# WISPy Direct Dark Matter Detection

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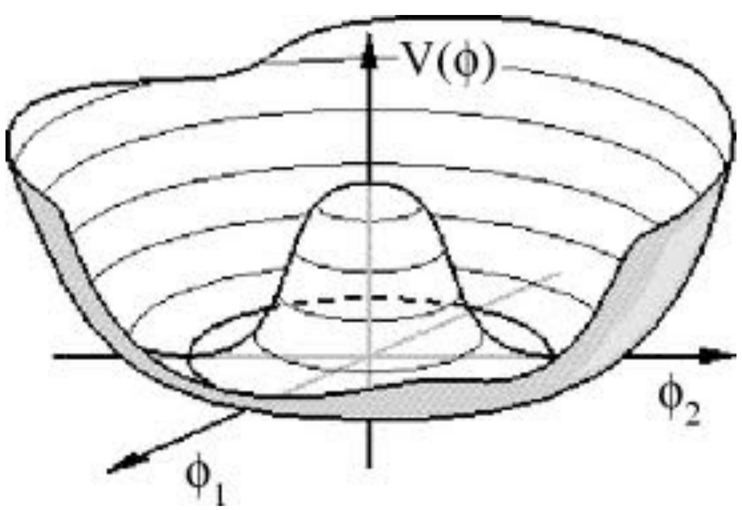
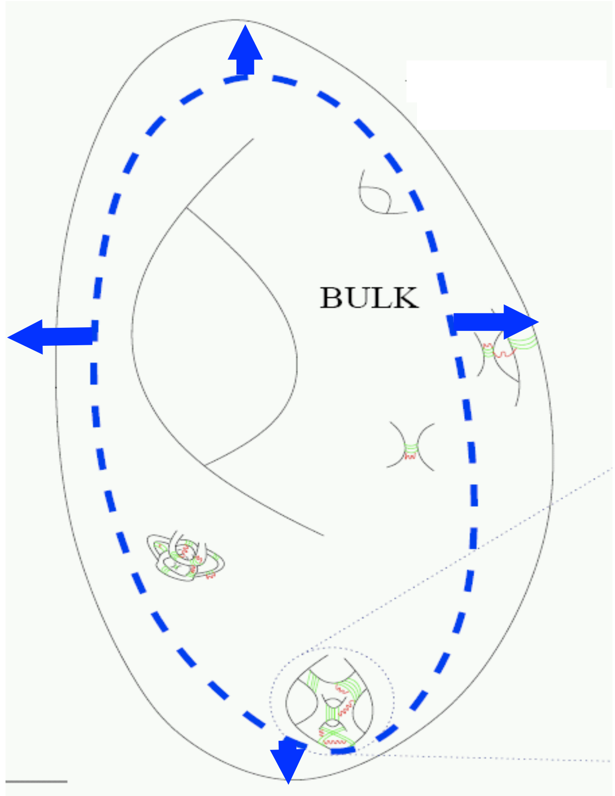
# Weakly Interacting Slim(sub-eV) Particles

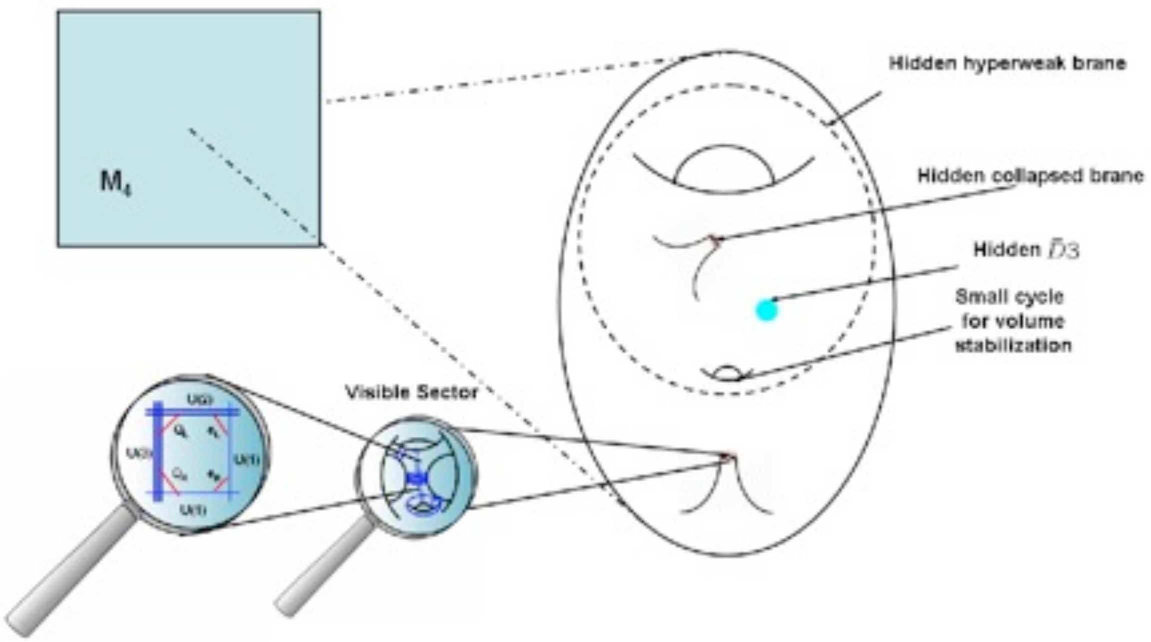
- Dark matter ultralight particle -> bosonic

- Pheno constraints: they must be extremely weakly interacting

- Theory: pseudoGoldstone bosons, string axions, stringy hidden U(1)'s
  (QCD axion, majoron, familons)

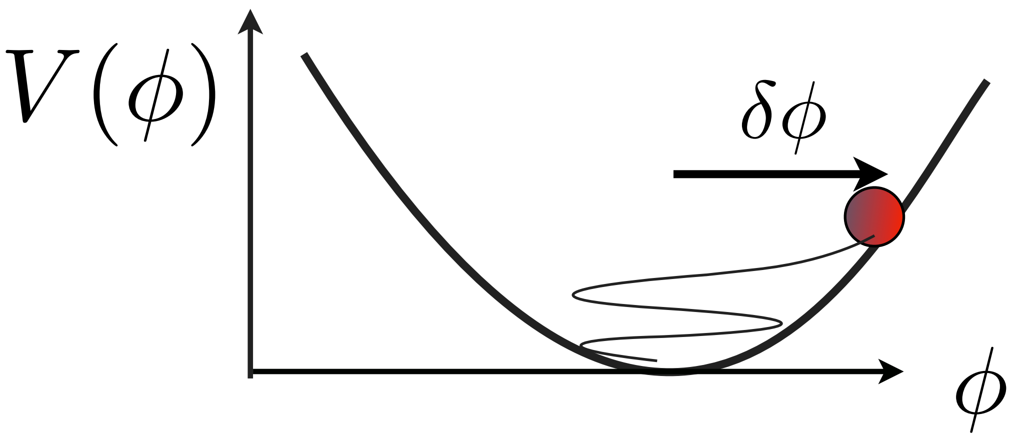


# WISPs as cold-Dark Matter

## - Non-thermal production mechanisms: vacuum realignment



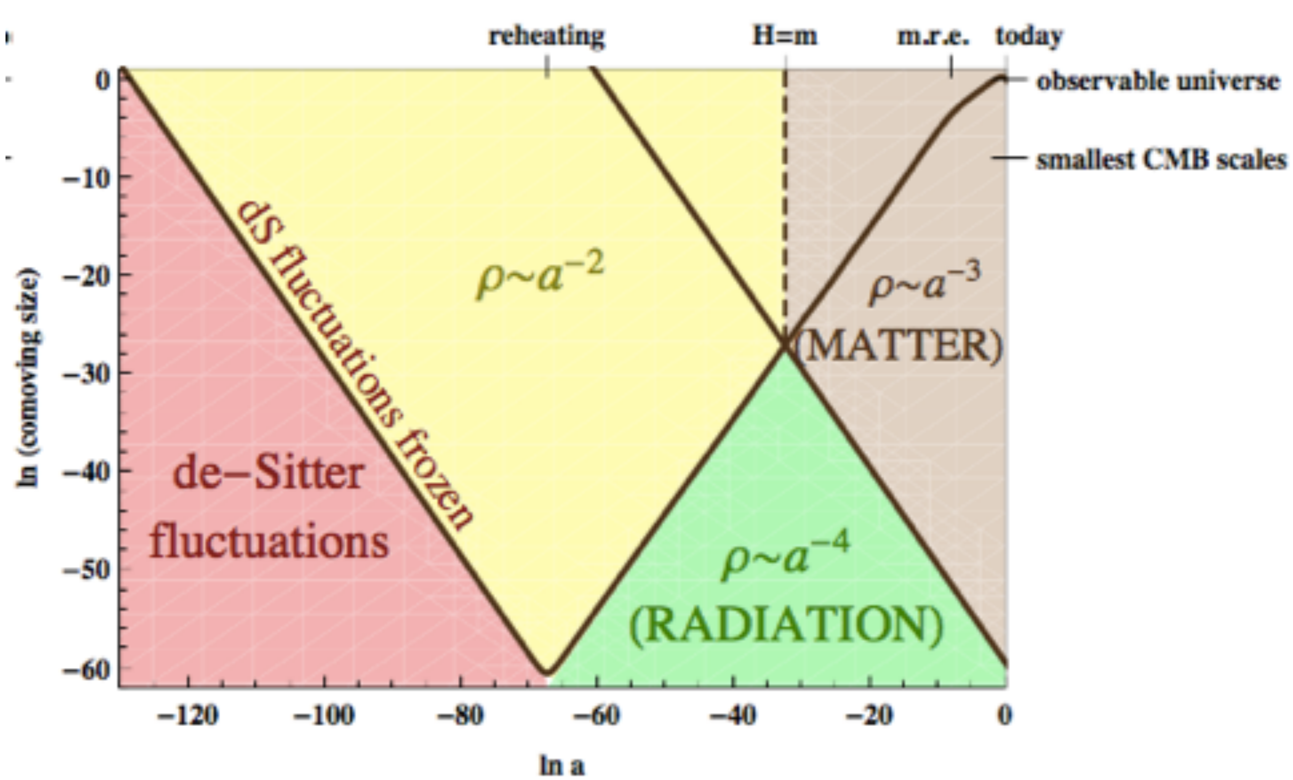

misaligned initial conditions $\delta\phi$

today $\phi \sim \phi_0 \cos mt$

$$\rho_{a,0} \simeq 1.2 \, \frac{\mathrm{keV}}{\mathrm{cm}^3} \times \sqrt{\frac{m_\phi}{\mathrm{eV}}} \left( \frac{\delta\phi}{5 \times 10^{11} \, \mathrm{GeV}} \right)^2 ,$$

## - Isocurvature constraints (Inflation on the CMB)

$$P_{\mathrm{iso}} = \frac{d\langle n_\phi \rangle}{n_\phi} \sim \frac{H_I^2}{\pi^2 (\delta\phi)^2} < 0.039 P_s = 0.88 \times 10^{-10}$$ (for scalar DM fluctuating during inflation)




