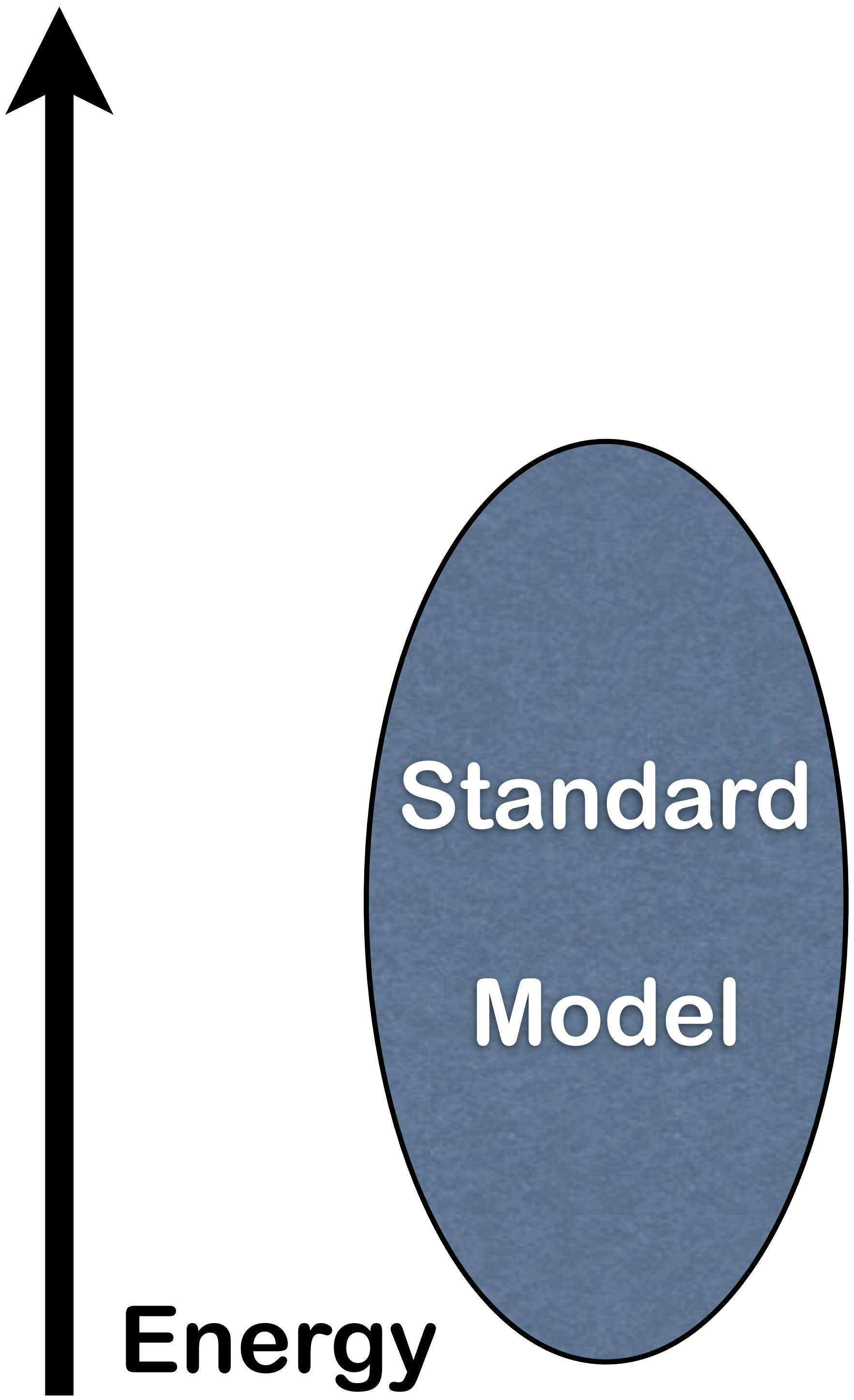
ウイスピダルクマッテル

サビエルレドンド

(LMU/MPP Munich)

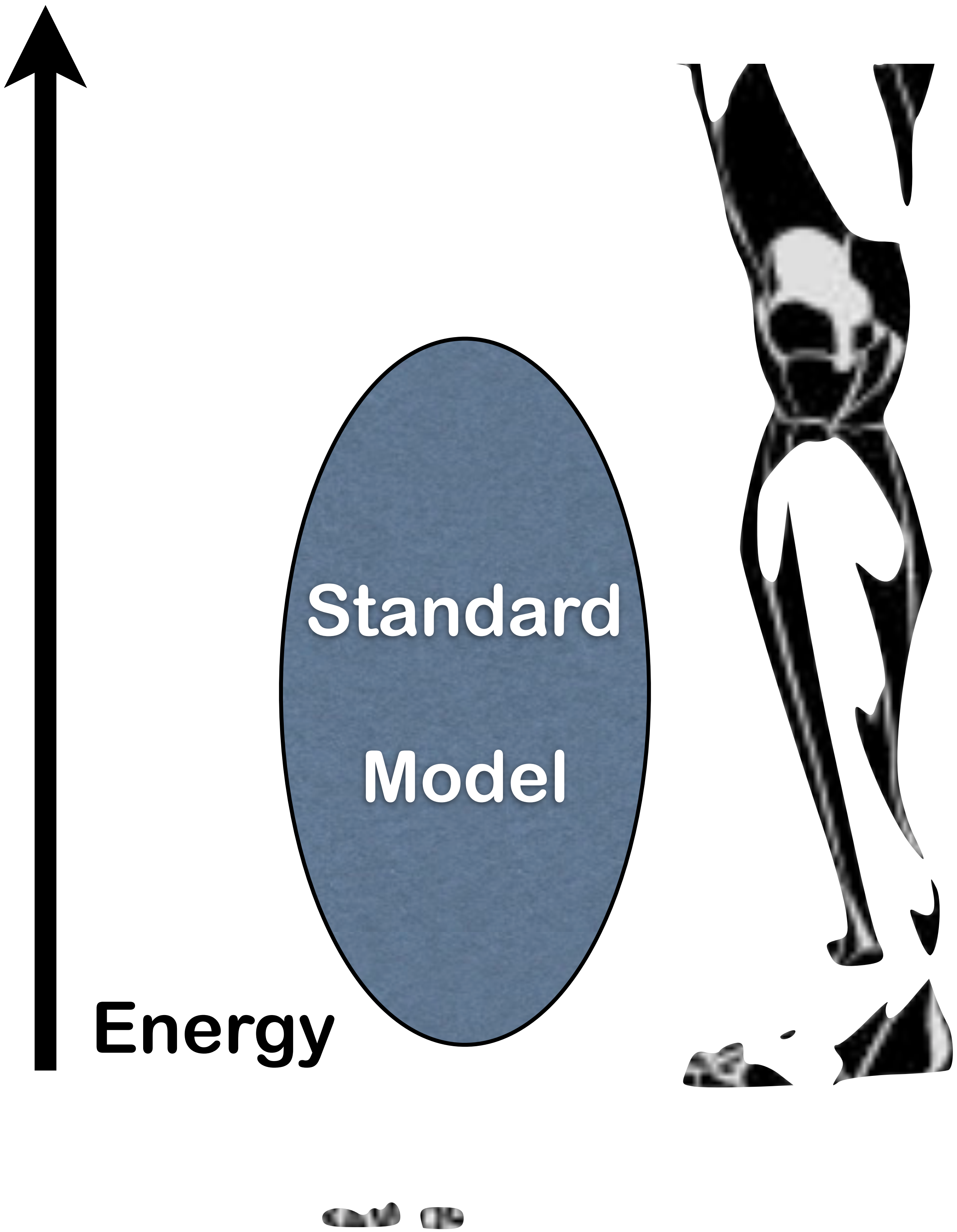
- Invitation
- Axion (and WISPy) dark matter
- Parameter space
- Detecting WISPy DM with photons
- Dish antenna
- Cavities
- Prospects

