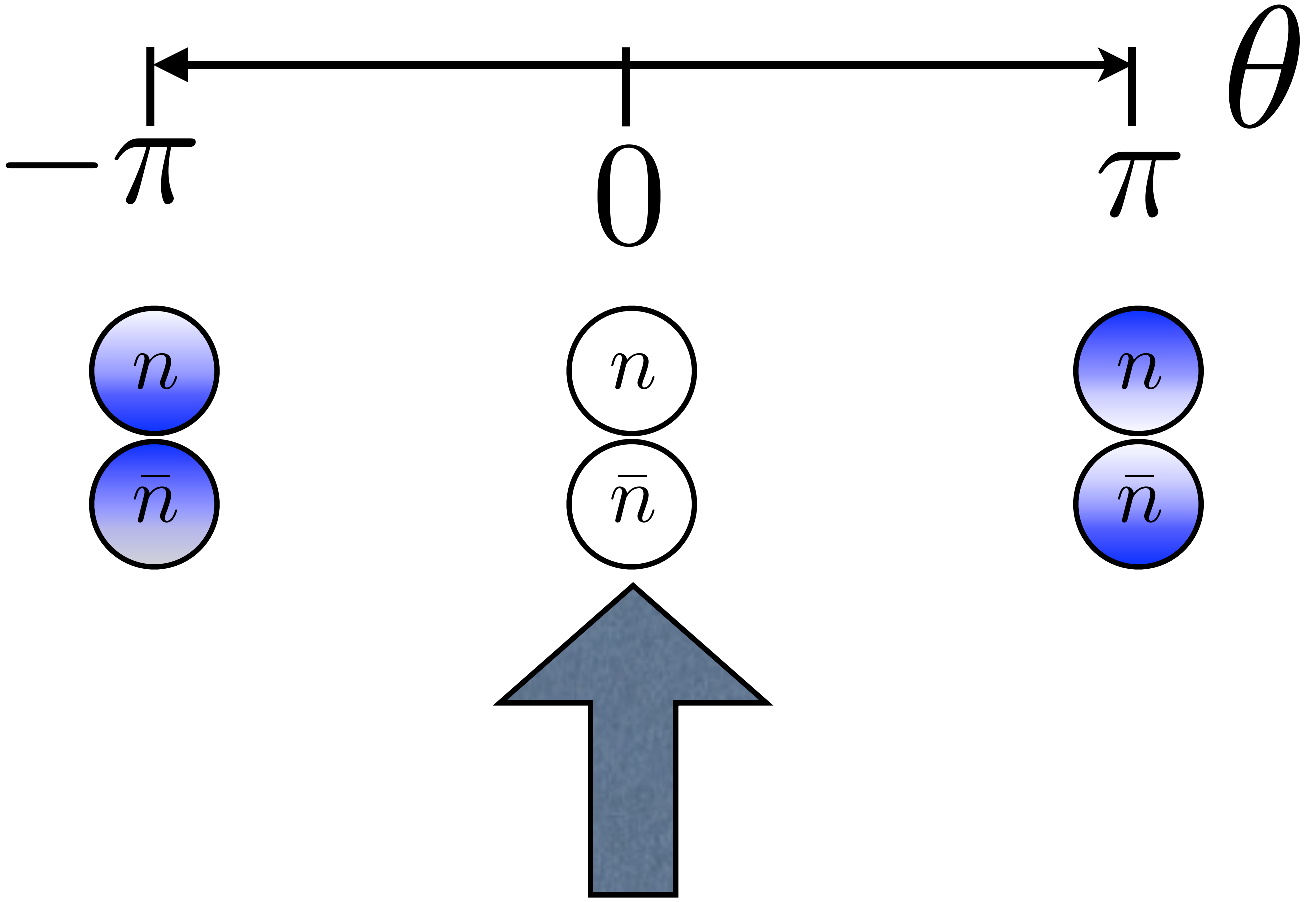
# Axion Dark matter
# Experimental review

**Javier Redondo**
**(Zaragoza U. & MPP)**

# The theta angle of the strong interactions

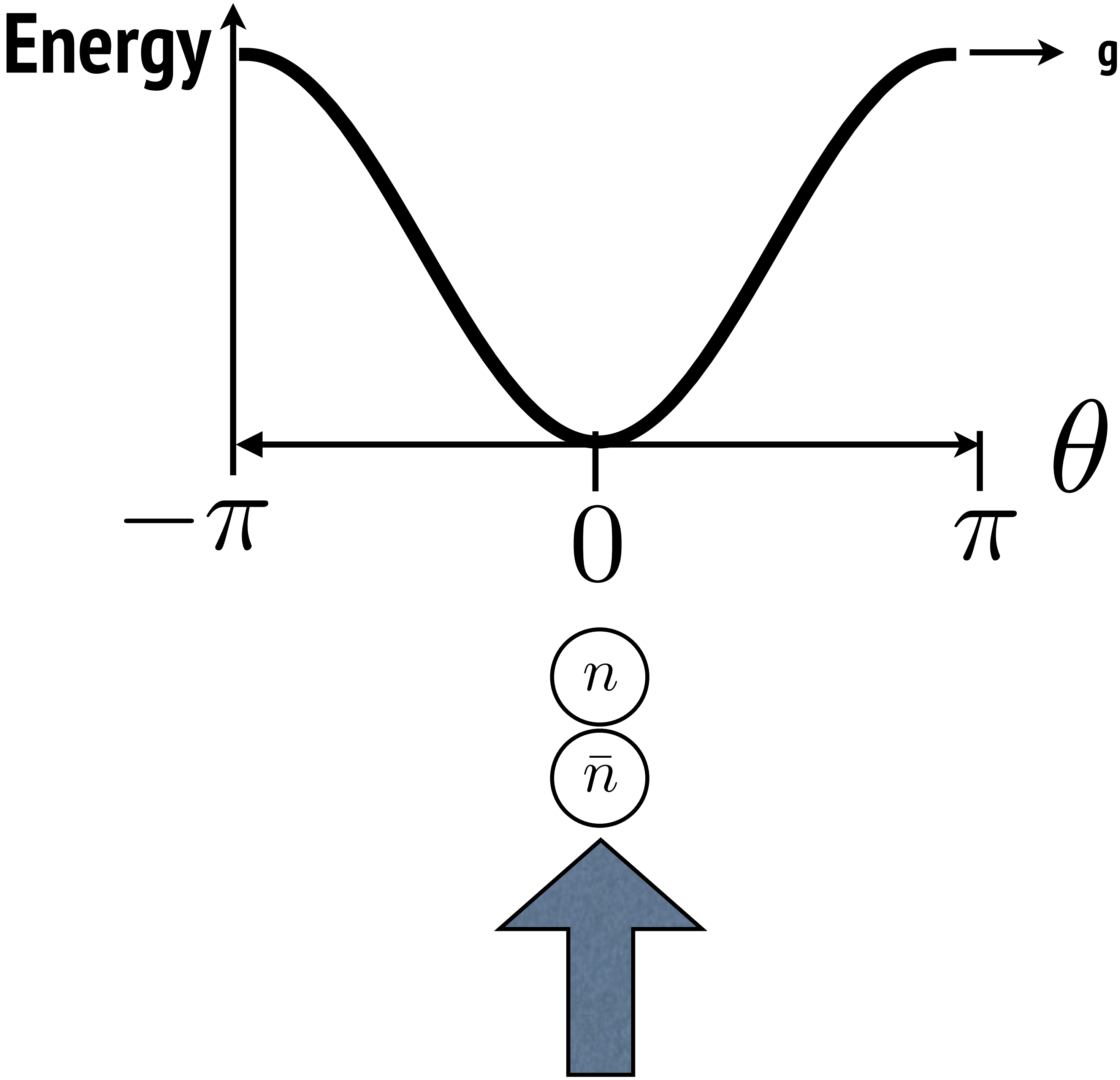
- The value of $\theta$ controls matter-antimatter differences in QCD
- In particular neutron (and proton) Electric dipole moment



Measured today $|\theta| < 10^{-10}$ (strong CP problem)

# Axions

- **is it a dynamical field?** $\theta(t, \mathbf{x})$



**generated by QCD!**

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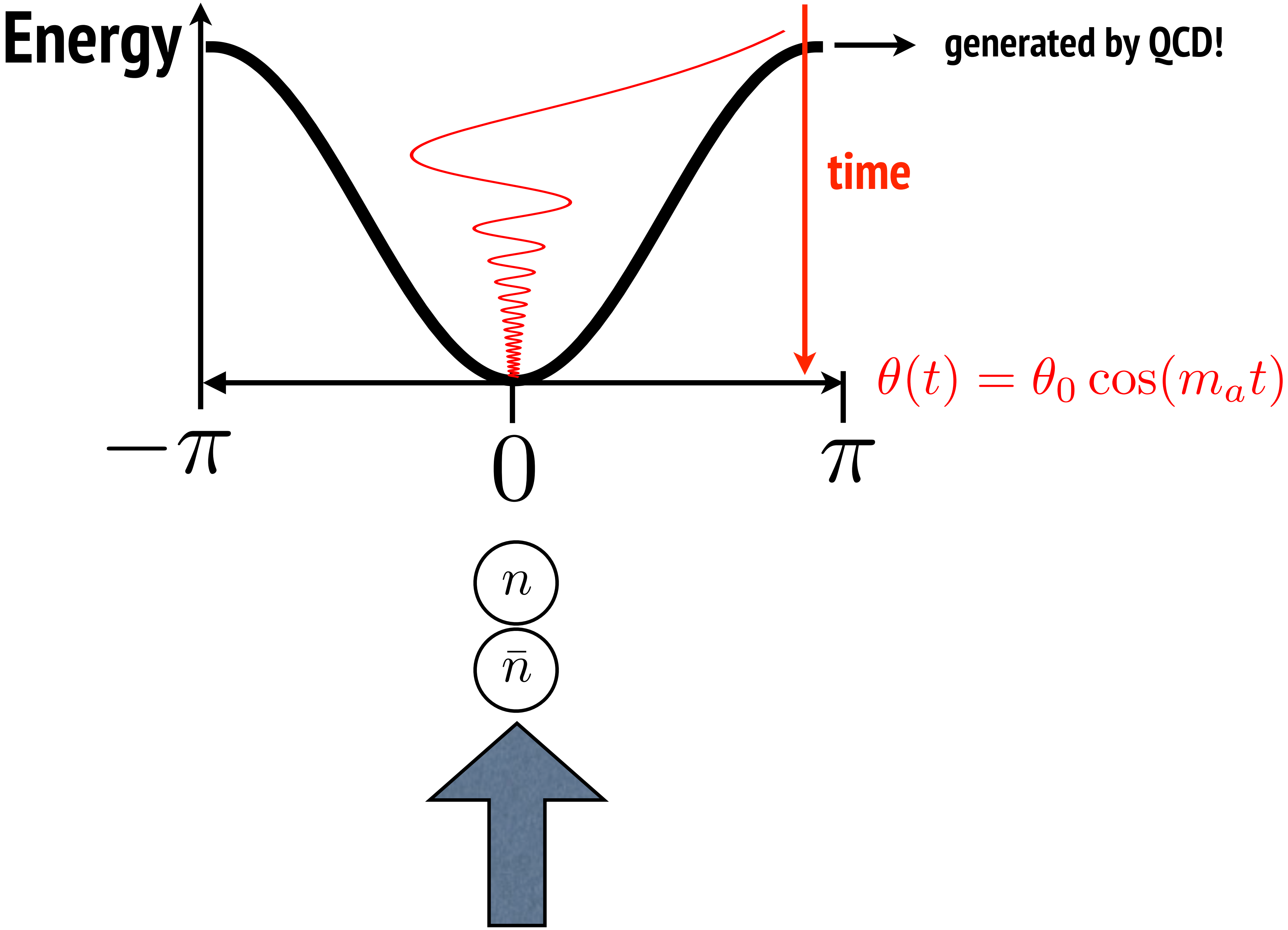

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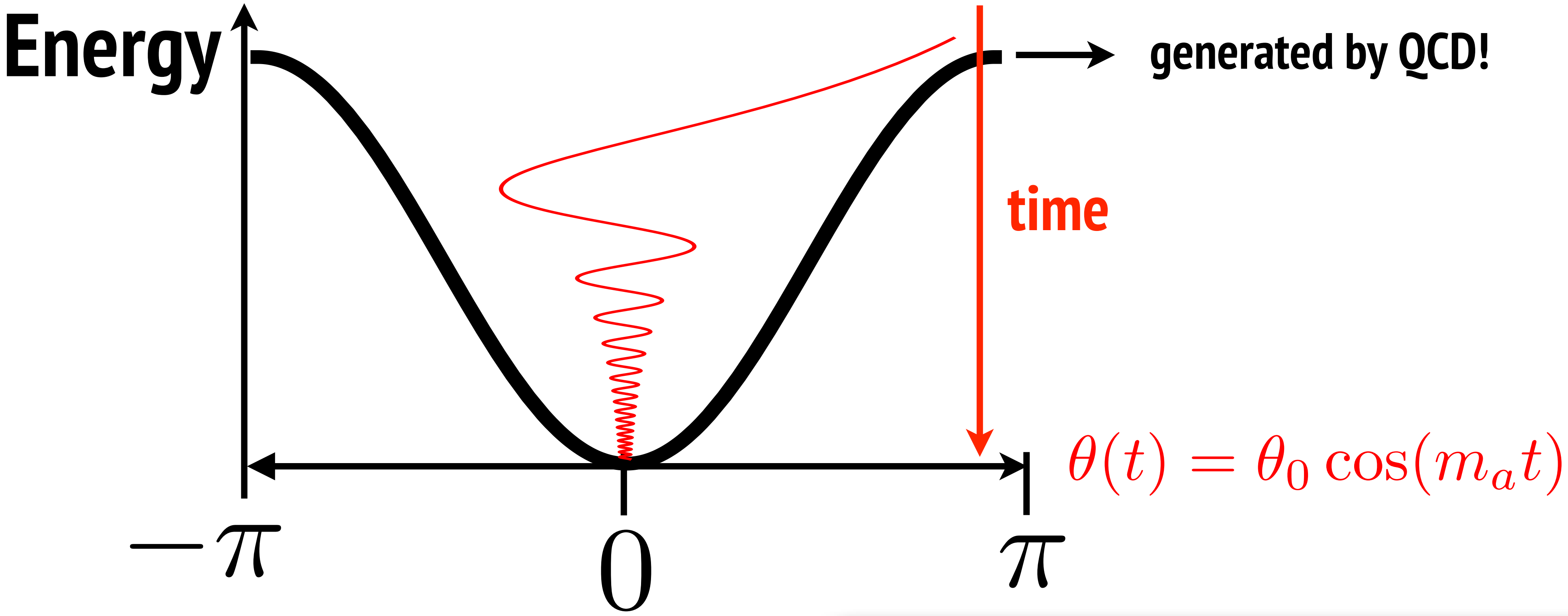
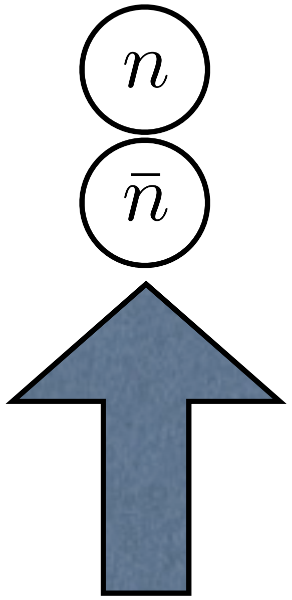
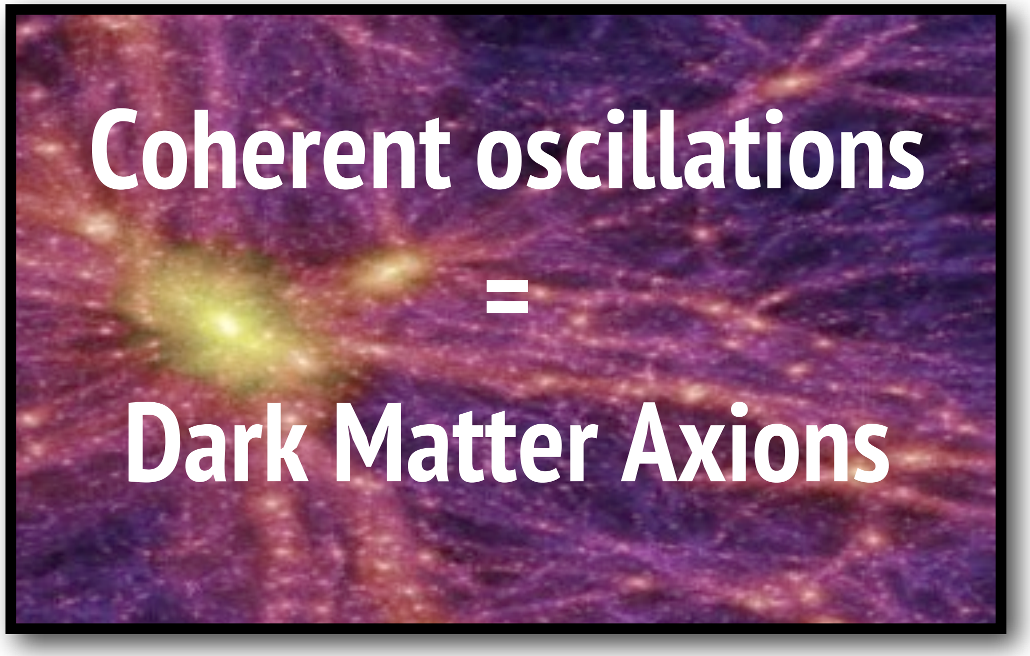


$$\theta(t) = \theta_0 \cos(m_a t)$$





**Coherent oscillations**

**=**

**Dark Matter Axions**

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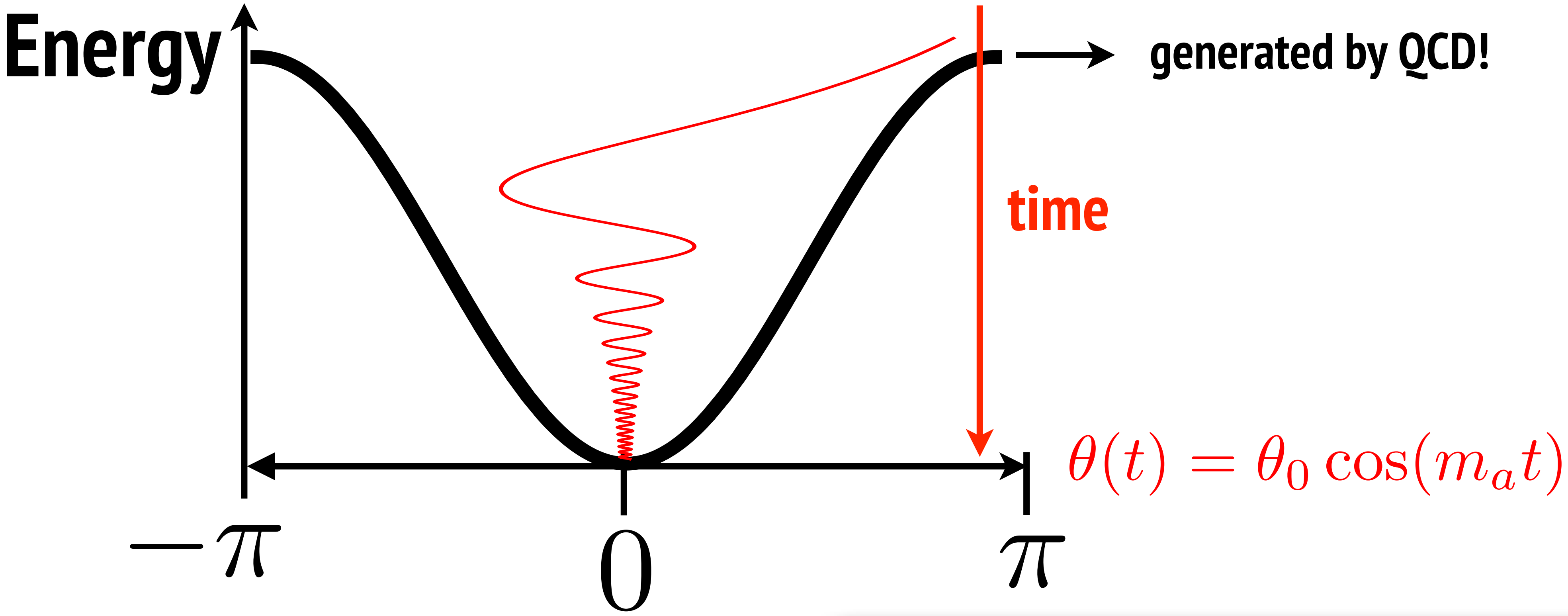
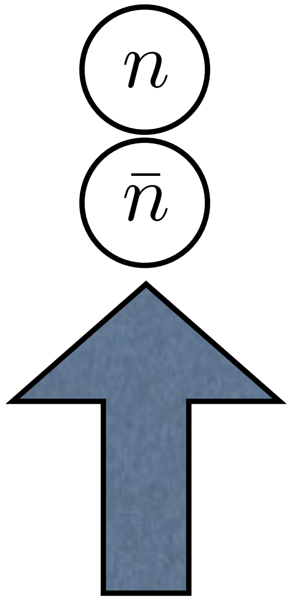