- Vector fluctuations are suppressed at large (CMB) scales -> no constraint
- Indeed Inflationary quantum fluctuations can provide initial displacement for DM

$$m_{\gamma'} \sim 10^{-5} \mathrm{eV} \left( \frac{H_I}{10^{14} \mathrm{GeV}} \right)^4$$

# WISP couplings

- Strongly constrained by: stellar evolution and 5th force searches

- Relevant operators at low energies

**pNGBs (axions and axion-like particles: ALPs)**

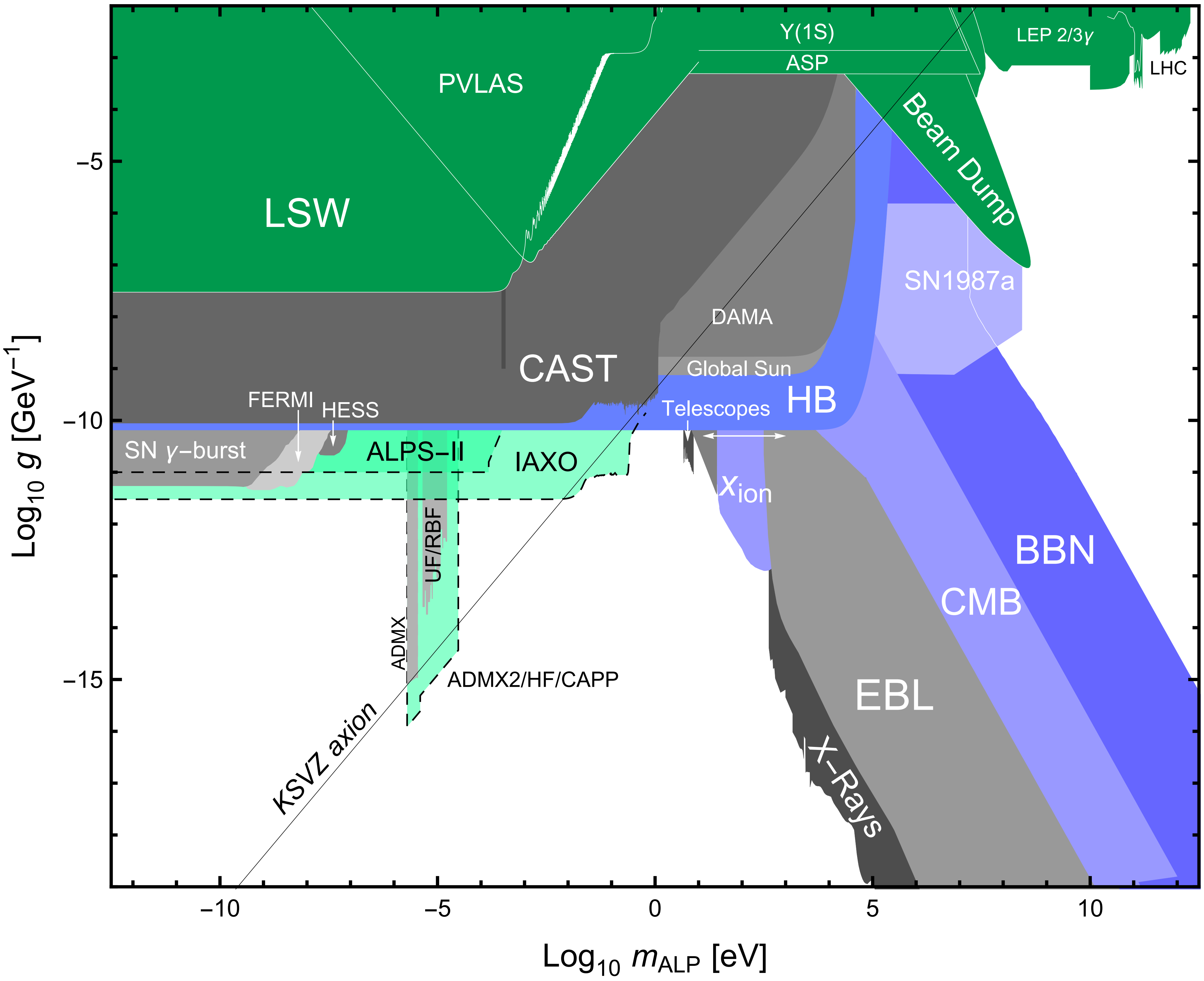
$$\mathcal{L}_i \in \sum_f g'_{\phi f} [\bar{f}\gamma^\mu \gamma_5 f]\partial_\mu \phi - \frac{g'_{\phi\gamma}}{4} F\widetilde{F}\phi - \frac{g_{\phi g}}{4} G\widetilde{G}\phi$$

$$\mathcal{L}_i \in \sum_f g_{\phi f} [\bar{f}\gamma^\mu \gamma_5 f]\partial_\mu \phi - \frac{g_{\phi\gamma}}{4} F\widetilde{F}\phi - i\frac{g_d}{2}\bar{N}\sigma^{\mu\nu}\gamma_5 N F_{\mu\nu}\phi$$

