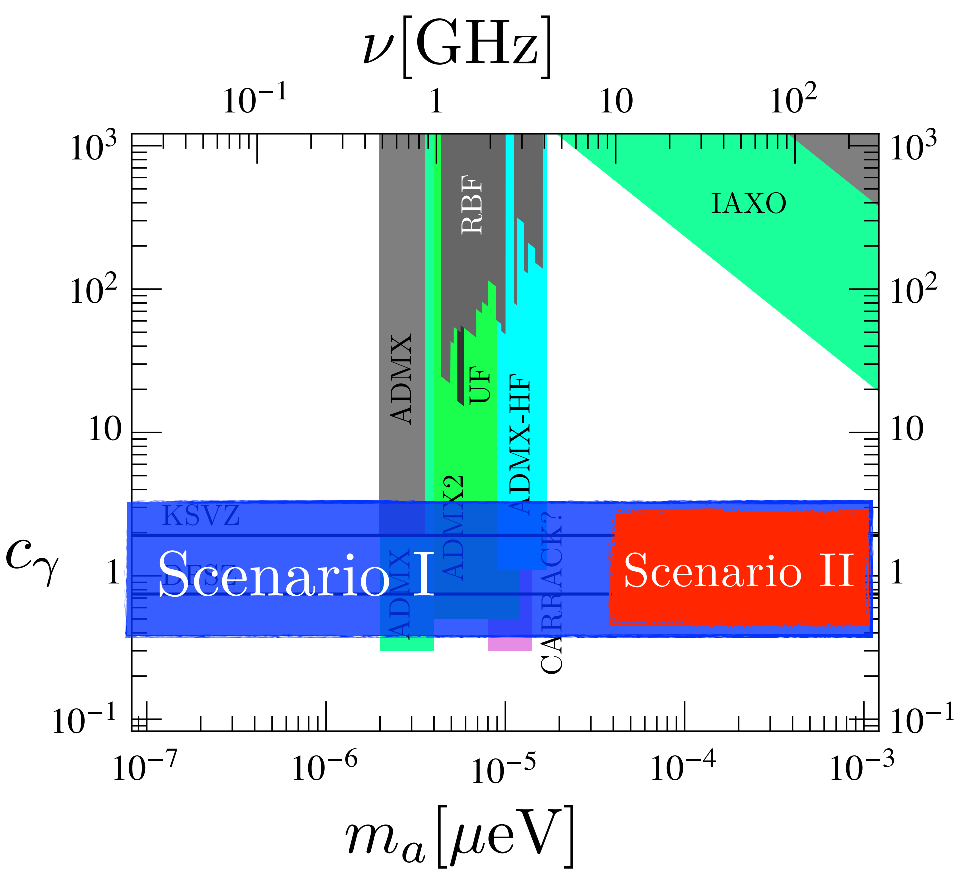

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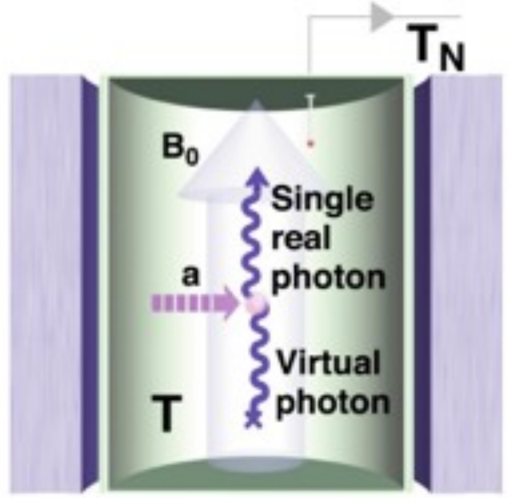

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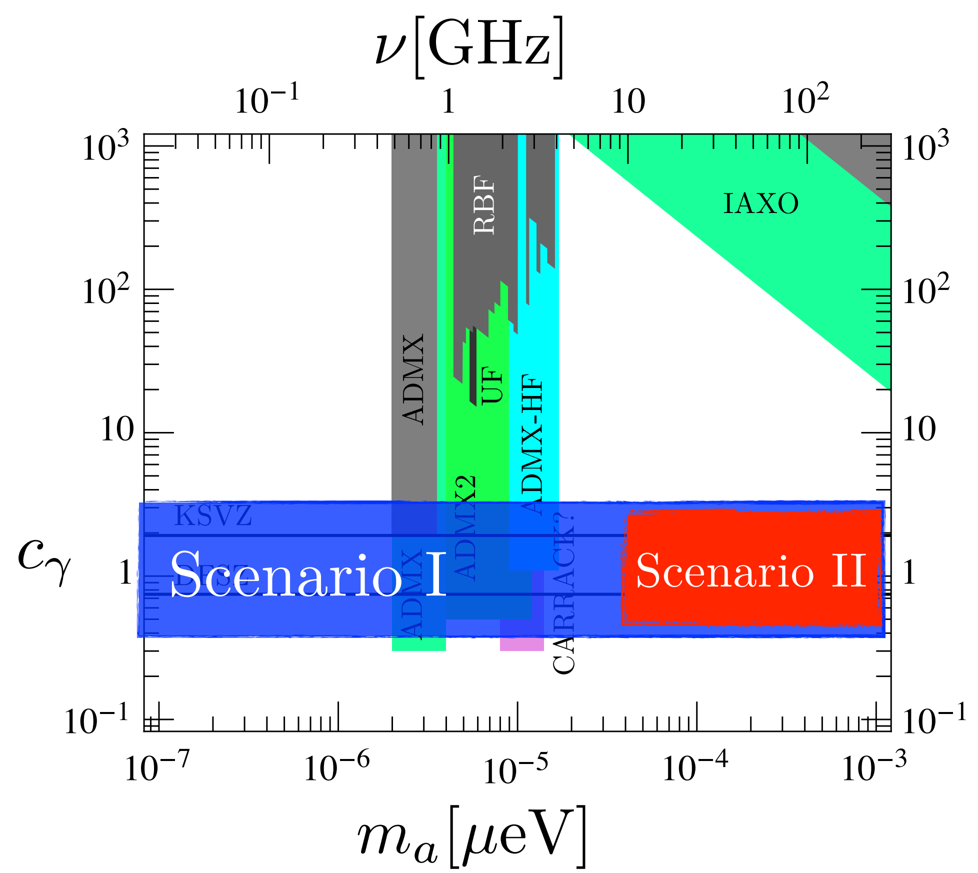

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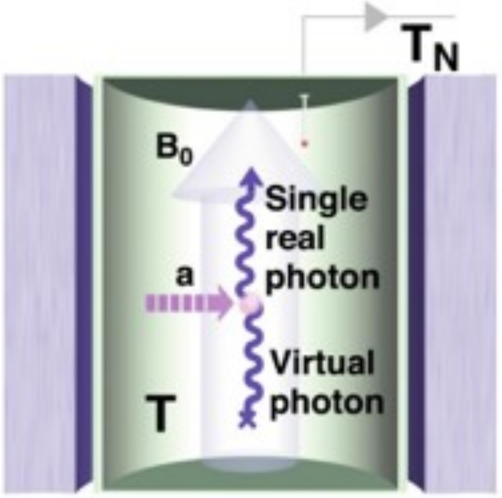

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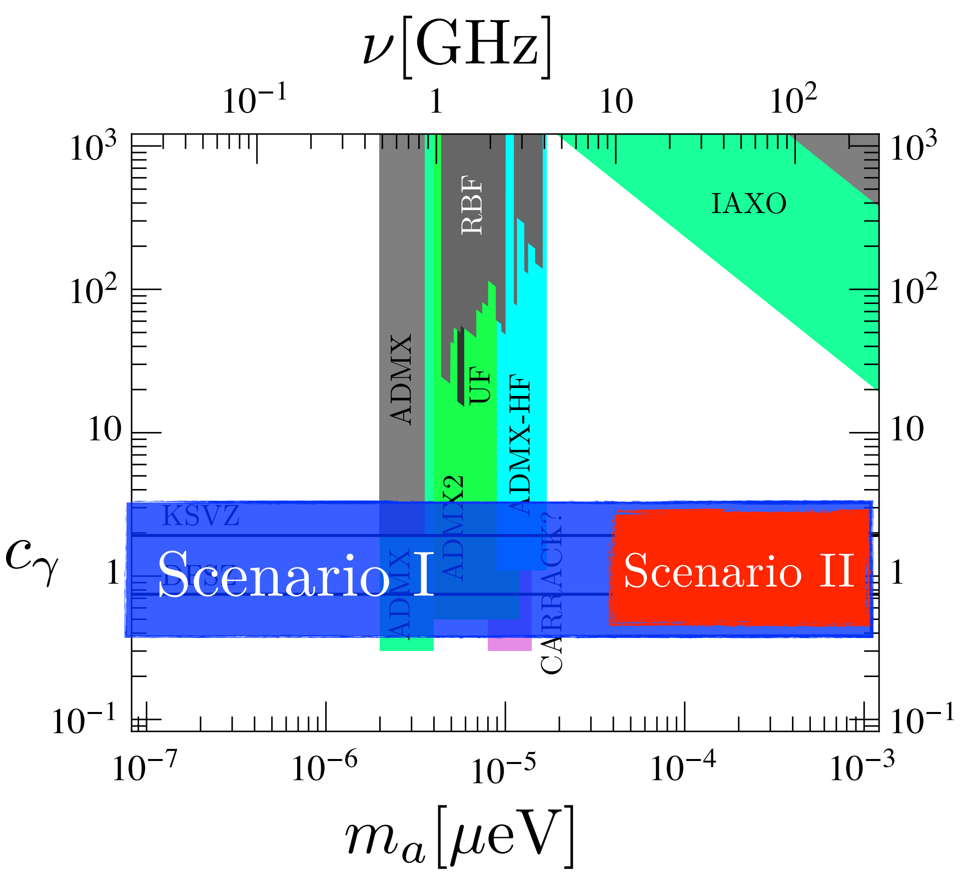

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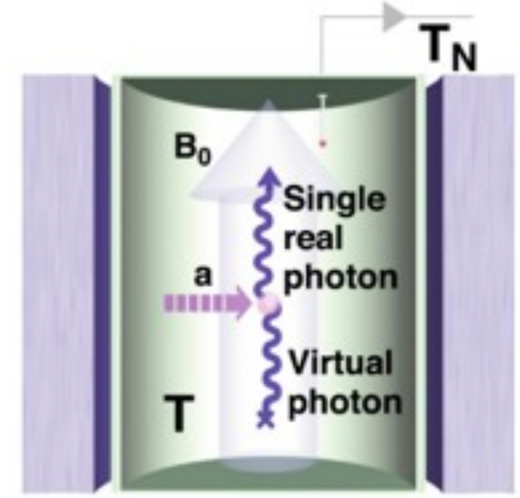

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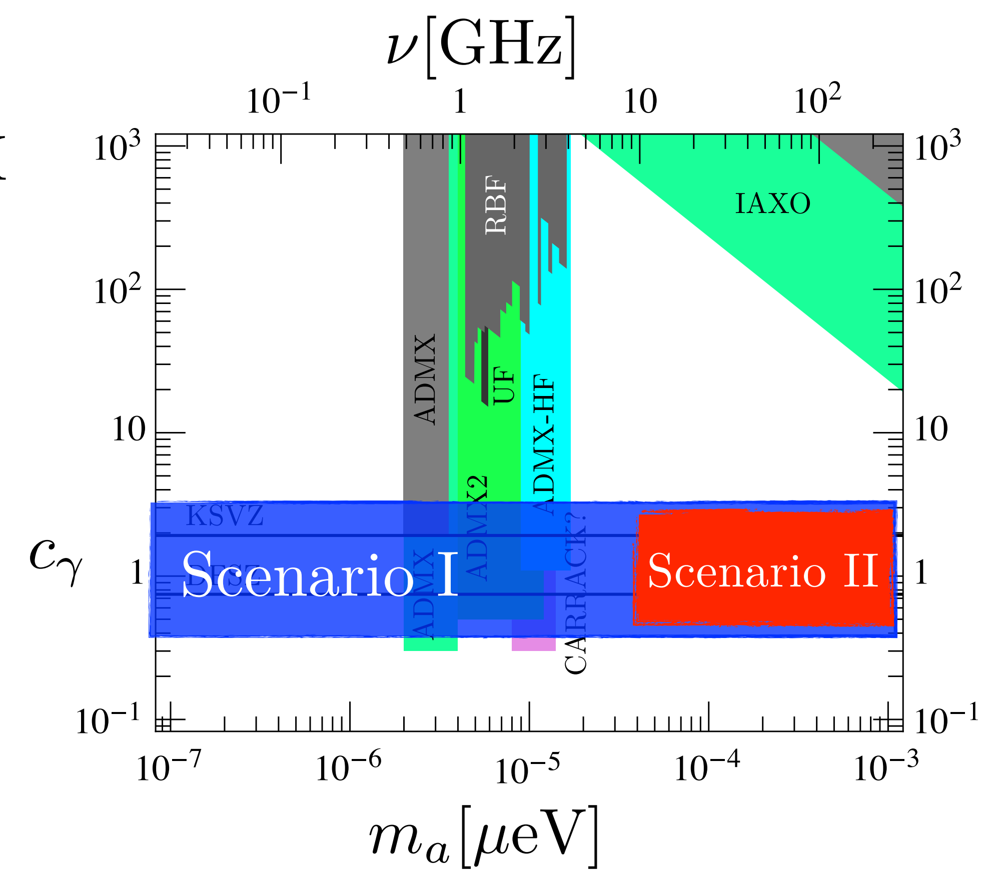

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- Noise $\quad P_{\rm noise} = T_{\rm sys} \Delta\nu_a \propto m_a^2$

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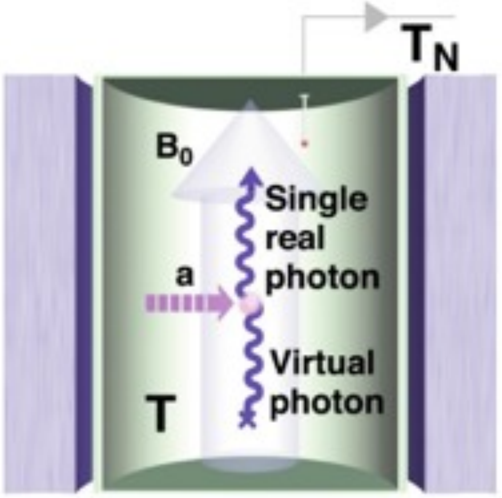

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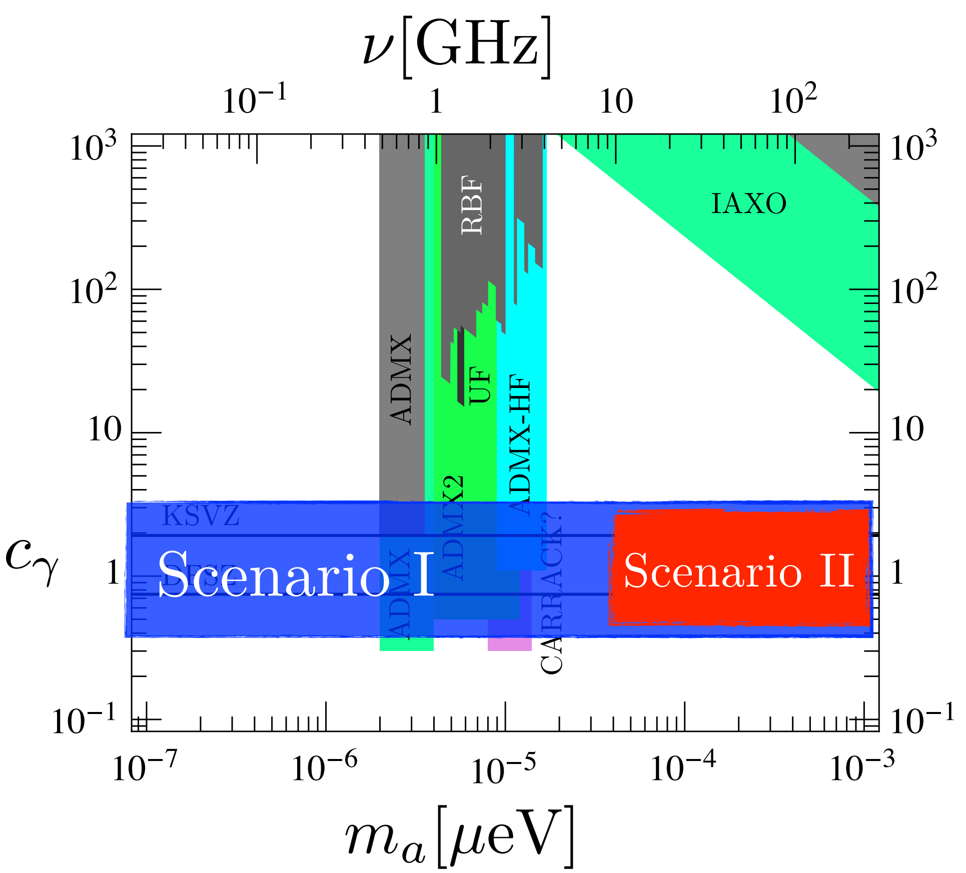

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- Signal/noise in $\Delta\nu_a$ of time, t, $\quad \dfrac{S}{N} = \dfrac{P_{\rm out}}{P_{\rm noise}}\sqrt{\Delta\nu_a t}$

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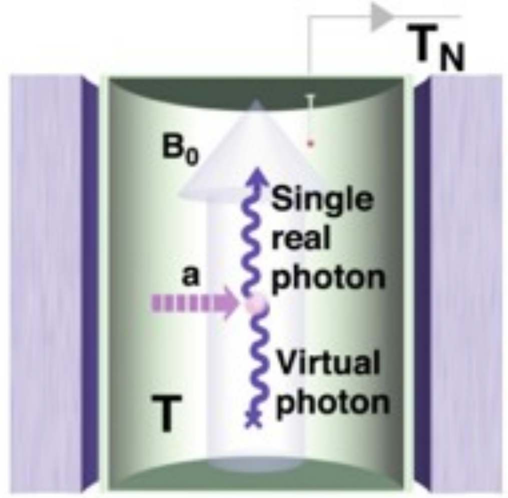

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$$|E_a|^2 \propto c_\gamma^2 B^2$$

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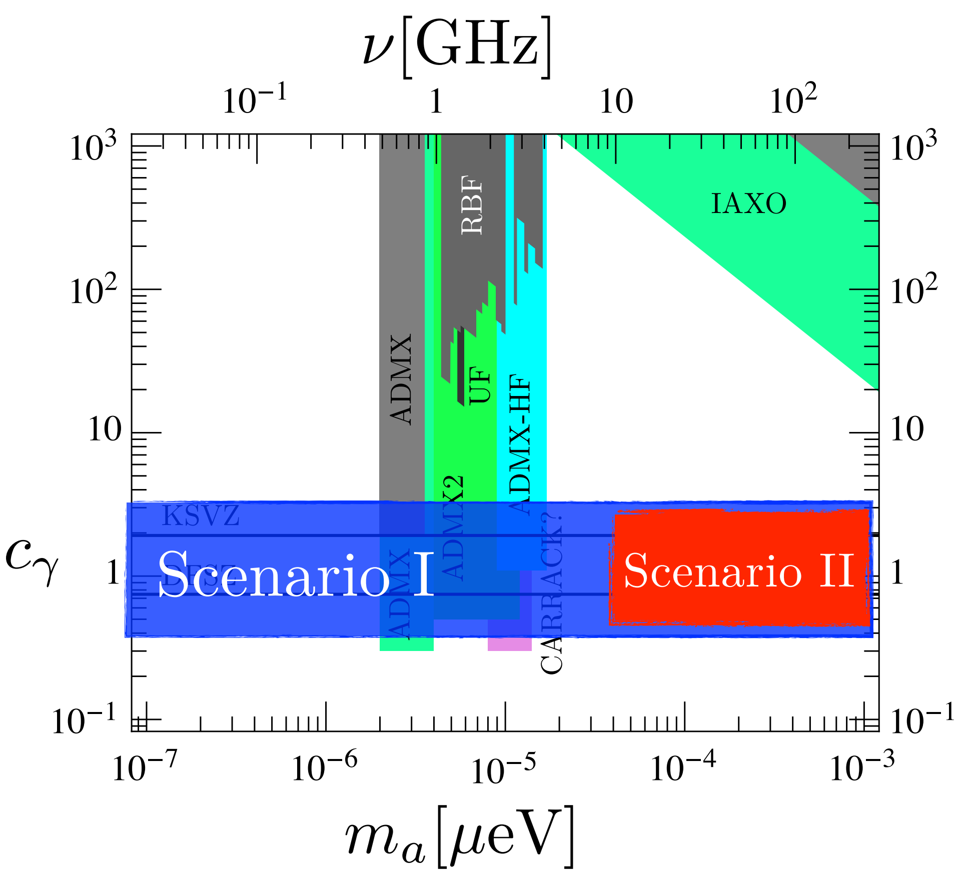