Beyond the SM ... at low energies



Describes extremely well fundamental physics (at low energies)

Beyond the SM ... at low energies

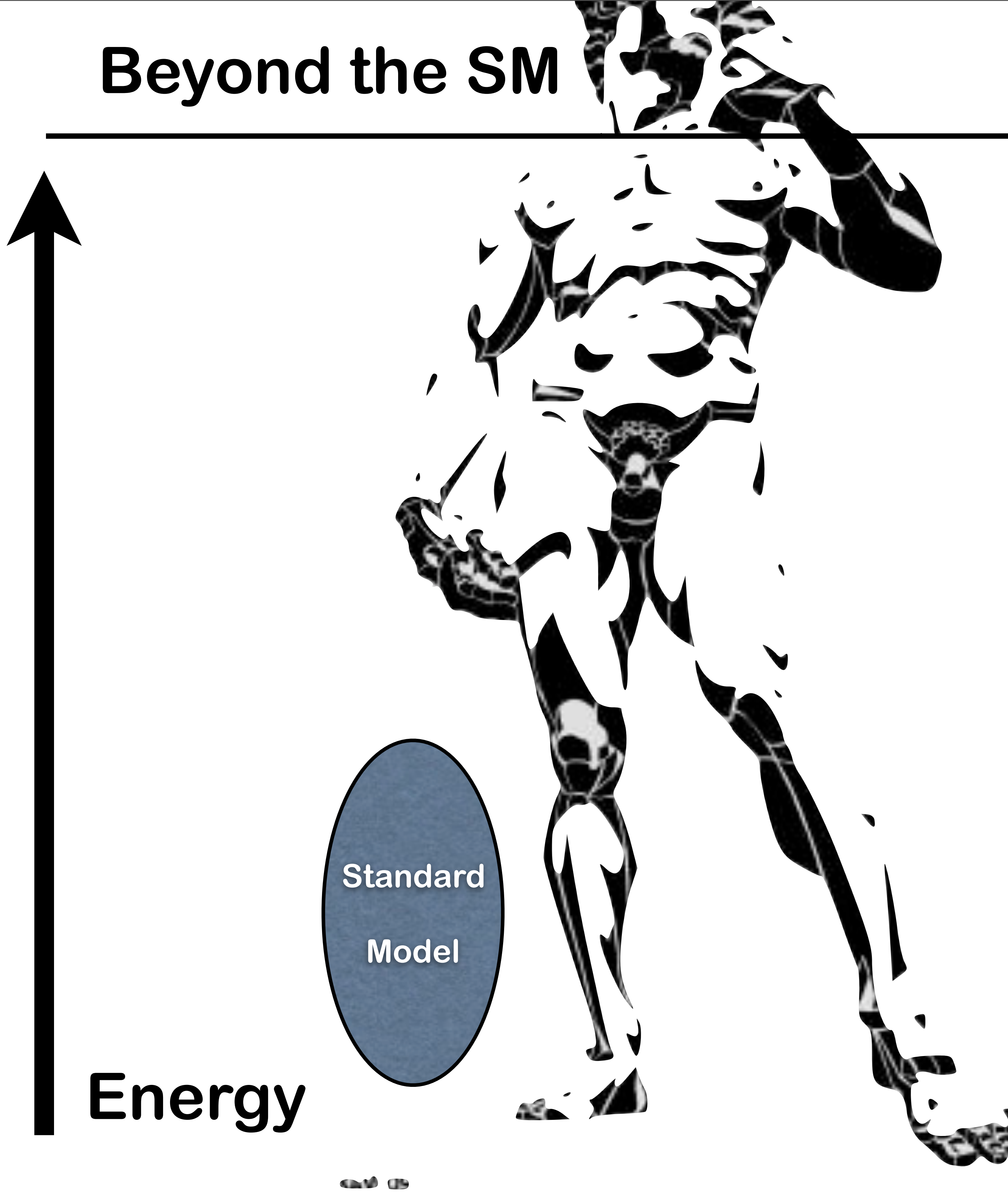


Describes extremely well fundamental physics (at low energies)

but feels certainly

INCOMPLETE

Beyond the SM ... at low energies



Answers are awaiting in the

high energy frontier

where more symmetric beautiful theories arise

... and can imply physics at low energies

Beyond the SM ... at low energies

Axions!