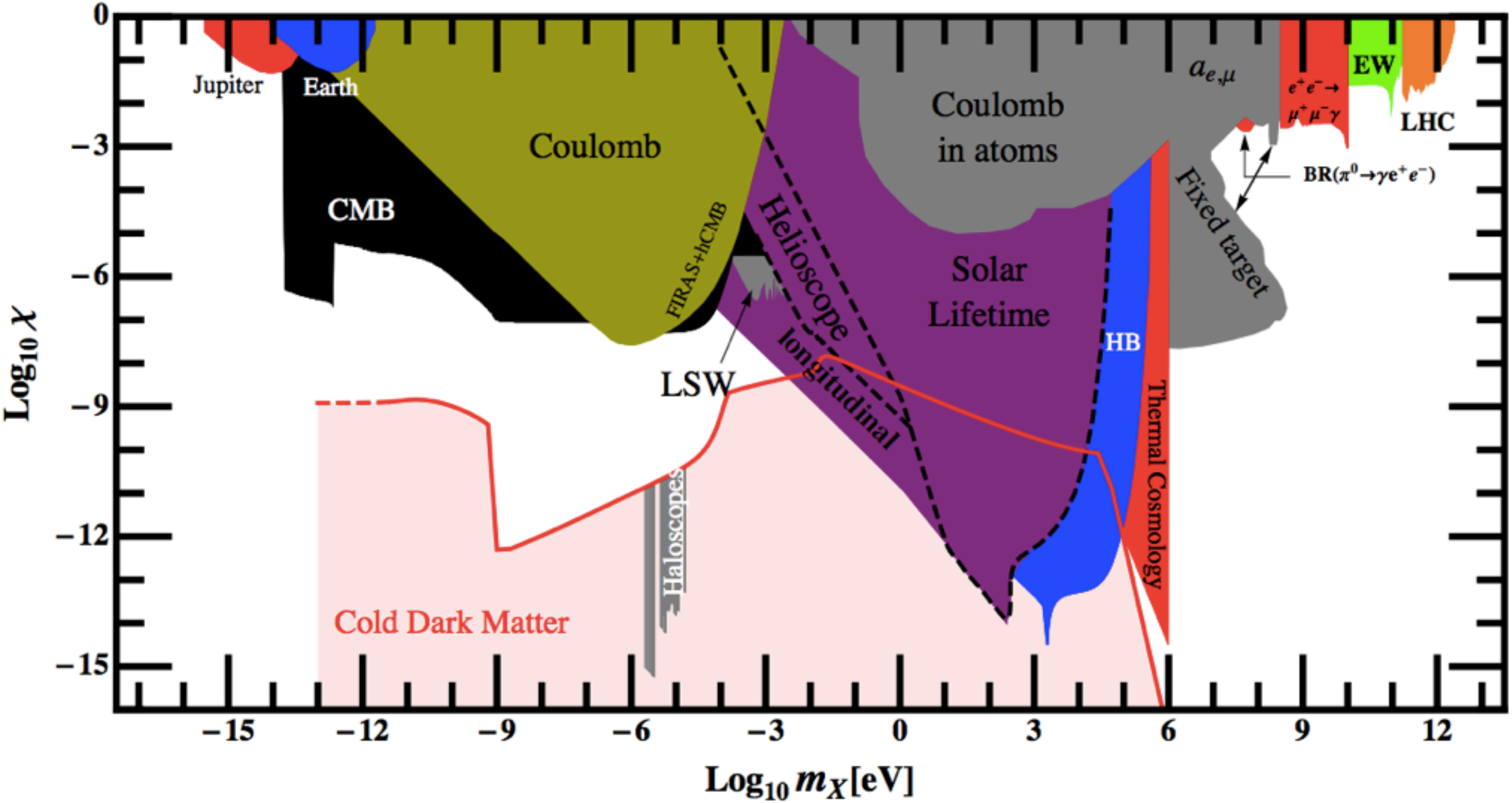
**Hidden U(1) vector bosons**

$$\mathcal{L}_i \in -\frac{\chi}{2} F_{\mu\nu} X^{\mu\nu} + \ldots$$

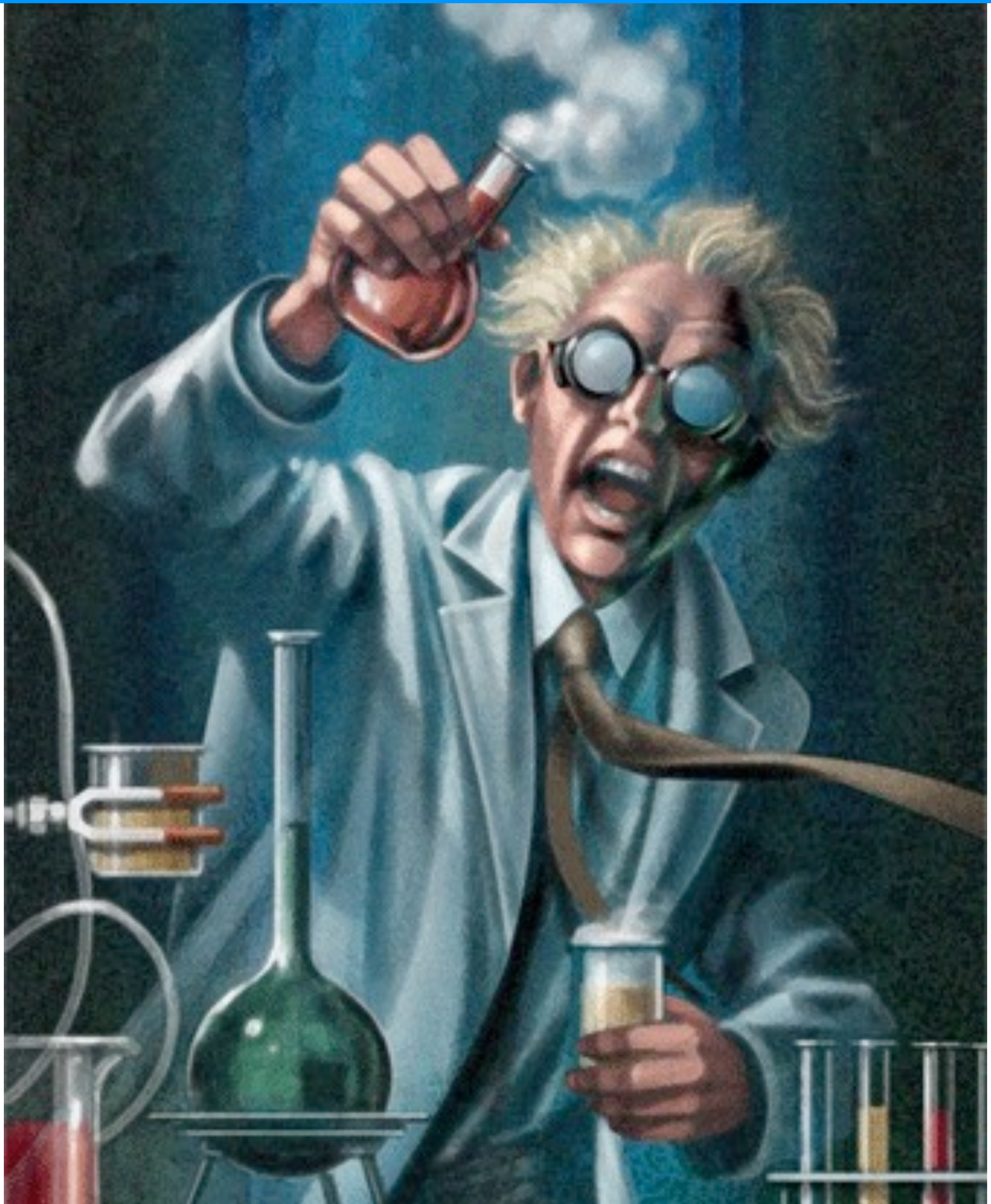
# Constraints on ALPs with a two photon coupling



# Constraints on Hidden Photons



# Direct Detection of WISPs



# WISPs in the galactic Halo

**Energy density** $\rho_\phi \simeq 0.4\frac{\mathrm{GeV}}{\mathrm{cm}^3} \simeq \frac{1}{2}(\dot\phi)^2 + \frac{1}{2}m^2\phi^2 = \frac{1}{2}m^2\phi_0^2$

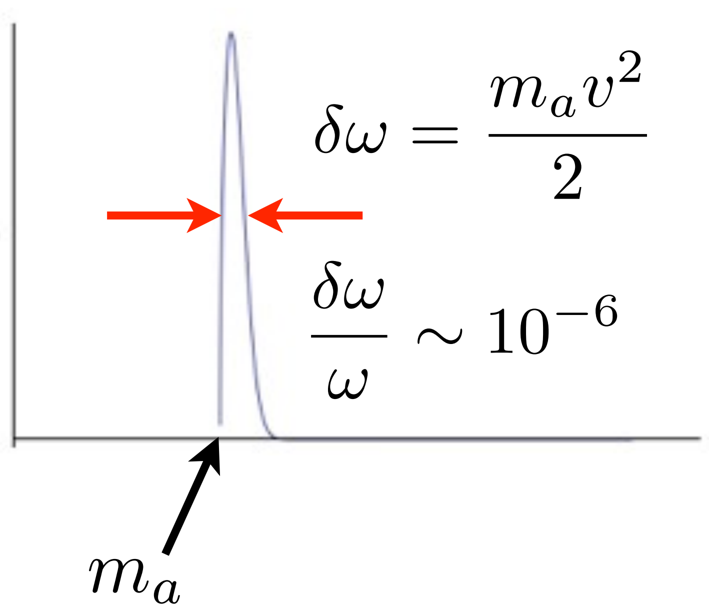
**velocity** $v \sim 10^{-3}c$

**occupation number** $\frac{n_\phi}{\frac{4\pi p^3}{3}} \sim \frac{m\phi_0^2}{(mv)^3} \propto 10^{30}\left(\frac{\mu\mathrm{eV}}{m}\right)^4$