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- Scanning rate $\quad \frac{1}{m_a}\frac{d\Delta m_a}{dt} \propto \frac{c_\gamma^4}{m_a^9}$

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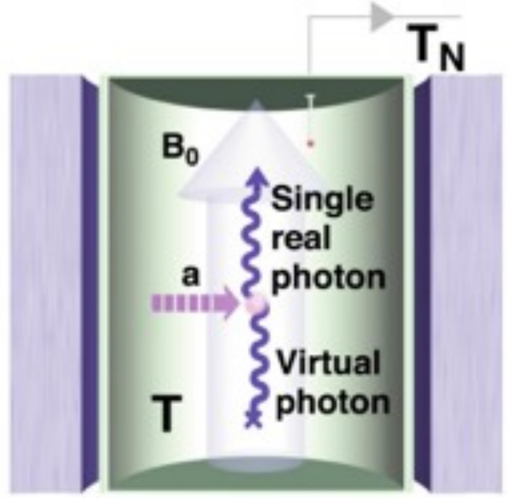
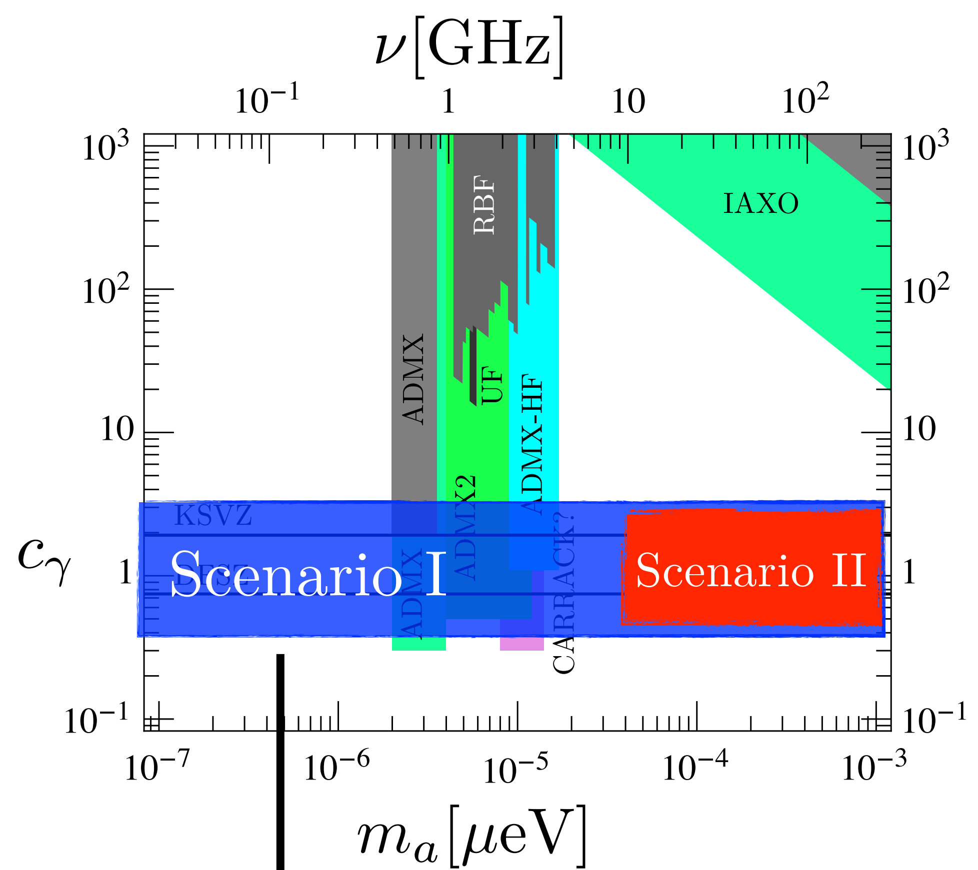
"Amplify resonantly the EM fields created by axionDM in a B-field in a cavity"



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

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



- Signal $\quad (V \propto m_a^{-3}) \qquad P_{\rm out} \propto V m_a \sim \dfrac{1}{m_a^2}$

- Noise $\qquad P_{\rm noise} = T_{\rm sys} \Delta\nu_a \propto m_a^2$

- Signal/noise in $\Delta\nu_a$ of time, t, $\quad \dfrac{S}{N} = \dfrac{P_{\rm out}}{P_{\rm noise}} \sqrt{\Delta\nu_a t}$

- Scanning rate $\quad \dfrac{1}{m_a}\dfrac{d\Delta m_a}{dt} \propto \dfrac{c_\gamma^4}{m_a^9}$

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

- Haloscope (Sikivie 83)

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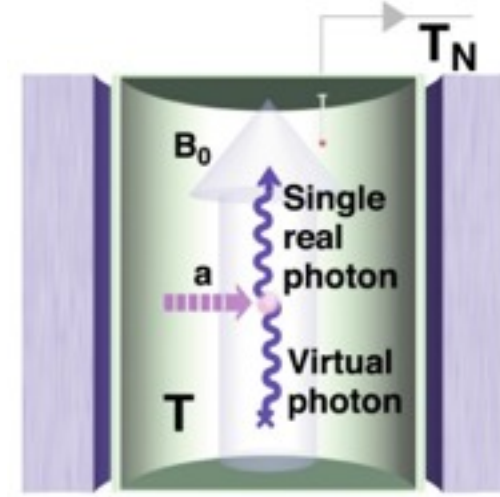

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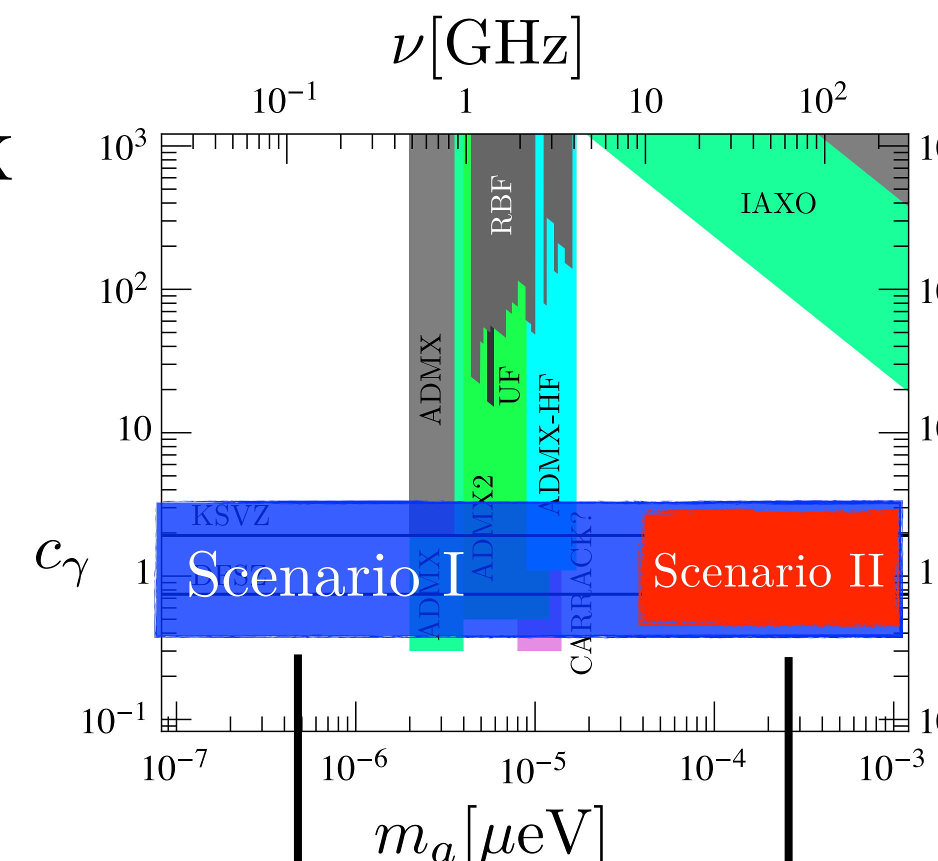

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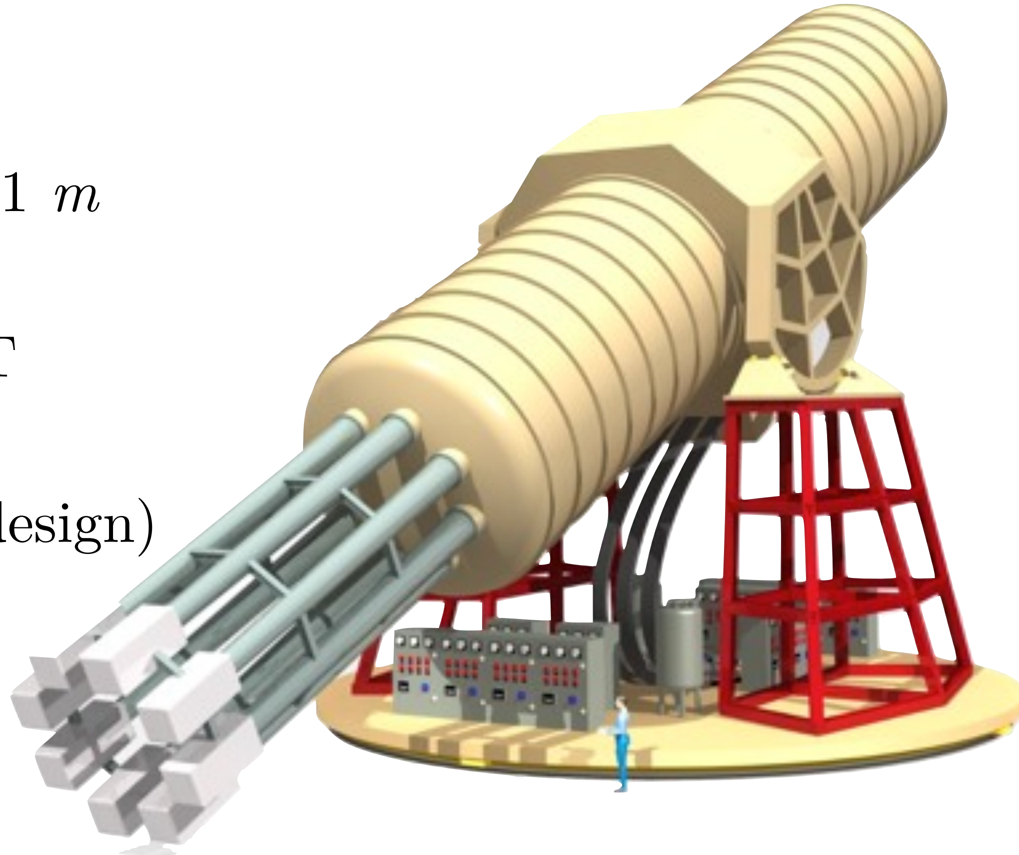
Very easy, but needs large magnet volume! IAXO!!!!!!!!!!!!!!!!!!!!

Very complicated, needs new ideas...

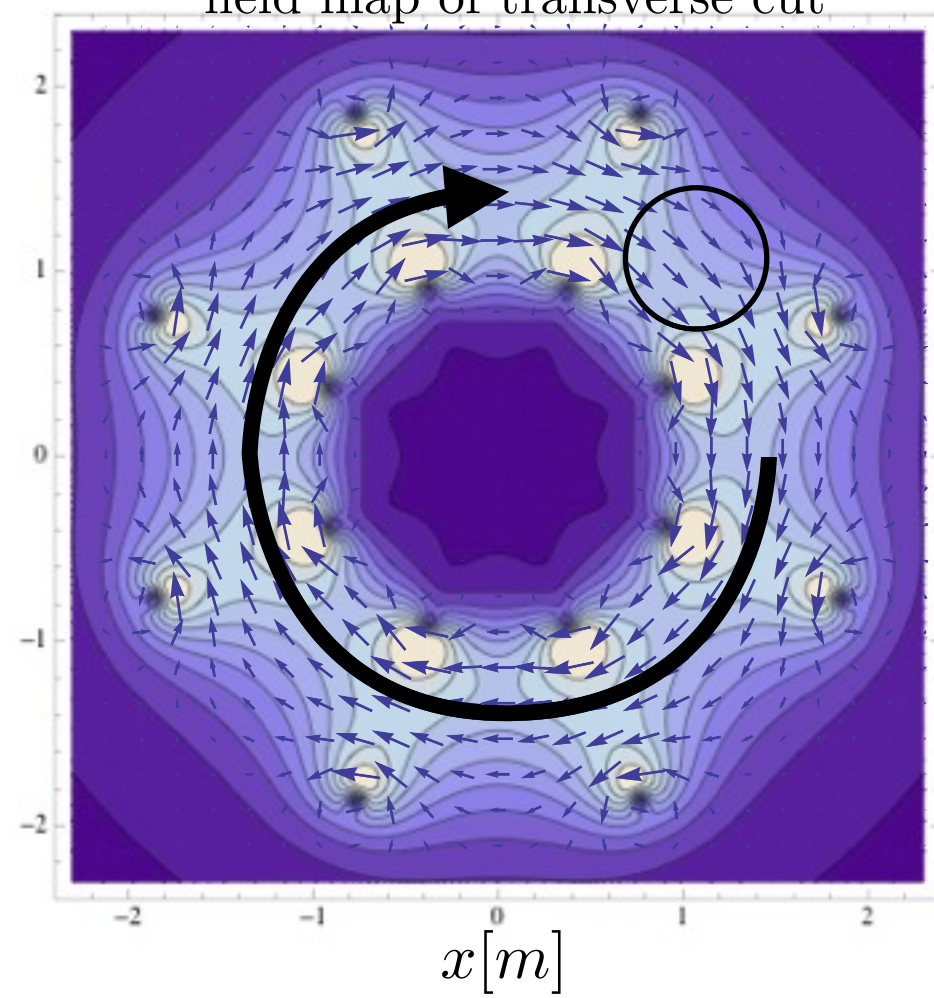
IAXO magnet

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

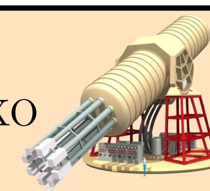
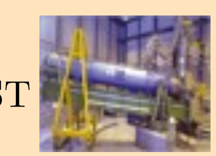
- Length = 20 m
- Magnetised radius ~ 1 m
- Peak value ~ 5.4 T
- Average in bore 2.5 T
- Available T ~ 4.5 K
  (but warm bores in design)



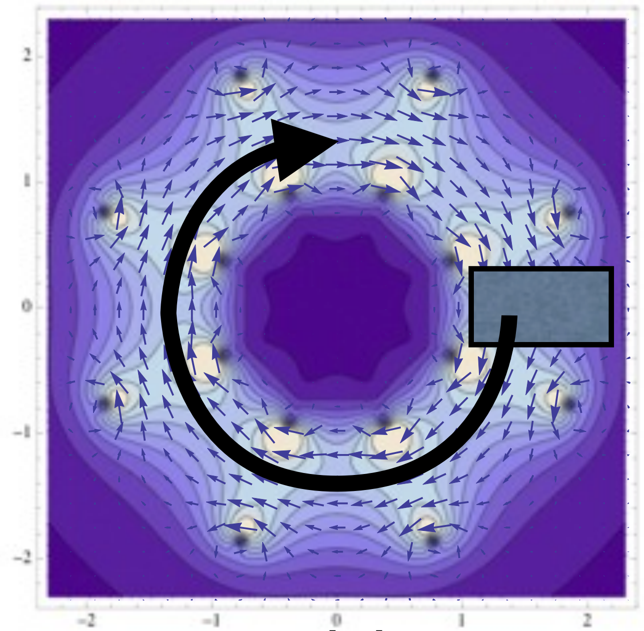
field map of transverse cut



- 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
$P_{\text{out}} \propto \|\mathbf{B}\|^2 V$ [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)

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

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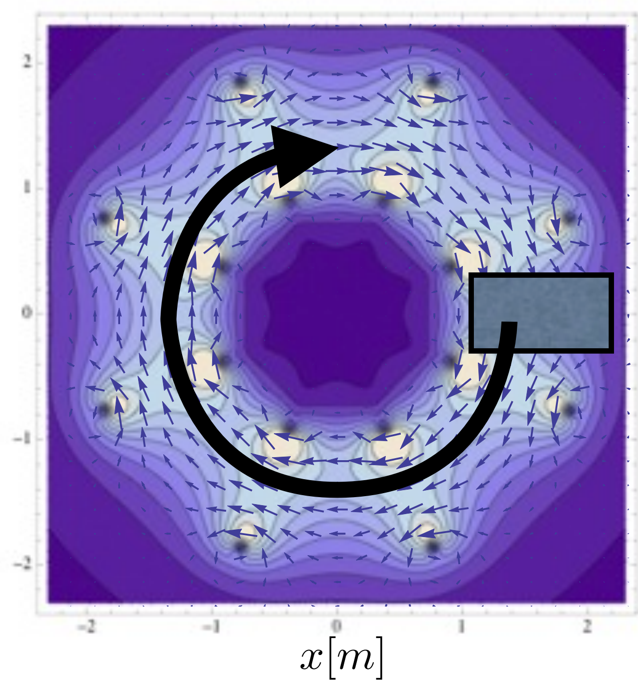

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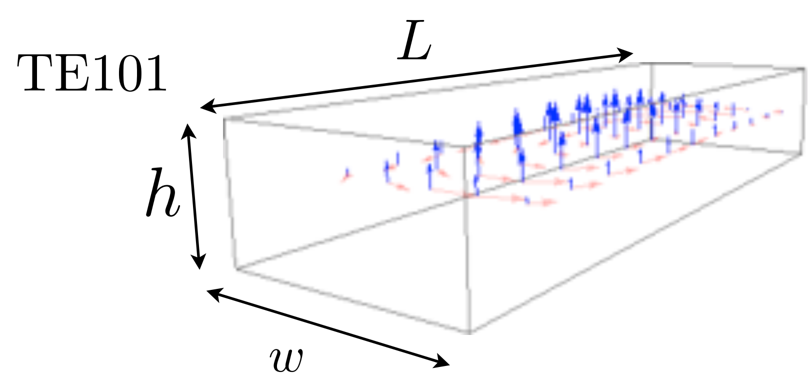

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$$\omega_{101} \sim \frac{\pi}{w} \sim 0.6\,\mu\mathrm{eV}\frac{1\,\mathrm{m}}{\mathrm{w}}$$