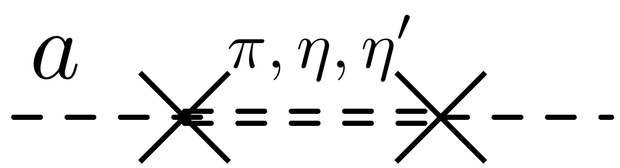
- **Strong CP: Quinn and Peccei solution: new anomalous U(1) symmetry**

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\left(\theta + \frac{a}{f_a}\right)$$

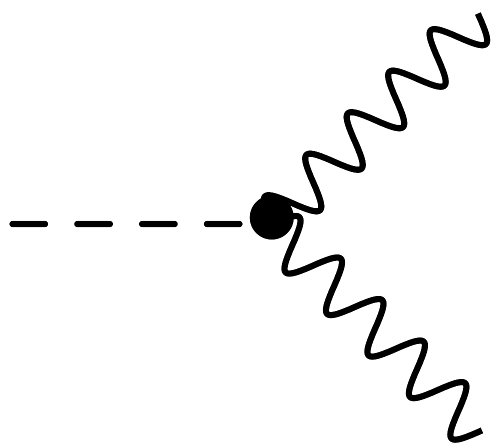
the QCD theta angle is dynamical !!

- **Axions have predictable properties, which depend mostly on** f_a
  (Energy scale at which the U(1) is spontaneously broken)

- **Axion properties**



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

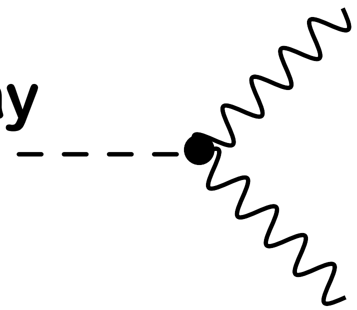


$$\frac{\alpha}{8\pi}(F_{\mu\nu}\widetilde{F}^{\mu\nu})\frac{c_{a\gamma\gamma}}{f_a}$$

$$g_{a\gamma} = c_{a\gamma\gamma}\frac{\alpha}{2\pi f_a}$$

WISP

Axion cold dark matter

- Axions decay  $\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$ **only low mass axions can be DM!**

- THERMAL PRODUCTION $p_{\rm today} \sim T_{\rm today} \sim {\rm meV}$

~~$m_a \sim {\rm eV}$???~~

- NON-THERMAL → $p \sim H \lll T$

$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$

  - initial conditions
  - decay of cosmic strings, domain walls

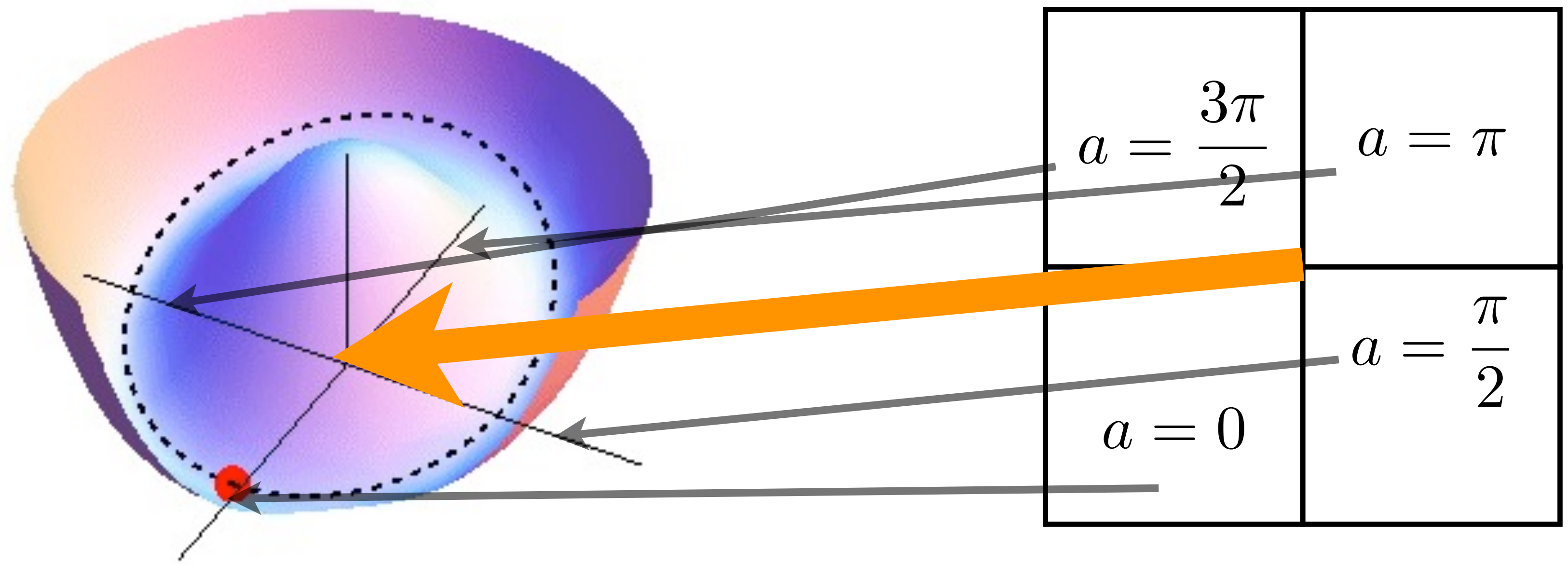
$$\frac{a(t_0)}{f_a} \in (-\pi, \pi)$$

At PQ phase transition

Axion cold dark matter I

Realignment mechanism

(Field space)



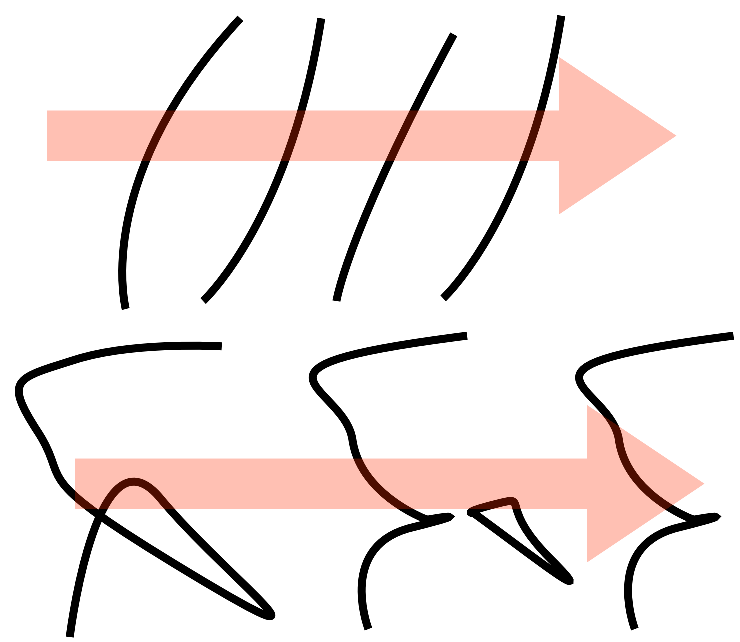
$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$