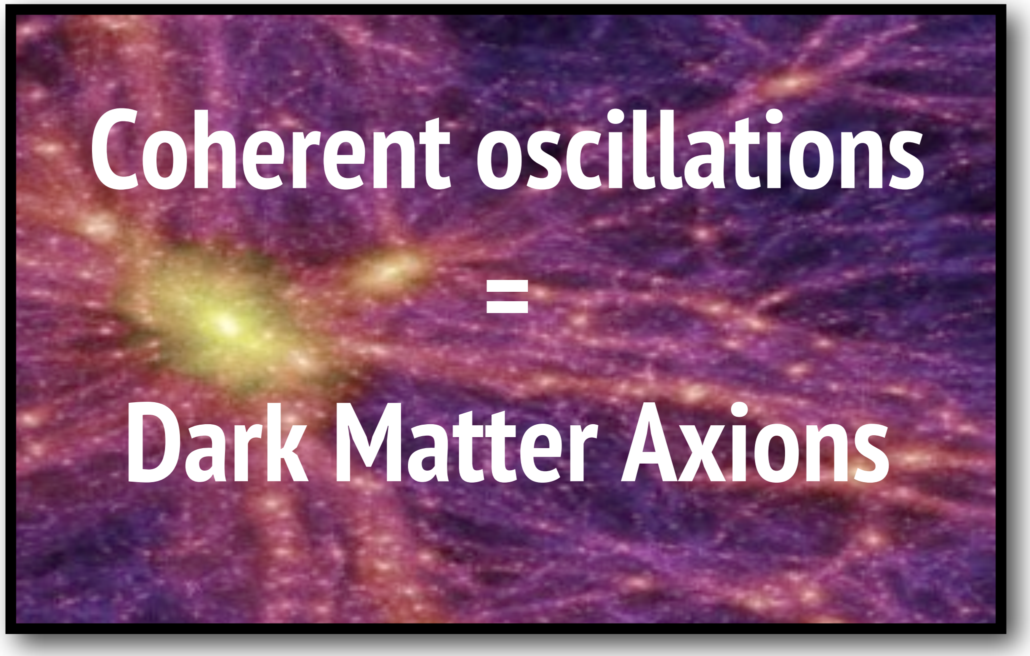
**~ One parameter theory**

$$\theta(t,x) = a(t,x)/f_a$$

**axion mass**

$$m_a = 6\,\mathrm{meV}\frac{10^9\,\mathrm{GeV}}{f_a}$$





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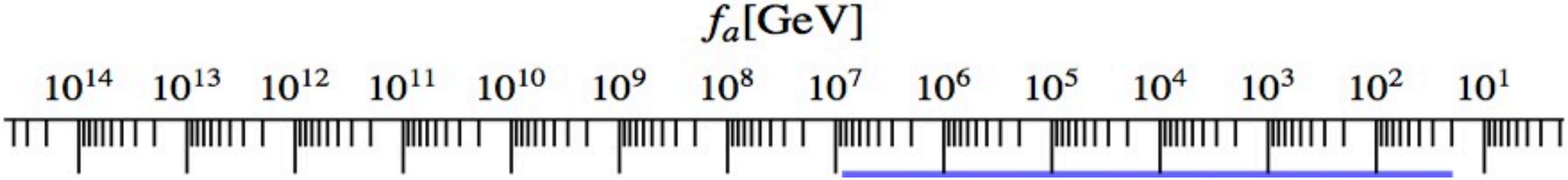
# Axion dark matter scenarios

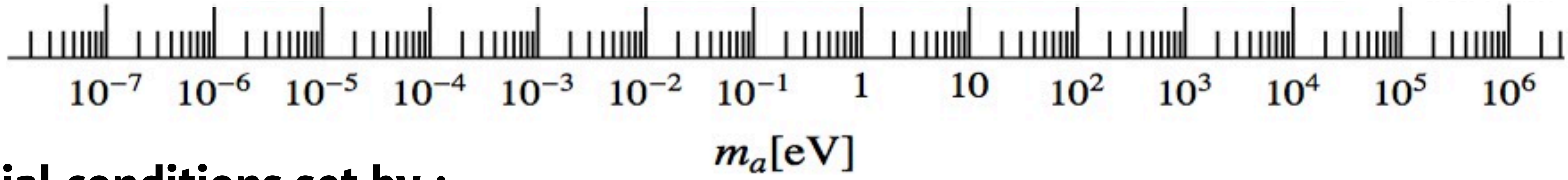


- **Axion DM scenarios**

tuned (anthropic?)

ok

tuned



**Initial conditions set by :**

**Inflation smooth**

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu\mathrm{eV}}{m_a}\right)^{1.19}$$

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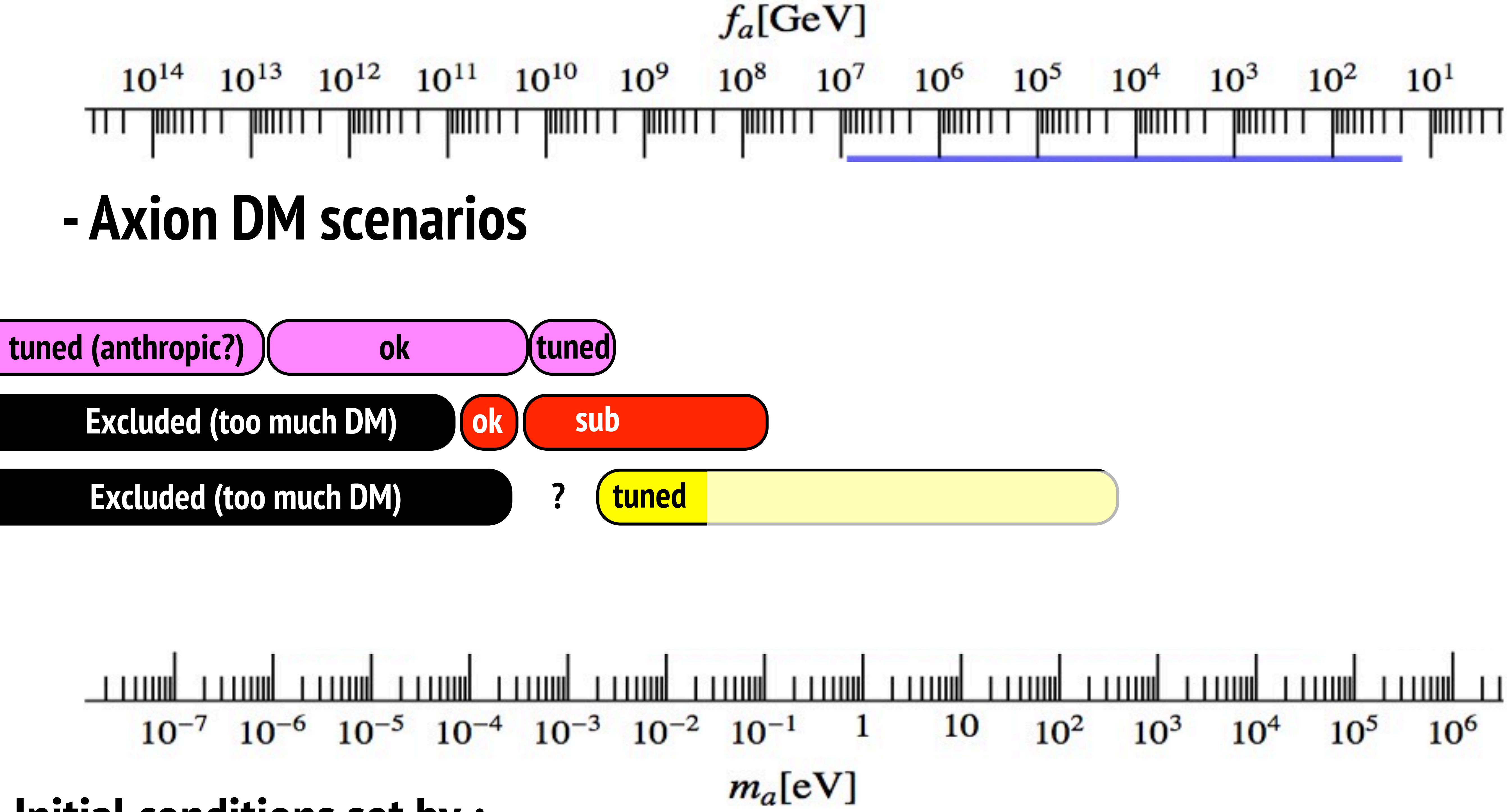

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strings+unstable DW’s

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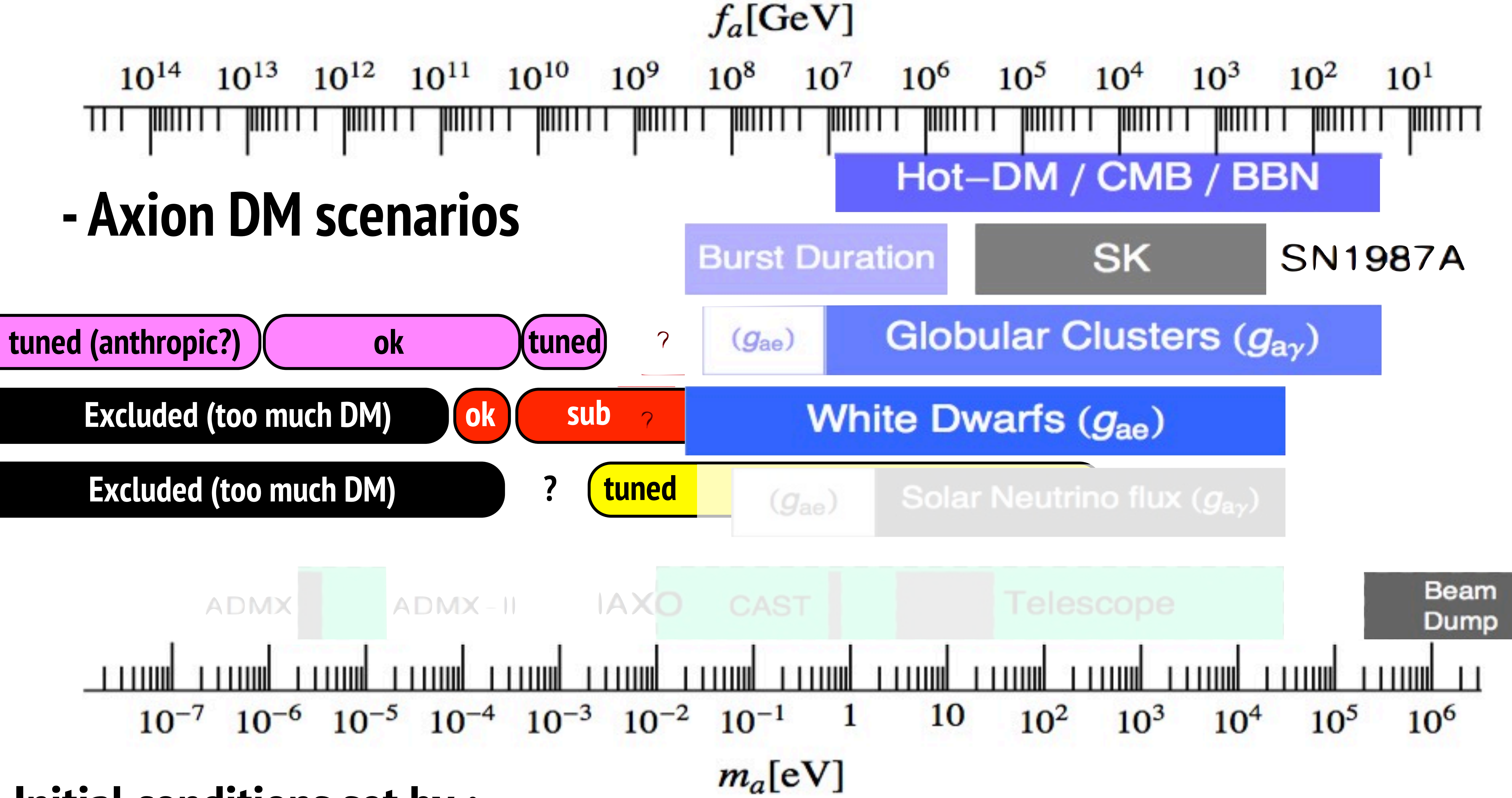

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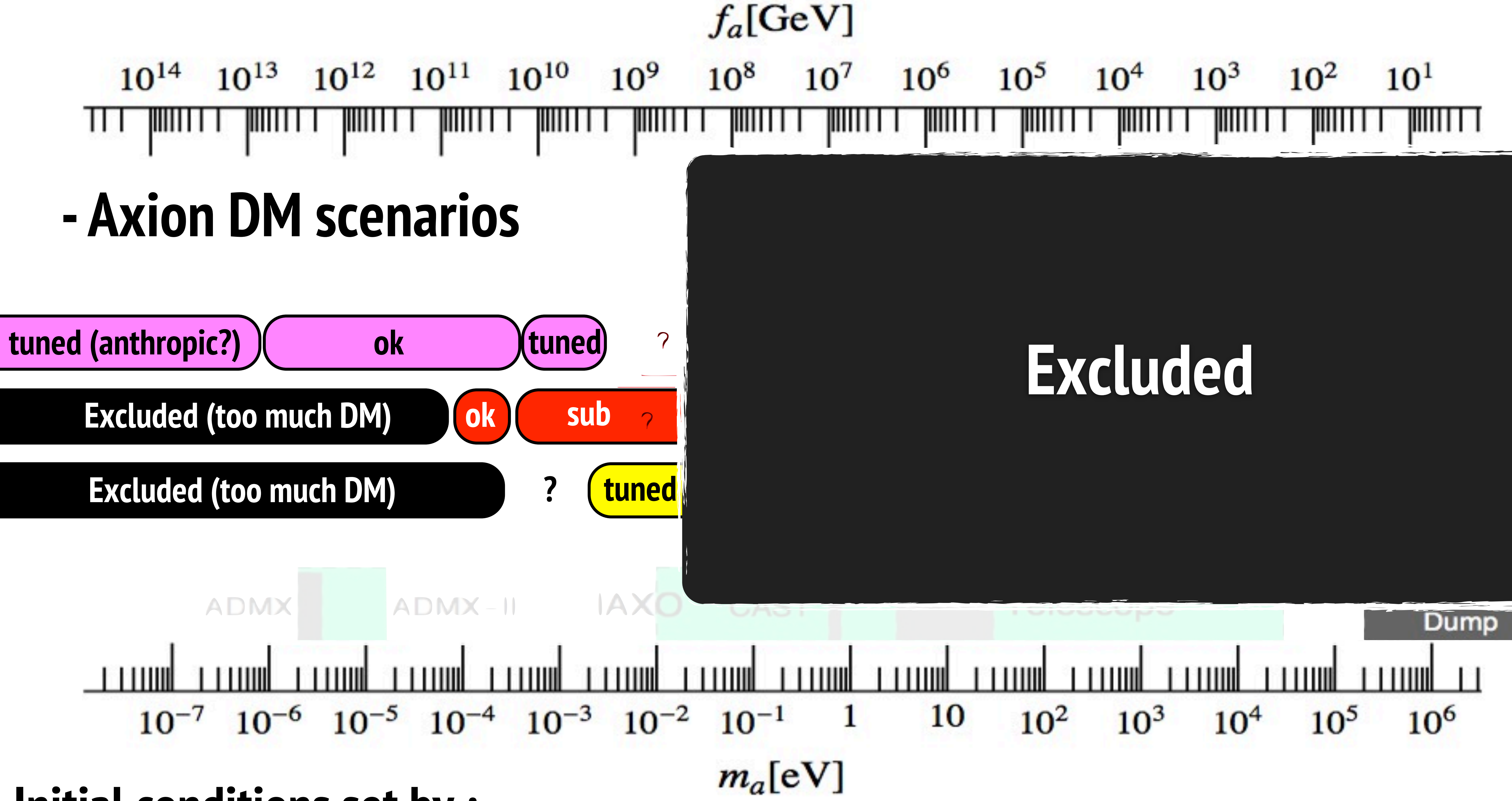

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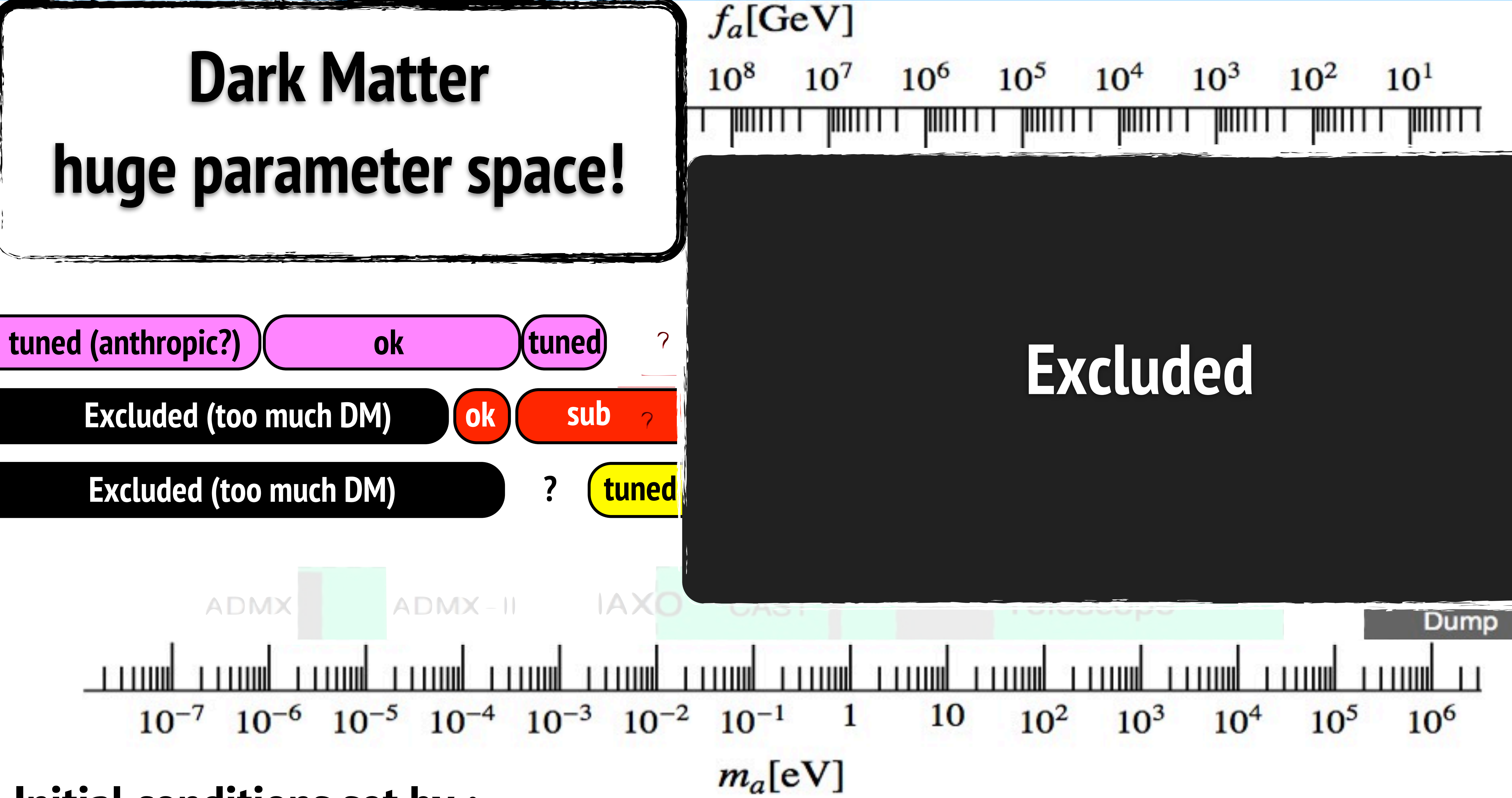
# Axion dark matter scenarios

**Dark Matter**
**huge parameter space!**



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# Axions in the galactic Halo

**Energy density** $\theta(t) = \theta_0 \cos(m_a t)$

$$\rho_{\mathrm{CDM}} = 0.3\frac{\mathrm{GeV}}{\mathrm{cm}^3} \equiv \frac{1}{2}(\dot{a})^2 + \frac{1}{2}m_a^2 a^2 = \frac{1}{2}m_a^2 f_a^2 \theta_0^2 \longrightarrow \theta_0 \sim 3.6 \times 10^{-19}$$

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$$\omega \simeq m_a(1 + v^2/2 + ...)$$

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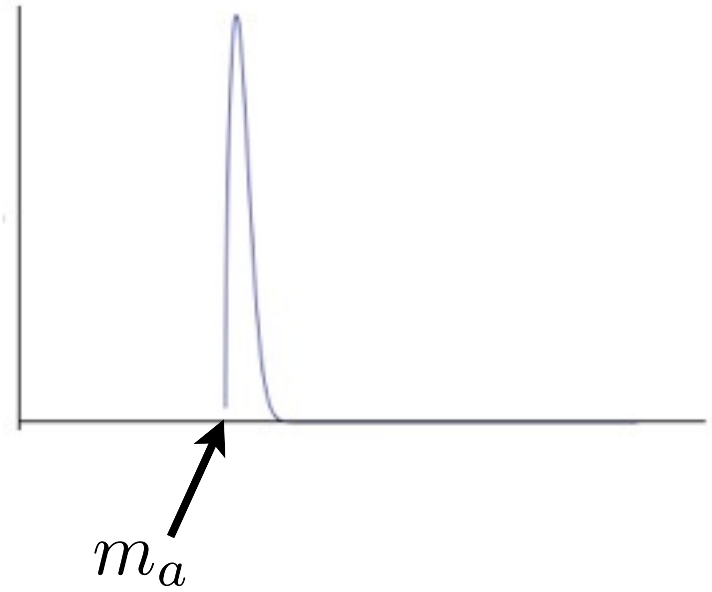