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

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

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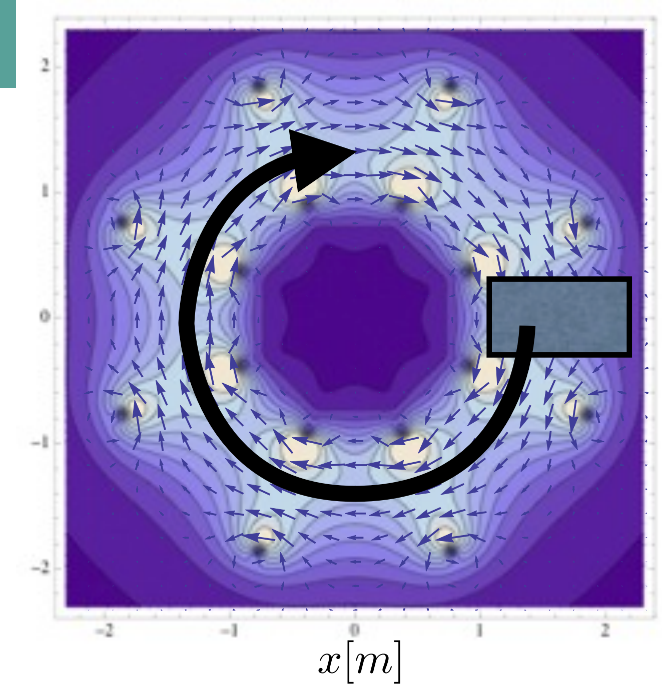

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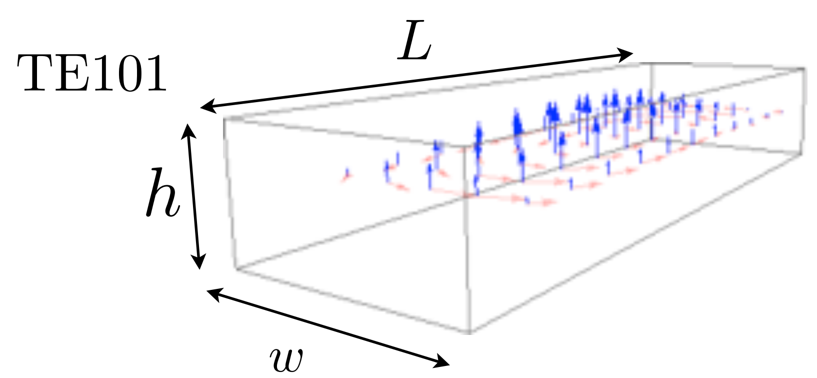

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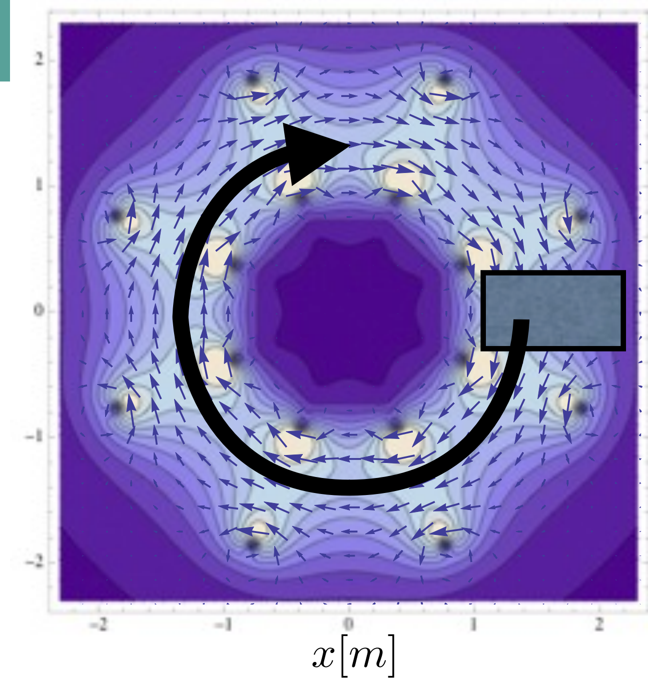

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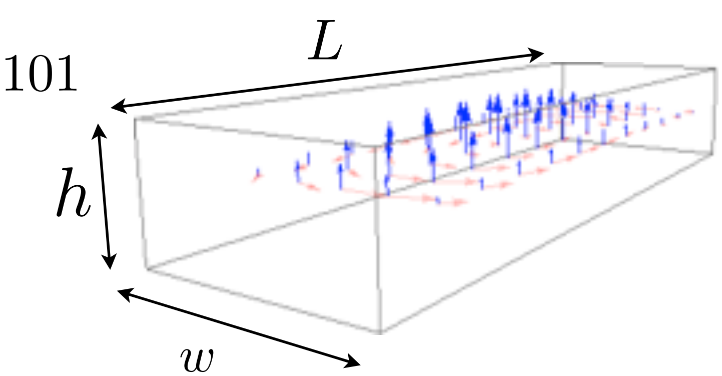

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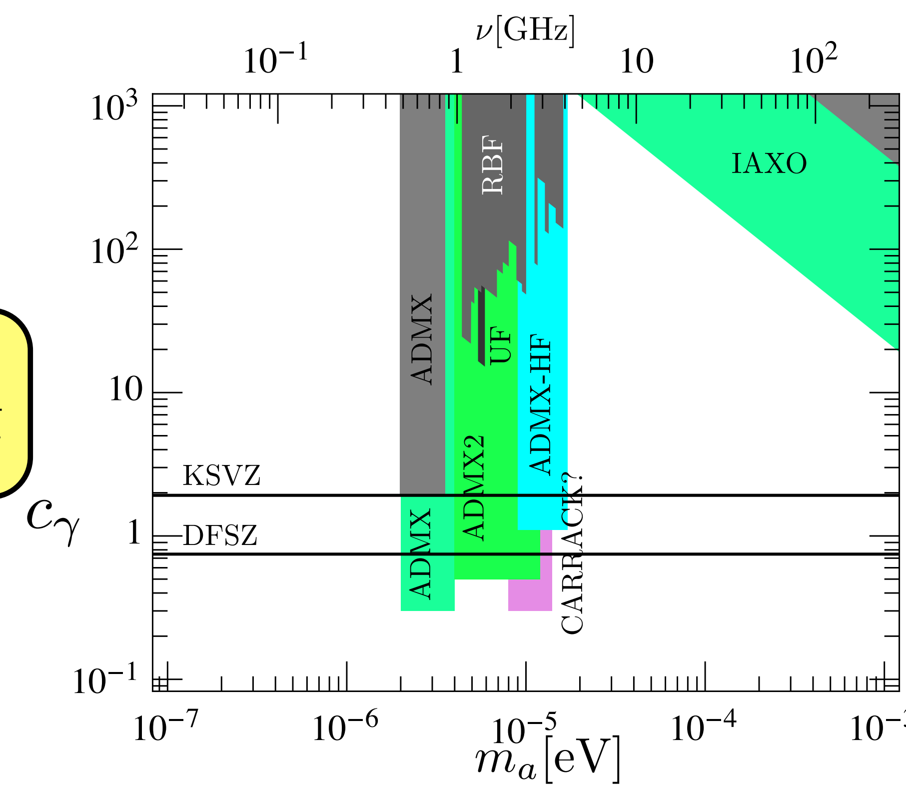
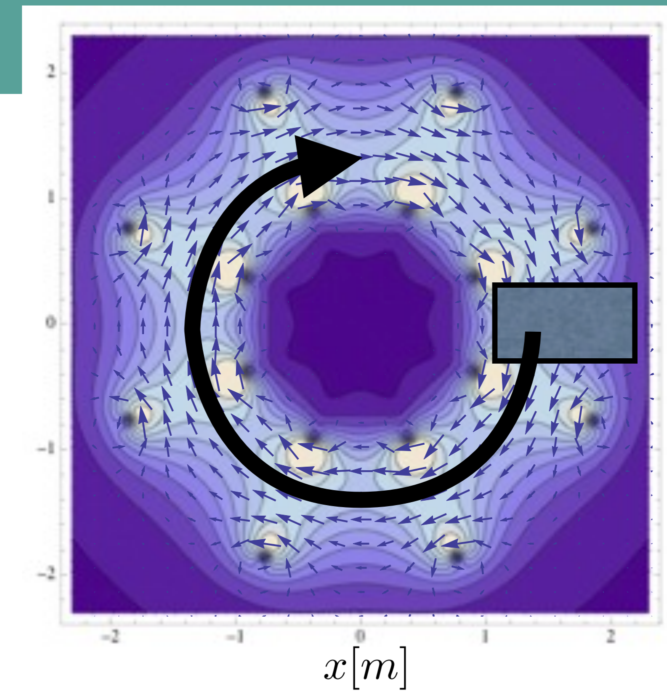


Low mass axion DM search in IAXO



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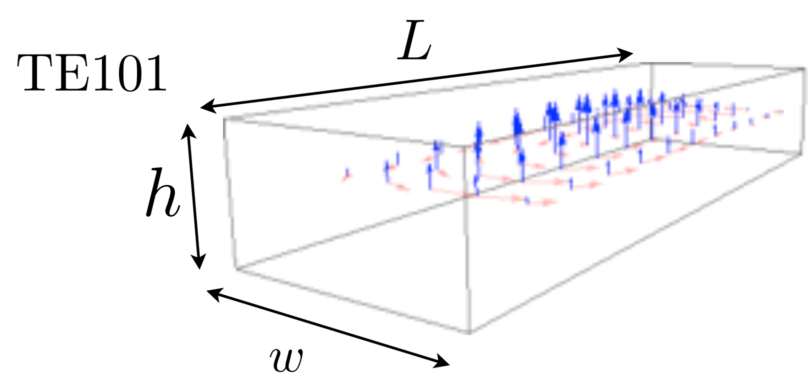

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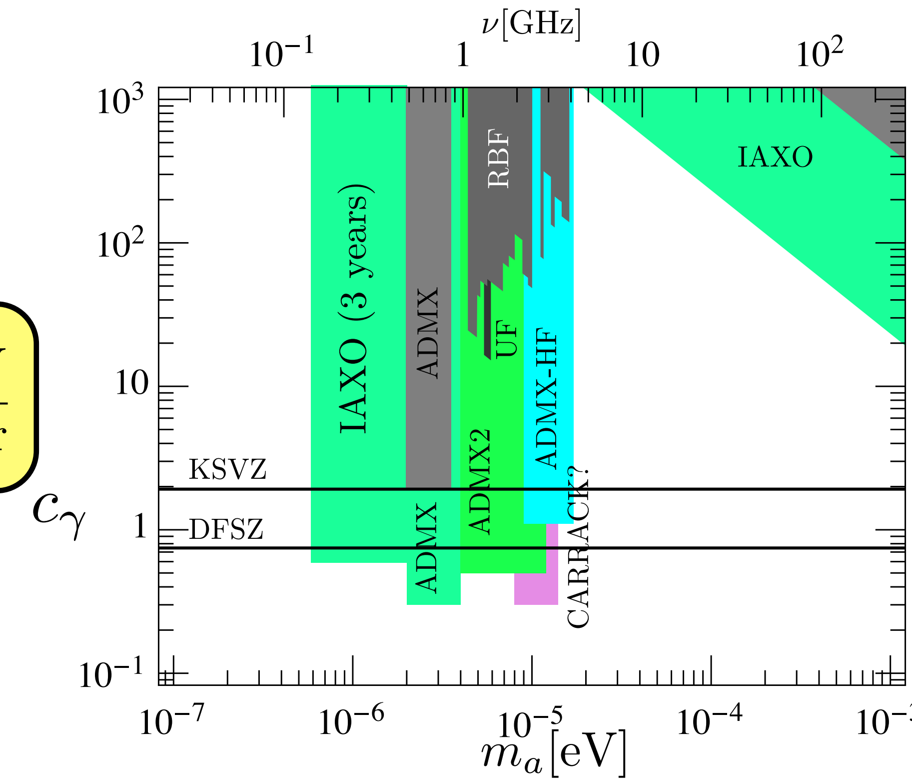

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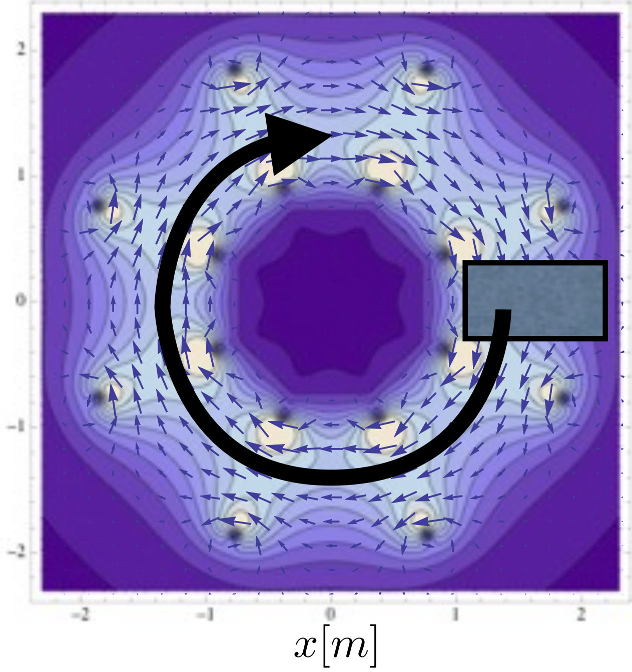

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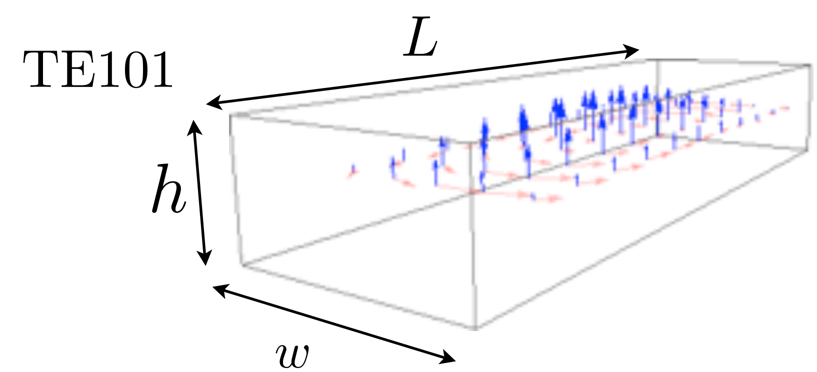

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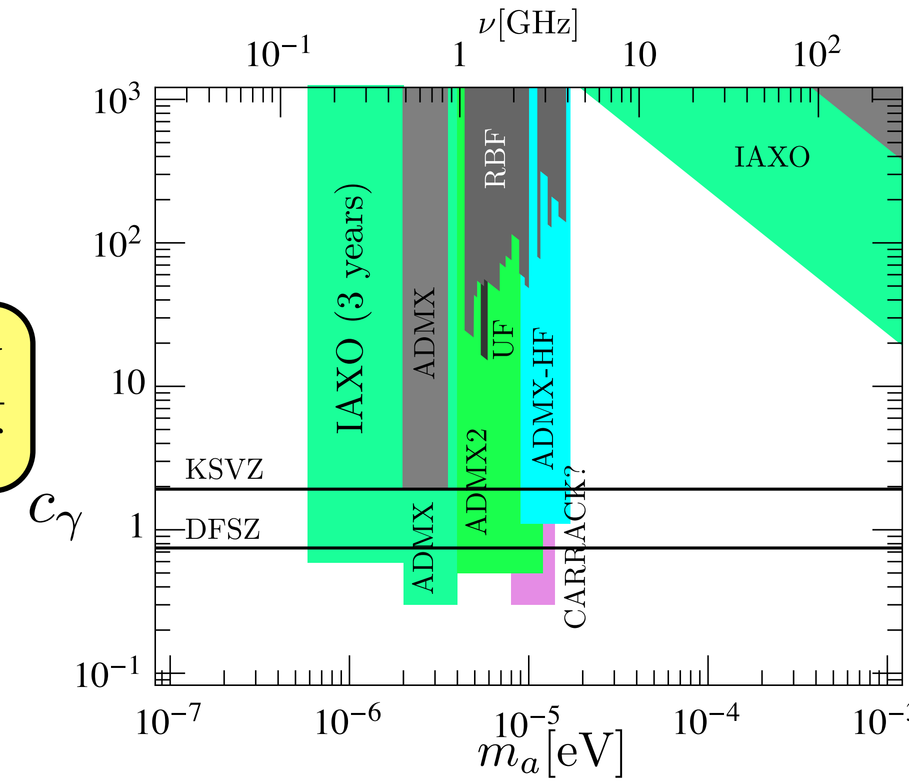

- Possible (cryo. to 1+ K, best magnet position)

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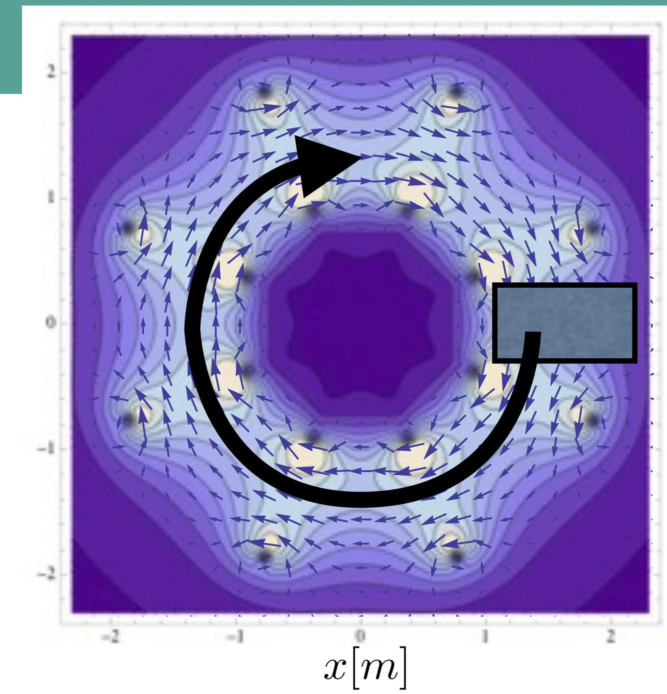

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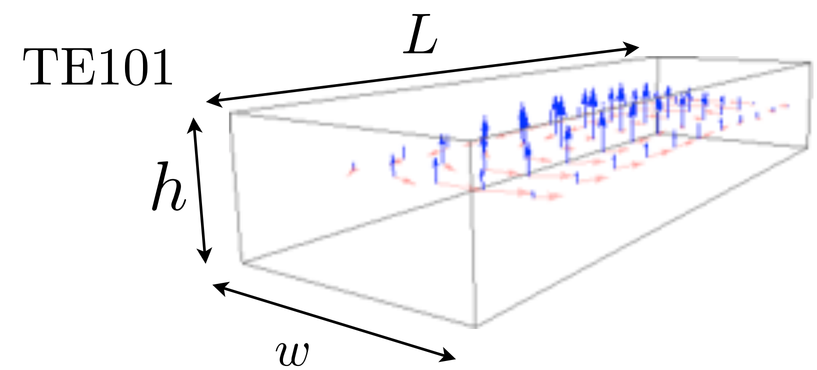

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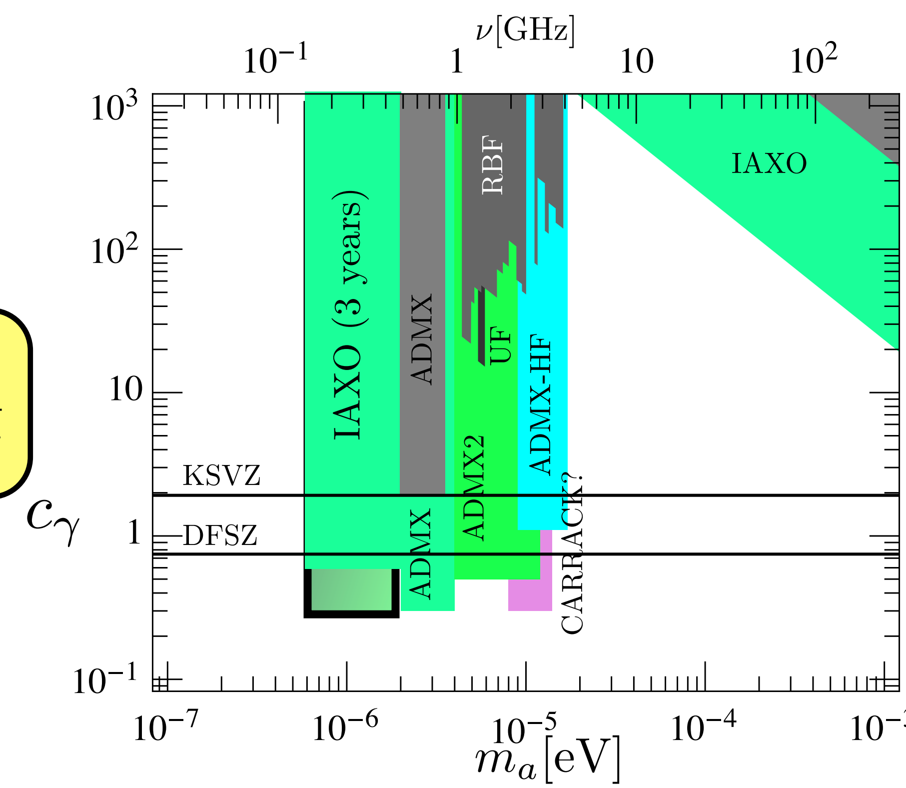