$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu\mathrm{eV}}{m_a}\right)^{1.184}$$

Cosmic Strings

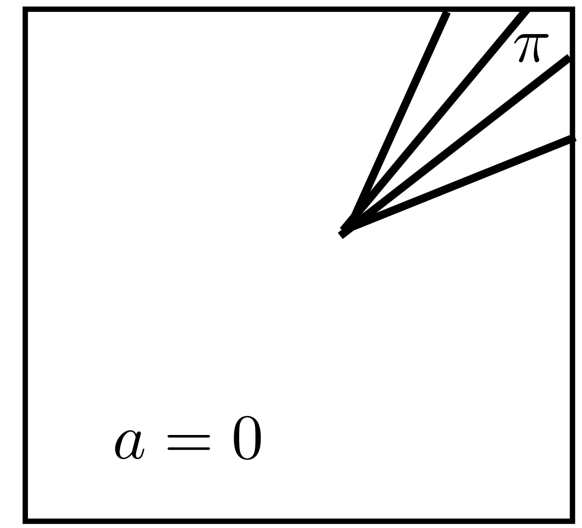
(Position space)

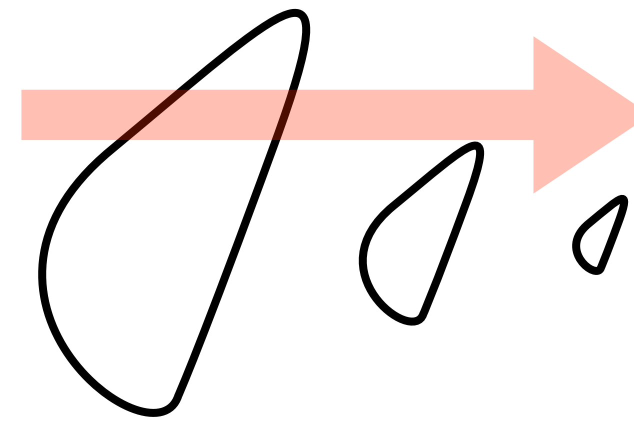
(T>QCD)



Domain Walls

(T<QCD)

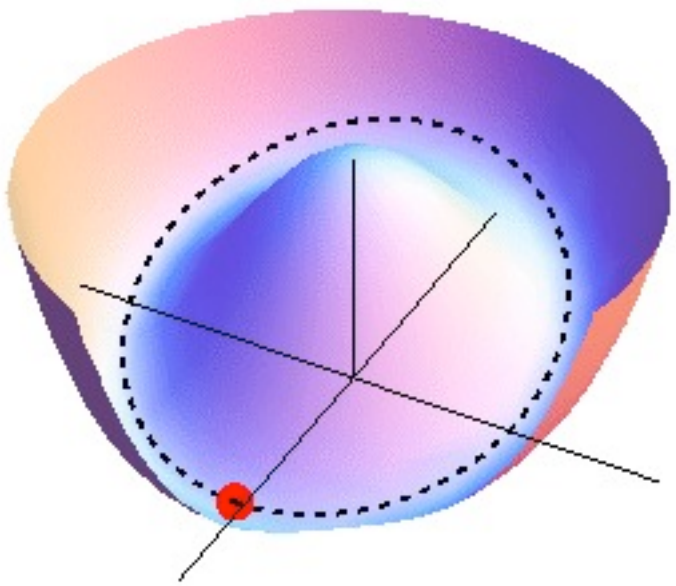




Axion cold dark matter I

Realignment mechanism

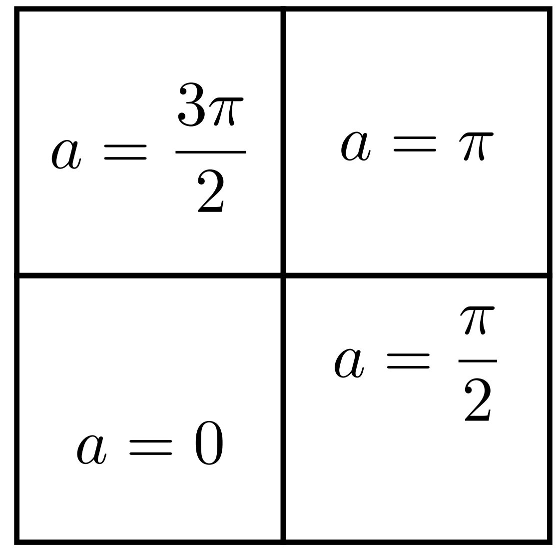
(Field space)



Cosmic Strings

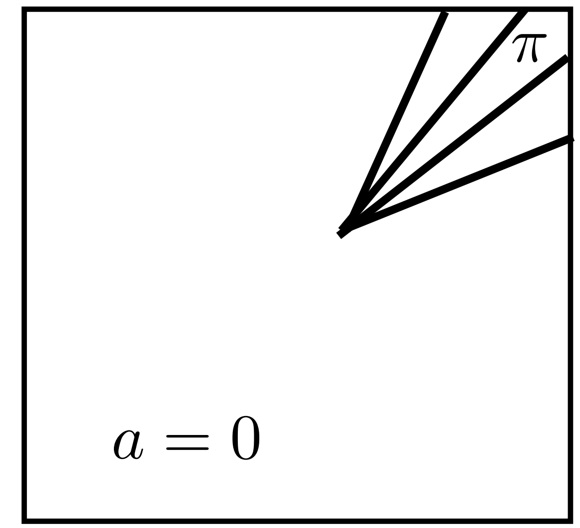
(Position space)

(T>QCD)



Domain Walls

(T<QCD)



$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu\rm eV}{m_a}\right)^{1.184}$$

$$\frac{\Omega_{a,DW+ST}}{\Omega_{\rm obs}} \begin{cases} \sim \left(\frac{40\mu\rm eV}{m_a}\right)^{1.184} \\ \sim \left(\frac{400\mu\rm eV}{m_a}\right)^{1.184} \end{cases}$$