$a \sim a_0 \cos mt$

**Fourier-transform** $a(x)$

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




$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

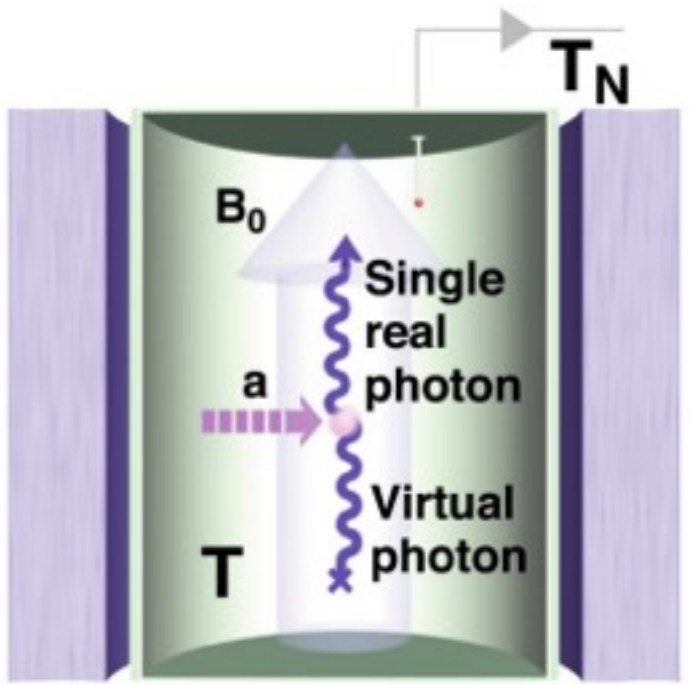
**coherence time**

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

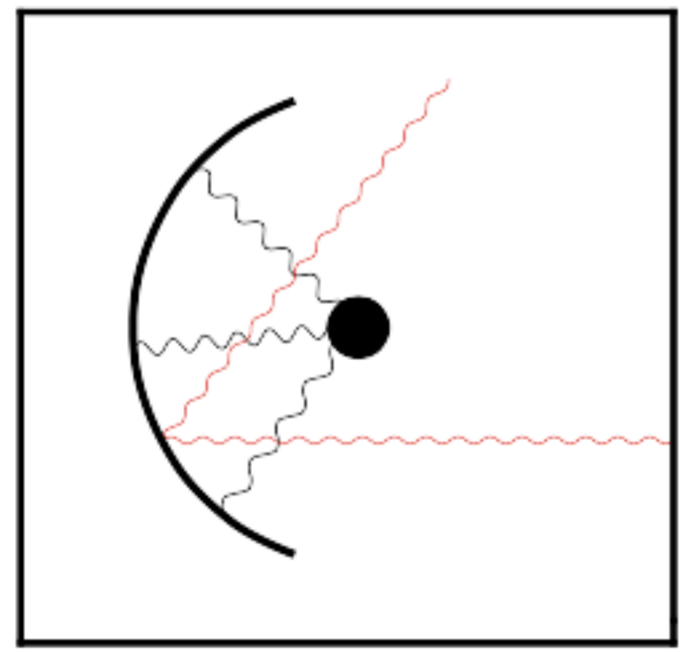
**coherence length**

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

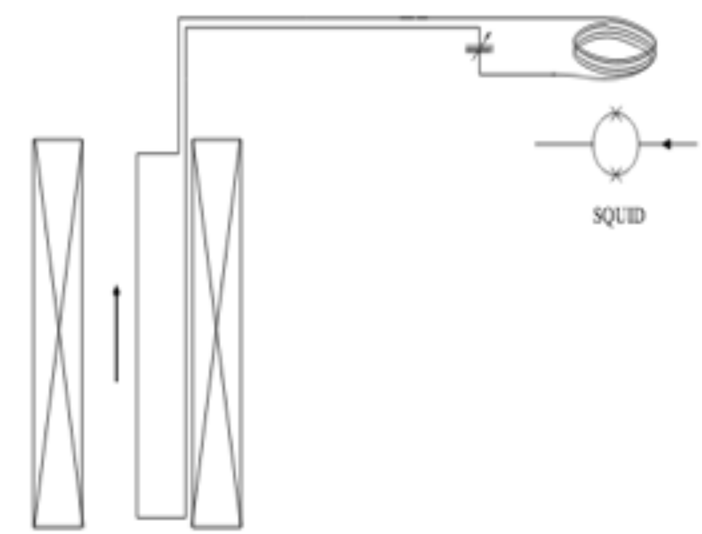
## Cavities



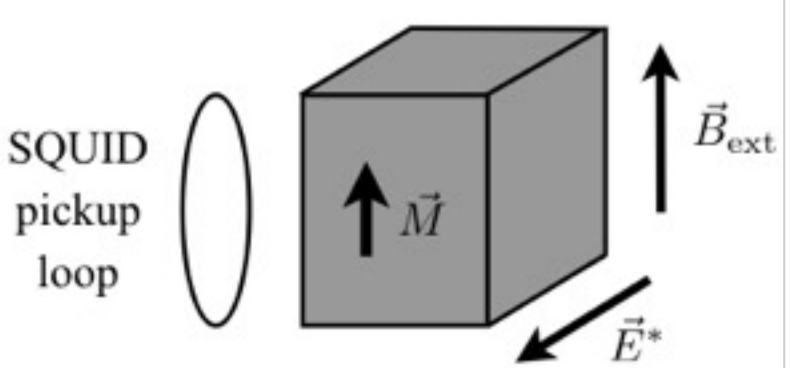

## Mirrors



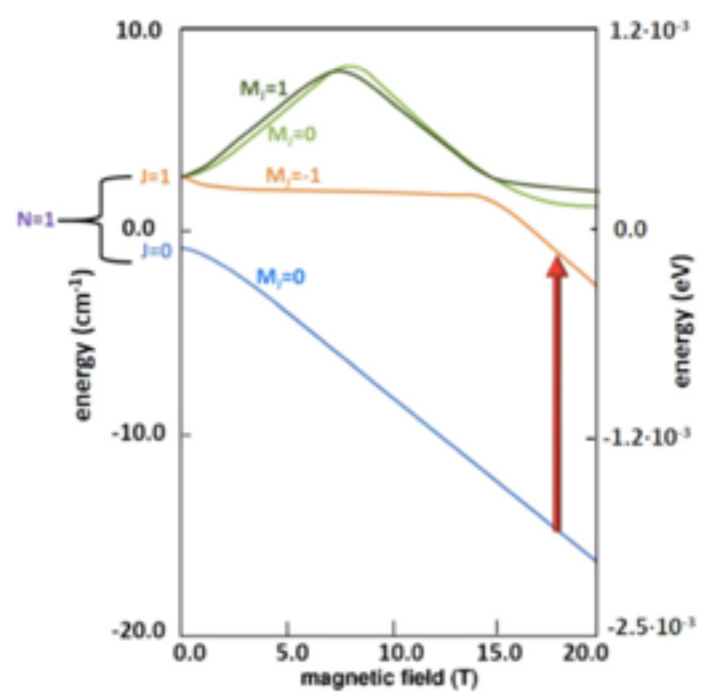
## LC-circuit



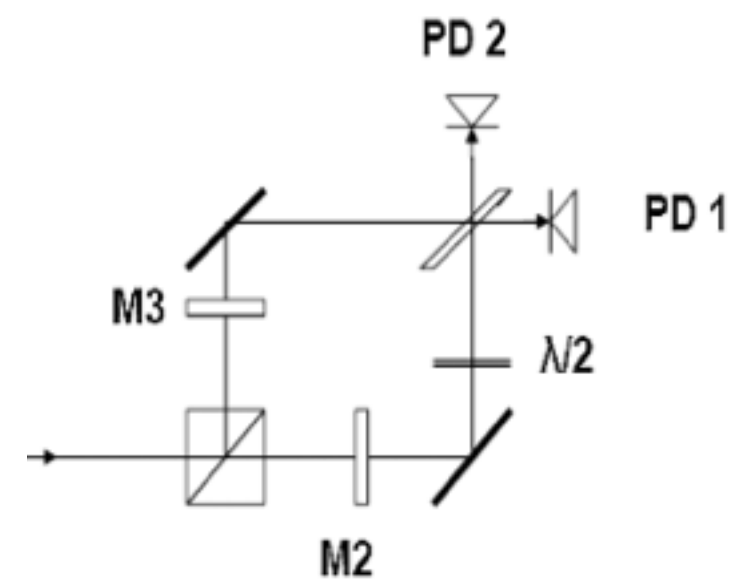

## Spin precession




## Atomic transitions




## Optical



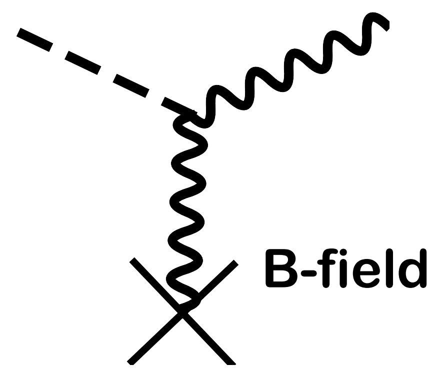
# ALP DM in a B-field

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

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

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

source




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

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

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

# HP DM in a ~~B-field~~

$$\mathcal{L}_I = \frac{\chi}{2}(\mathbf{E}' \cdot \mathbf{E} - \mathbf{B}' \cdot \mathbf{B})$$

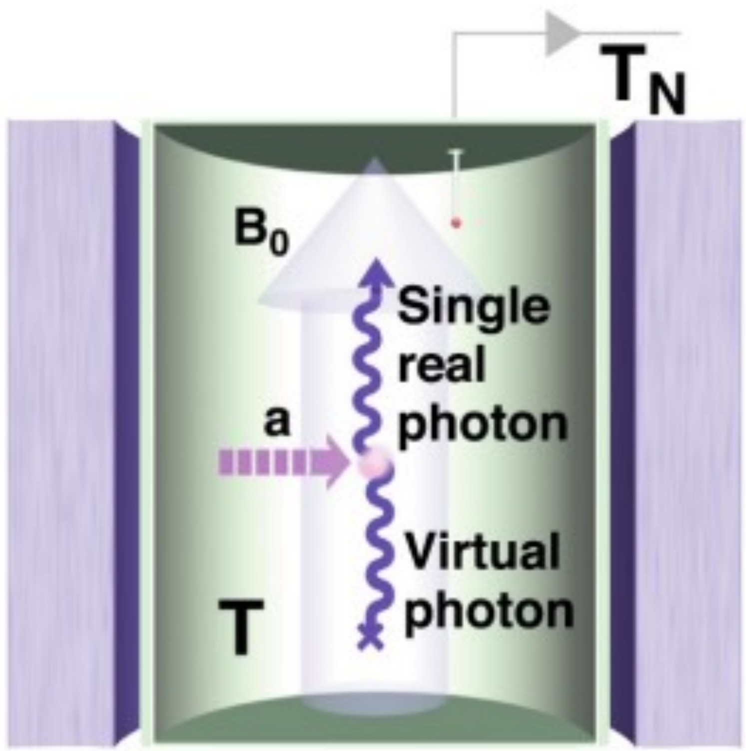
- The oscillating HP field generates ordinary E-field

$$\mathcal{L}_I = -\chi\mathbf{E}' \cdot \mathbf{E}$$

source

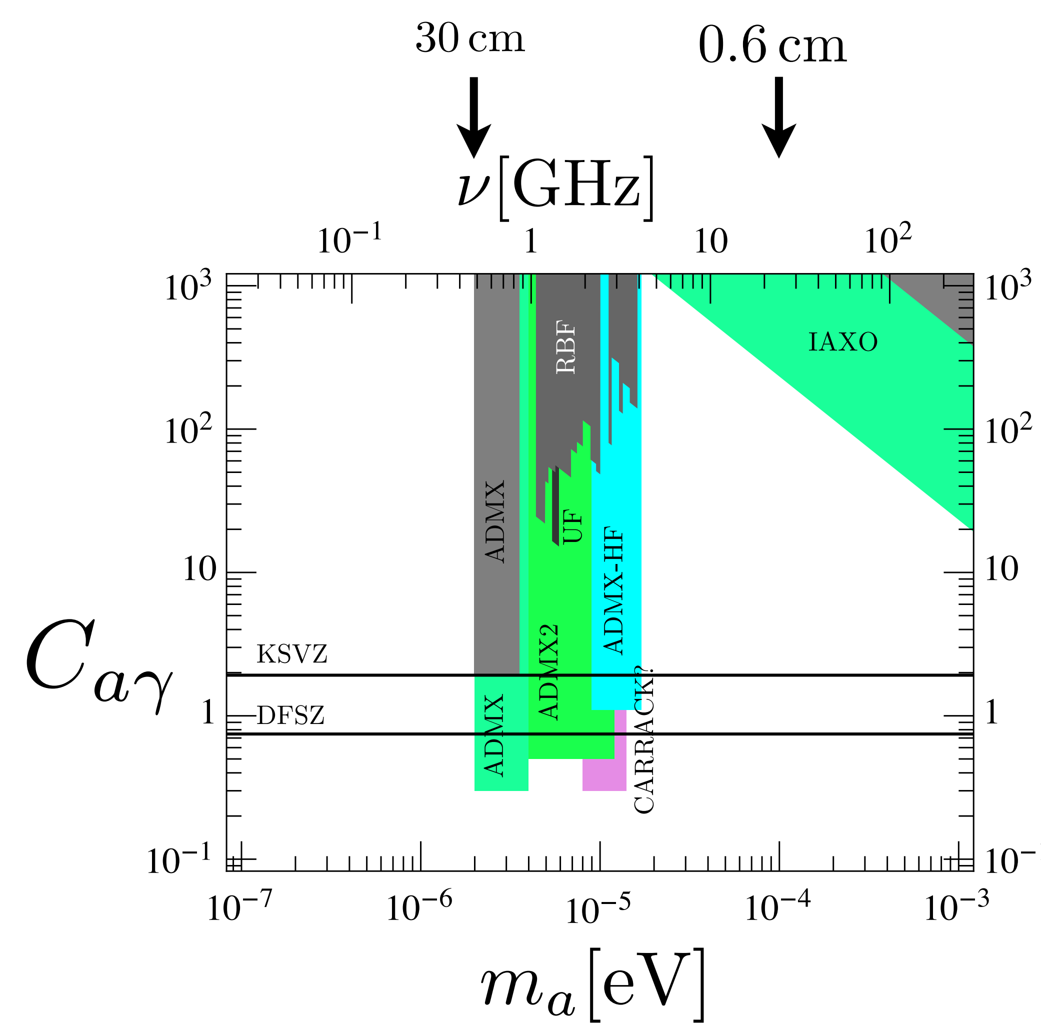
# Resonant cavity experiments

- **Haloscope (Sikivie 83)**
  **"Amplify resonantly the EM field in a resonant cavity"**