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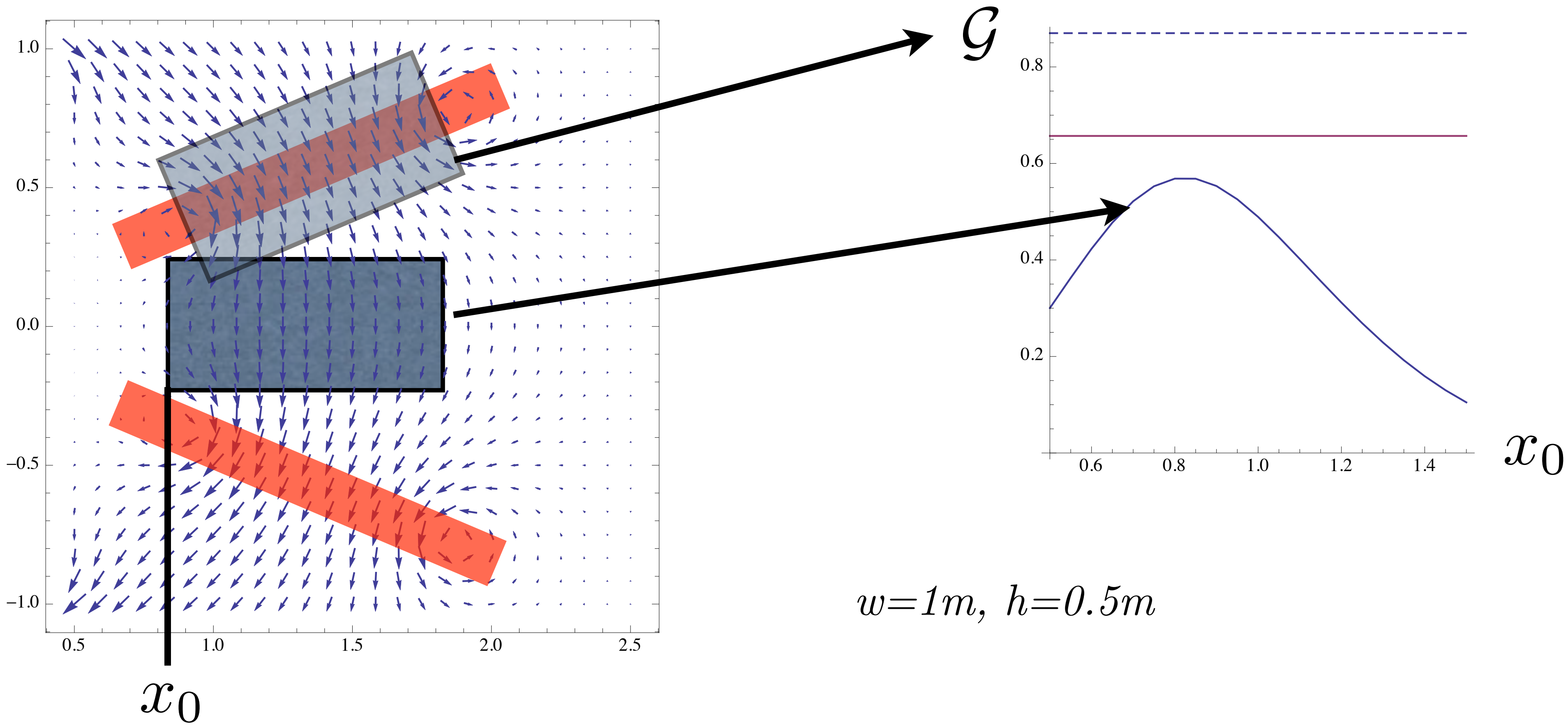
more...

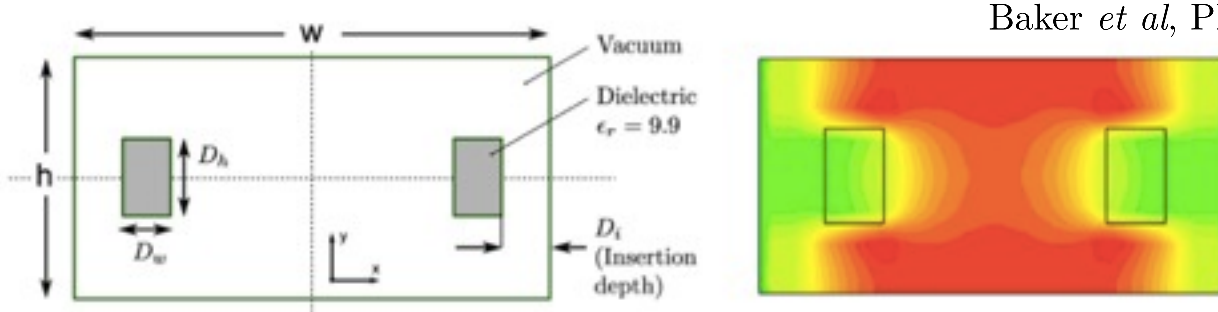
- High Q cavity requires good stability of temperature, mechanical vibrations, etc...
- Not compatible with solar tracking (?)
- After IAXO solar run
- Up to 8 cavities!

- Optimise the location and compare with in-coil configuration



Baker *et al*, PRD D85 035018

- Tunning; dielectric rods, other ideas



high mass axion DM searches ... ideas

- Boost all ADMX-like parameters (with ADMX-HF), CAPP
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    - bolometers (CARRACK, Lamoreaux 1306.3591)
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    - \+ combine cavities (Kinion, UMI-30-19020)

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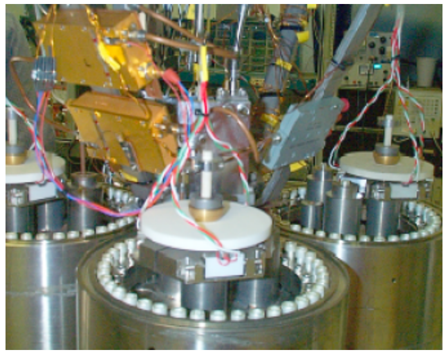

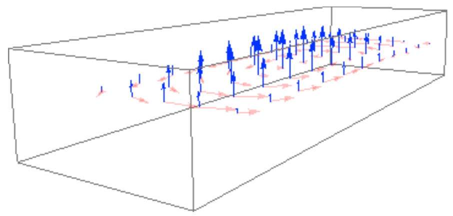

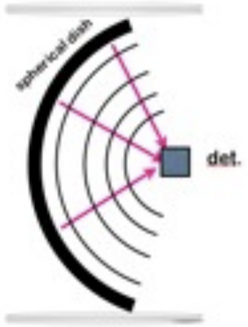

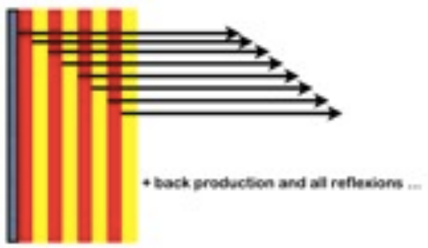

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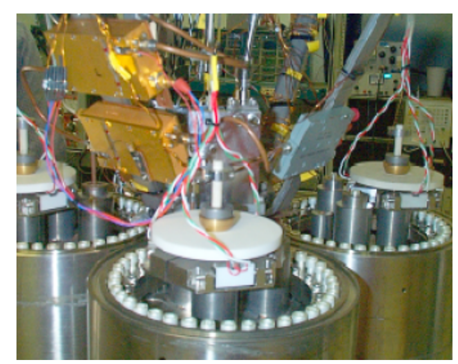

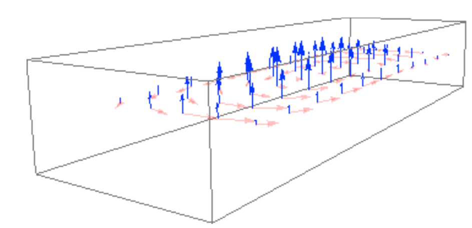

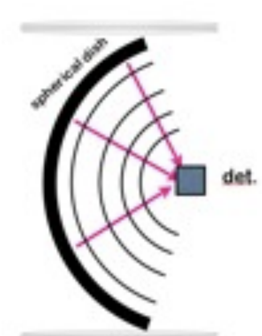

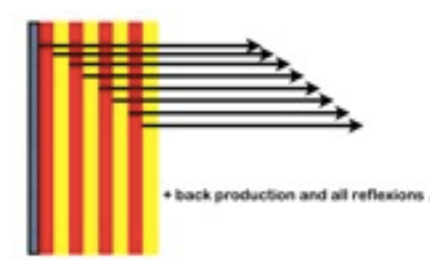

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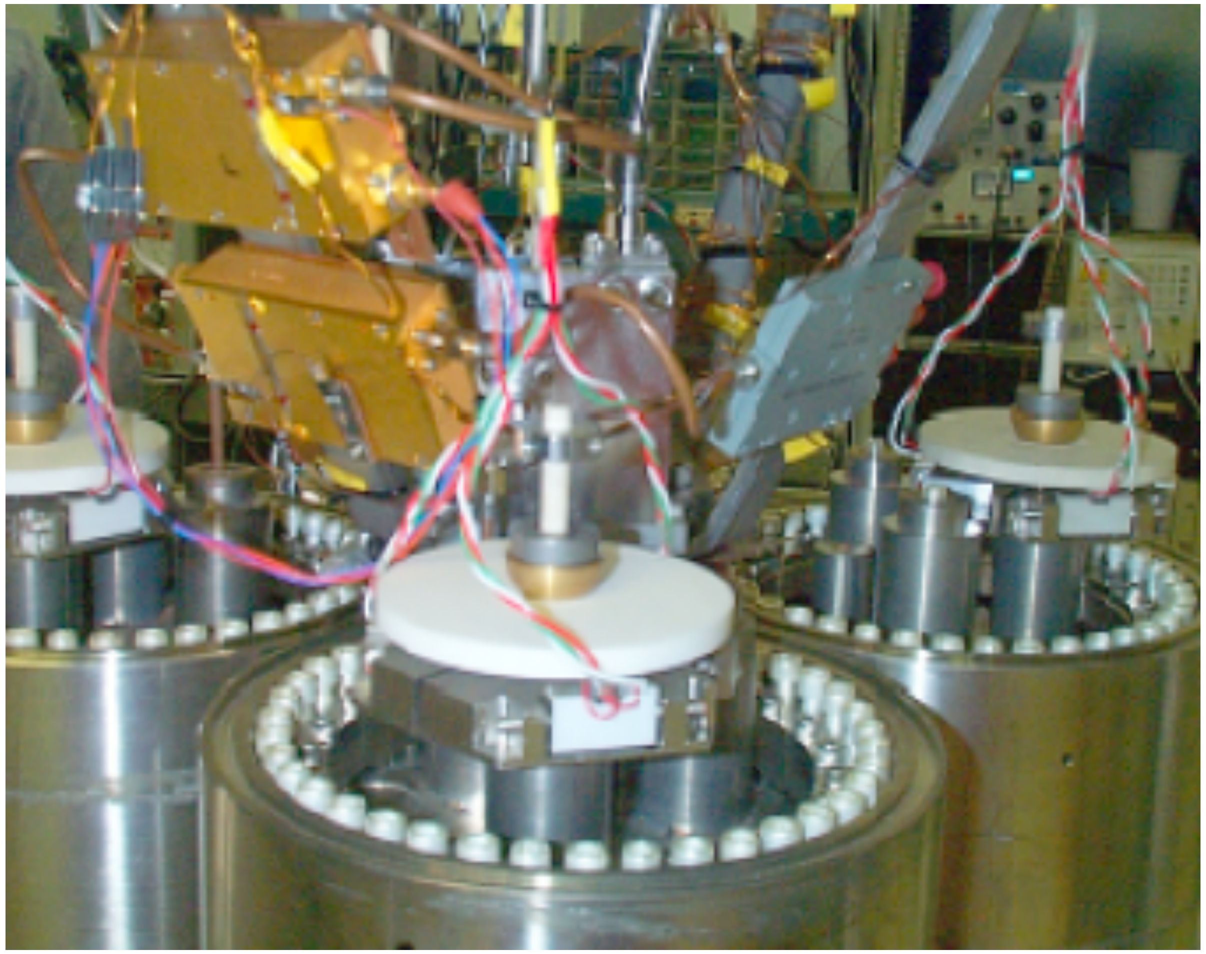

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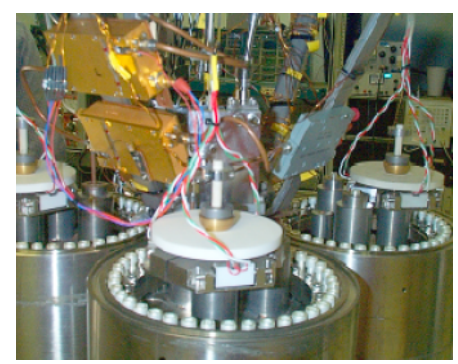

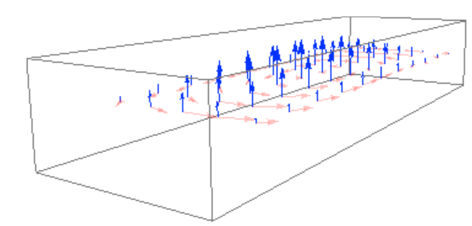

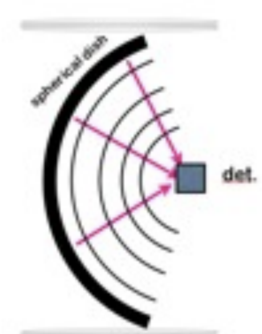

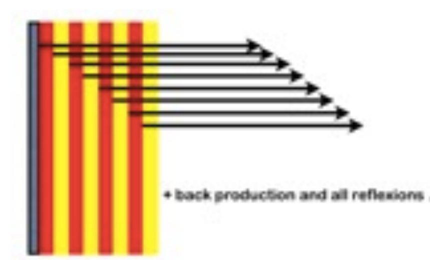

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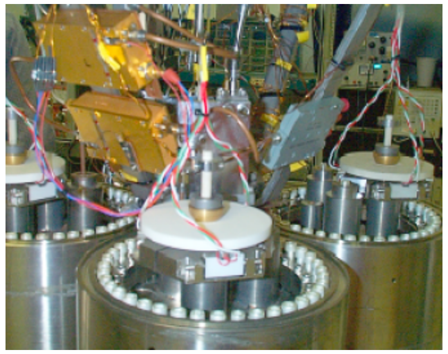

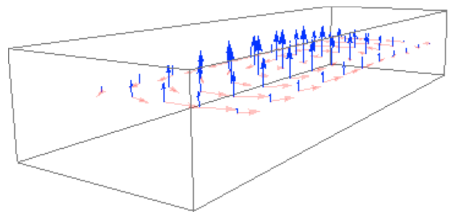

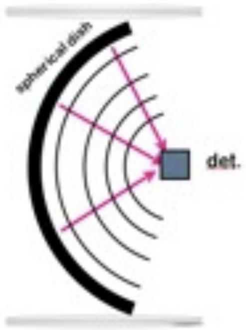

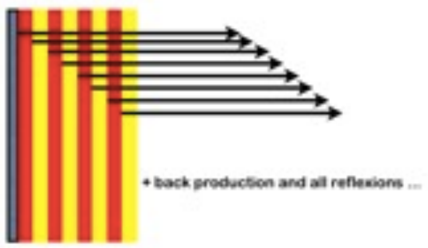

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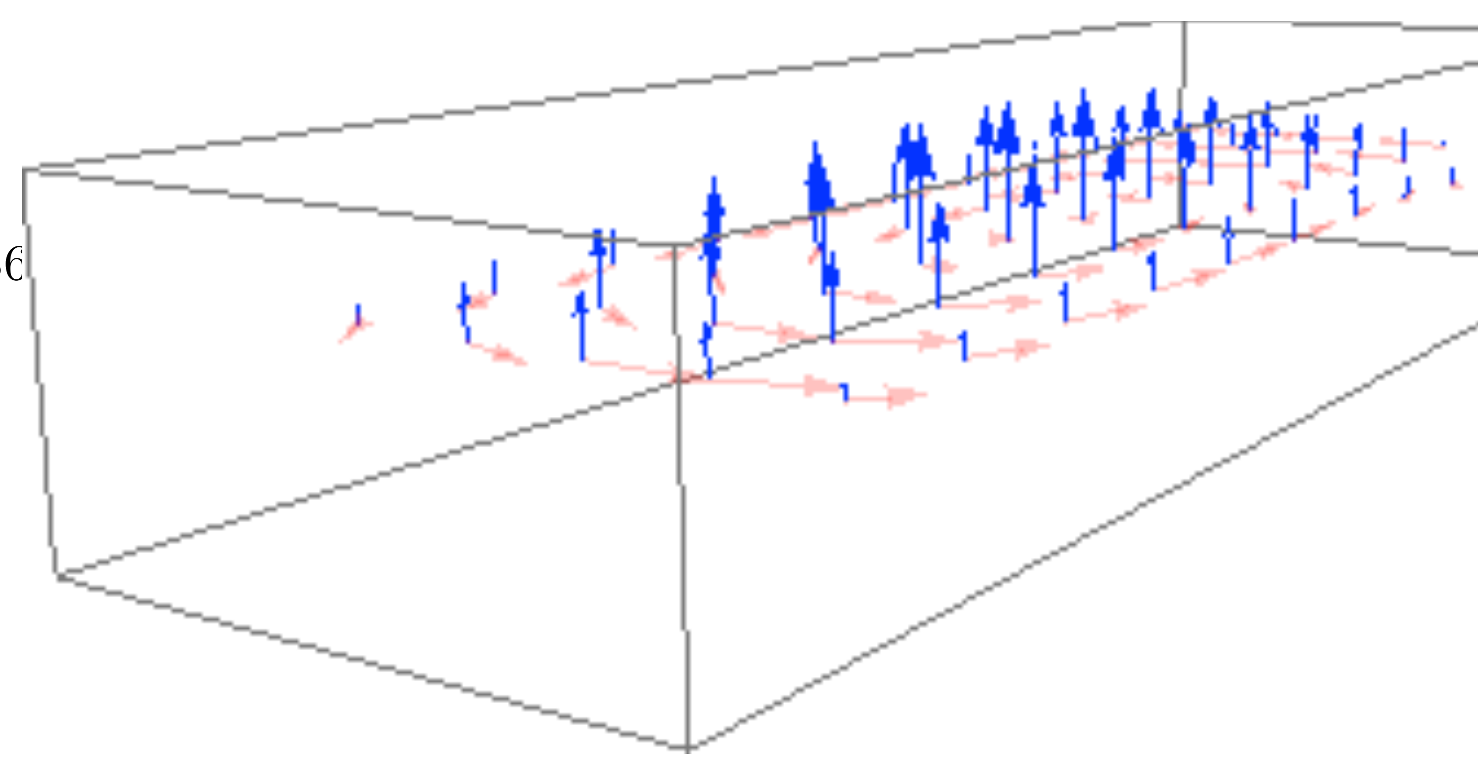