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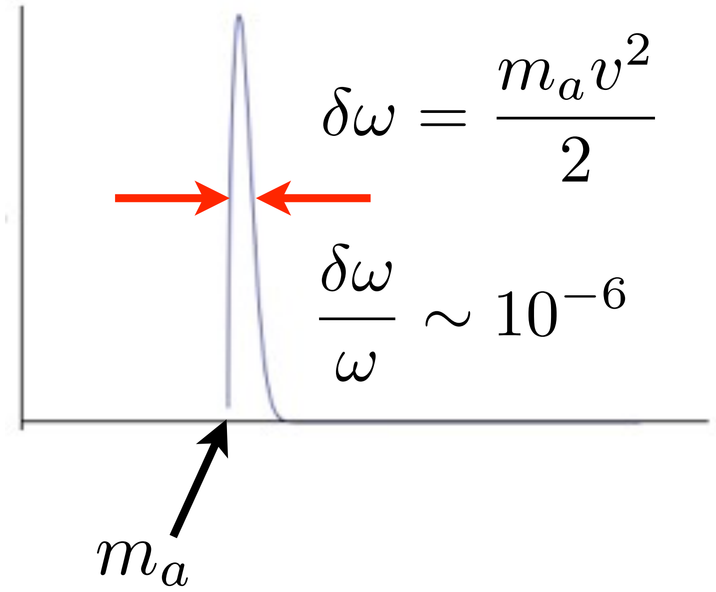

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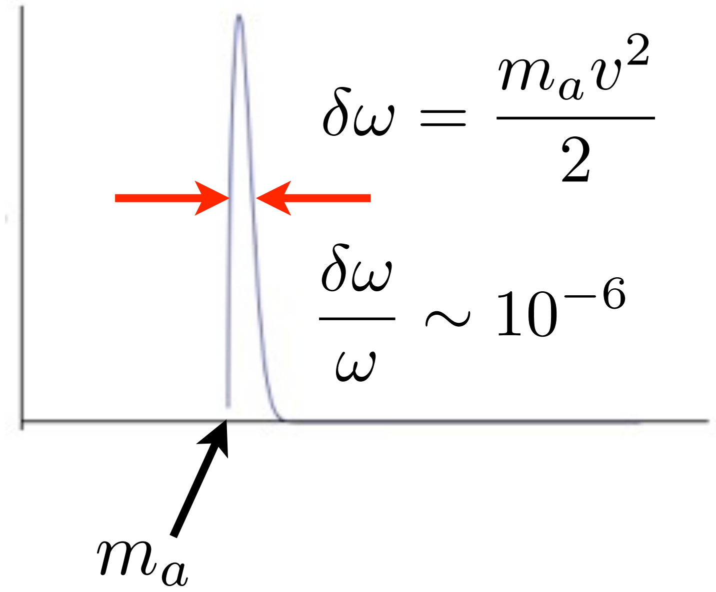
**coherence time**

$$\boxed{\delta t \sim \frac{1}{\delta\omega} \sim 0.13\mathrm{ms}\left(\frac{10^{-5}\mathrm{eV}}{m_a}\right)}$$



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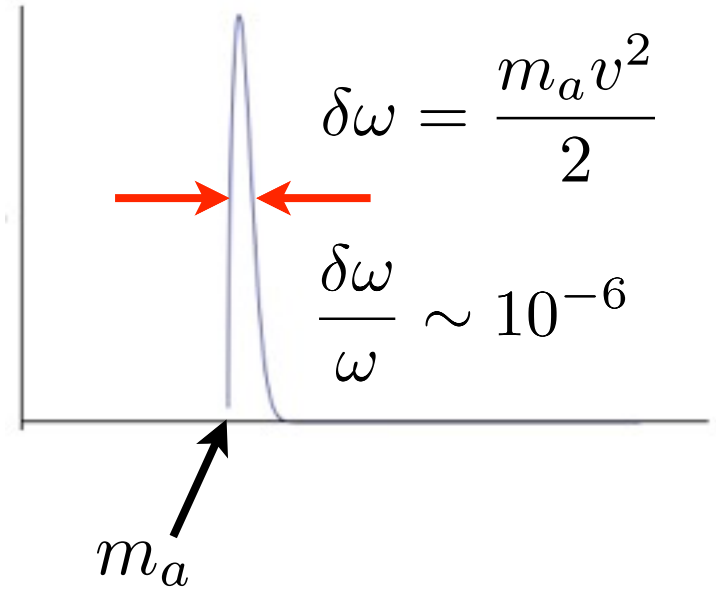

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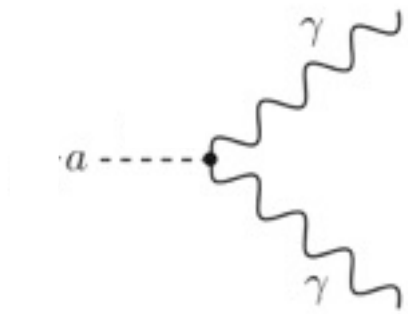
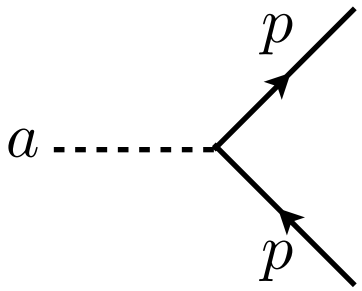
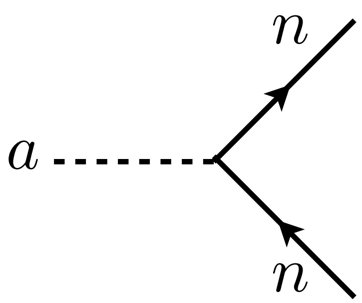
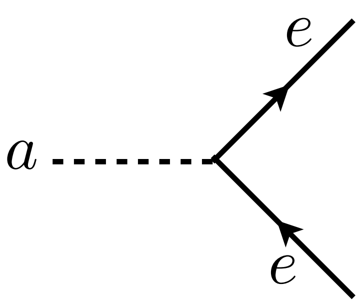
**coherence length**

$$\boxed{\delta L \sim \frac{1}{\delta p} \sim 20{\rm m}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)}$$

# Detection channels, Axion Couplings

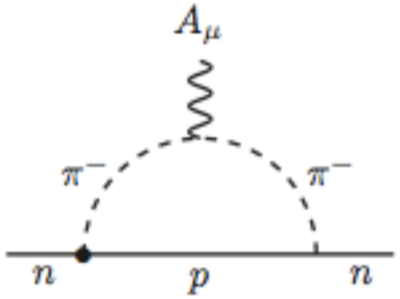
$$\frac{\alpha_s}{8\pi}\theta G_{\mu\nu}\widetilde{G}^{\mu\nu} + \mathrm{m.d.} \rightarrow$$

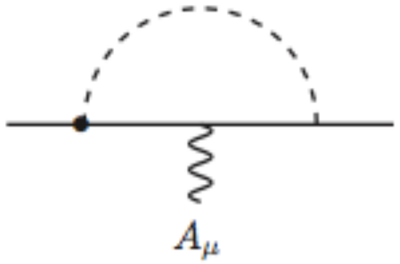
| **2 photon** | **proton** | **neutron** | **electron** |
|---|---|---|---|
| $\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}$ | $+ C_{ap} m_p \frac{a}{f_a}[i\bar{p}\gamma_5 p]$ | $+ C_{an} m_n \frac{a}{f_a}[i\bar{n}\gamma_5 n]$ | $+ C_{ae} m_e \frac{a}{f_a}[i\bar{e}\gamma_5 e] +$ |
|  |  |  |  |

**Pions, etc...**

**CP conserved at $\theta = 0$, but otherwise, CP violation $\propto \theta$**

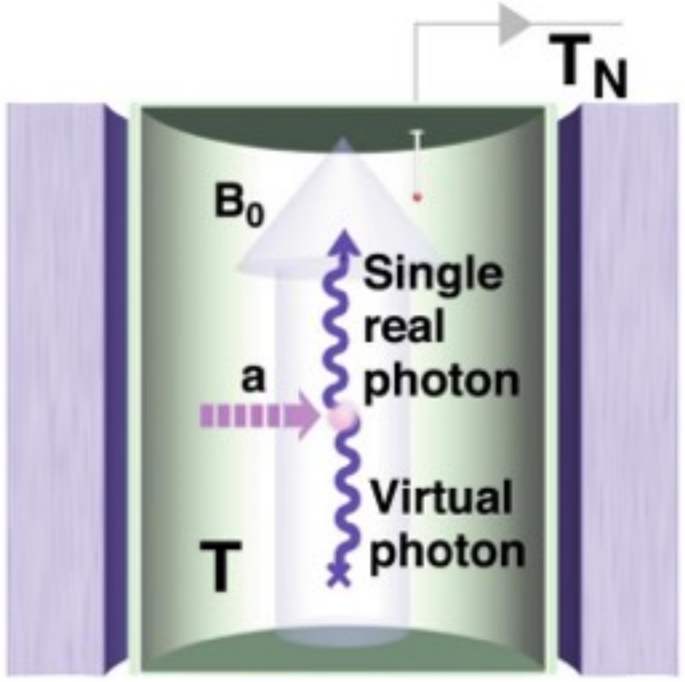
**Neutron EDM**



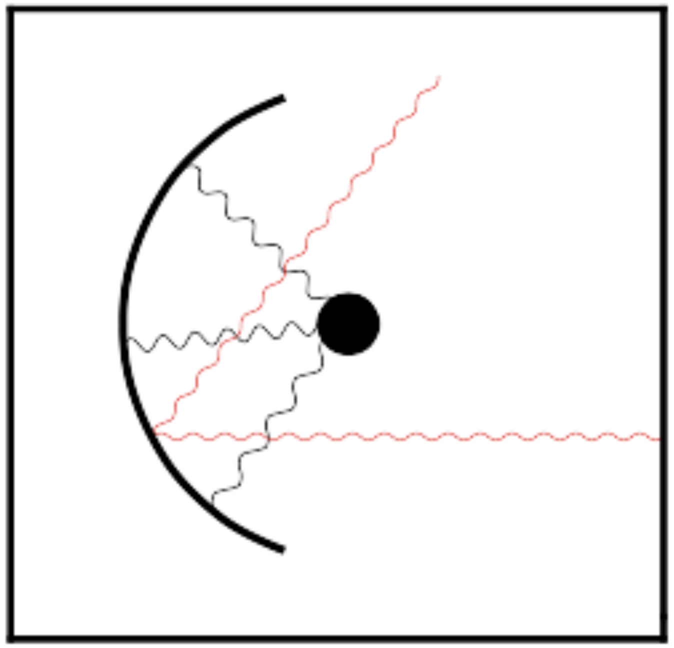


$$d_n \sim \theta \times \mathcal{O}(10^{-15})[e\,\mathrm{cm}]$$

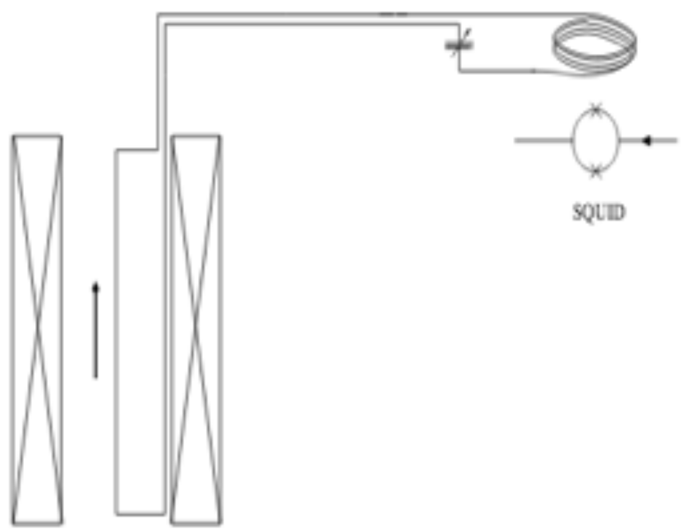
## Cavities



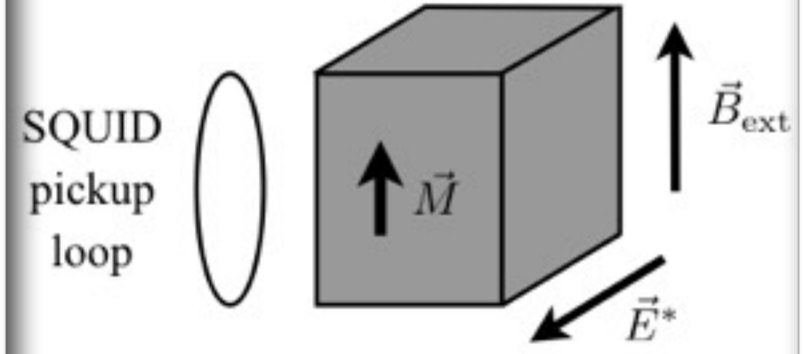
## Mirrors



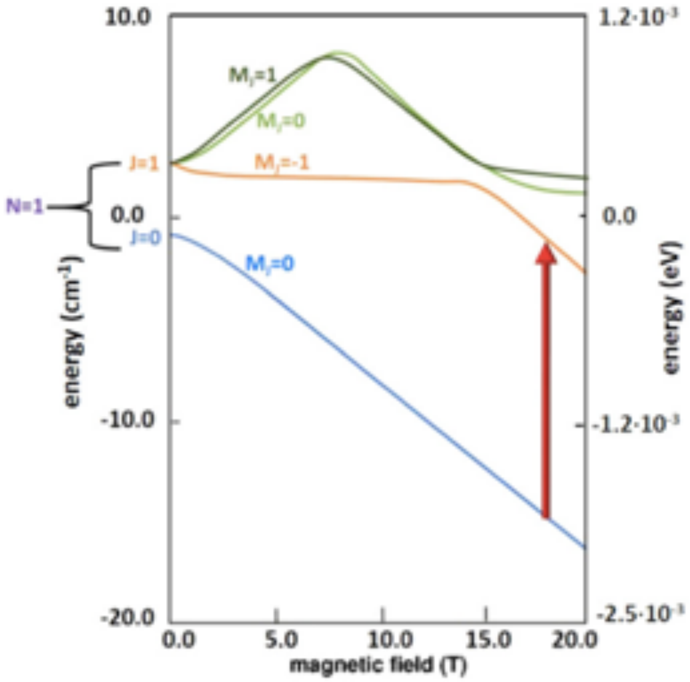
## LC-circuit



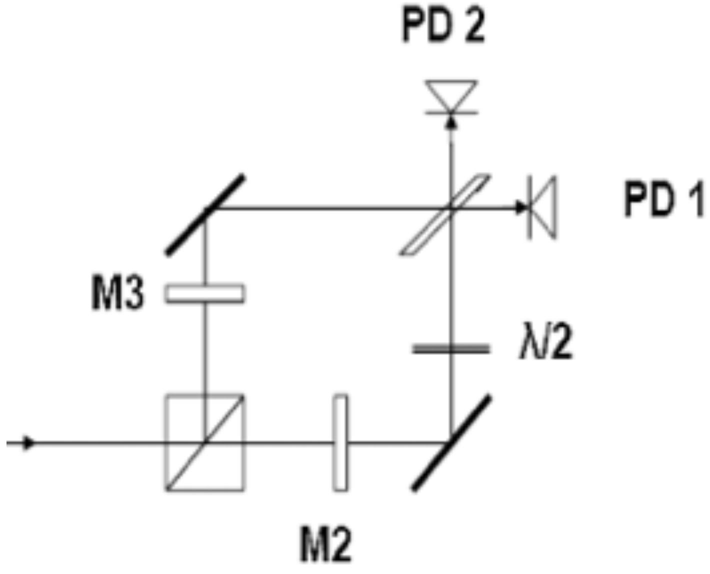
## Spin precession



## Atomic transitions



## Optical

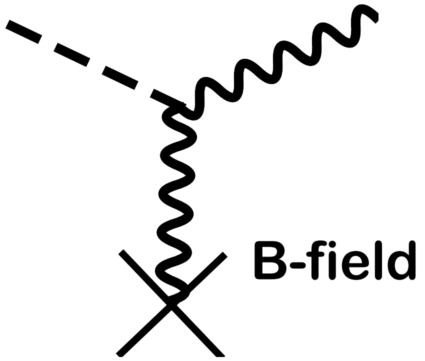


# Axion DM in a B-field

$$\mathcal{L}_I = -C_{a\gamma}\frac{\alpha}{2\pi}\frac{a}{f_a}\mathbf{B}\cdot\mathbf{E}$$

- In a static magnetic field, the oscillating axion field generates EM-fields

$$\mathcal{L}_I = \underbrace{-C_{a\gamma}\frac{\alpha}{2\pi}\theta(t)\,\mathbf{B}_{\text{ext}}}_{\text{source}}\cdot\mathbf{E}$$



- Electric fields $\mathbf{E}_a = C_{a\gamma}\frac{\alpha\mathbf{B}_{\text{ext}}}{2\pi}\theta_0\cos(m_a t)$ **(amp independent of mass!)**

- Oscillating at a frequency $\omega \simeq m_a$

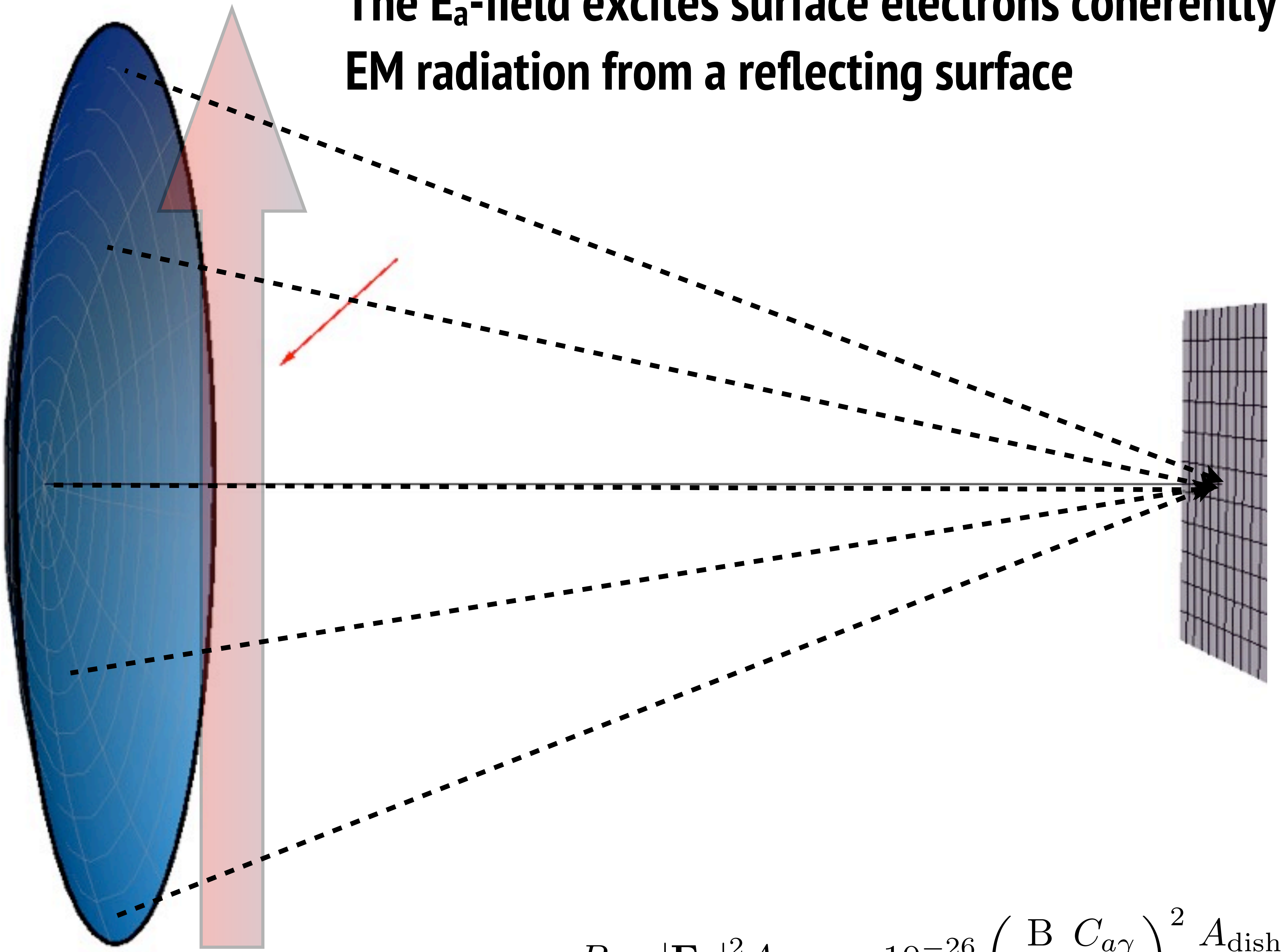
- B-fields $\propto \nabla\theta$ $|\mathbf{B}_a| \sim \langle v\rangle|\mathbf{E}_a|$

# Dish antenna experiment?

Horns 2012

The $E_a$-field excites surface electrons coherently

EM radiation from a reflecting surface



spherical reflecting dish

$$P \sim |\mathbf{E}_a|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\frac{C_{a\gamma}}{2}\right)^2 \frac{A_{\rm dish}}{1\,{\rm m}^2}{\rm Watt}$$