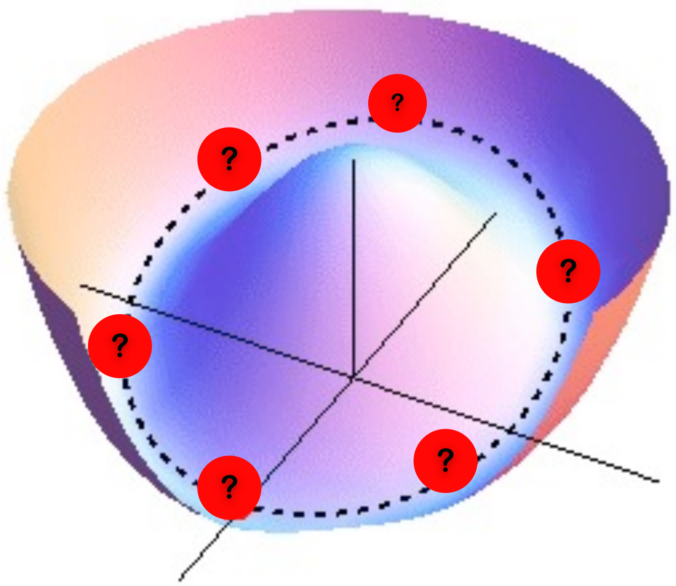
Sikivie, Harari et at.

Shellard, Davis et at.
Kawasaki, Hiramatsu et at

Axion cold dark matter II (PQ before inflation)

Realignment mechanism

(Field space)



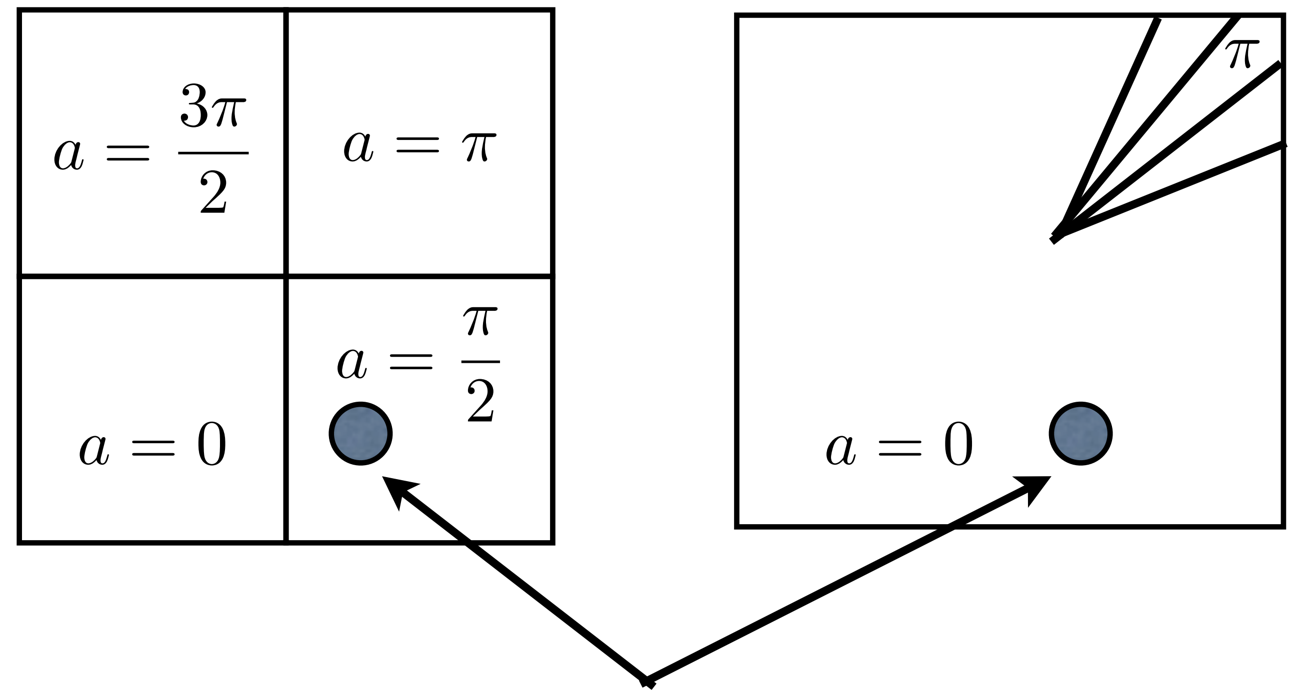
Cosmic Strings

(Position space)

(T>QCD)

Domain Walls

(T<QCD)



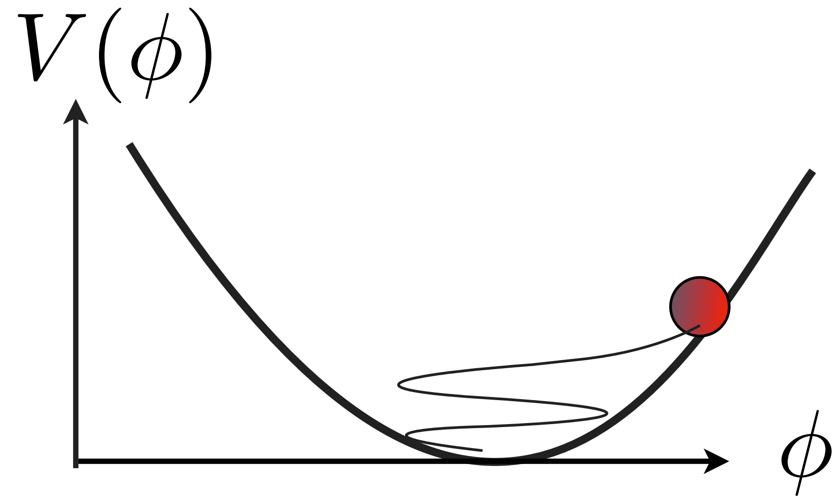
$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{40\mu{\rm eV}}{m_a}\right)^{1.184}$$