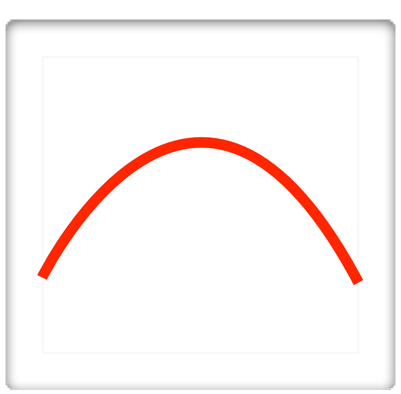

**Output EM power** $P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa$

**on resonance** $\nu_{\rm res} = \frac{m_a}{2\pi}$



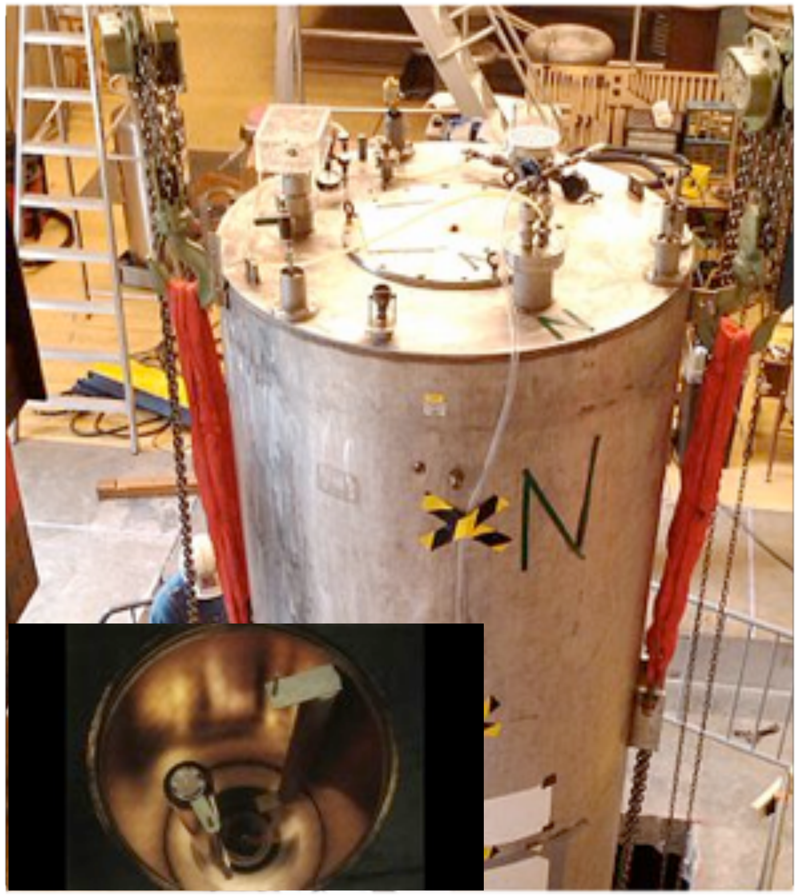

- Noise $P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$

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

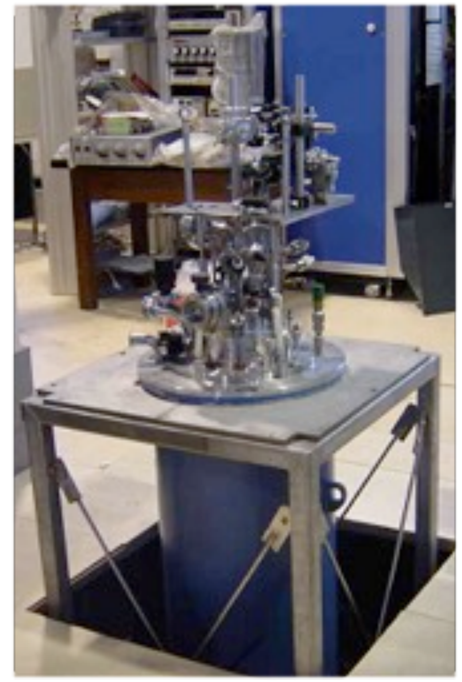


# Cavity experiments

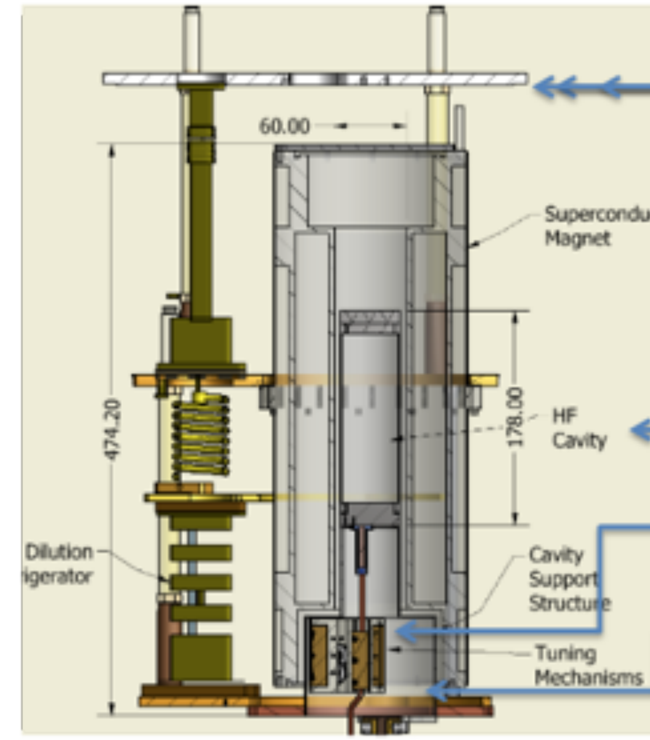
ADMX



CARRACK (discontinued)