# Cavity experiments

Sikivie 2013

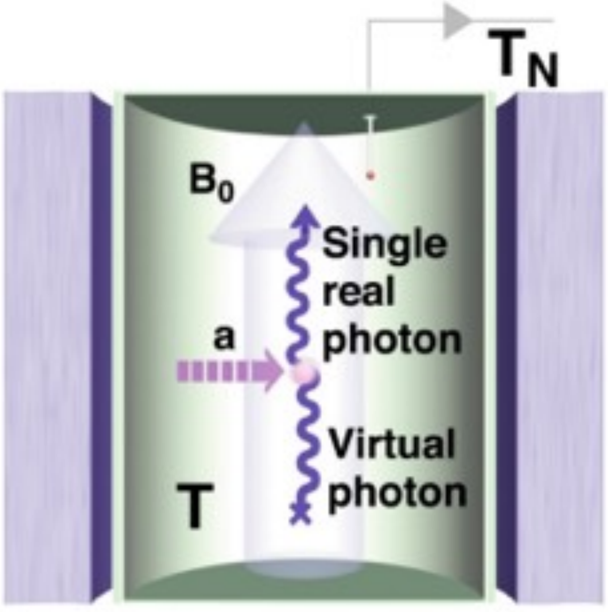
- Haloscope (Sikivie 83)

  "Amplify resonantly the EM field in a cavity"

$$P \sim \overset{\downarrow}{Q}|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa$$

(on resonance)

(integrate the power in a coherent time)



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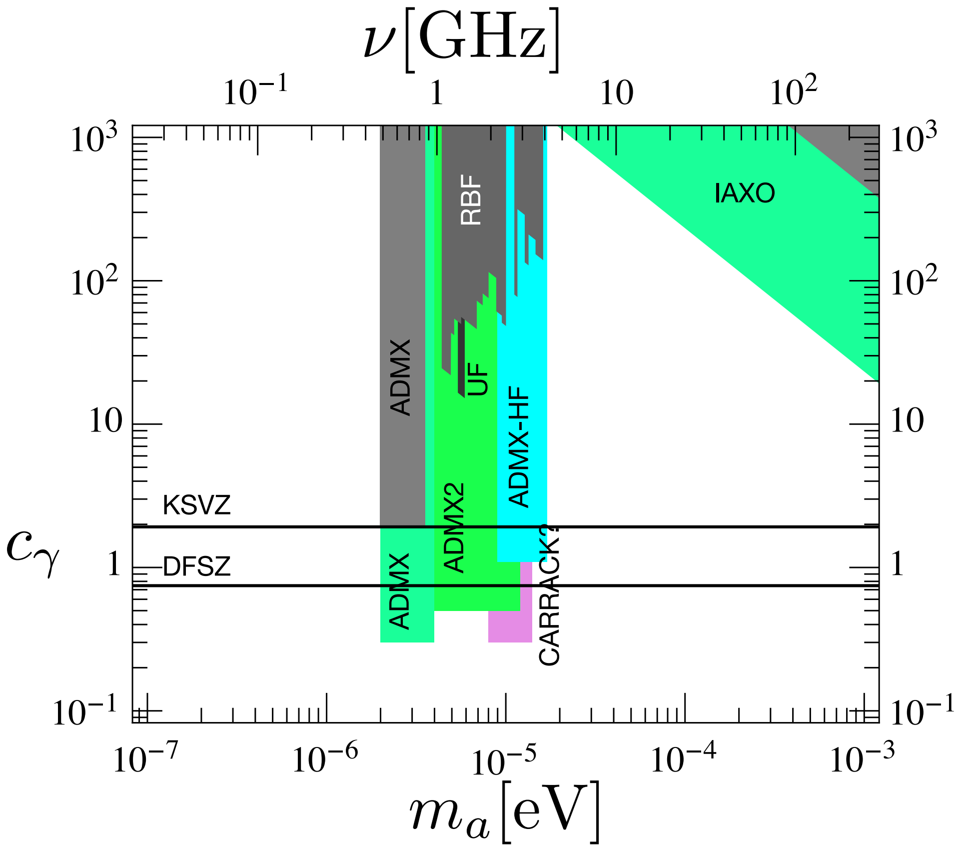
- Future endeavors: ADMX, ADMX-HF, YMCE, CAPP



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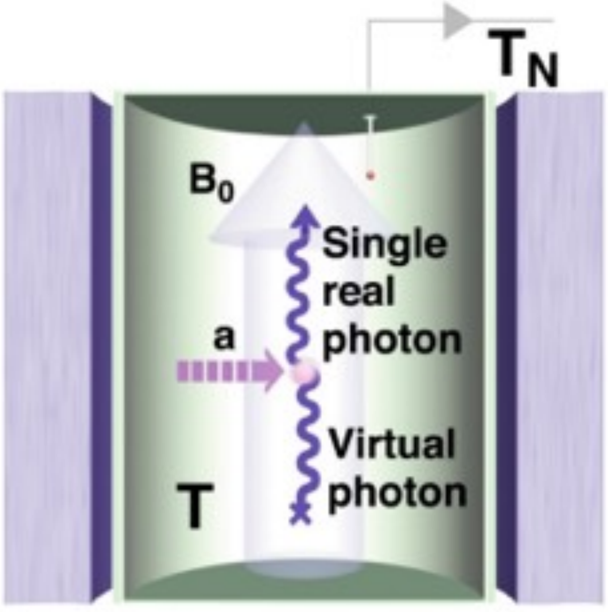

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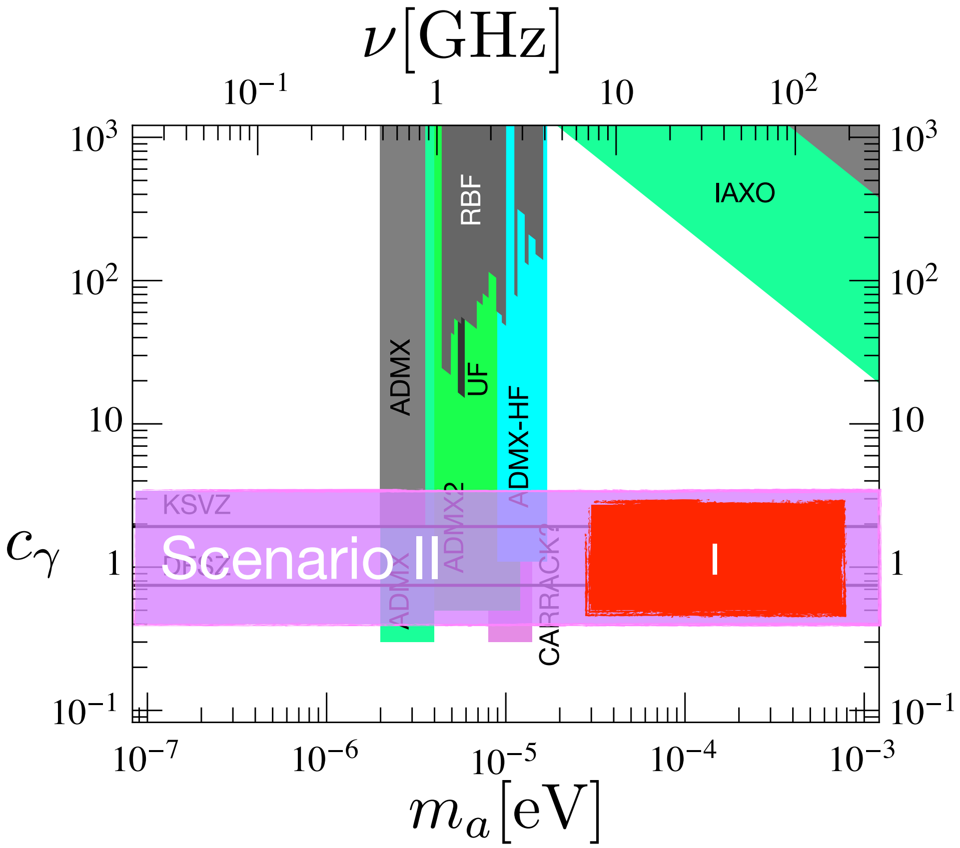

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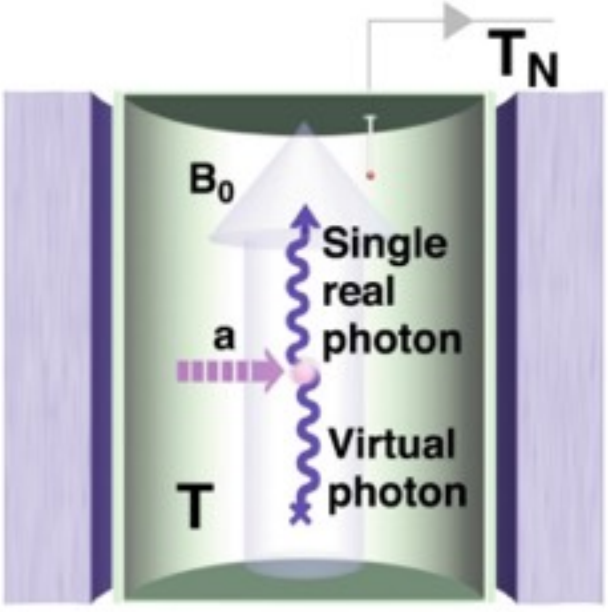

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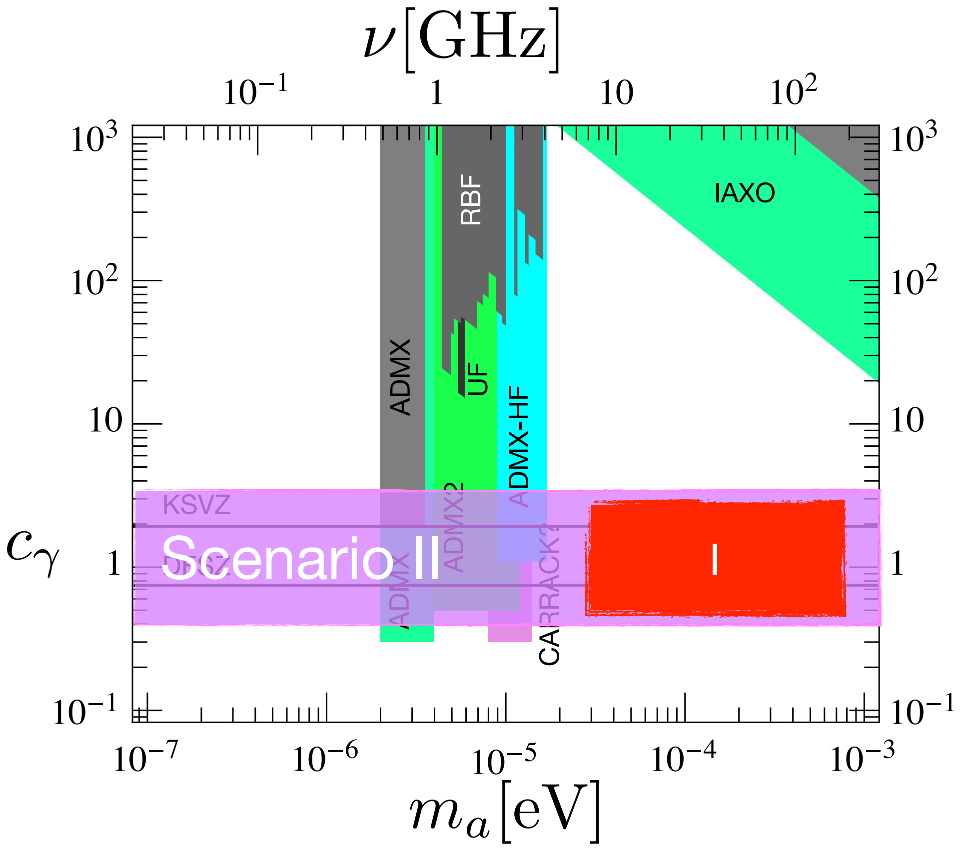

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$$\downarrow$$

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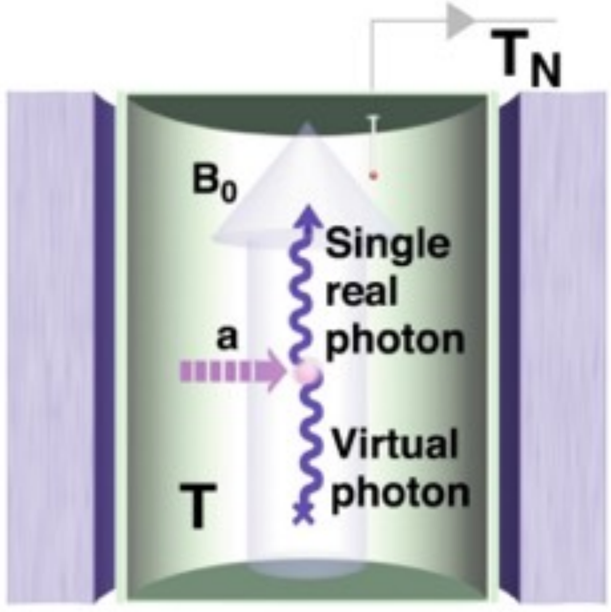

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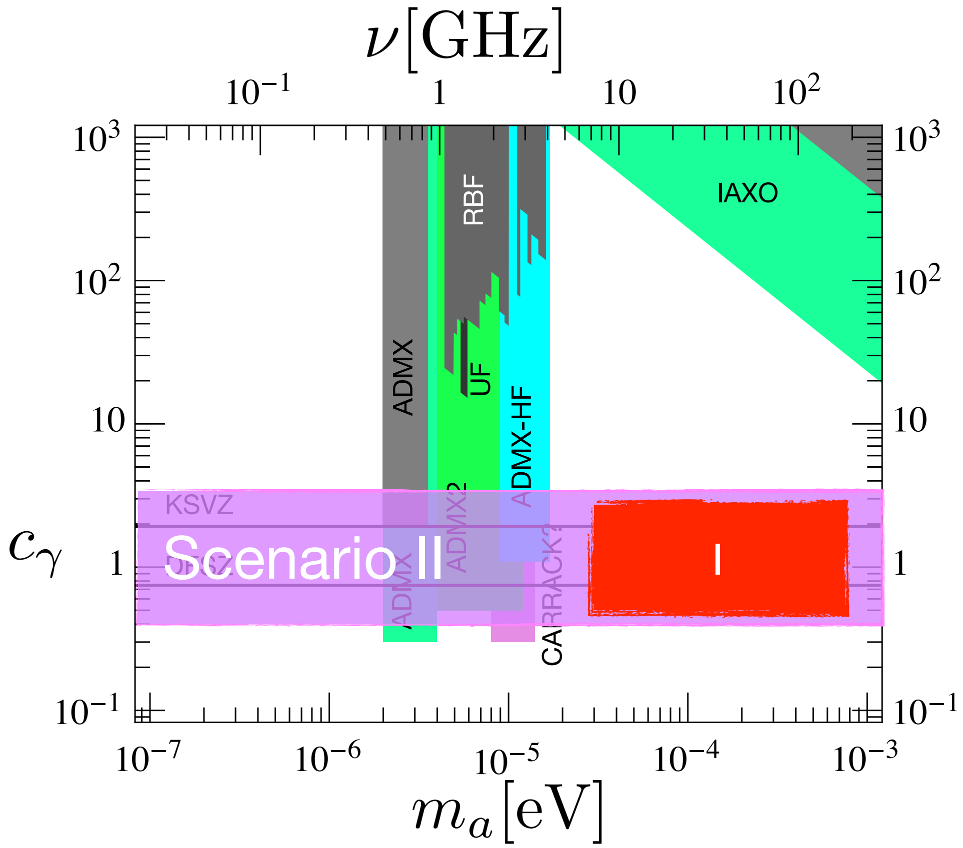

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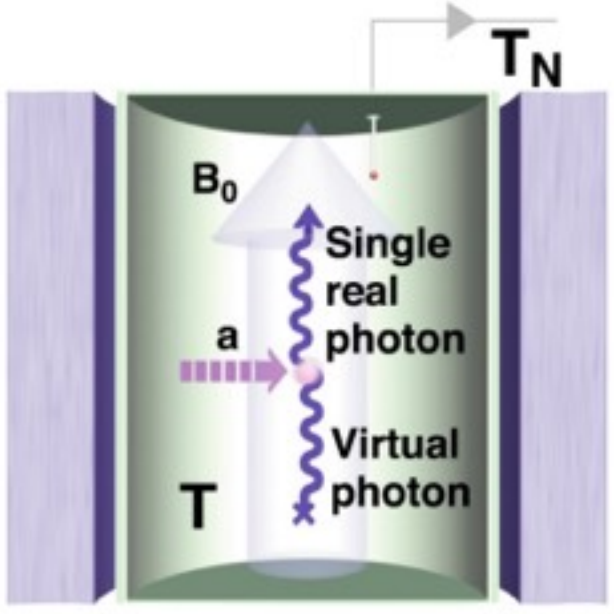

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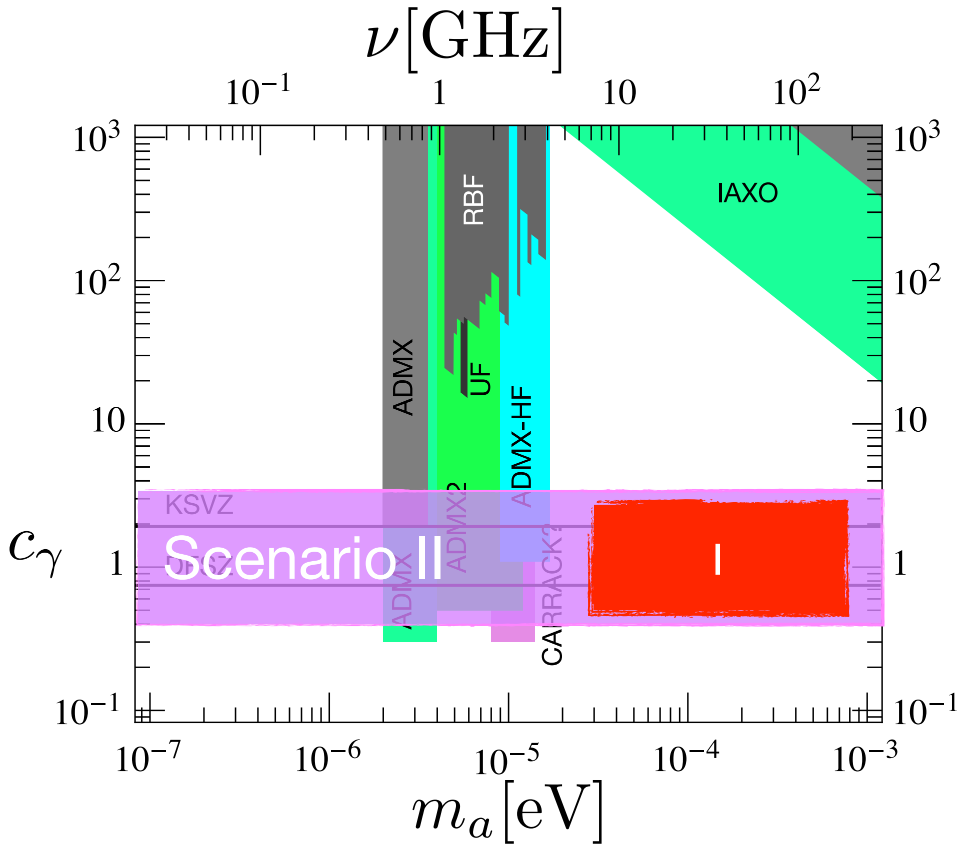
- **Signal** $(V \propto m_a^{-3})$ $\quad P_{\rm out} \propto V m_a \sim \dfrac{1}{m_a^2}$
- **Noise** $P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$



# Cavity experiments

Sikivie 2013

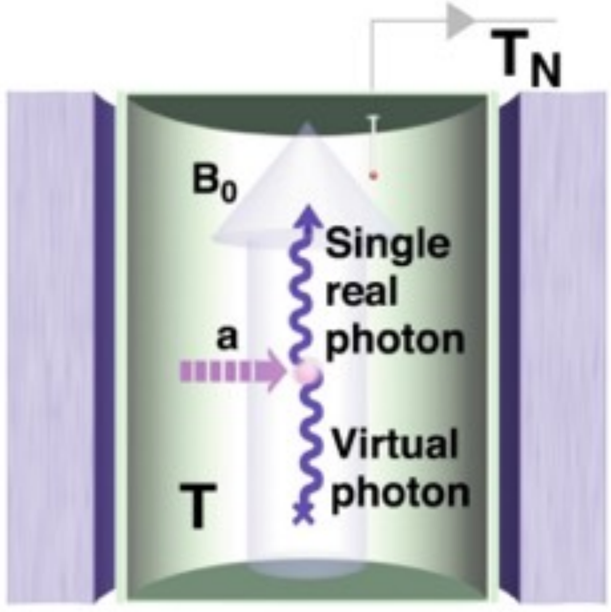
- **Haloscope (Sikivie 83)**

  **“Amplify resonantly the EM field in a cavity”**

$$\downarrow$$

$$P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa$$ **(on resonance)**

**(integrate the power in a coherent time)**



- **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**

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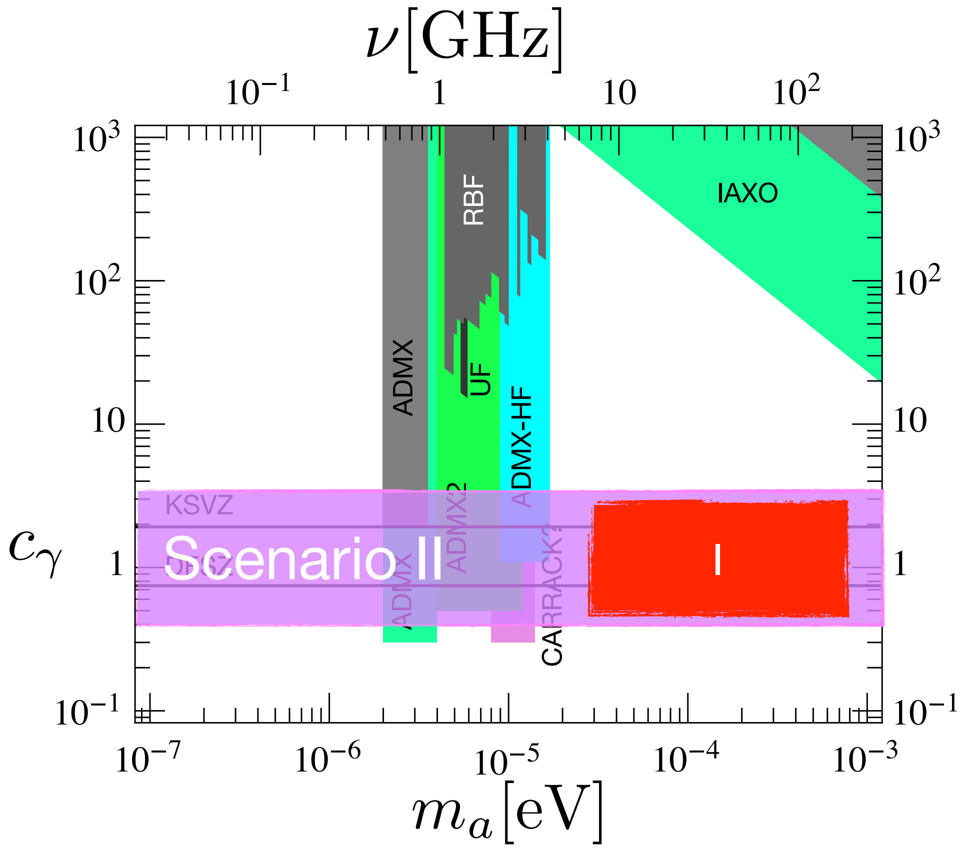
- **Signal/noise in $\Delta\nu_a$ of time, t,** $\quad \frac{S}{N} = \frac{P_{\rm out}}{P_{\rm noise}}\sqrt{\Delta\nu_a t}$