Size of our universe after inflation fits inside one of these domains

- CSs and DWs are diluted by expansion

- Whole universe has 1 initial value for a

Relic abundance of WISPy Dark matter (realignment)



$$\rho_{a,0} \simeq 1.2\,\frac{\mathrm{keV}}{\mathrm{cm}^3} \times \sqrt{\frac{m_\phi}{\mathrm{eV}}}\left(\frac{\phi_{\mathrm{initial}}}{4.8\times 10^{11}\,\mathrm{GeV}}\right)^2 \mathcal{F},$$

recall $\rho_{\mathrm{CDM}} = 1.2\frac{\mathrm{keV}}{\mathrm{cm}^3}$

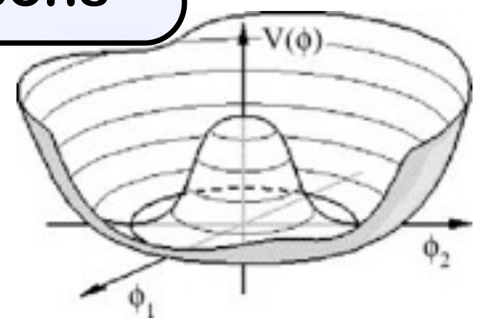
- **Initial amplitude, physics at <u>very high energies</u>**
- **WISPy DM opens a window to HEP**

Weakly interacting slim particles

Axion-like particles (ALPs) 0^{-}

pseudo Goldstone bosons

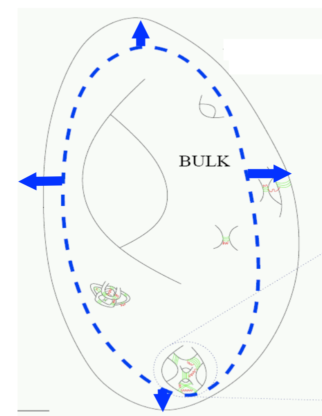
Global continuous symmetry
spontaneously broken at
high energy scale f



$\pi^0 \; \eta' \; \eta \; a$ MAJORONS R-AXION FAMILONS

String 'axions'

Sizes and deformations of
extra dimensions,
gauge couplings

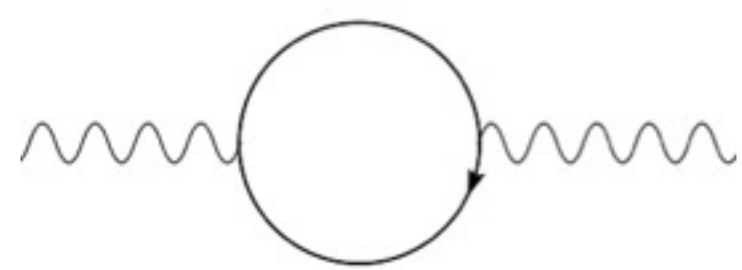


DILATONS RADION
MODULI

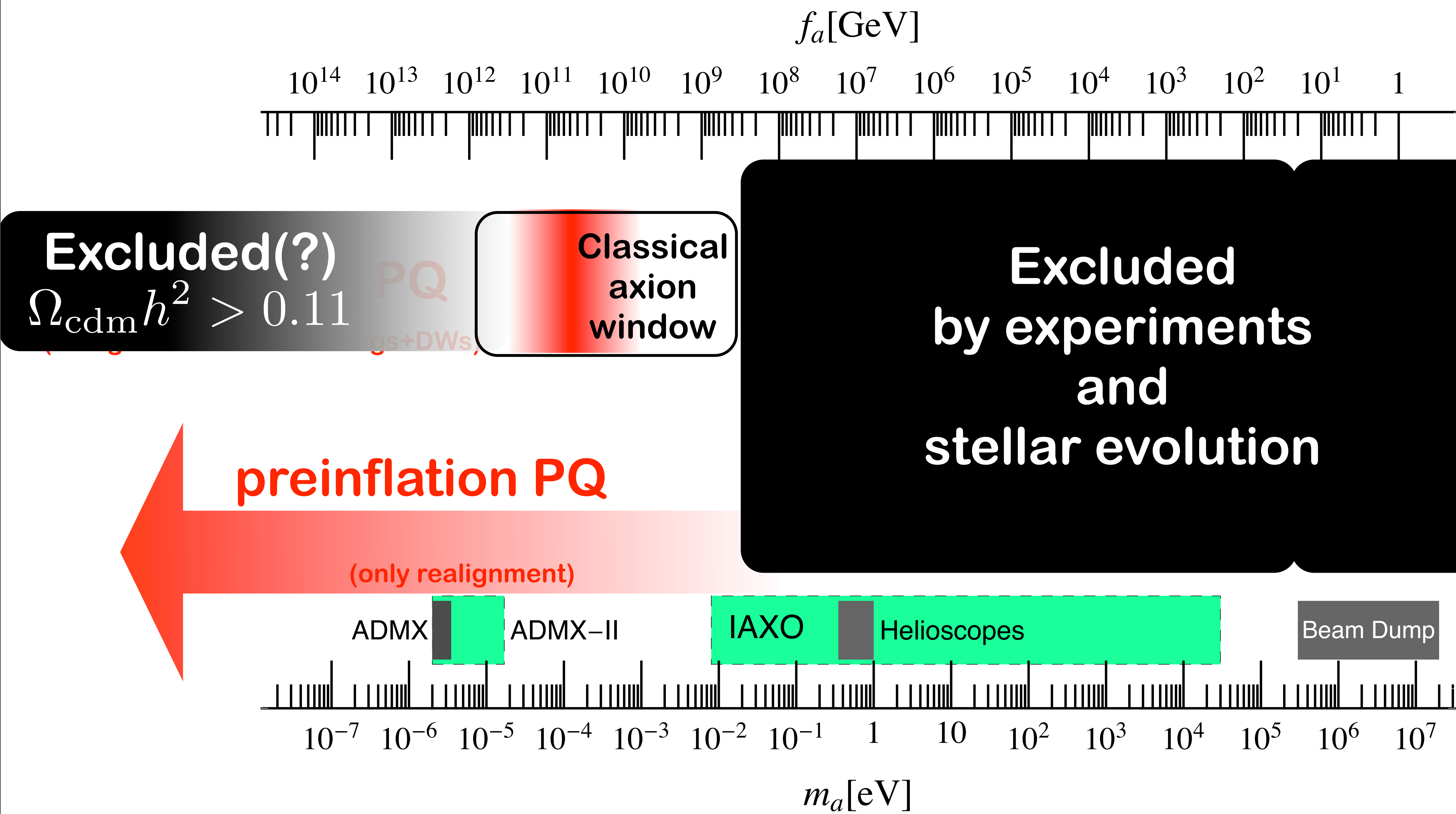
Hidden gauge bosons

Hidden (Dark) Photons, paraphotons

- Extra U(1) factors ubiquitous in string theory
- Hidden sectors required sor SUSY breaking
- Stueckelberg or Higgs masses ...