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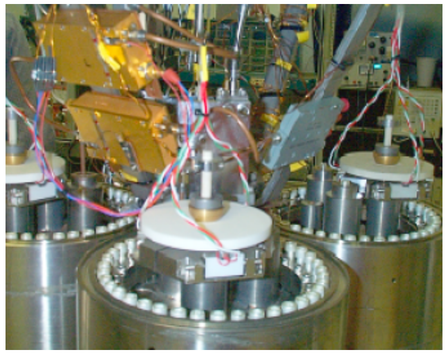

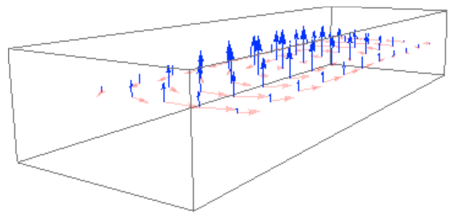

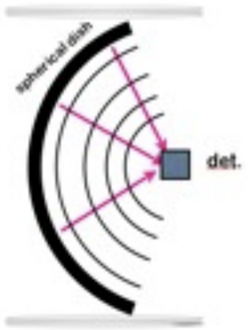

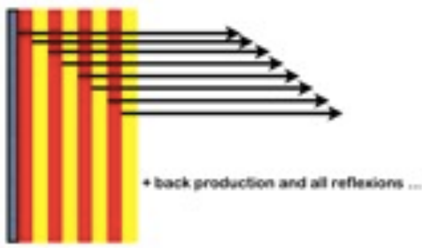

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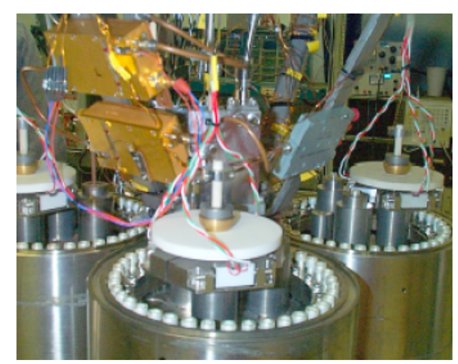

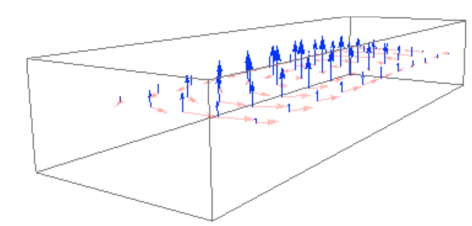

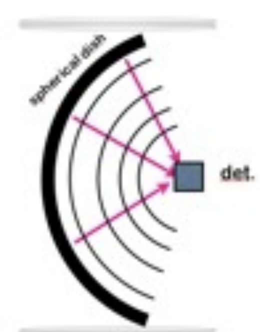

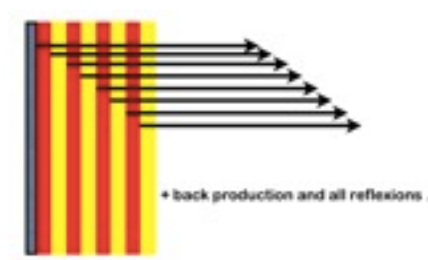

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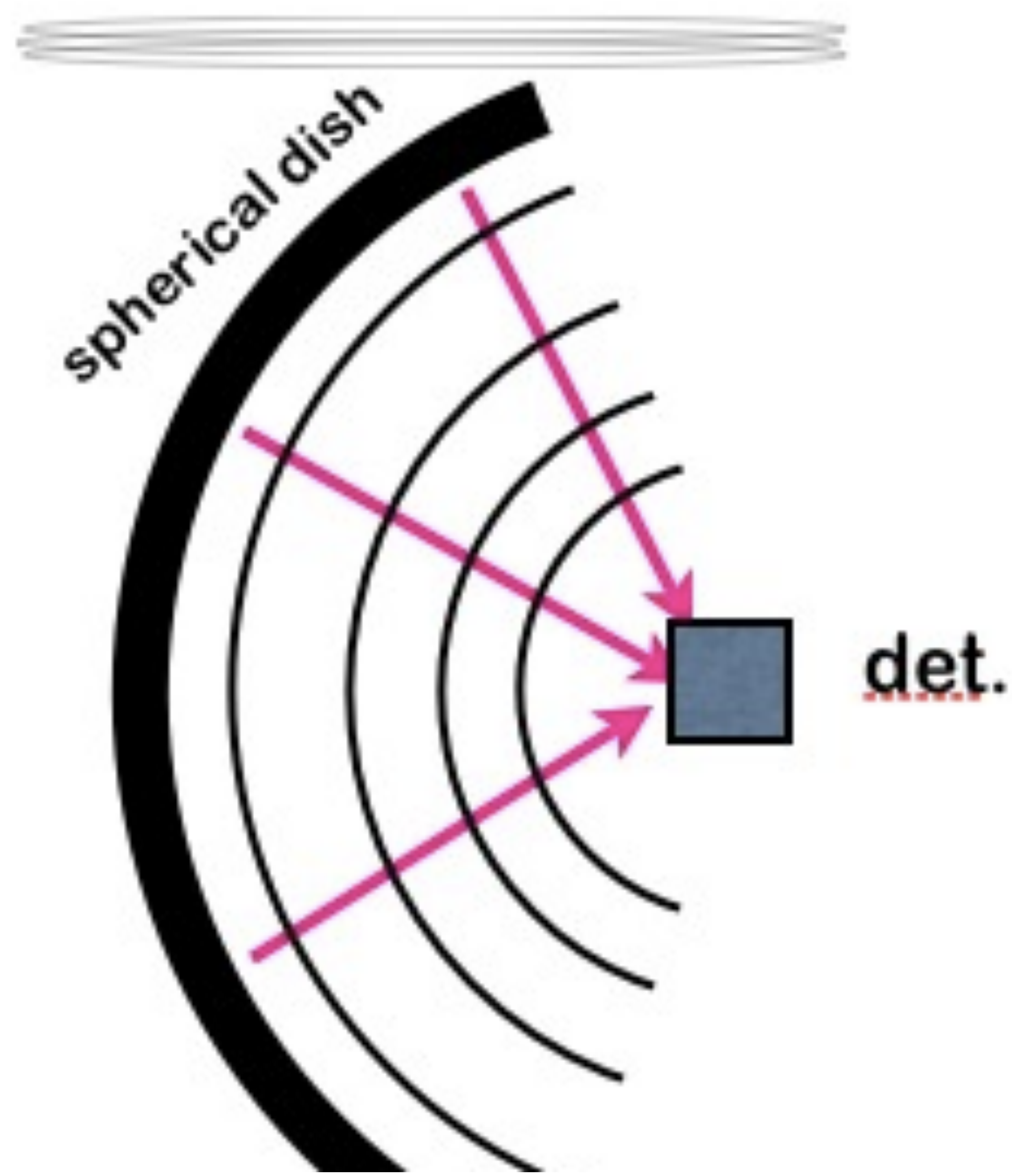

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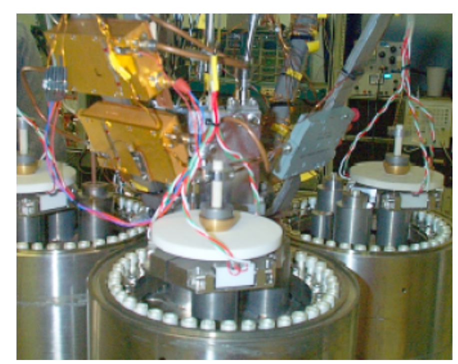

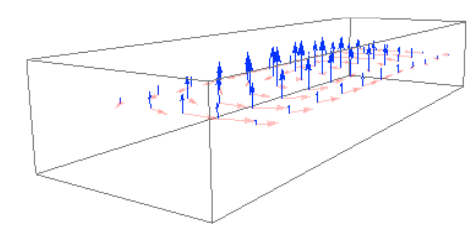

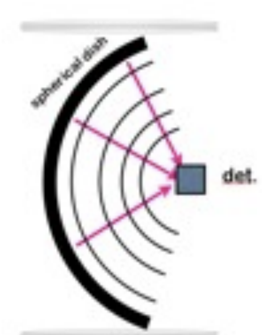

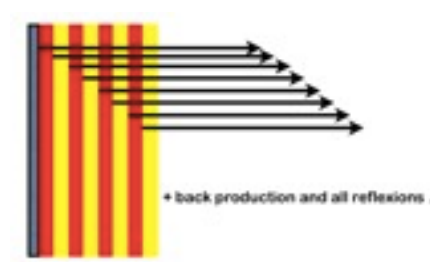

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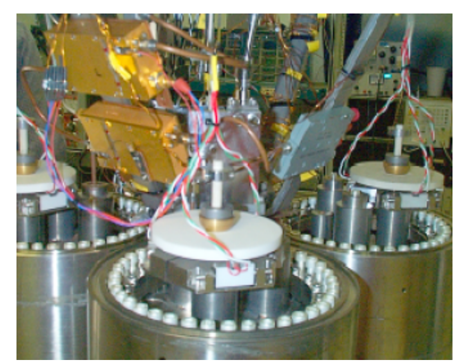

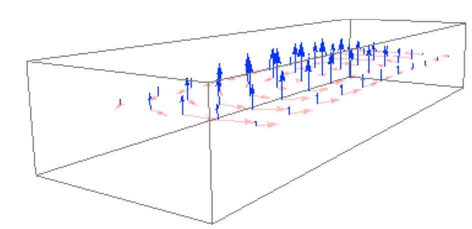

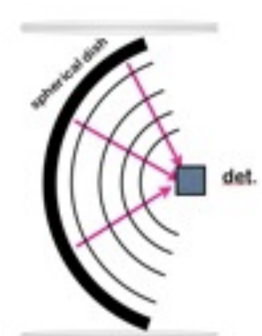

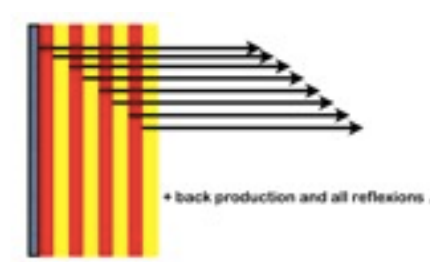

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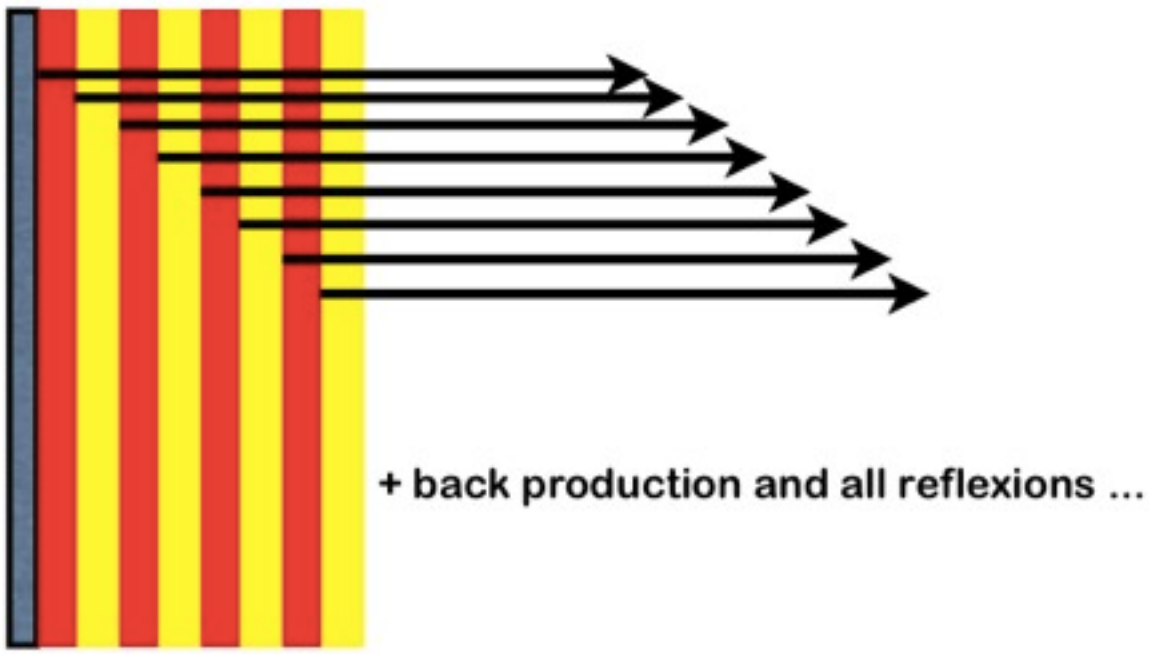

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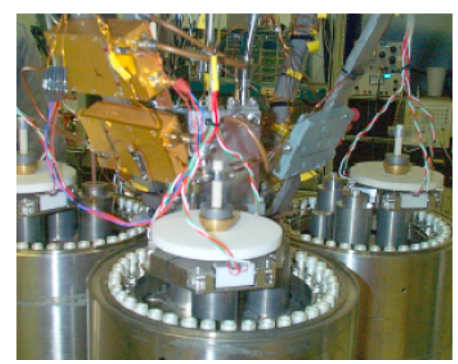
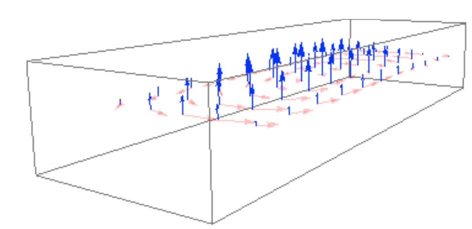
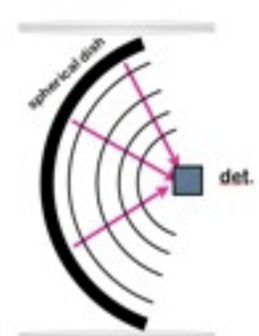
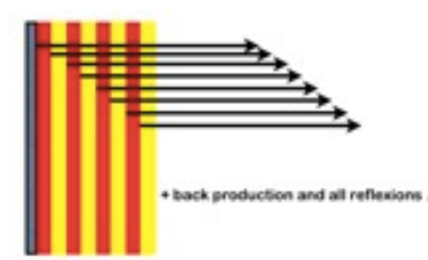




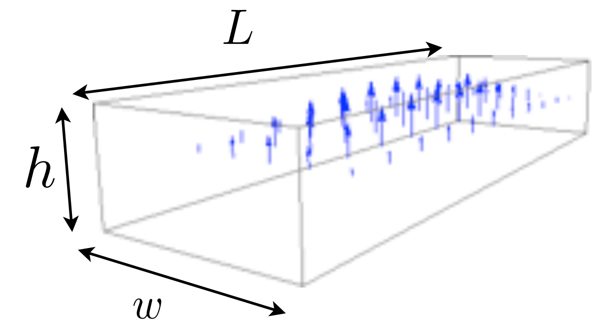




Rectangular cavities

- fixed m_a, maximise power?

TE101



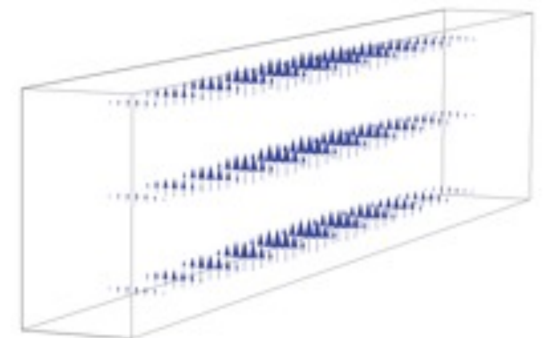
$$P \propto [V m_a] \mathcal{G} Q \sim [whLm_a] \frac{64}{\pi^4 n^2} \frac{1}{\omega\delta} \frac{h}{4h+2w} \to hL \frac{1}{m_a}$$

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

(independent of n...)

maximise transverse area!

TE101



not the fundamental!

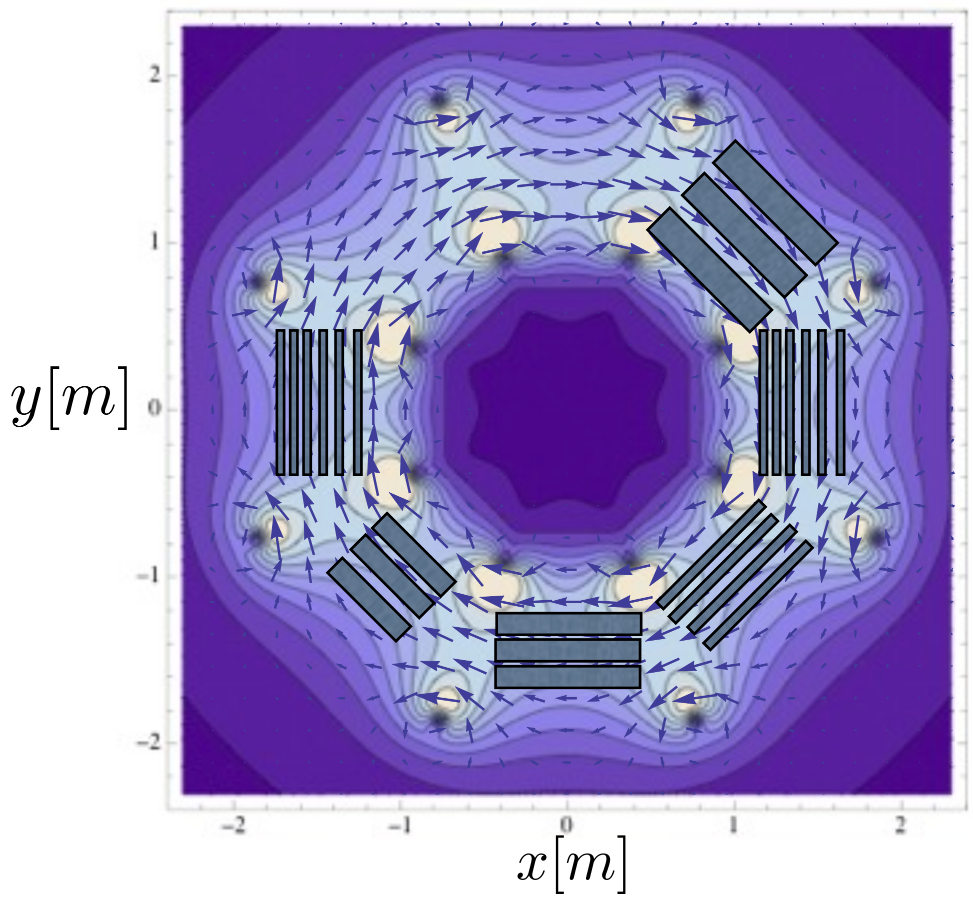
Crossings with TE0ml (avoided?, coupling?)