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  ↓

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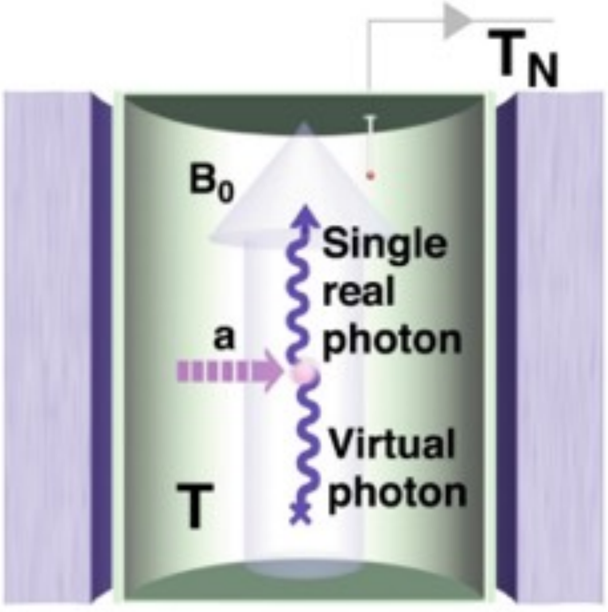

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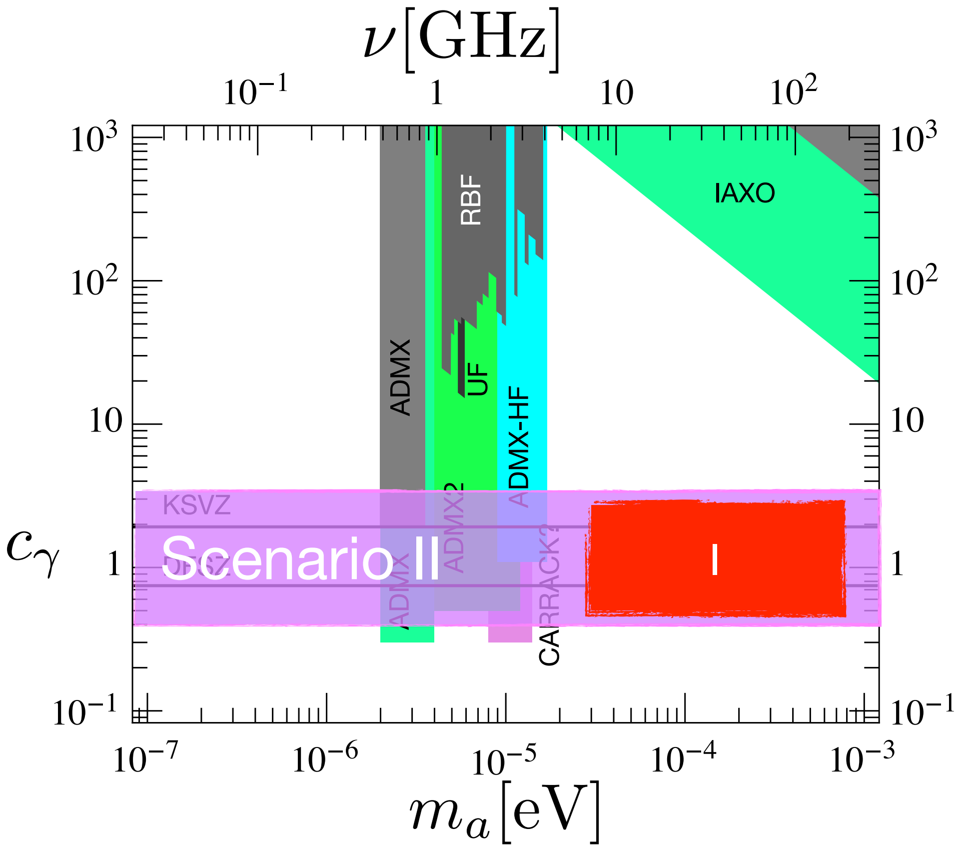
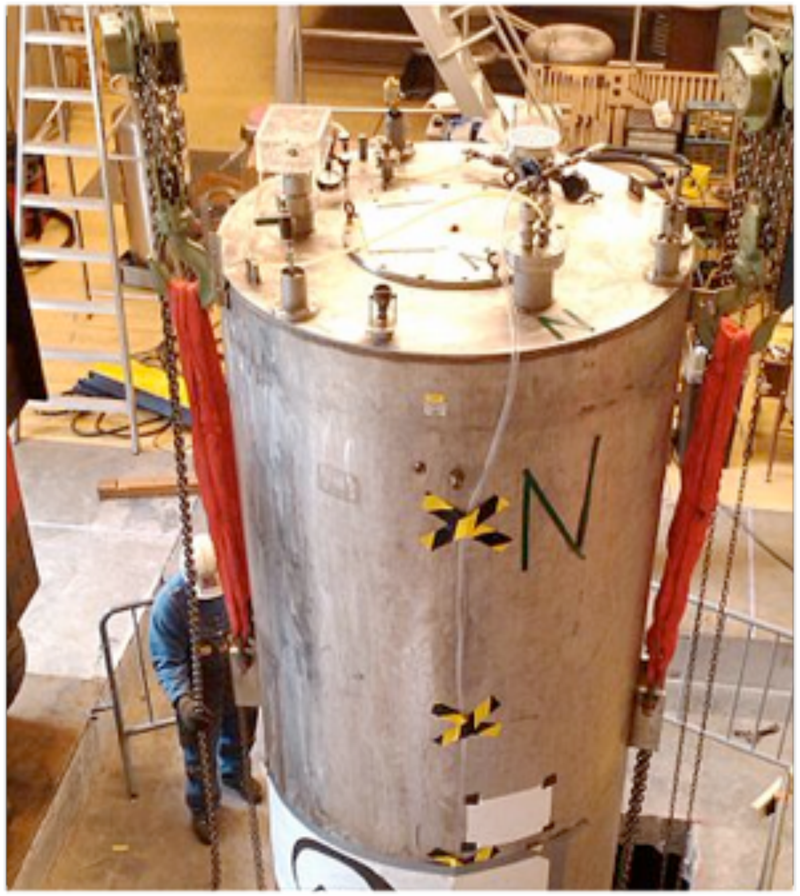
- **Scanning rate** $\dfrac{1}{m_a}\dfrac{d\Delta m_a}{dt} \propto \dfrac{C_{a\gamma}^4}{m_a^9}$