γ  γ'

bounds and prospects



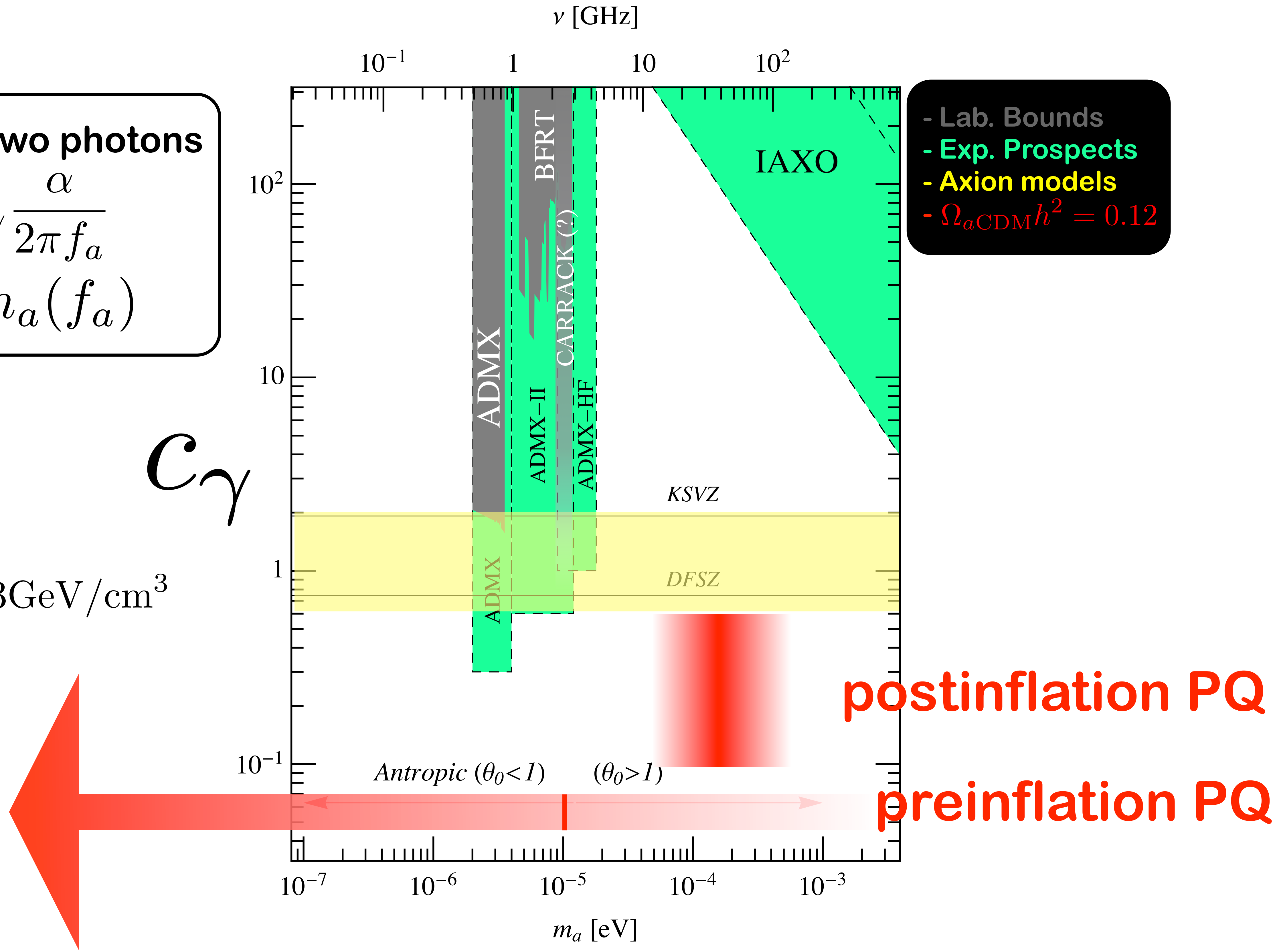
bounds and prospects

coupling to two photons

$$g_{a\gamma} = c_\gamma \frac{\alpha}{2\pi f_a}$$

$$m_a = m_a(f_a)$$

$$\rho_{\rm CDM} = 0.3 {\rm GeV/cm^3}$$



General Axion-like particles (ALPs)