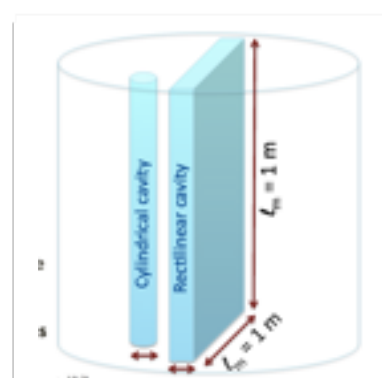


CULTASK - CAPP -Korea

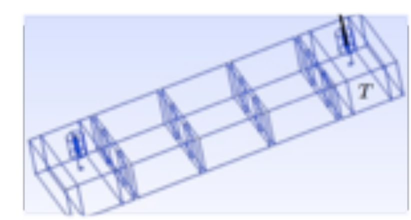



ADMX-HF

ADMX-Fermilab

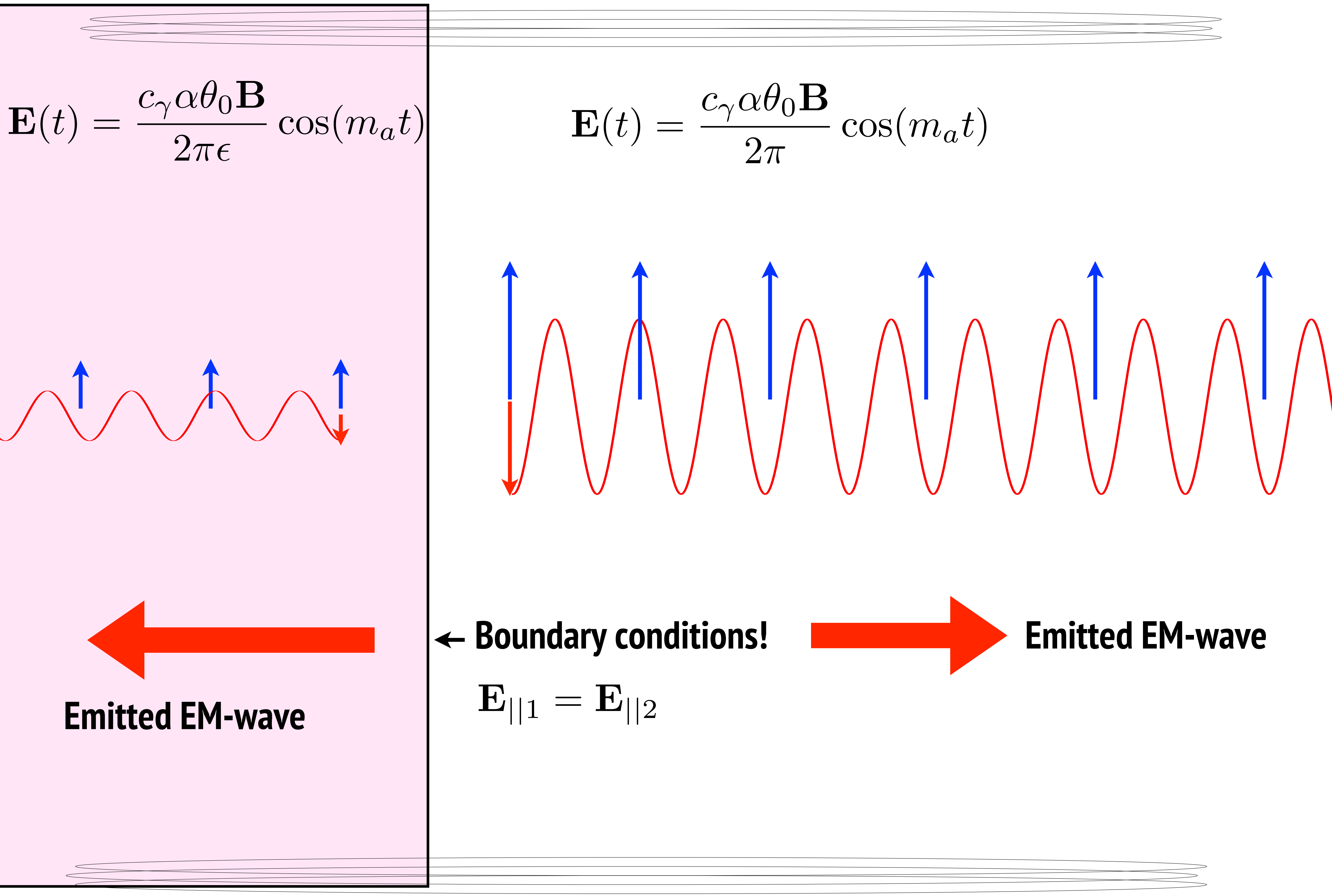



RADES



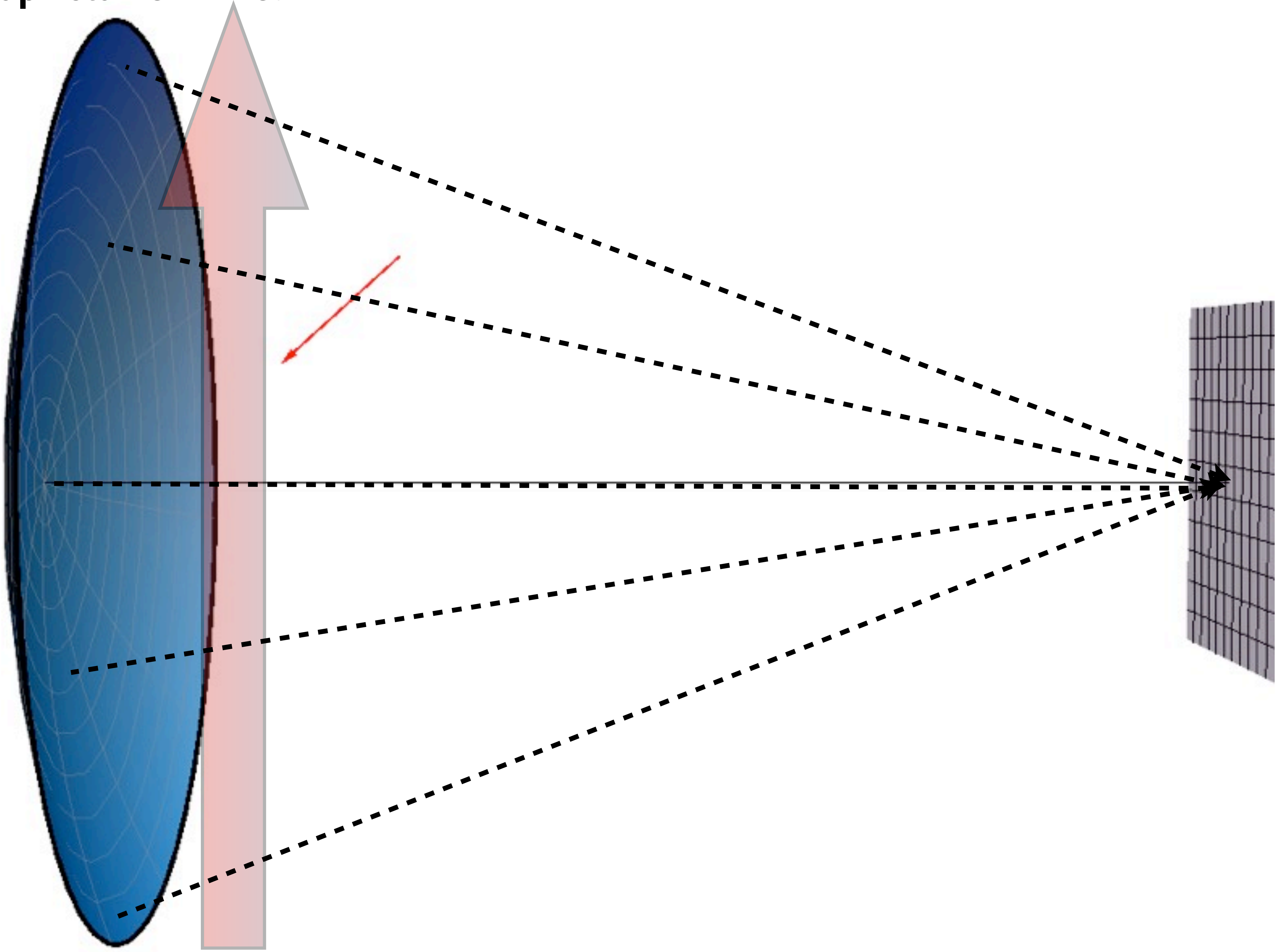
CAST-CAPP

# Radiation from a dielectric interface ...



# Dish Antenna

- Do not give up volume -> Area

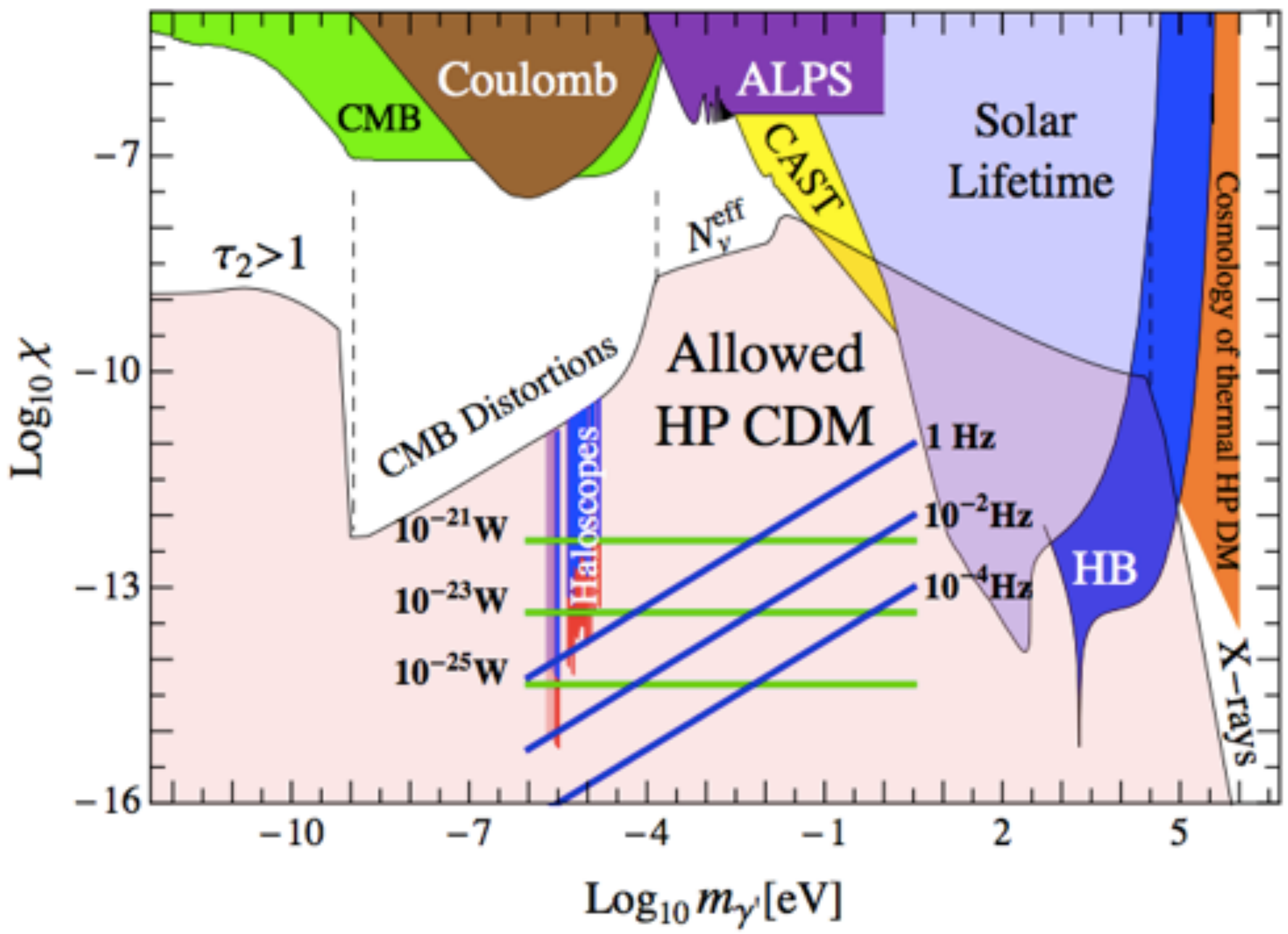


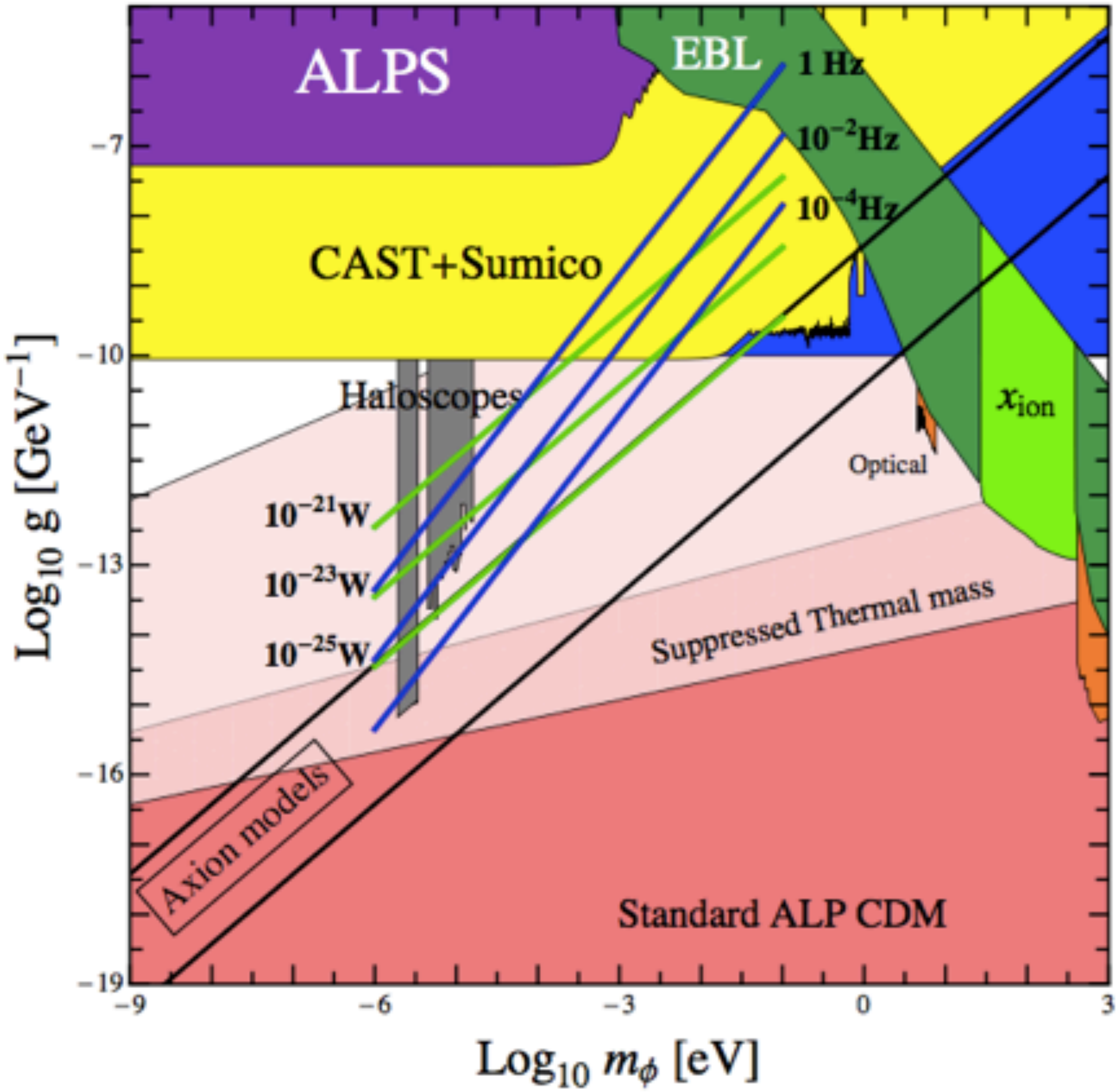
$$D \gg \frac{1}{m_a}$$

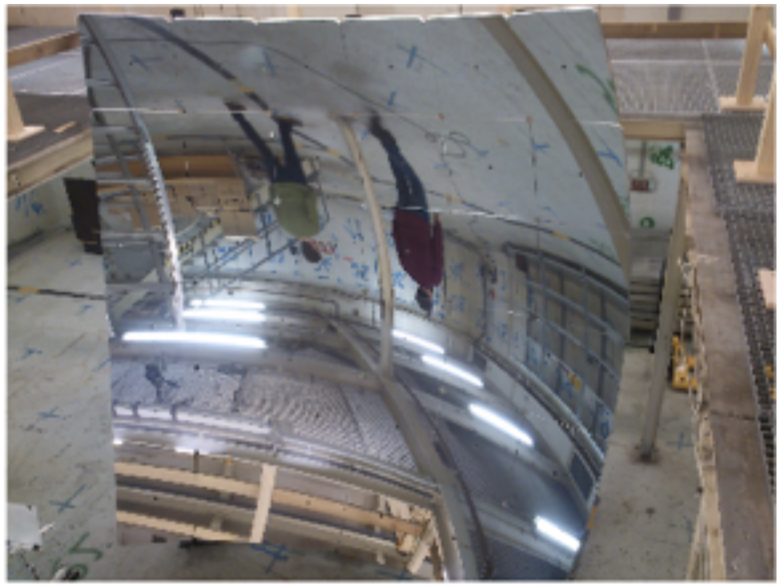
spherical reflecting dish

$$P \sim |\mathbf{E}_a|^2 A$$