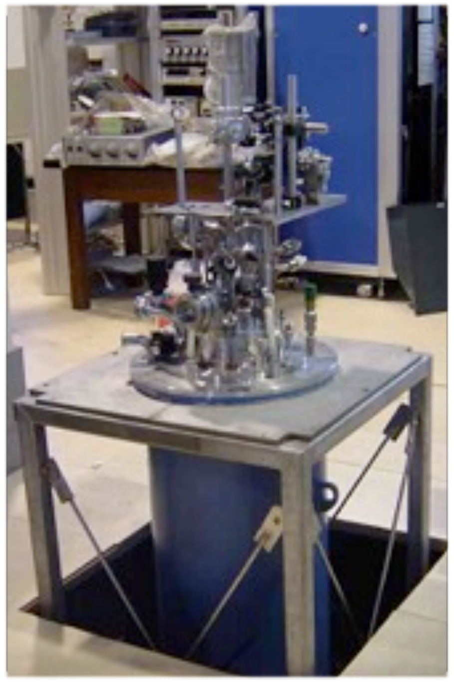


# Cavity experiments

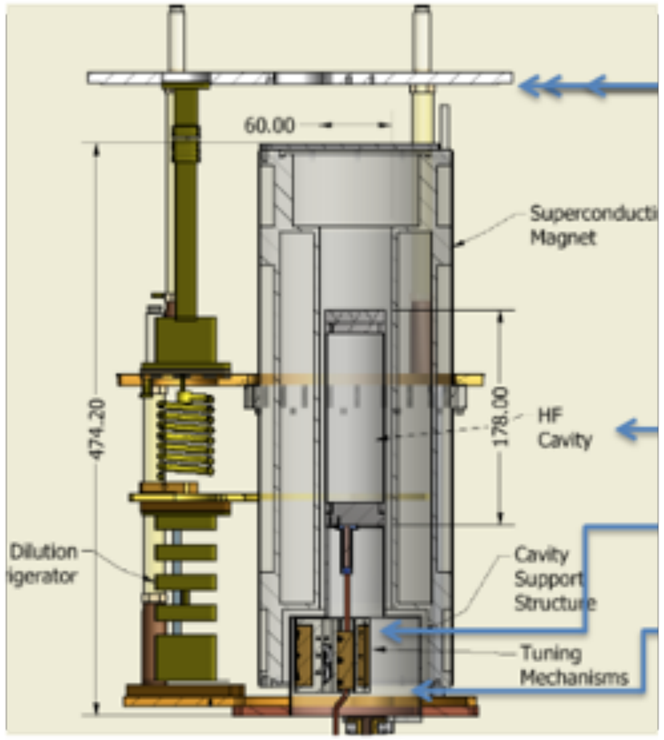
**ADMX**



**CARRACK (discontinued)**

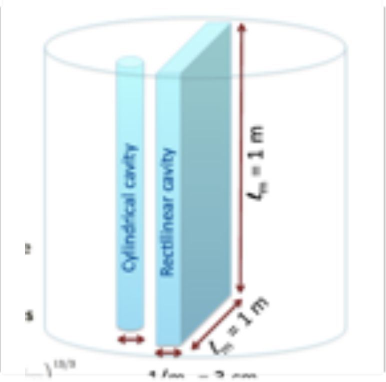


**CULTASK - CAPP -Korea**

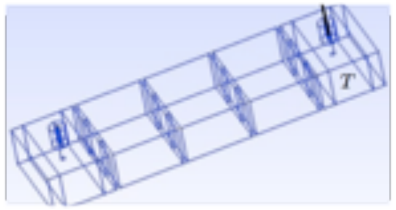


**ADMX-HF**

**ADMX-Fermilab**



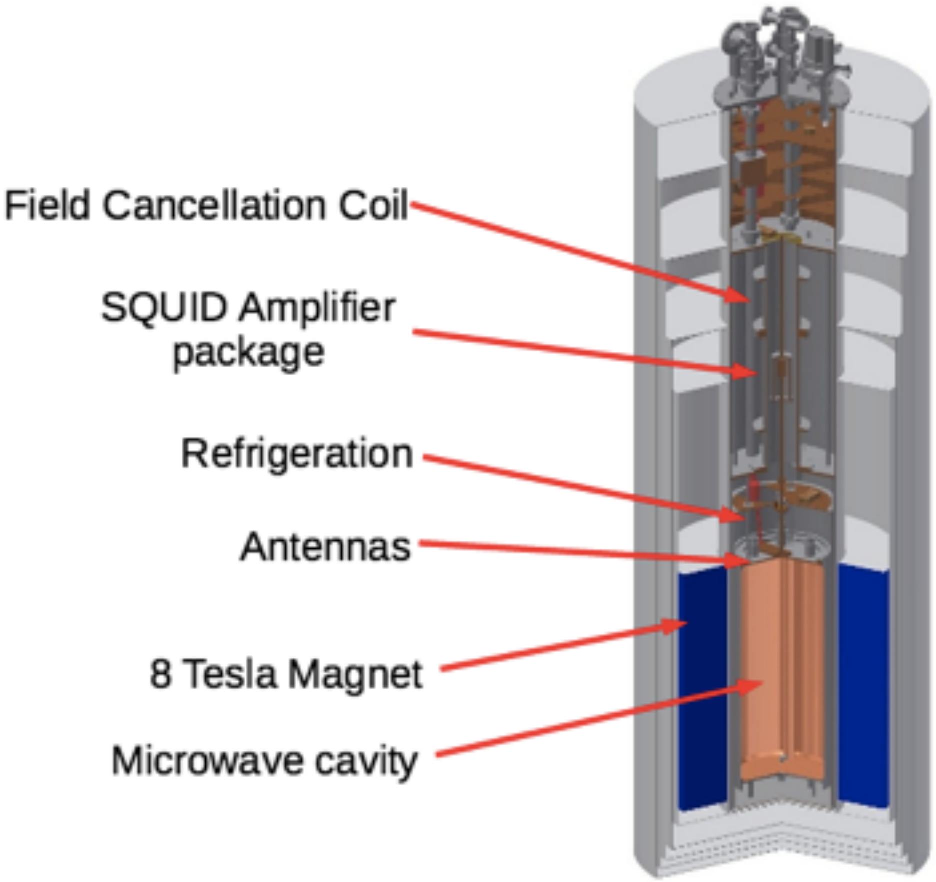
**RADES**



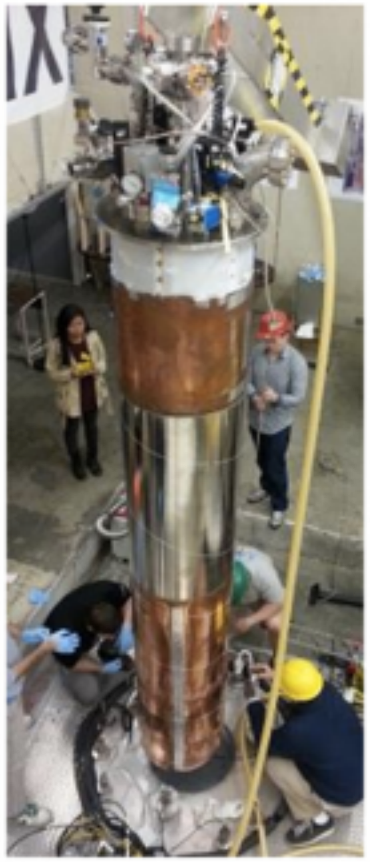
**CAST-CAPP**

# ADMX

Washington University, DOE, NSF

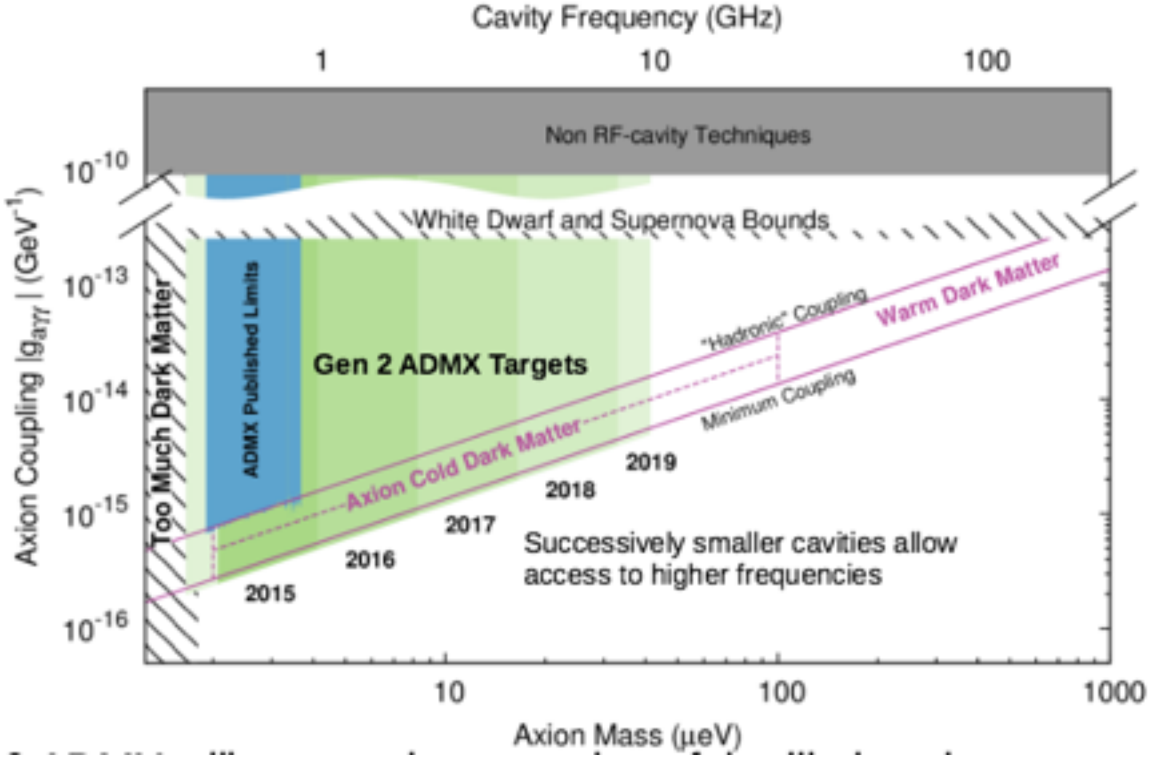


Insert + Magnet Schematic

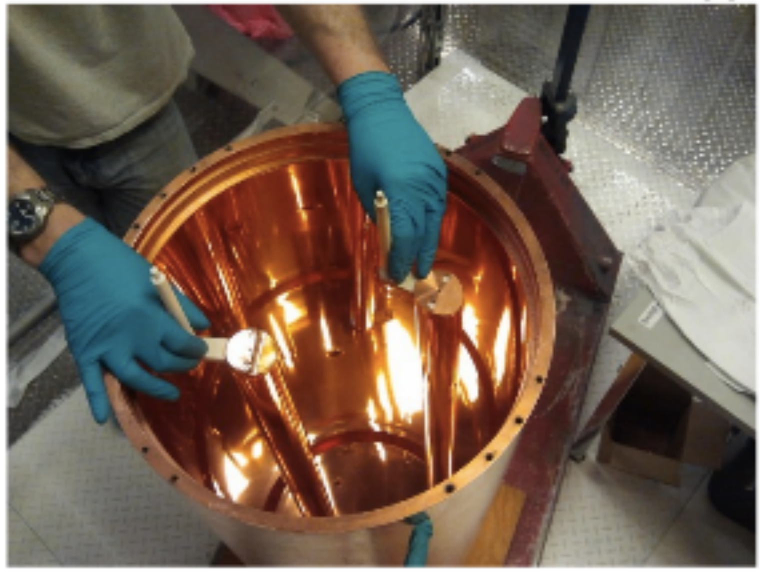


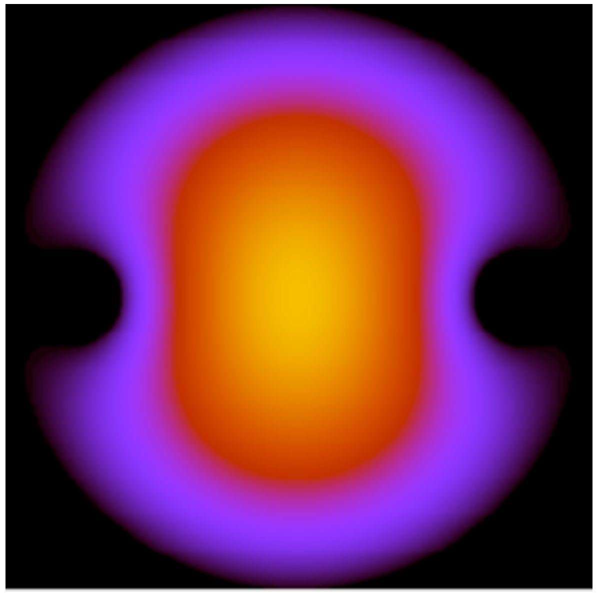
Insert extraction from magnet

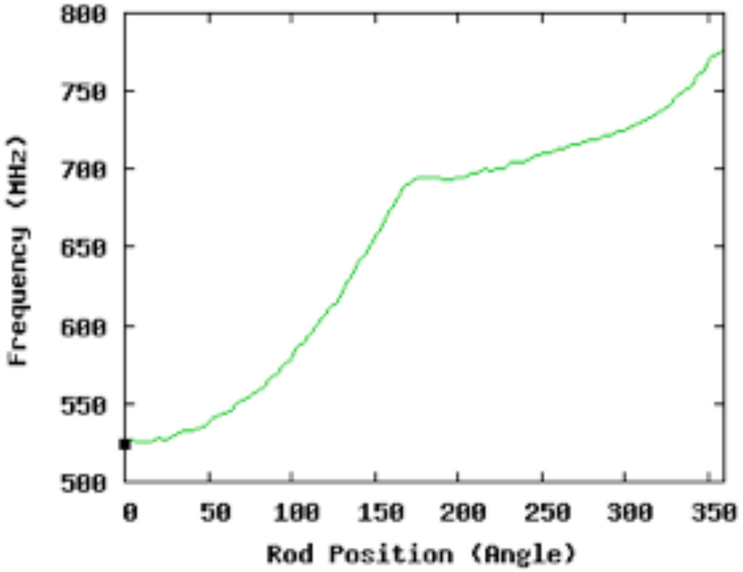
## Goals



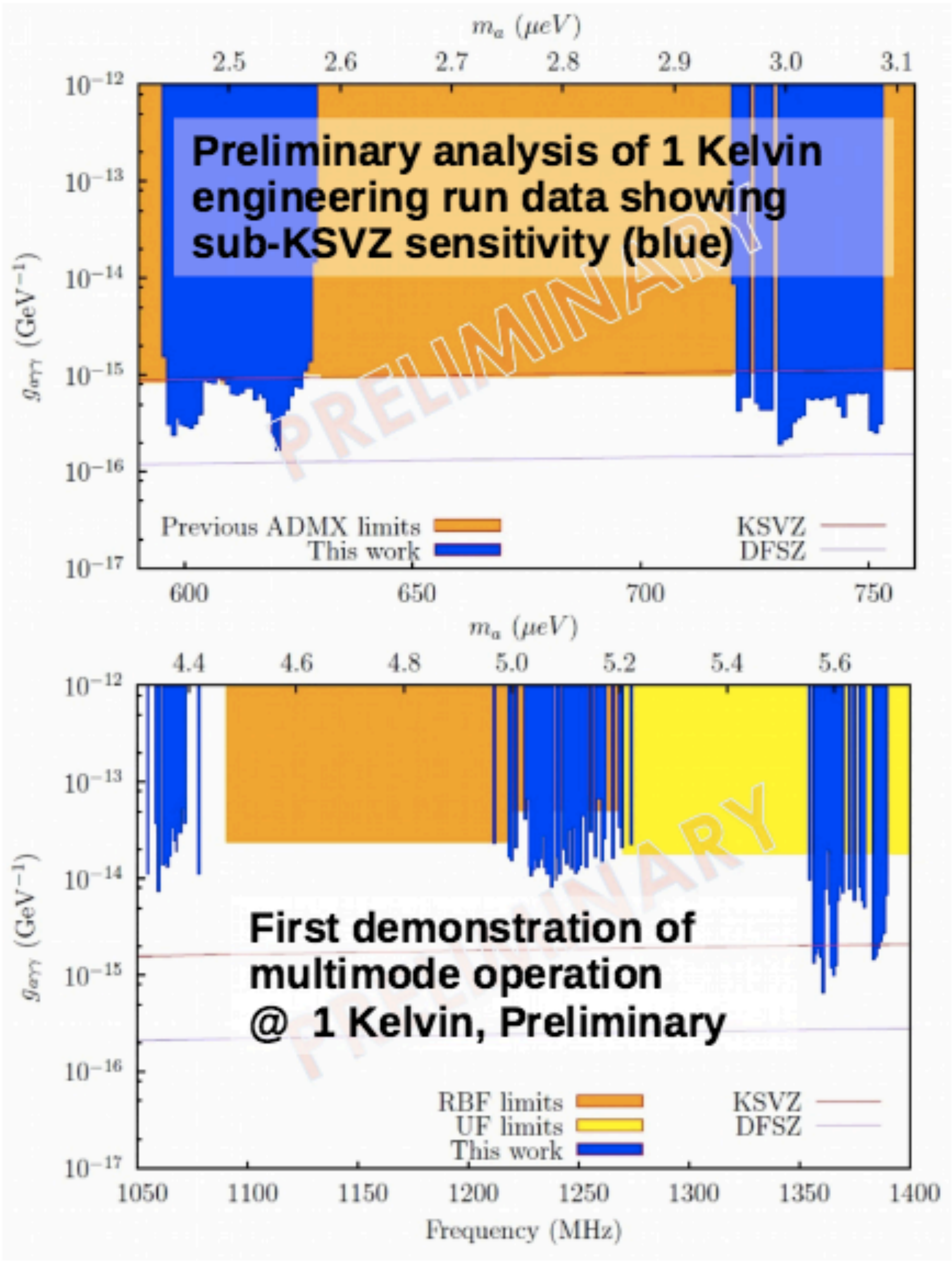
## Scanning over frequencies







# ADMX 2015



**Preliminary analysis of 1 Kelvin engineering run data showing sub-KSVZ sensitivity (blue)**

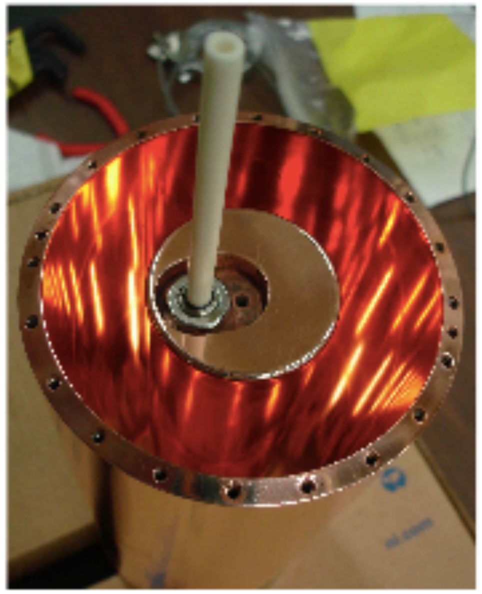
**First demonstration of multimode operation @ 1 Kelvin, Preliminary**

# ADMX HF

Yale, L

- Test bench for higher frequencies
- Hybrid Superconducting cavities
- Josephson parametric amps
- Single photon detectors at > 10 GHz

Set up running at f ~ 5.6 GHz, 25 mK temperatures, 9T

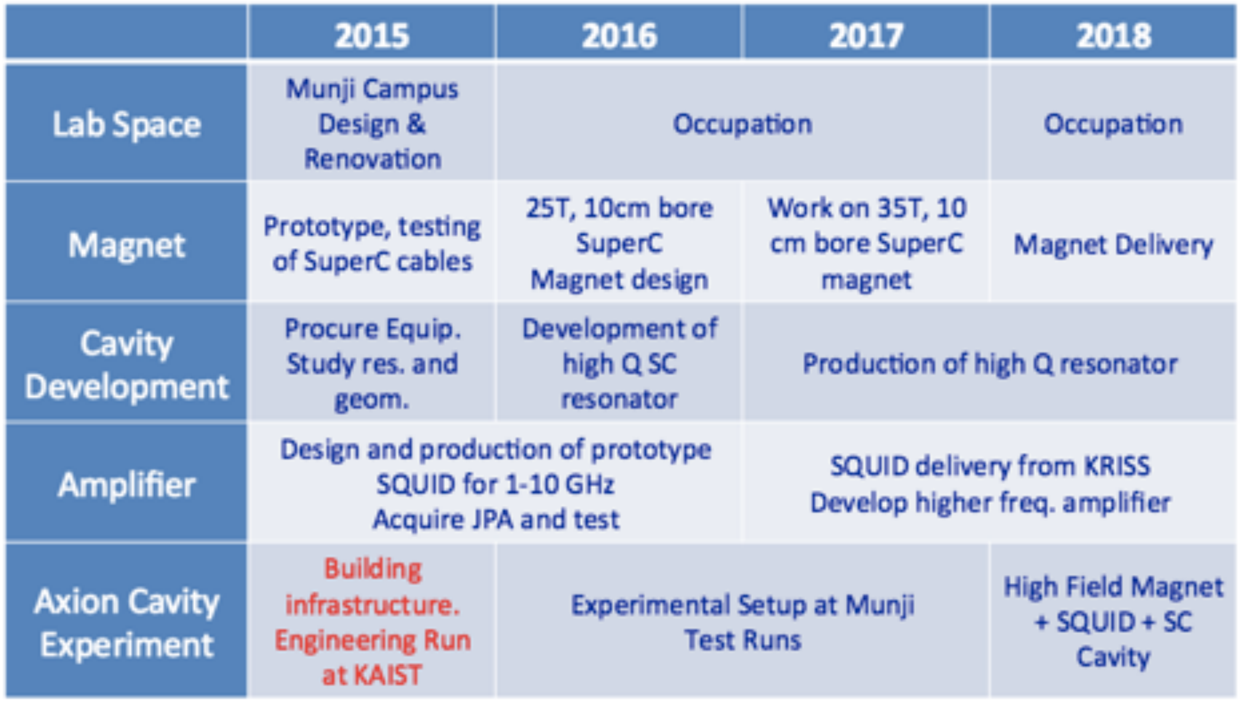


# CAPP

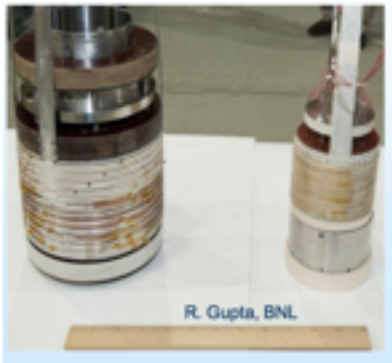
Daejeon, Korea

- Korean IBS Center for Axion and Precision Physics
+ proton EDM experiment (with Fermilab)
+ Axion DM experiments
  * CULTASK at ~ 6-10 GHz?
  * Lots of R+D

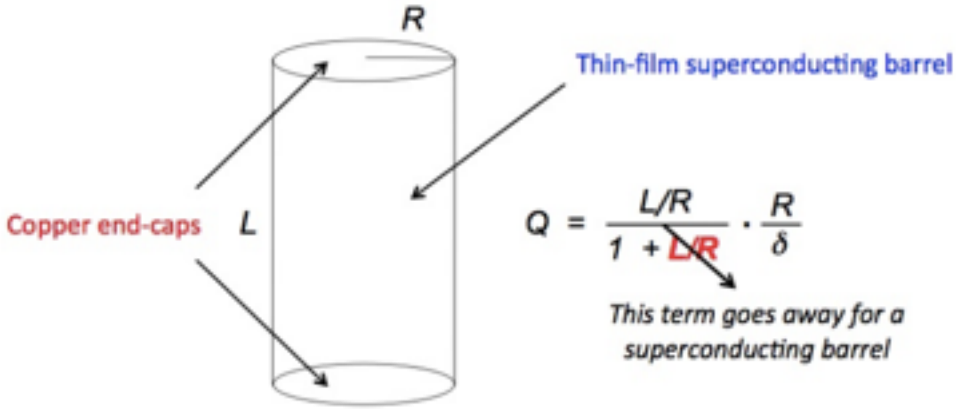
- High Tc superconducting magnets (25,35 T !)
- hybrid resonant cavities, toroidal?
- SQUIDS at HF
- Add up cavity outputs



| | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|
| **Lab Space** | Munji Campus Design & Renovation | Occupation | | Occupation |
| **Magnet** | Prototype, testing of SuperC cables | 25T, 10cm bore SuperC Magnet design | Work on 35T, 10 cm bore SuperC magnet | Magnet Delivery |
| **Cavity Development** | Procure Equip. Study res. and geom. | Development of high Q SC resonator | Production of high Q resonator | |
| **Amplifier** | Design and production of prototype SQUID for 1-10 GHz<br>Acquire JPA and test | | SQUID delivery from KRISS<br>Develop higher freq. amplifier | |
| **Axion Cavity Experiment** | Building infrastructure. Engineering Run at KAIST | Experimental Setup at Munji Test Runs | | High Field Magnet + SQUID + SC Cavity |

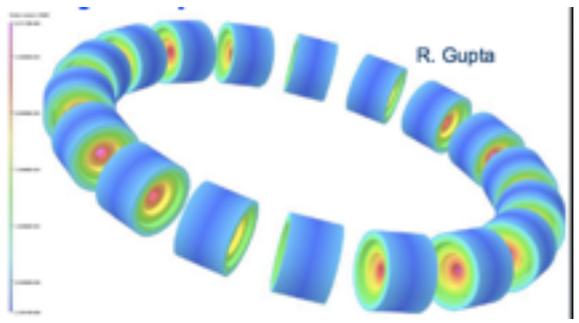


R. Gupta, BNL



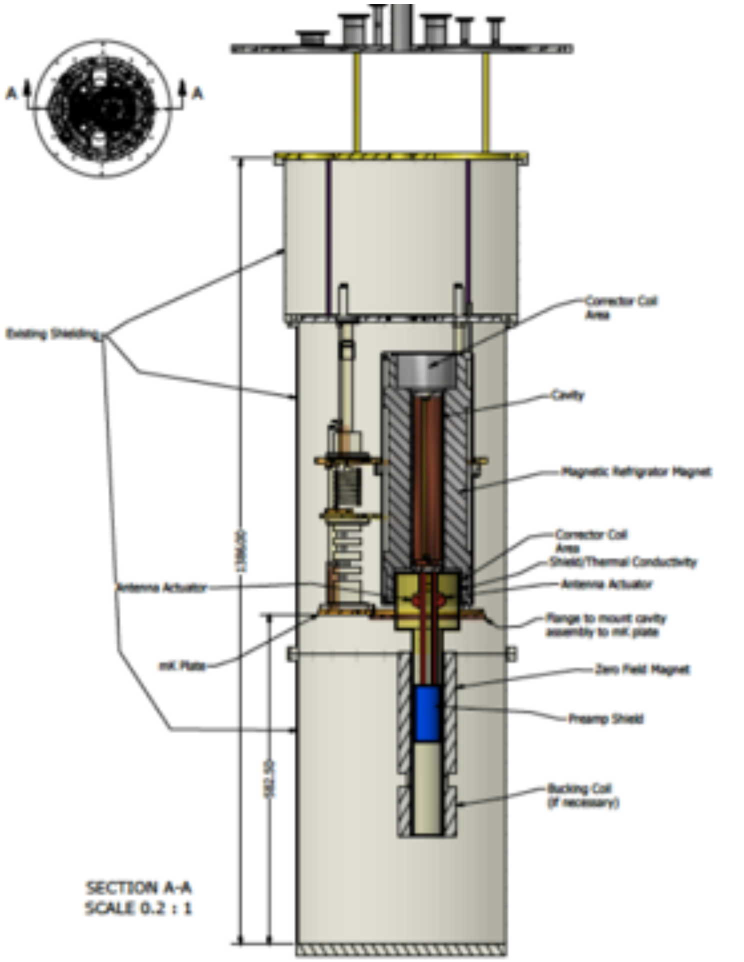
$$Q = \frac{L/R}{1 + \cancel{L/R}} \cdot \frac{R}{\delta}$$

*This term goes away for a superconducting barrel*



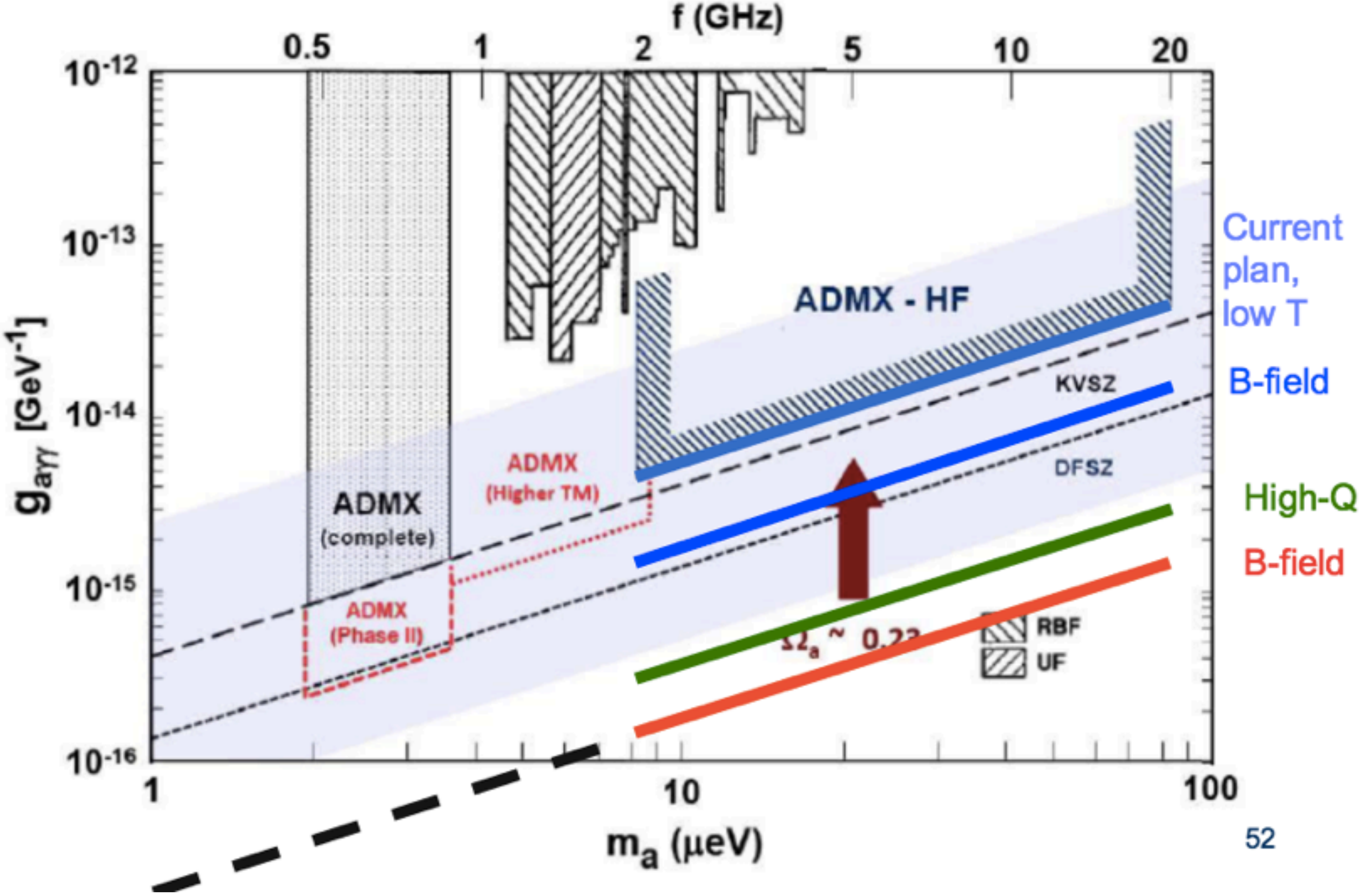
R. Gupta

Capp Ultra Low Temp Axion Search in Korea



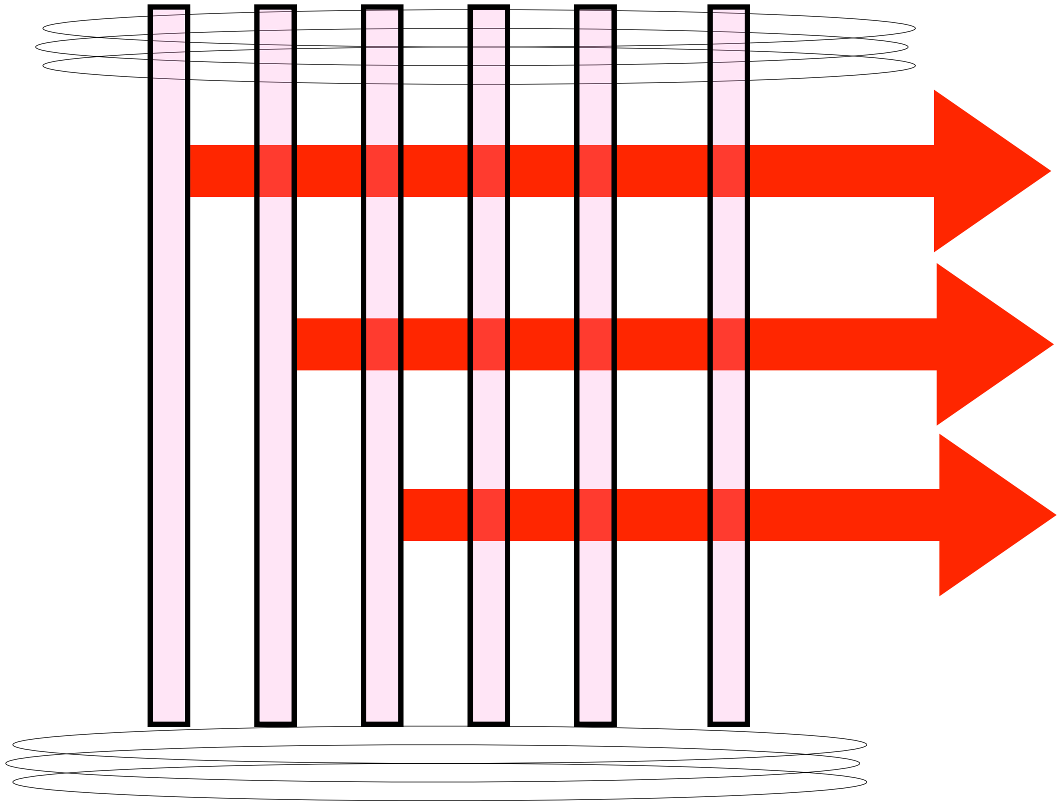
# CAPP plans

## ADMX goals and CAPP plan



# Dielectric multi-mirror

Jaeckel, JR 2013



**Emitted EM-waves from each interface**
**+ internal reflections ...**

$$P \sim |\mathbf{E}_a|^2 \text{Area} \times \mathcal{O}(N^2)$$

**Simulated**

# Dielectric multi-mirror

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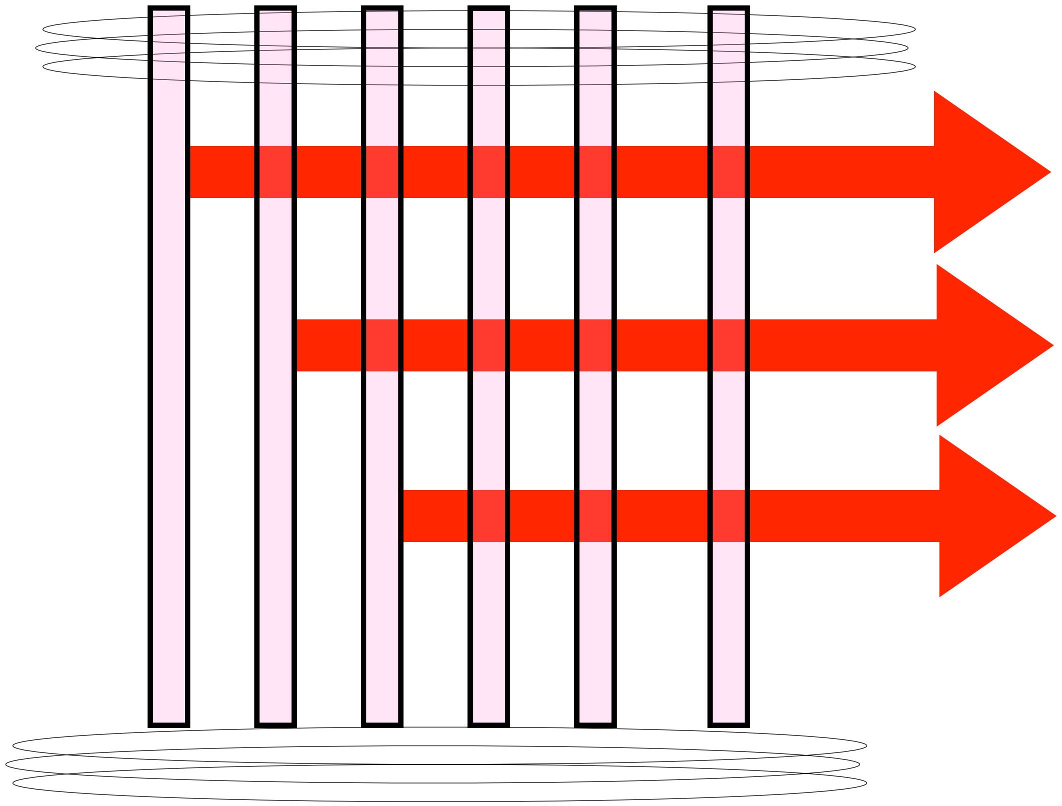