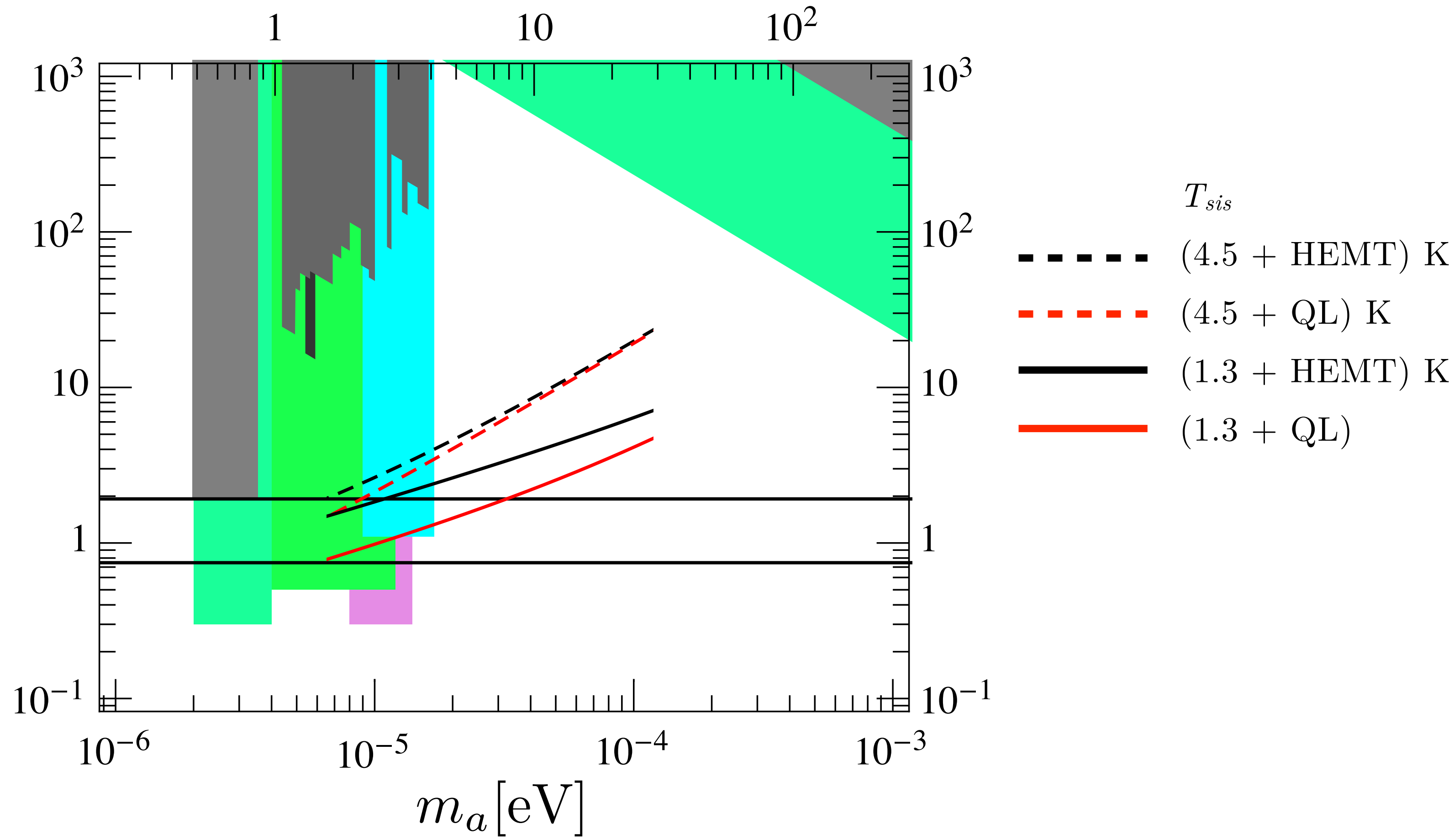
R+D in progress (B. Gimeno Valencia U., J.D. Gallego, Yebes O.)

- 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





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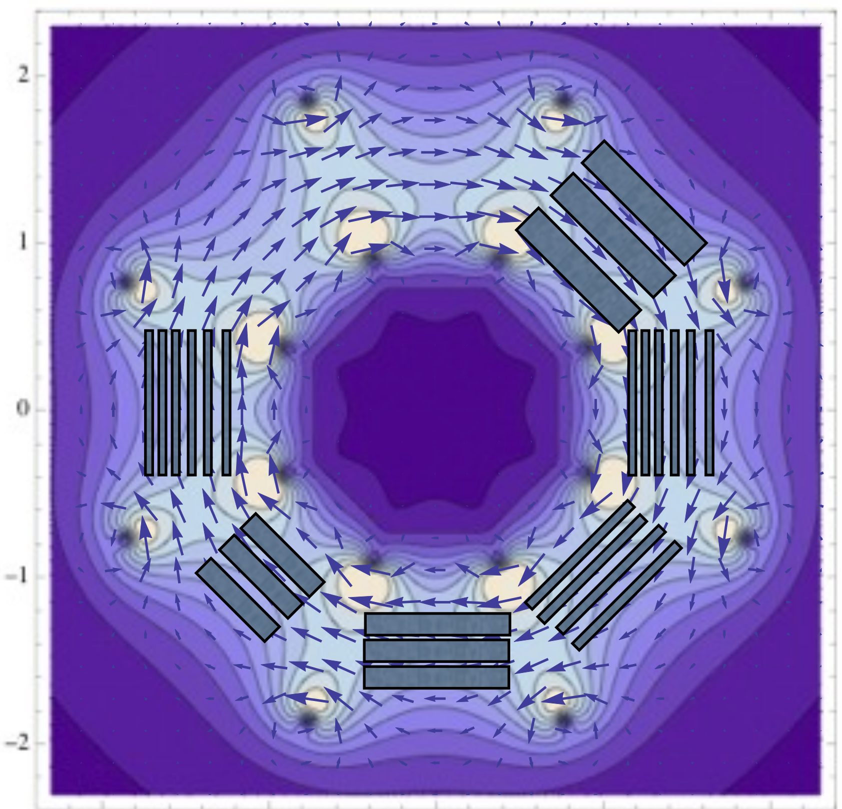
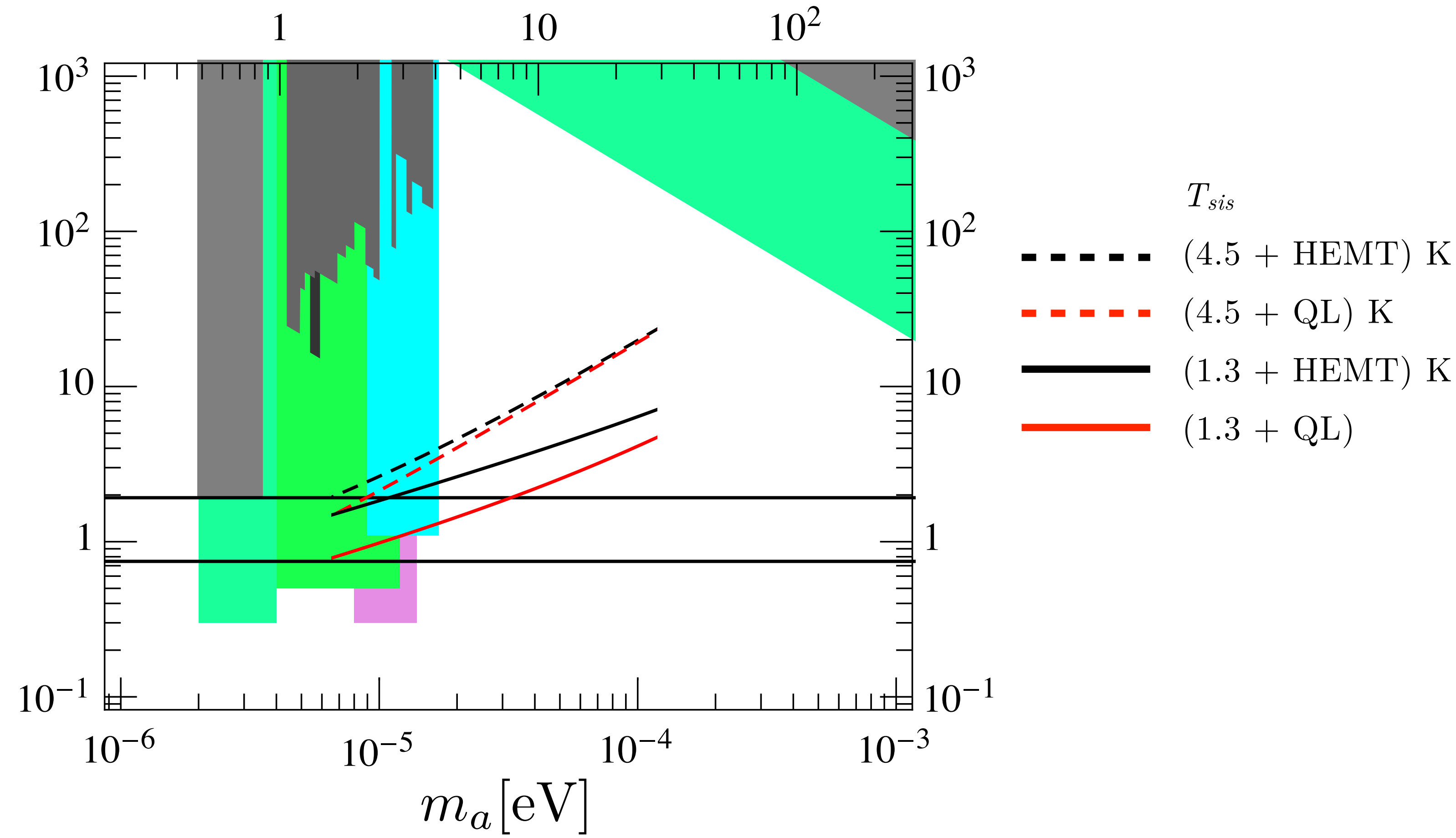
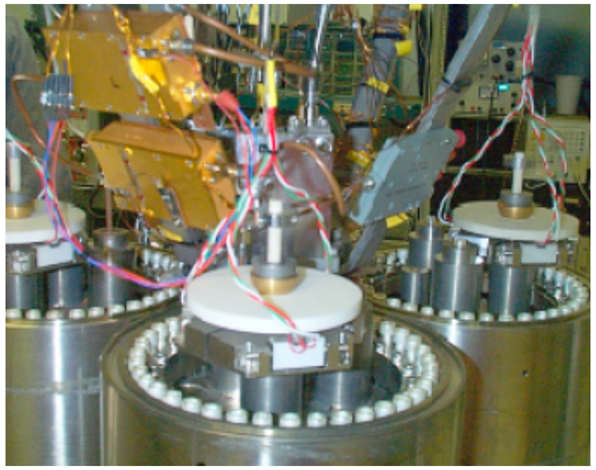




- Boost the power even more by combining N equal cavities coherently (high Q?)

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

trade part of the Q for a large number



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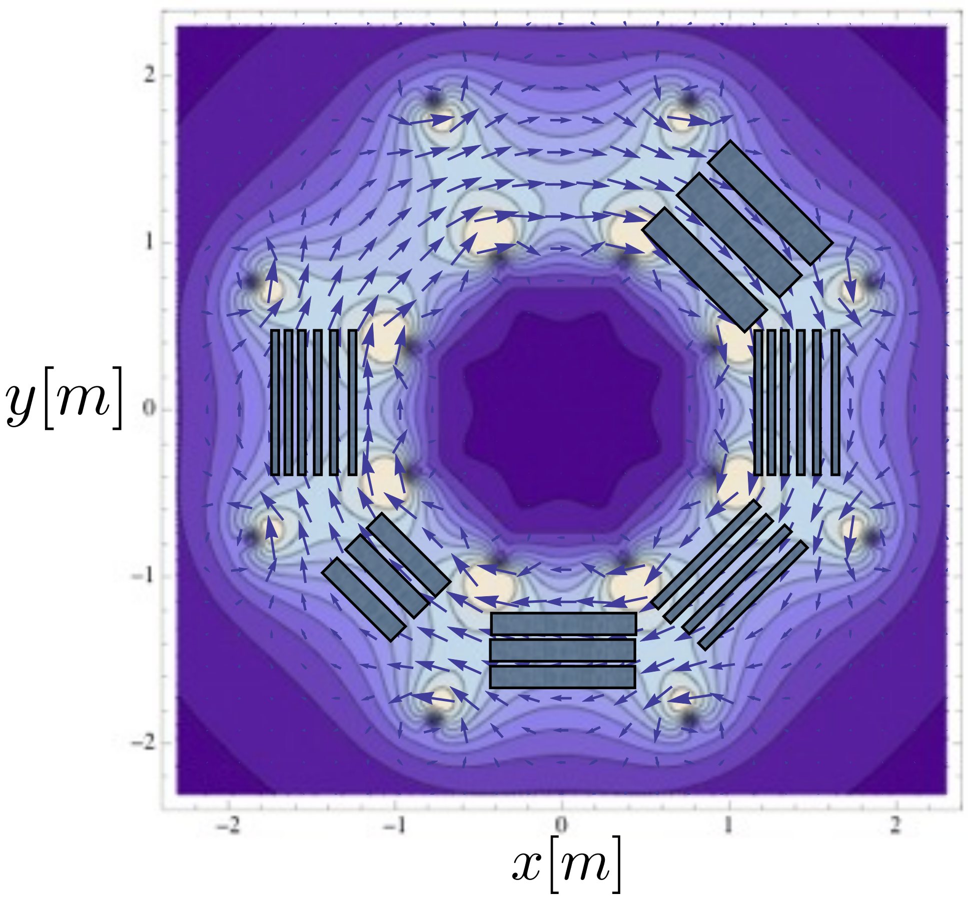

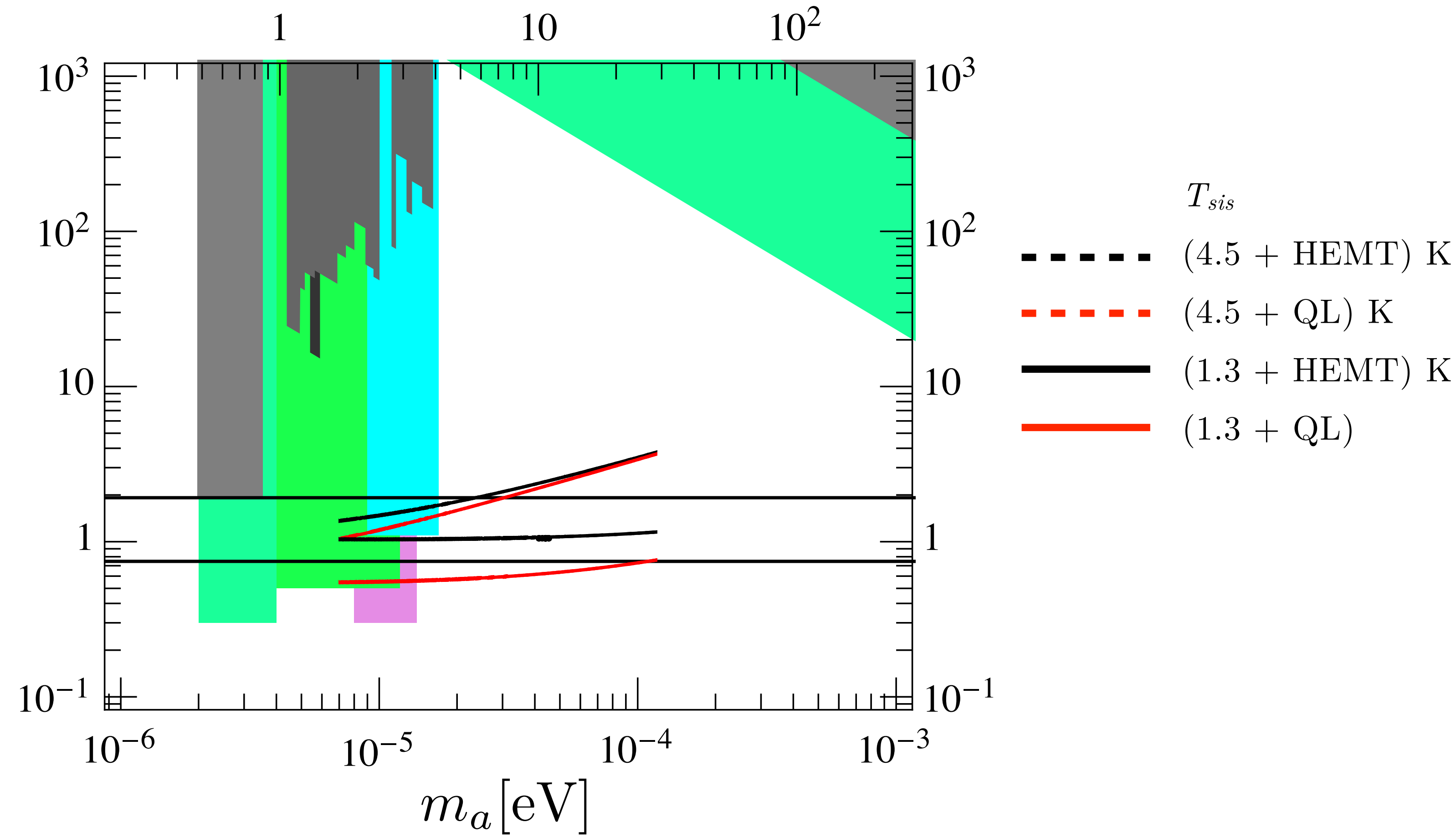

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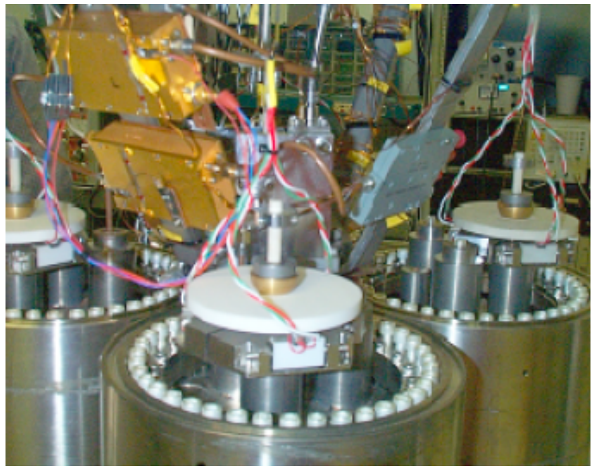
prospects ranging 1-100 (# with increasing mass), (Q=3000 to 500)



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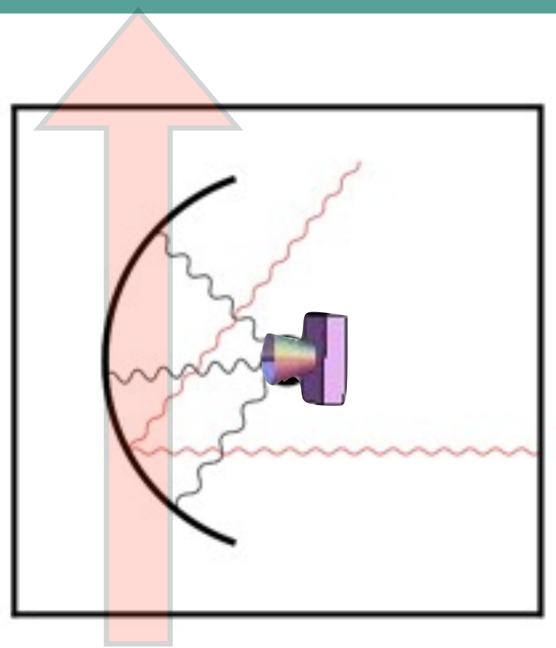
Dish Antenna

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

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

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

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



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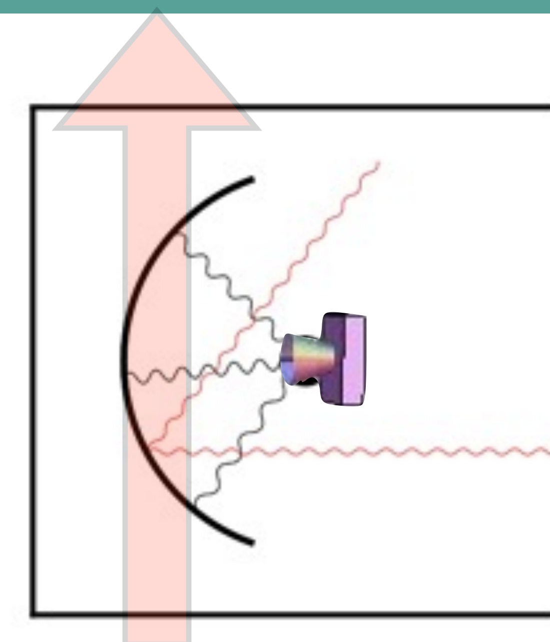