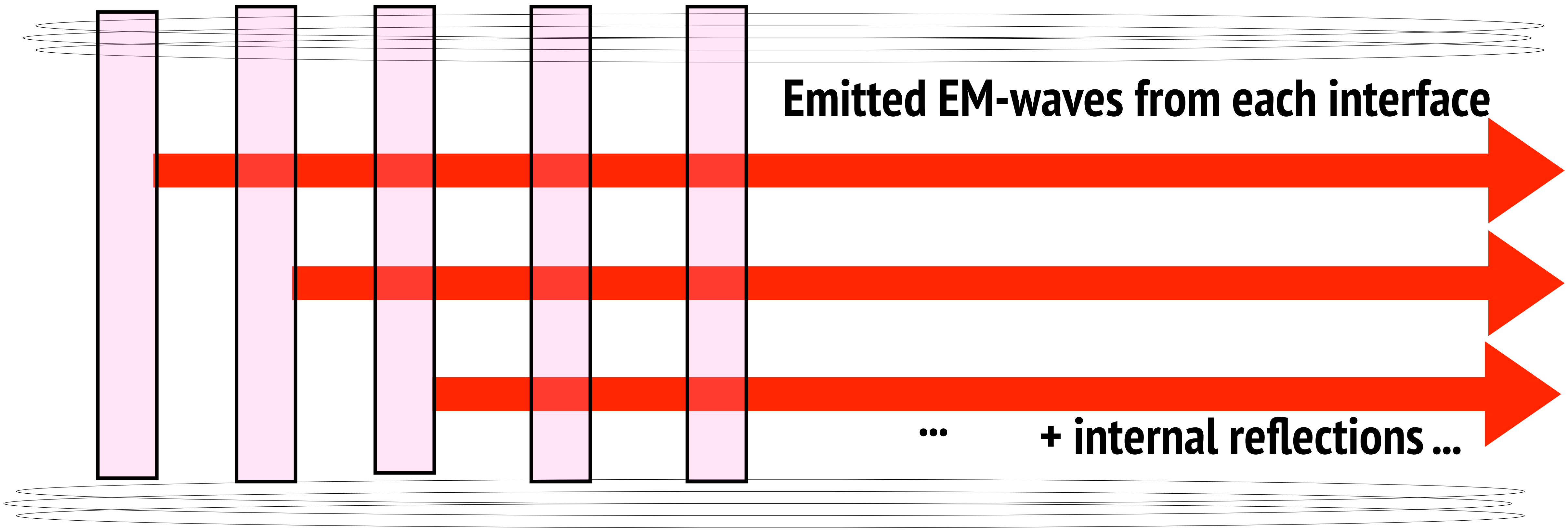
# Dish Antenna



# Many dielectrics : MADMAX at MPP Munich

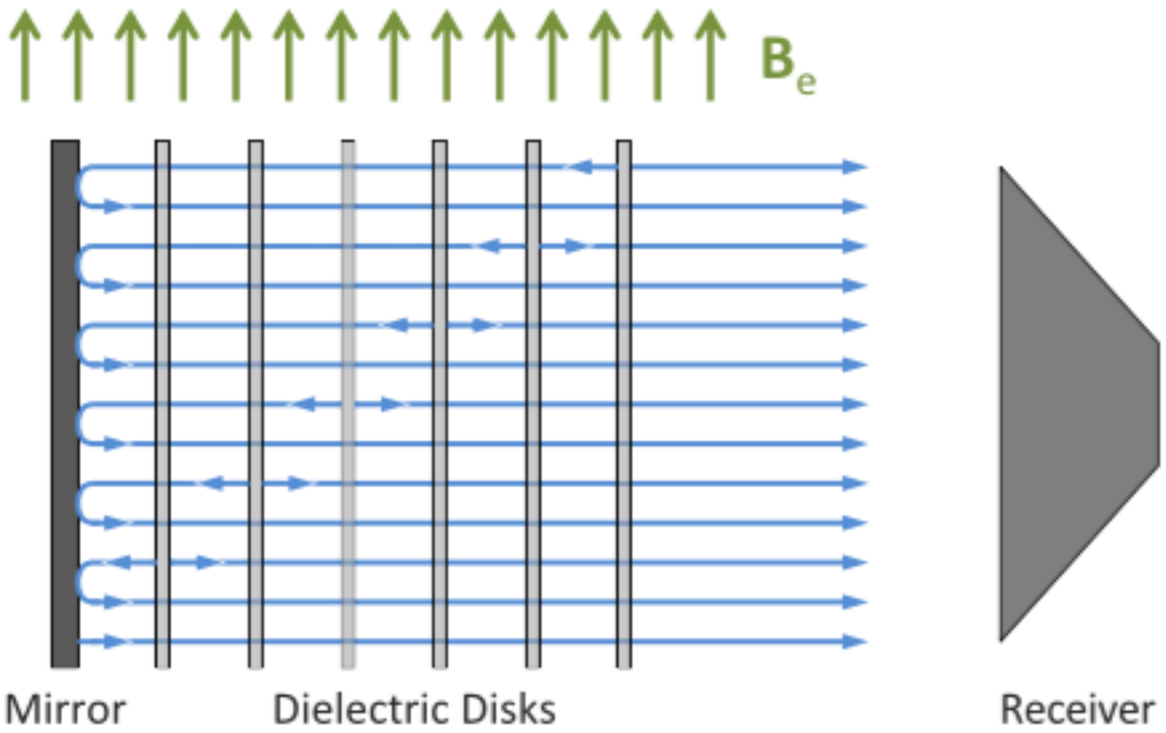



- Emission has large spatial coherence; adjusting plate separation -> coherence

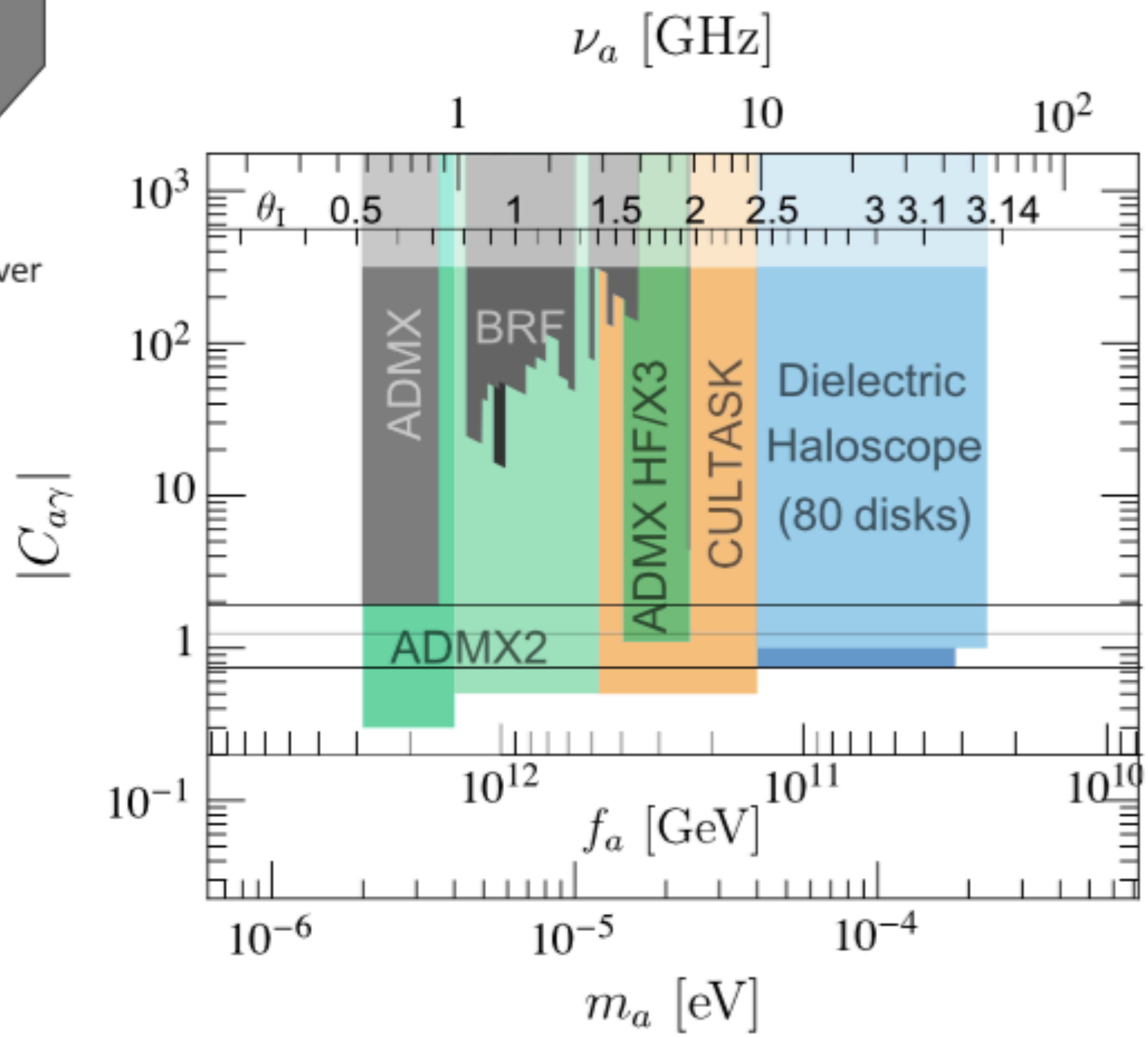
$$\frac{P}{Area} \sim 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left( C_{a\gamma} \frac{B_{||}}{10\mathrm{T}} \right)^2 \times \beta^2(\omega)$$

**boost factor**

# Many dielectrics : MADMAX

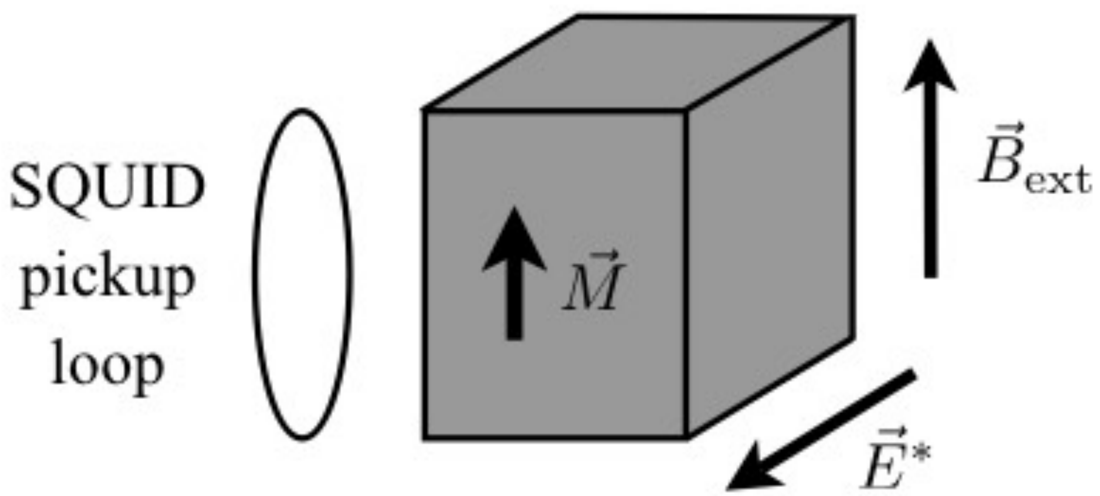


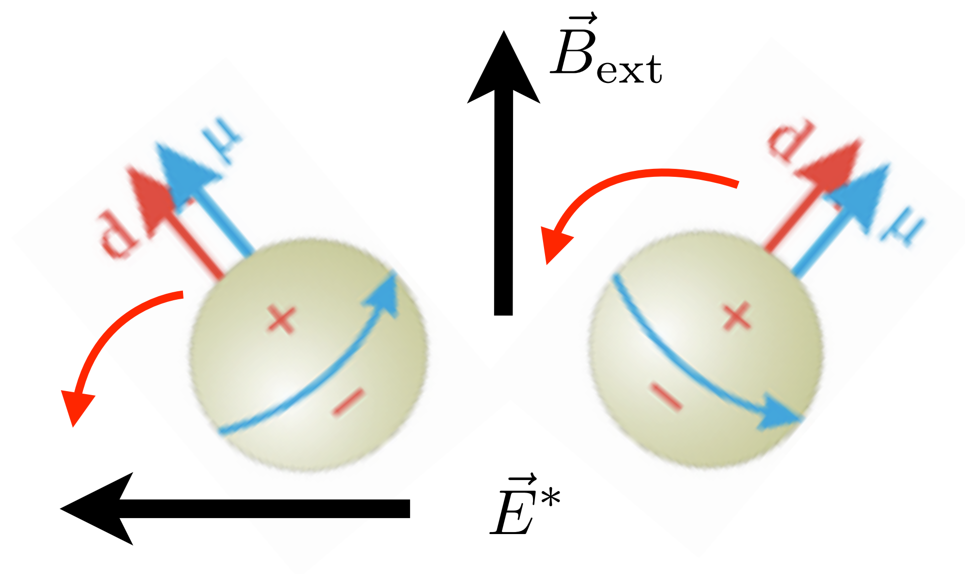

PRL 118, 091801 (2017)