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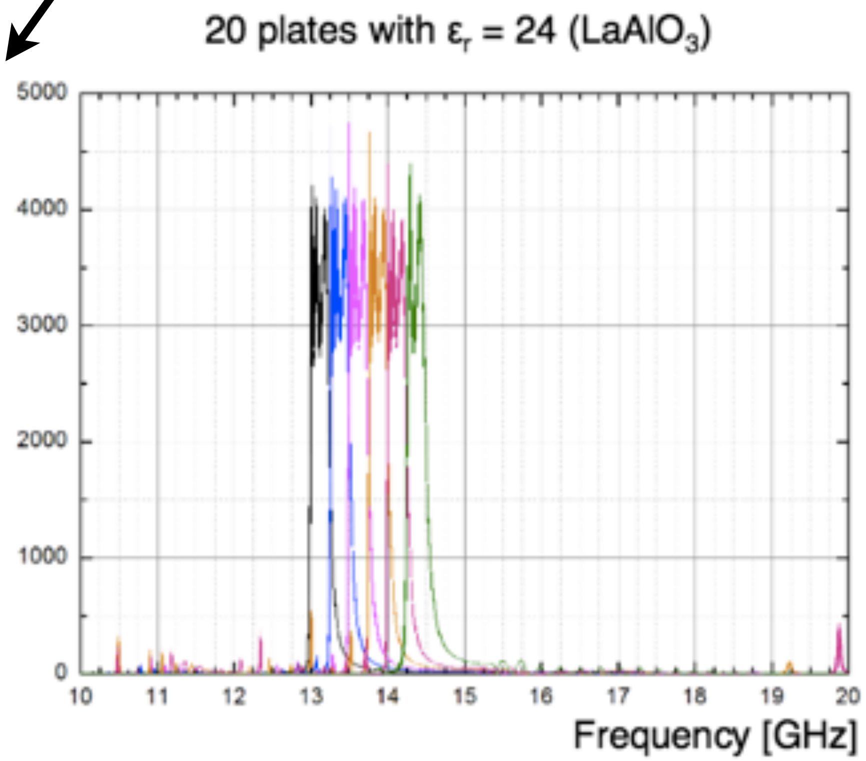
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



**Simulated**

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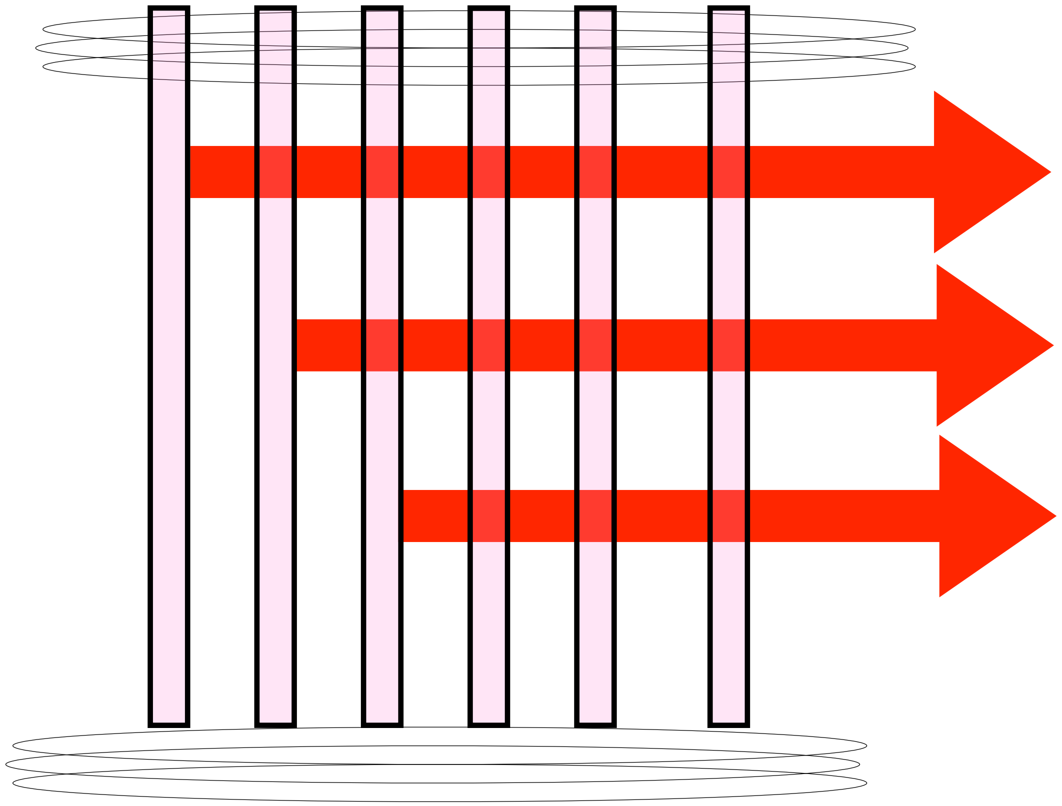

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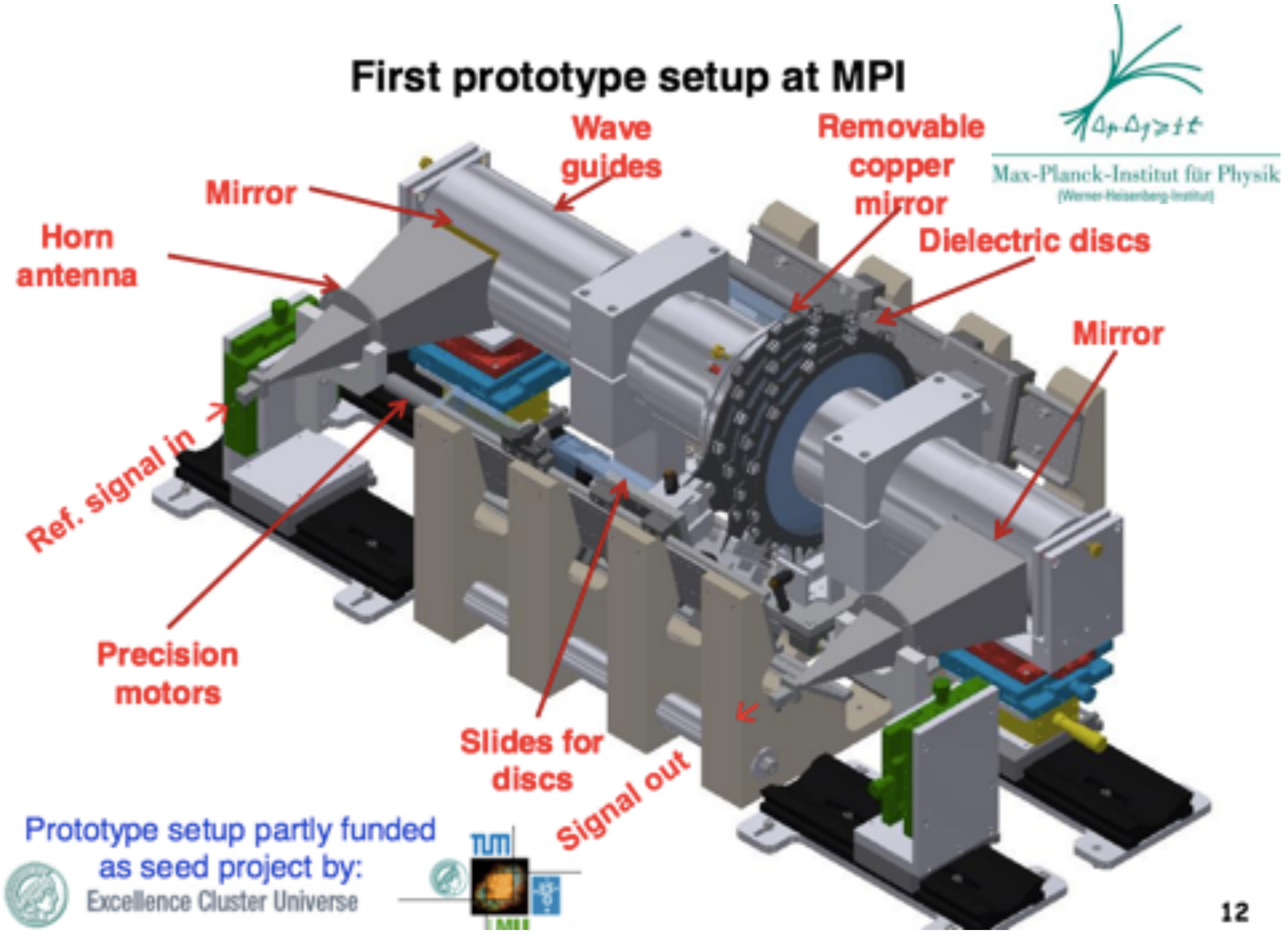
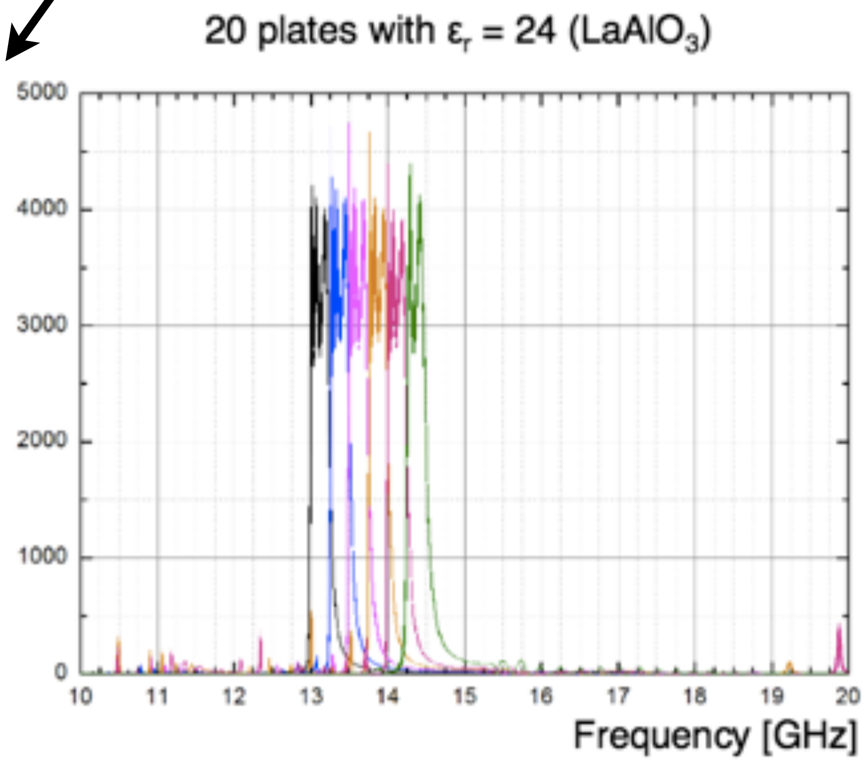


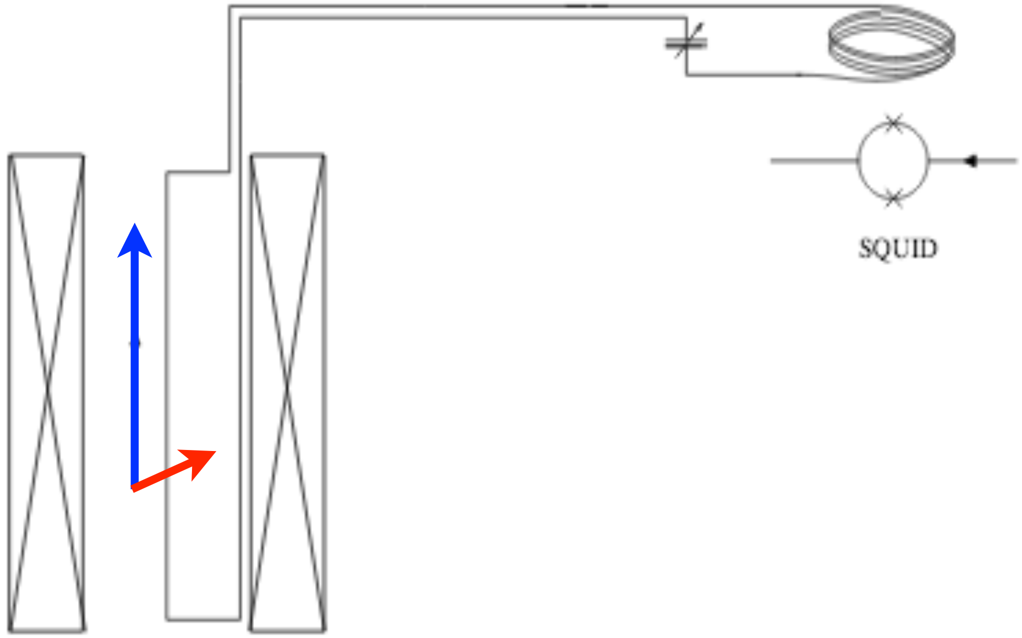
**Simulated**



# LC- circuit

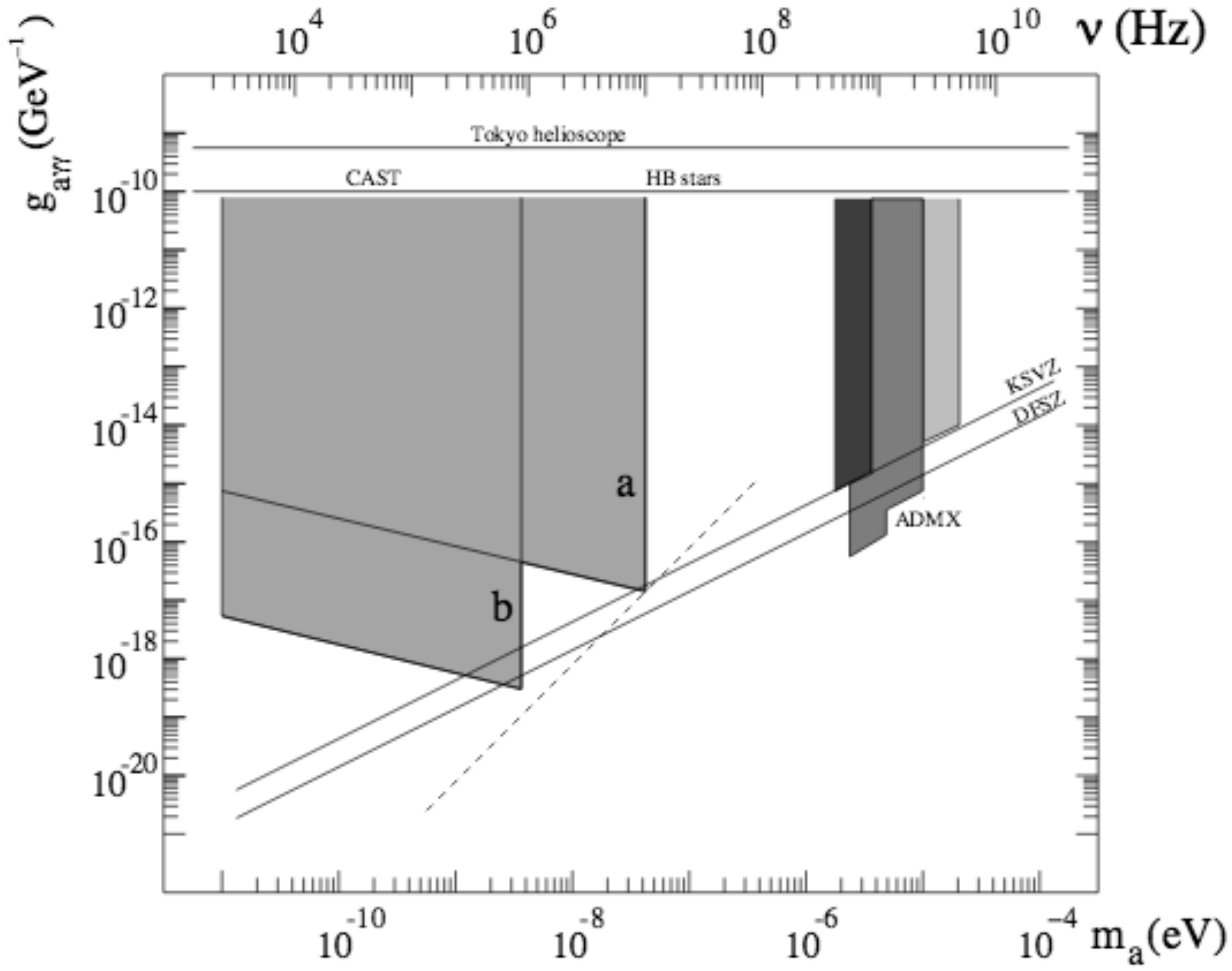
Sikivie 2012

- Detect low-frequency B-field with a tunable LC
- First moves in Florida U.