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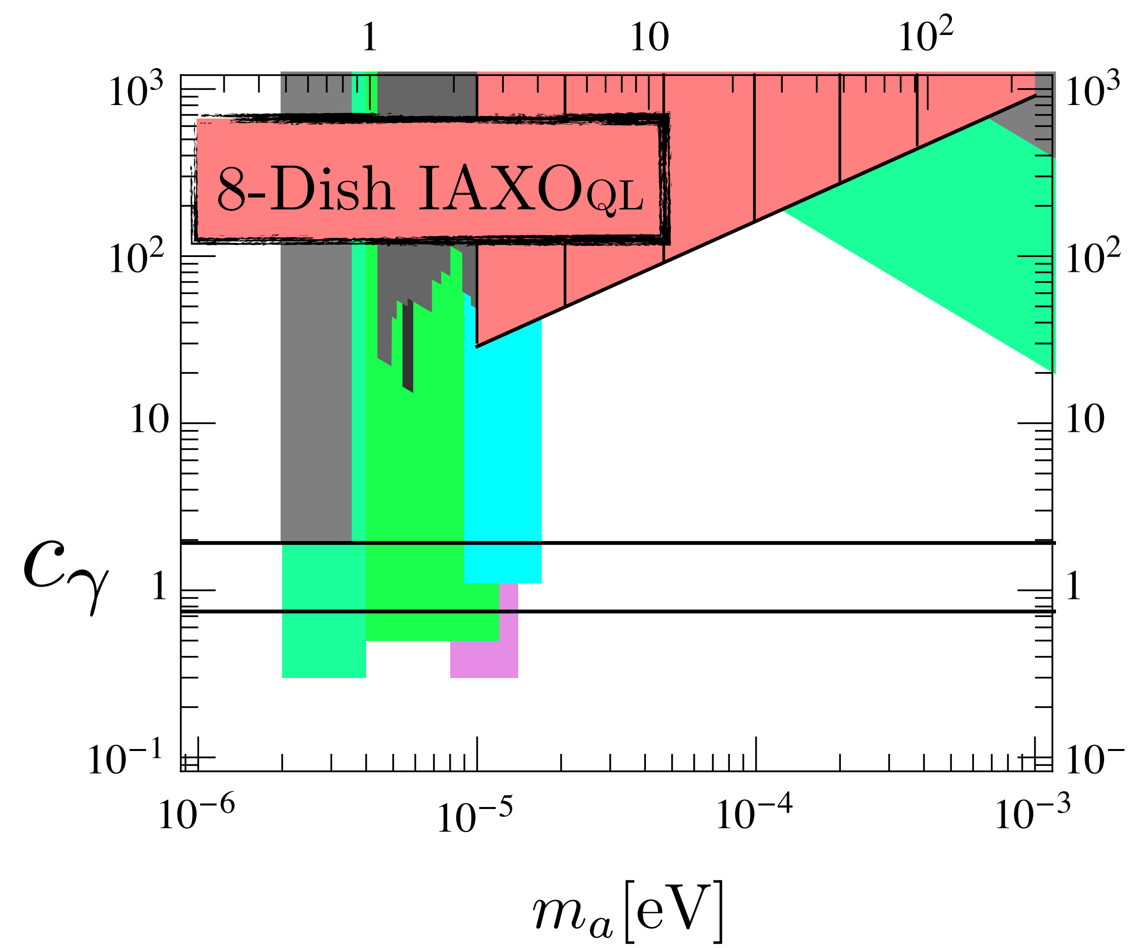
- IAXO (B~ 2.5 T, $A\sim 1\ m^2$, t=*year*, T_{sis}=QL)
  is NOT enough for $\rho_{\rm CDM} = 0.3{\rm GeV/cm^3}$



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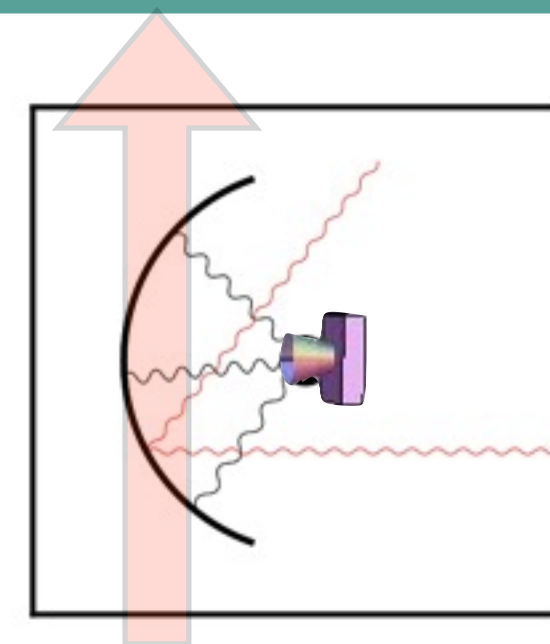

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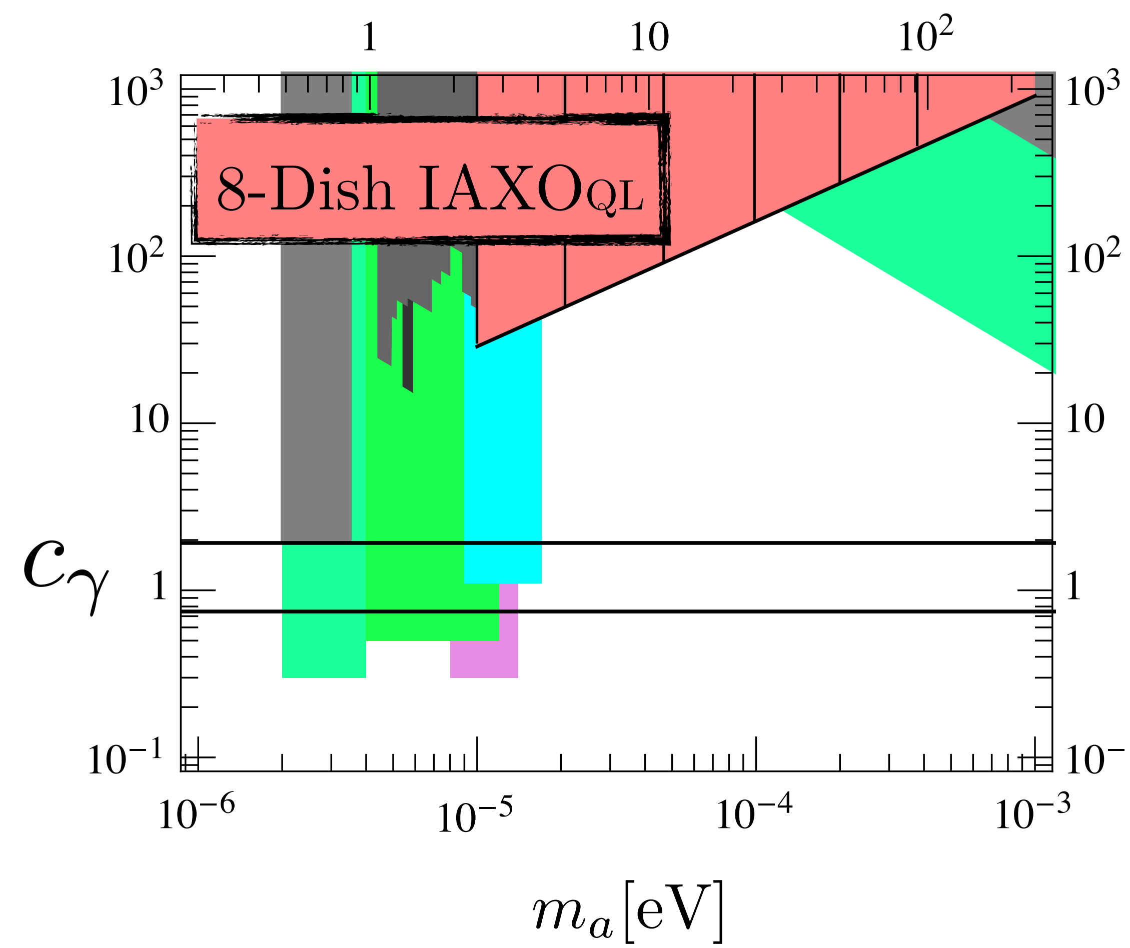
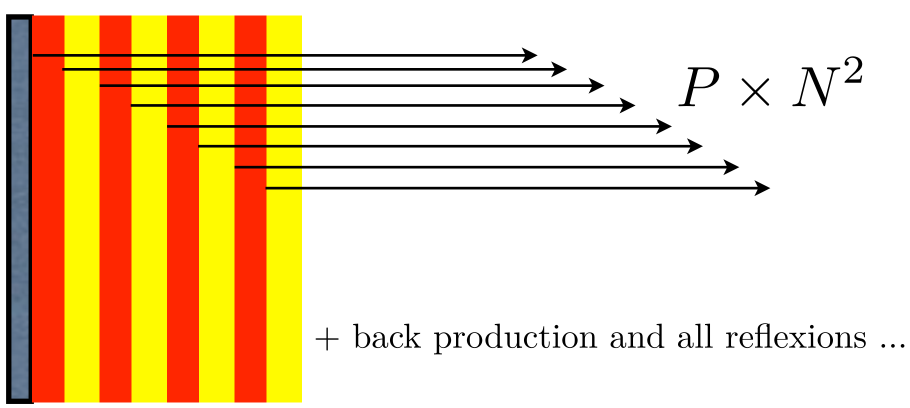


- Dielectric layers enhance the emission (in phase)



Alternating N layers of low/high, $\lambda/2$

turn your "dielectric mirror" into a resonator, (+narrows the band)

Enhancements $Q \sim N^2$ 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)

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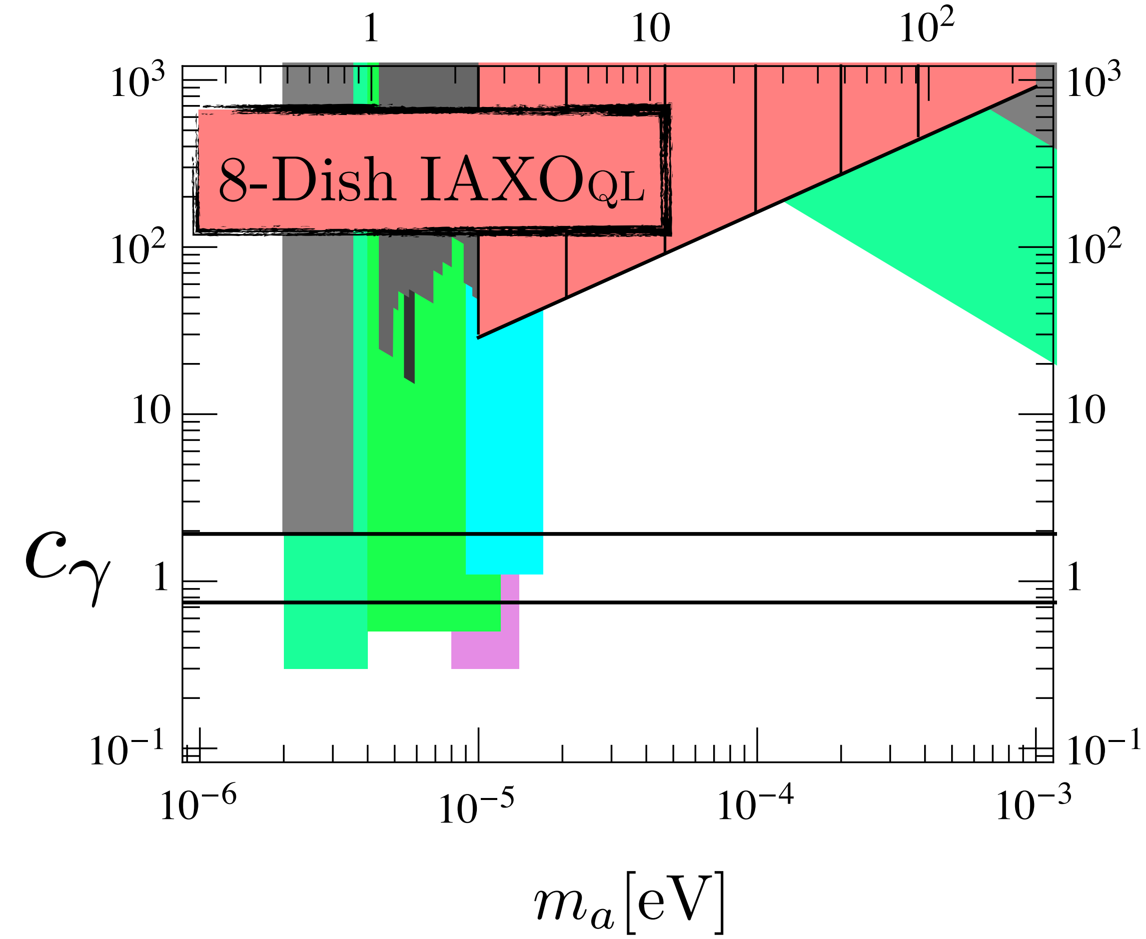

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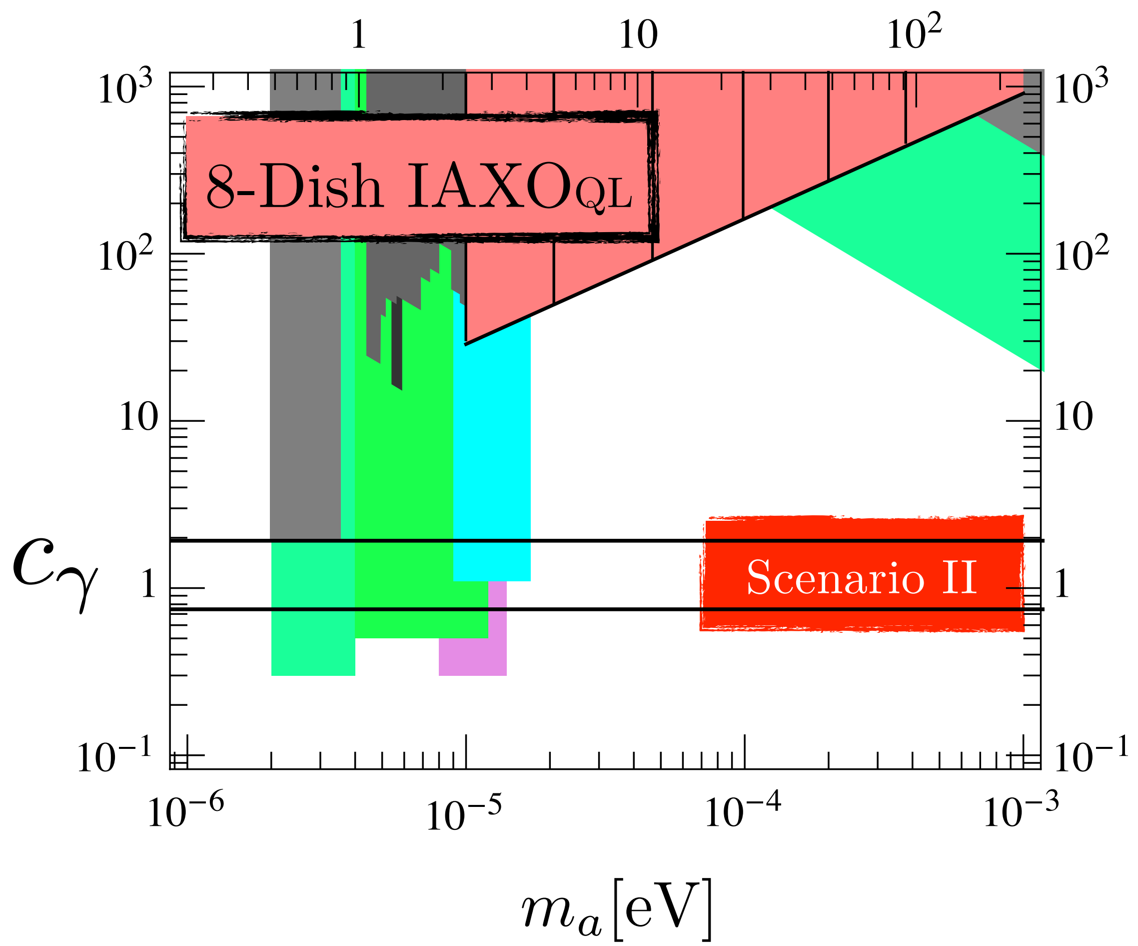

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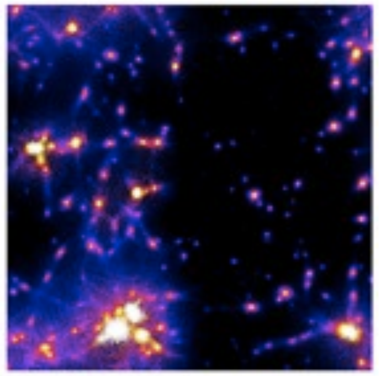
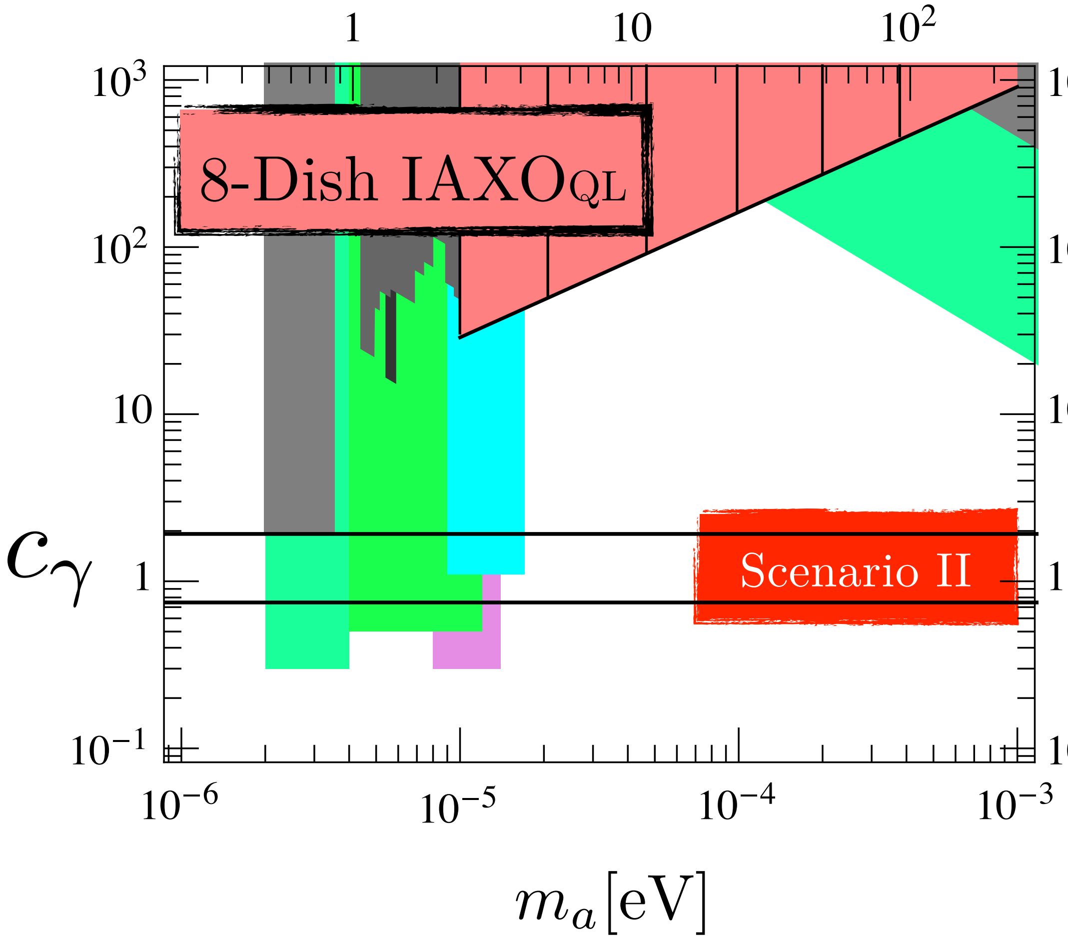


$$M_{\rm mc} \sim 10^{-12} M_\odot$$
$$\Omega_{mc}/\Omega_{a{\rm CDM}} \sim O(1)$$