# CASPER : Spin precession

Mainz, Berkeley



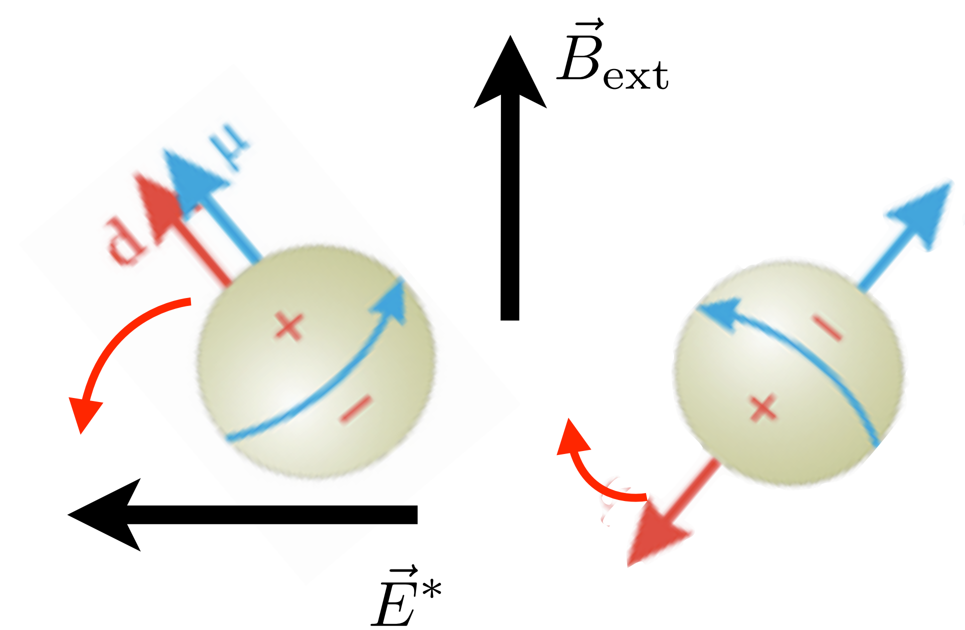




**Static EDM, effects cancel in a period**

magnetic signal $\propto n p \varepsilon_S d E^* T_2$

number density, nuclear spin polarization, Schiff suppression, nuclear spin coherence time

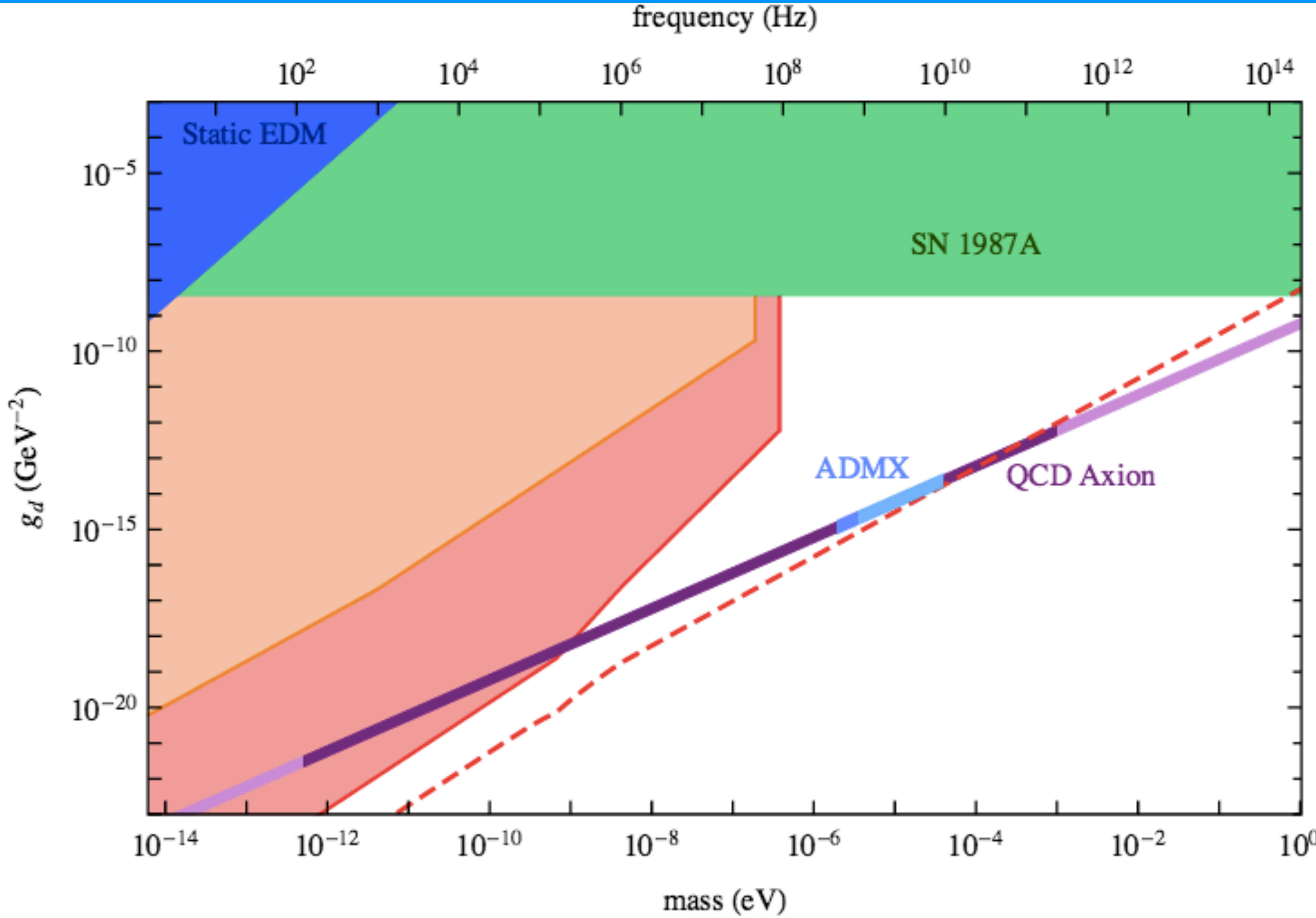
- EDM + Large E-fields in PbTiO3
- Mainz (D. Budker's group) & Berkeley
- B-field, coherence time, sensitivity to m < neV
- Phase I starts in 2016, Phase II physics results
- Mass range limited by B-field strength




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

# CASPER : Spin precession

Mainz, Berkeley

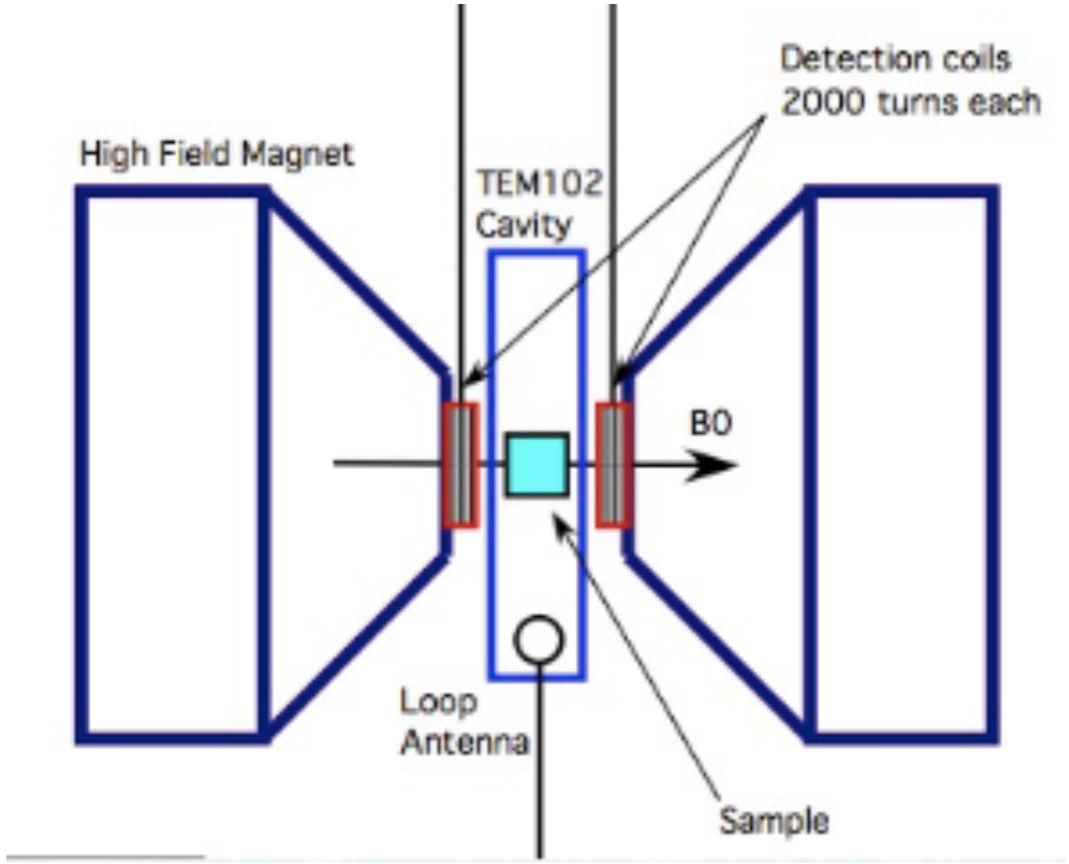


# QUAX : electron Spin precession

INFN, Legnaro

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

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




- Use Electron Spin Resonance (similar to NMR but with electrons) $\omega = \mu_B \vec{B}_{\rm ext} = m_a$
- 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 $\omega \sim \mu_B|\vec{B}_{\rm ext}| - m_a$

# Conclusions

- Ultralight particles can be Dark matter

- Require very different detection techniques

- Coupling to photons mostly exploited

- Oscillating EDMs, Electron Spin couplings getting more important

# Axion experiments (target areas)