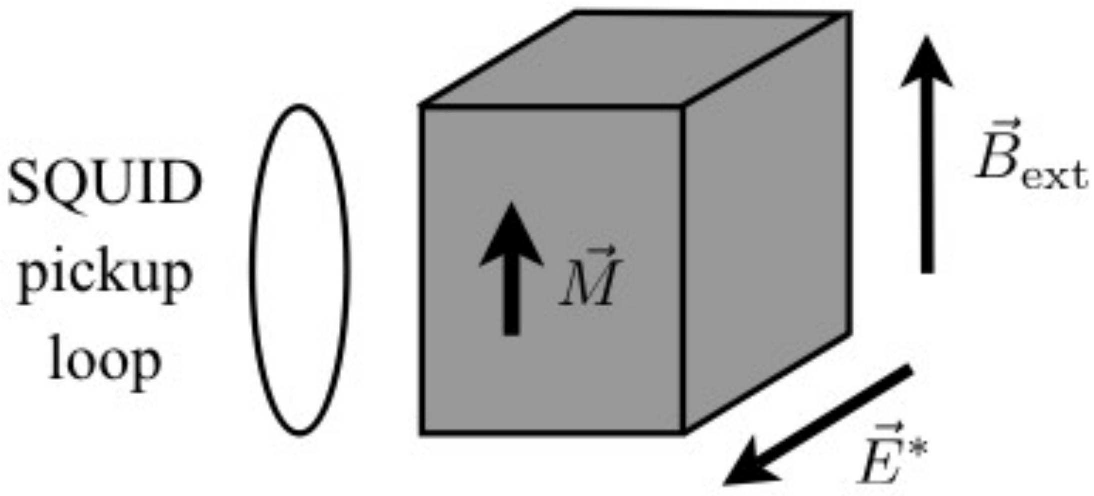
$$\boxed{|\mathbf{B}_a|} \sim \langle v \rangle \boxed{|\mathbf{E}_a|}$$

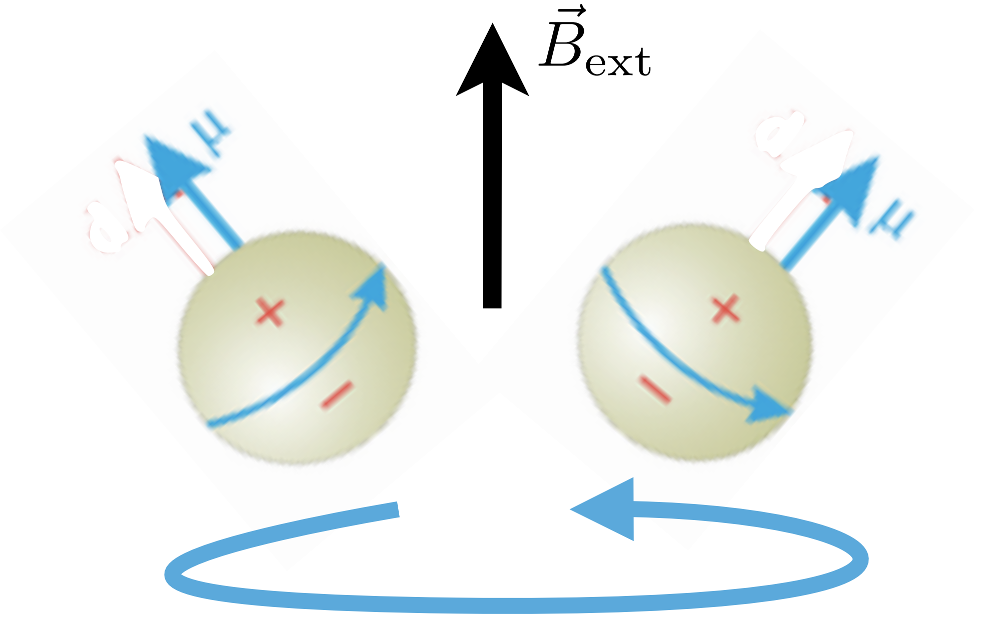
Earth-DM relative velocity



# CASPER : Spin precession

Graham 2012



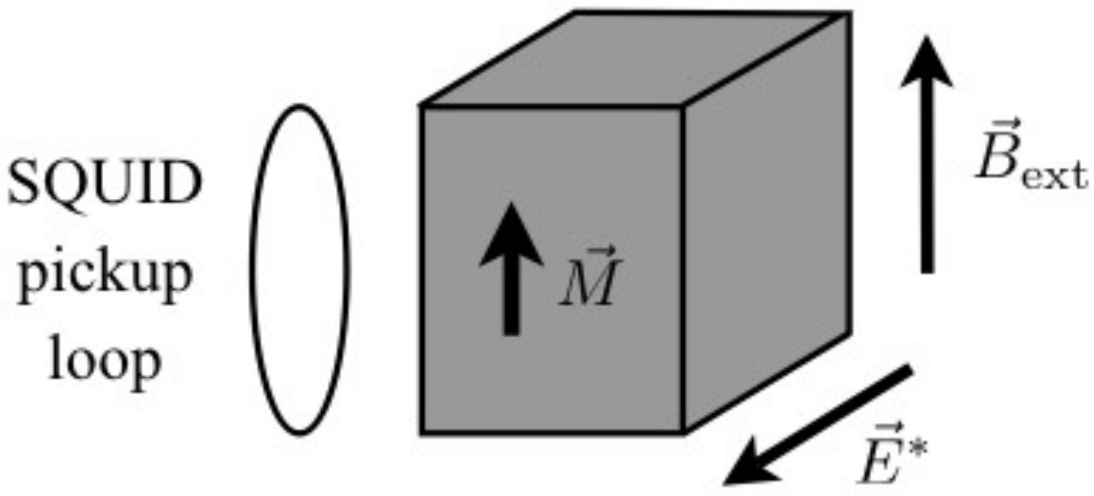


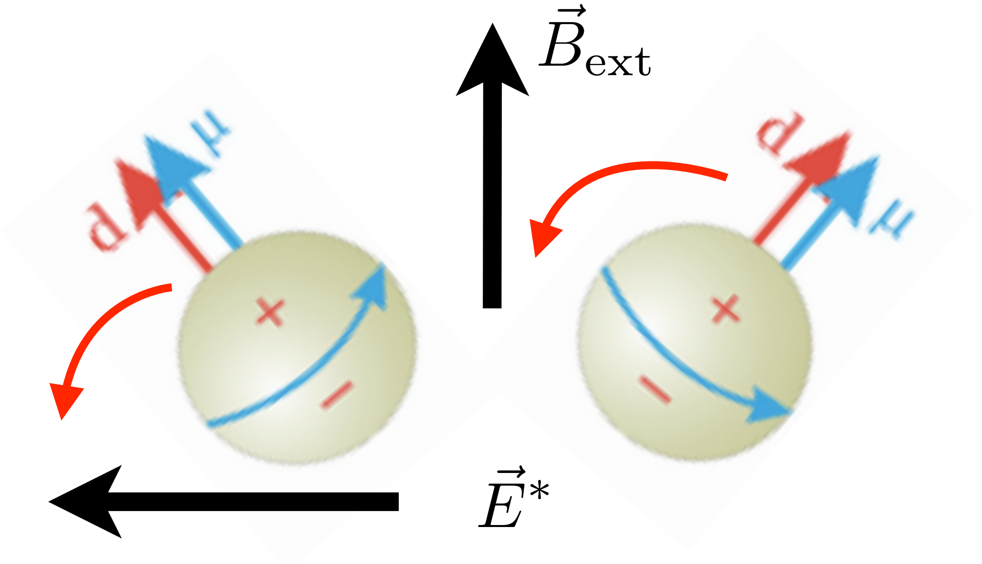
**Spin precesion**

$$\omega = \mu|\vec{B}_{\text{ext}}|$$

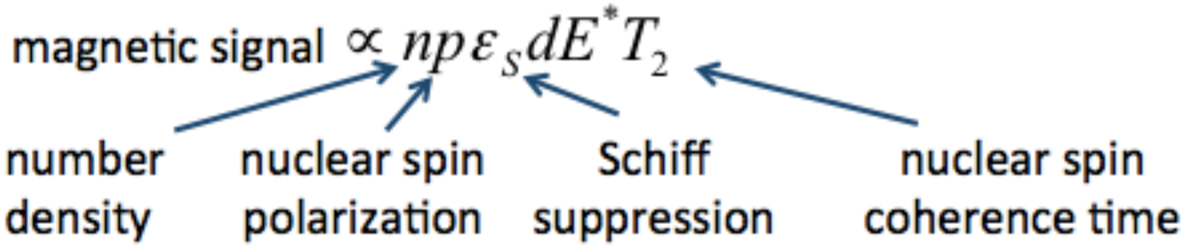
# CASPER : Spin precession

Mainz, Berkeley





Static EDM, effects cancel in a period

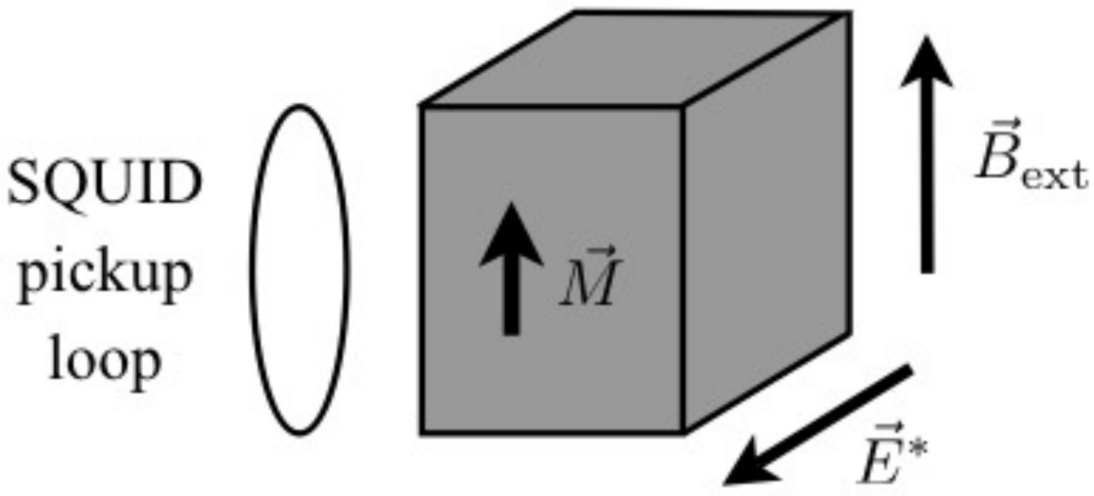


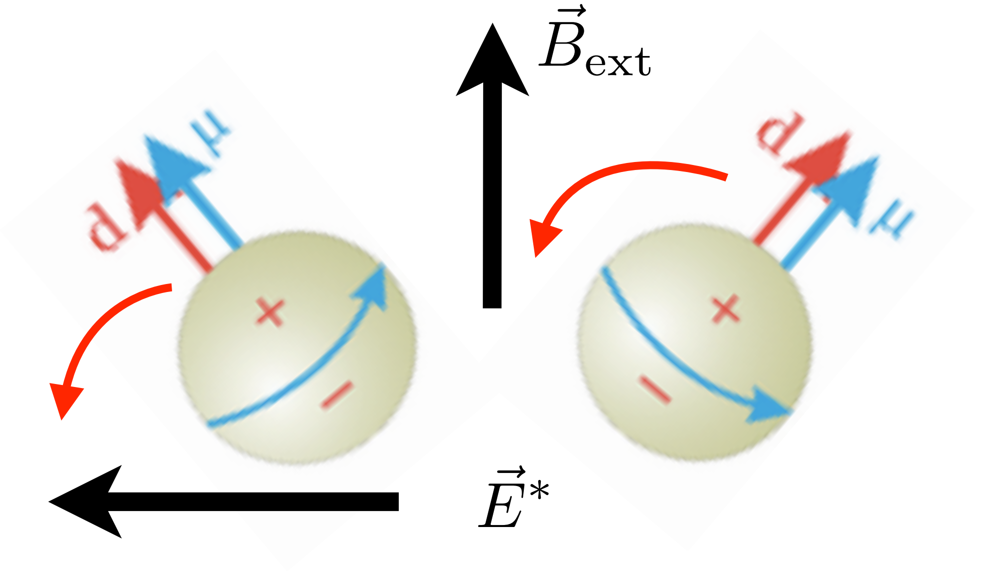
magnetic signal $\propto np\varepsilon_S dE^* T_2$

- EDM + Large E-fields in PbTiO3
- Mainz (D. Budker's group) & Berkeley
- B-field, coherence time, sensitivity to m < neV
- Phase I starts in 2016, Phase II physics results
- Mass range limited by B-field strength

# CASPER : Spin precession

Mainz, Berkeley





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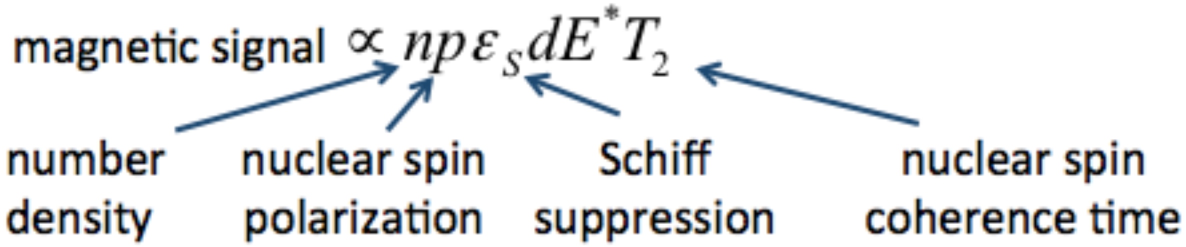

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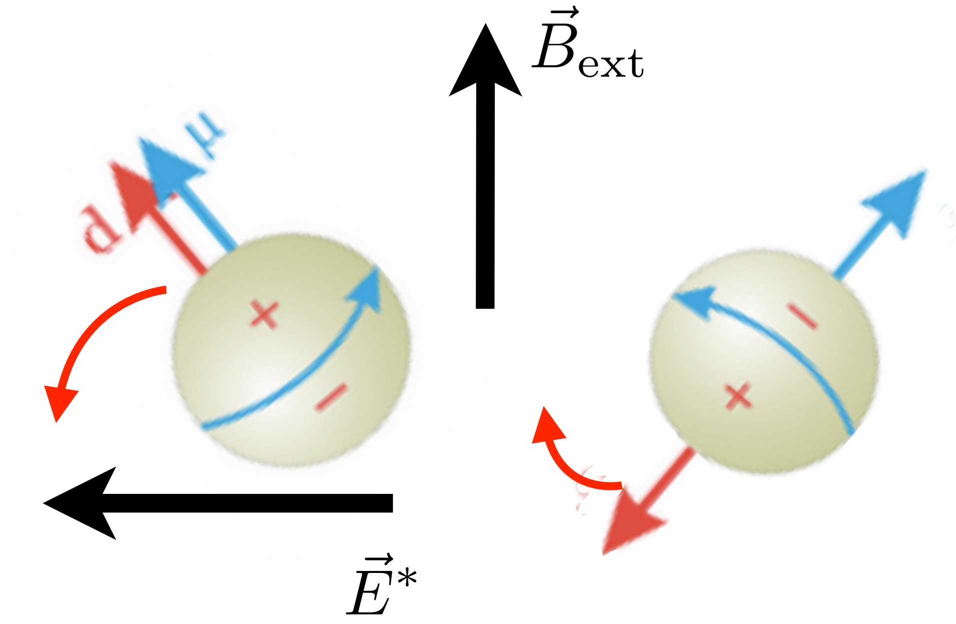
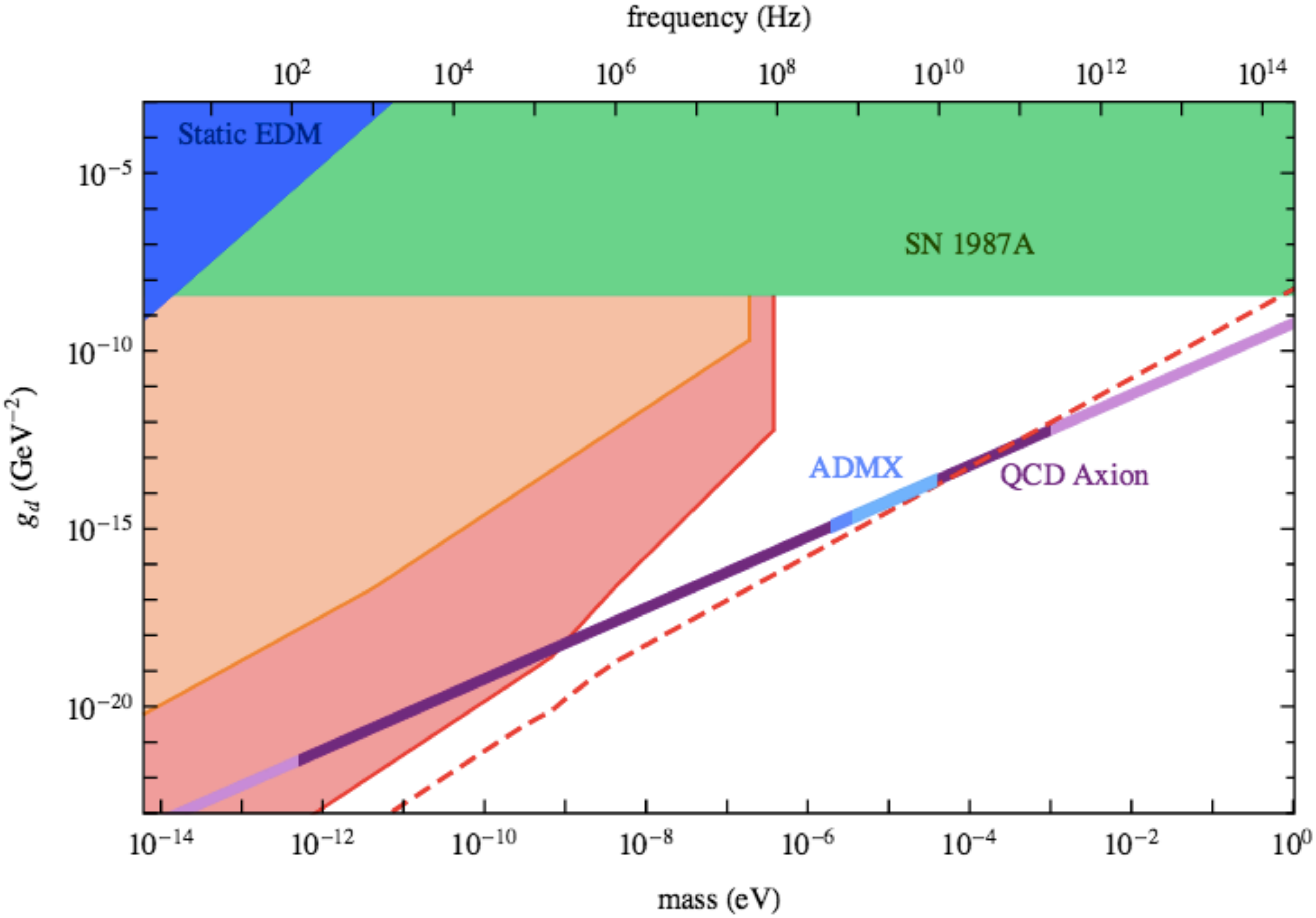


Oscillating EDM, effects add up, transverse magnetisation grows if $m_a = \omega = \mu|\vec{B}_{\mathrm{ext}}|$

# CASPER : Spin precession

Mainz, Berkeley



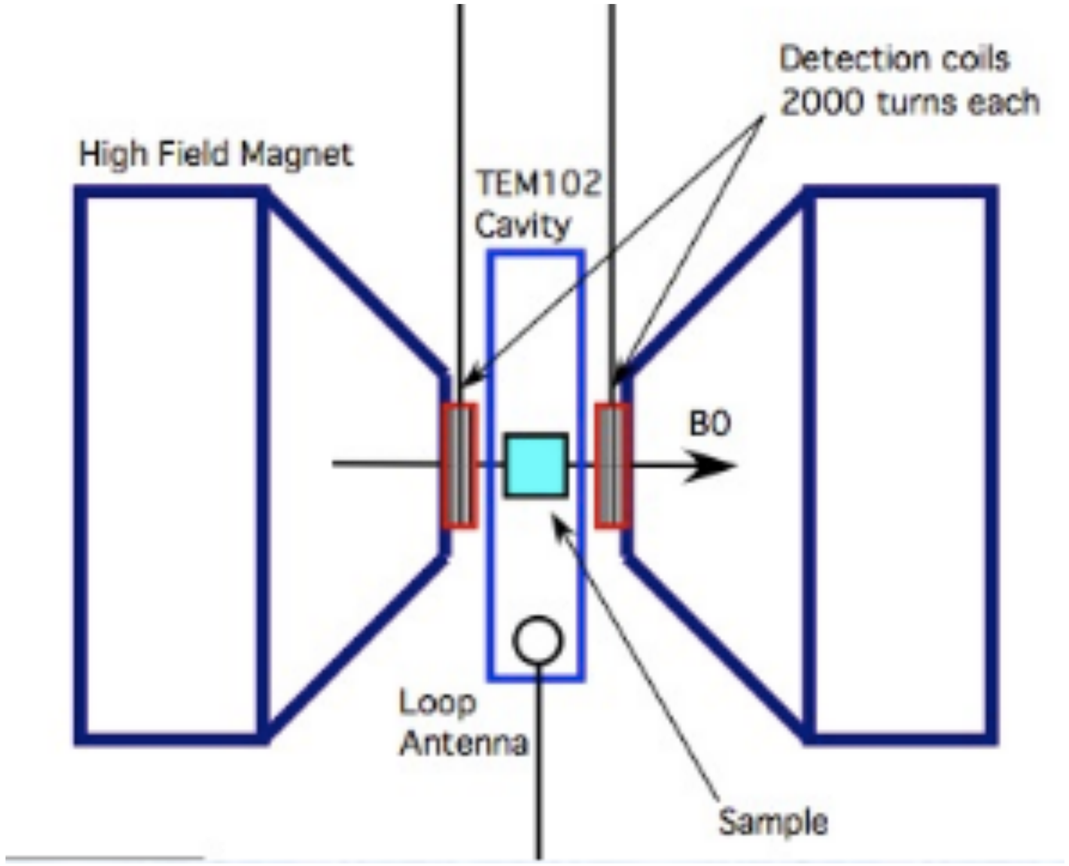
# QUAX : electron Spin precession

INFN, Legnaro

- Electron coupling in the non-relativistic limit, Electron spin - axion “wind”

$$\mathcal{L}_{ae} = C_{ae}[\bar{e}\gamma^{\mu}\gamma_5 e]\partial_{\mu}\theta \quad \rightarrow \quad C_{ae}(\nabla\theta)\cdot\sigma_e\mu_B \quad \sim \quad \underbrace{C_{ae}m_a\langle\vec{v}\rangle\theta}\cdot\sigma_e\mu_B$$

**Effective Magnetic field**



- Use Electron Spin Resonance (similar to NMR but with electrons) $\omega = \mu_B\vec{B}_{\text{ext}} = m_a$
- Bohr magneton much larger, smaller B-fields required for large axion mass
- Short coherence times, radiation damping (R+D)
- HF detection ? Use non-linearity and search for LF oscillations $\omega \sim \mu_B|\vec{B}_{\text{ext}}| - m_a$

# Axion DM : A developing picture