Zurek et al 07, See also Kolb & Tkachev 94



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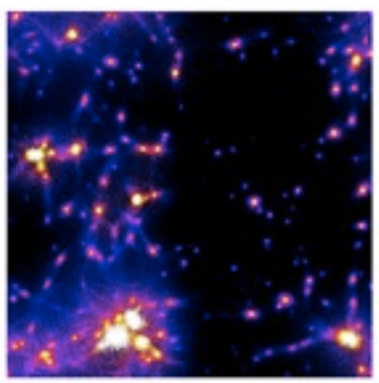

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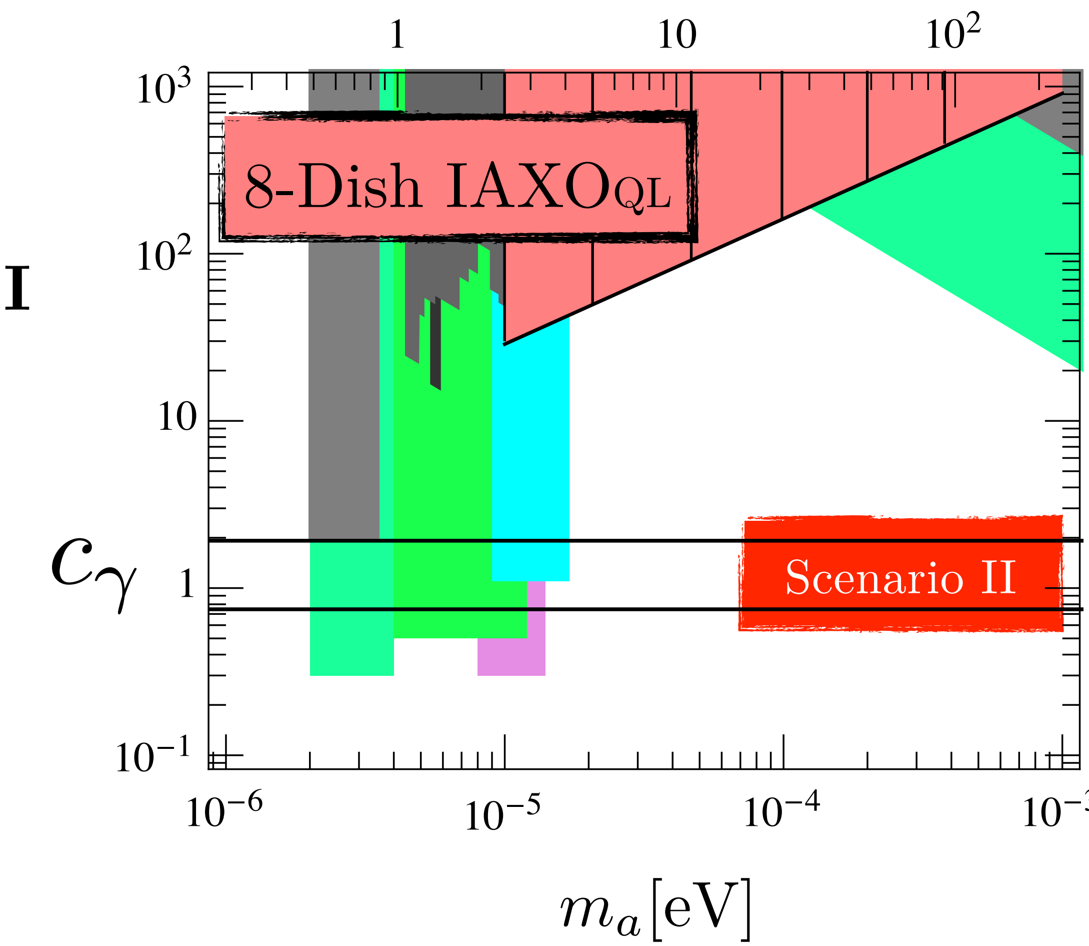

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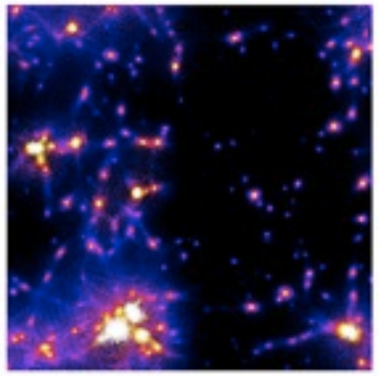

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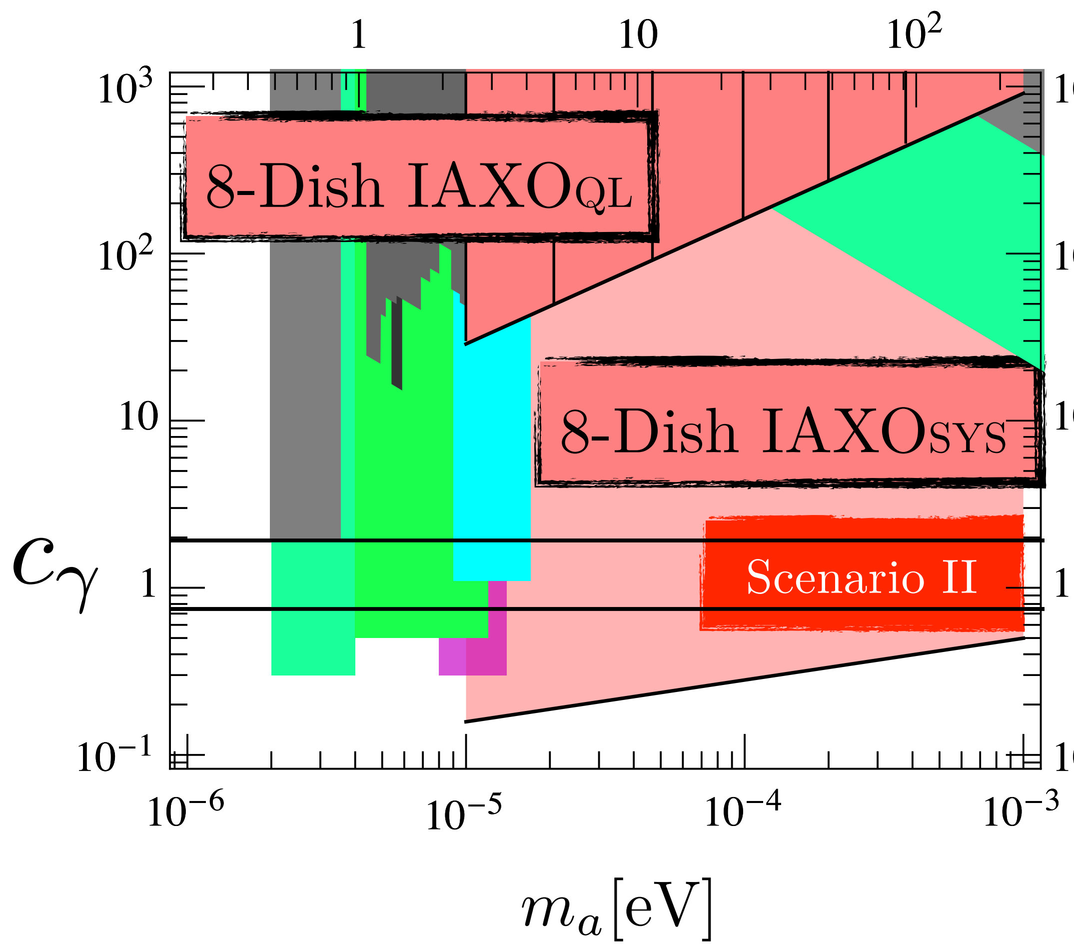

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WISPy dark matter? ... hidden photons

- U(1) **Vector bosons** hidden from SM particles;
- Extensions of the SM, **string compactifications**
- Residual Interaction with photons at low energies: **kinetic mixing**

$$\mathcal{L} \in \frac{1}{2}\chi F^{\mu\nu}F'_{\mu\nu}$$

- Dark matter through misalignment mechanism (Nelson 1105.2812, Arias 1201.5902)
  Misalignment reason: phase transition, Q-fluctuations inflation (Mardon et al 2014)

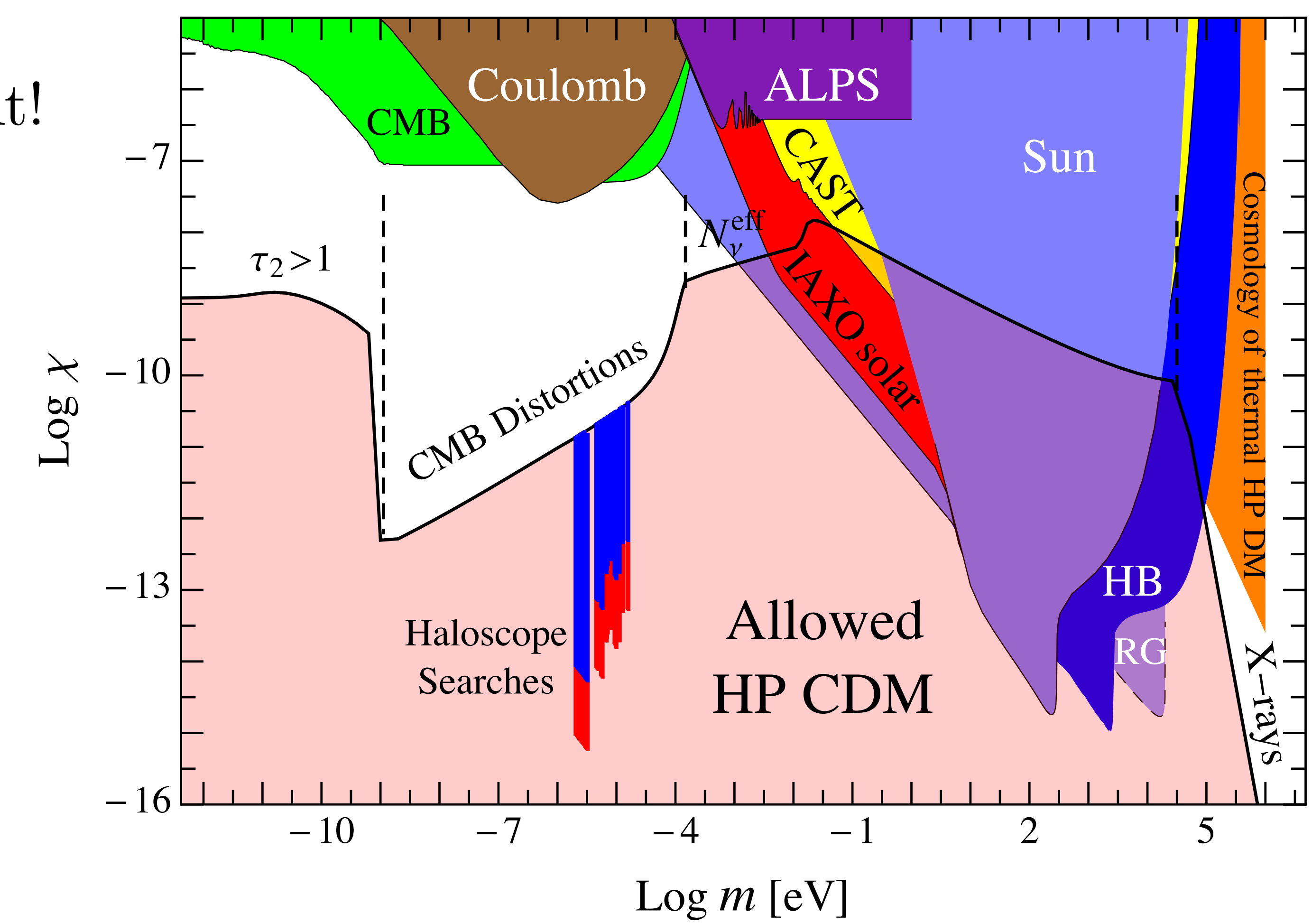
- Detection with cavities/dish equivalent!

$$E(t) \sim \chi E'_0 \cos(mt)$$

$$\chi\mathbf{E}' \leftrightarrow c_\gamma \frac{\alpha}{2\pi}\mathbf{B}_{\text{ext}}\theta$$

- Translate sensitivities

- Solar hidden photons as well



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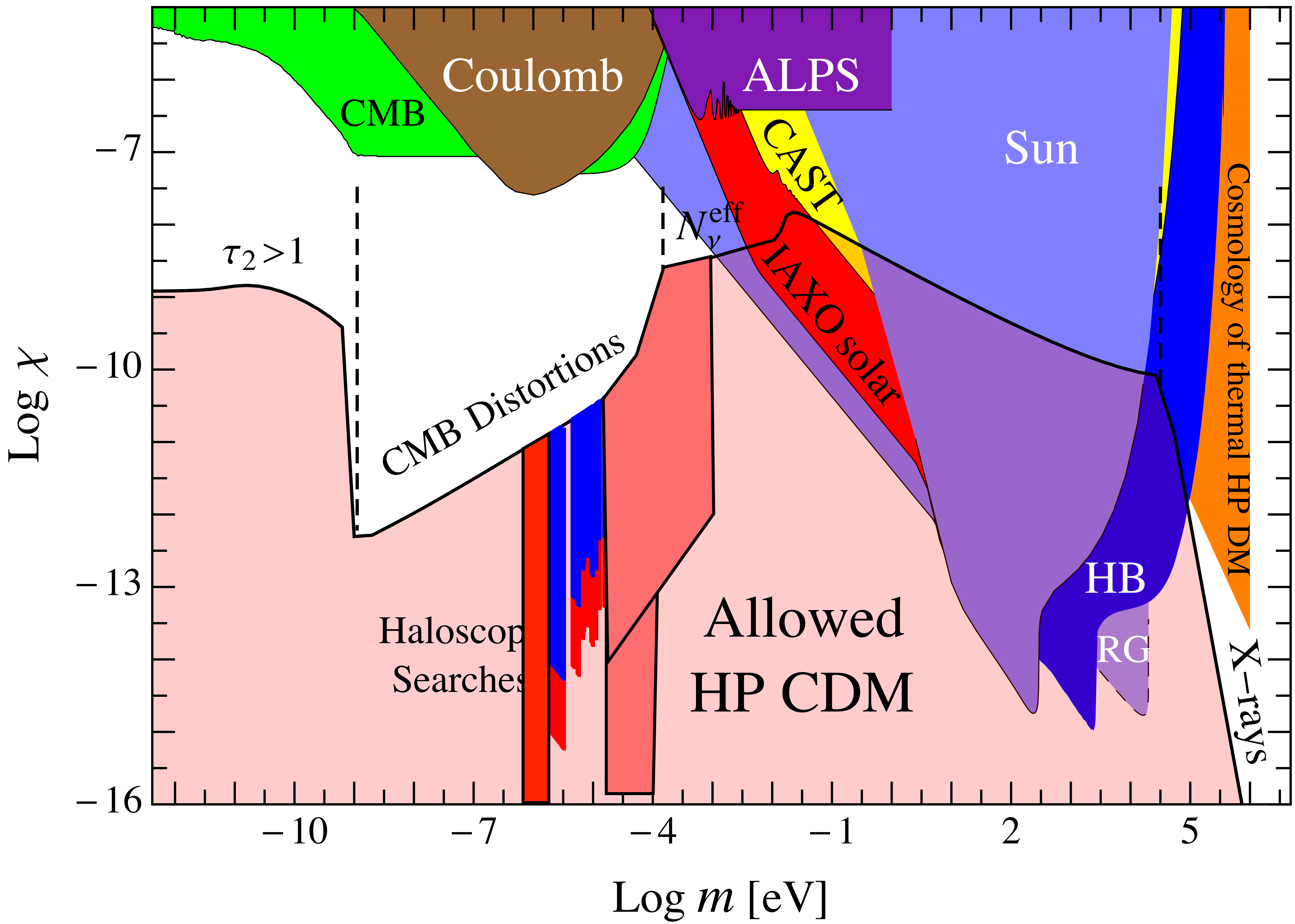
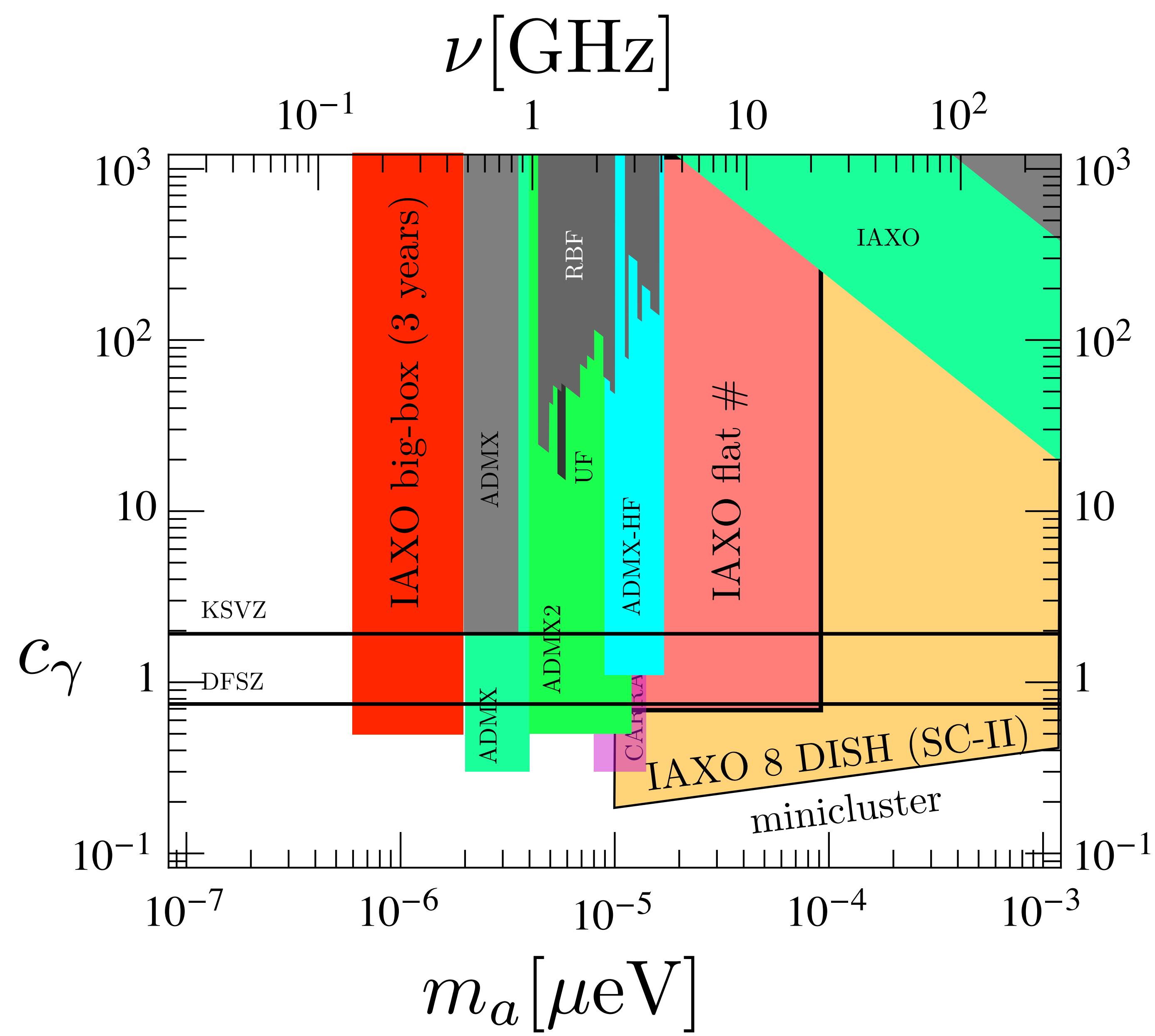


Conclusions

- 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!