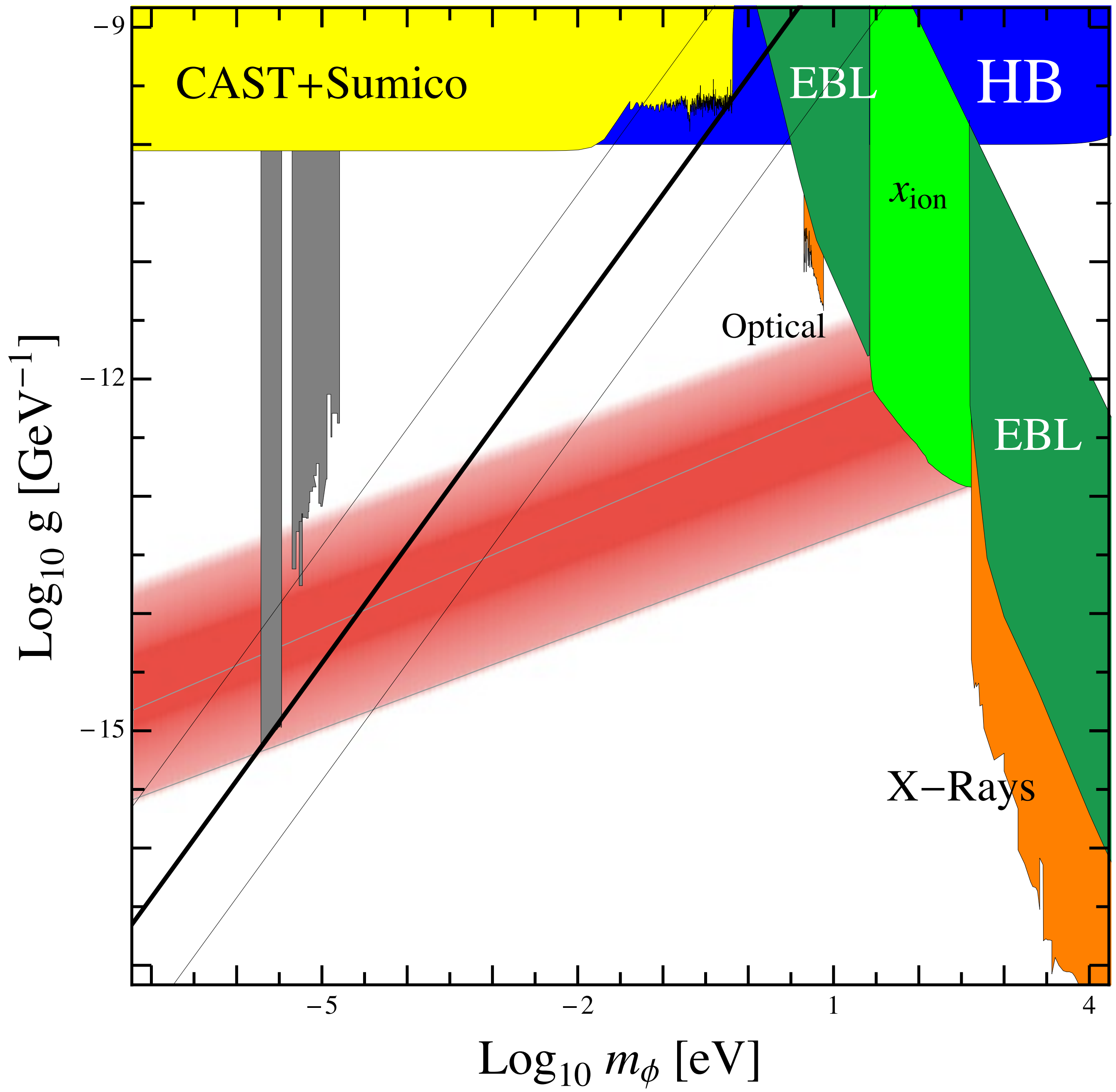
- Mass and coupling unrelated

$$g = \frac{\alpha}{2\pi f_a} \times O(1)$$

- Scenario 1

$$f_a < H_I$$

(realignment+cosmic strings, DWs..)



General Axion-like particles (ALPs)

- Mass and coupling unrelated

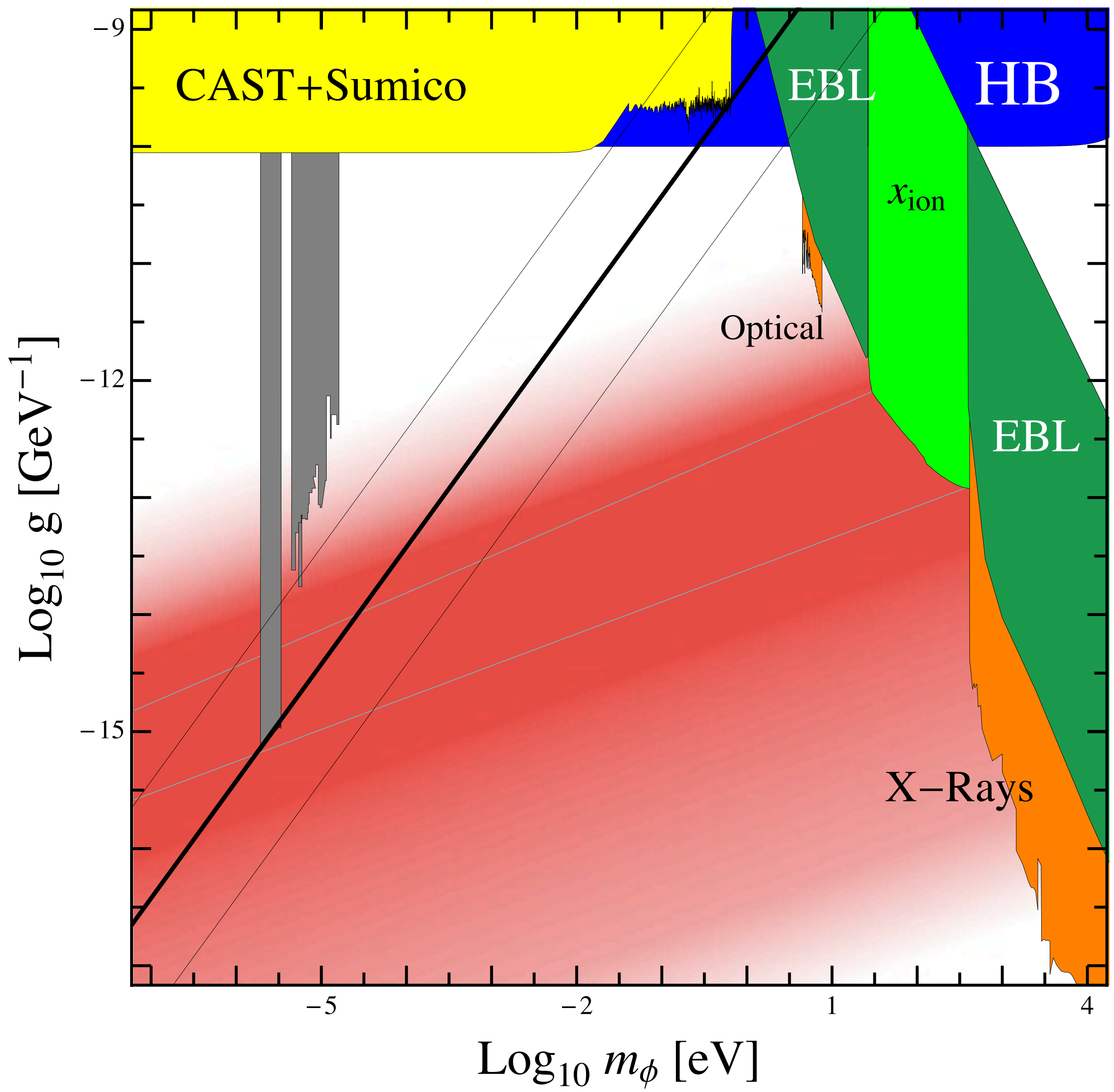
$$g = \frac{\alpha}{2\pi f_a} \times O(1)$$

- Scenario 2

$$f_a > H_I$$

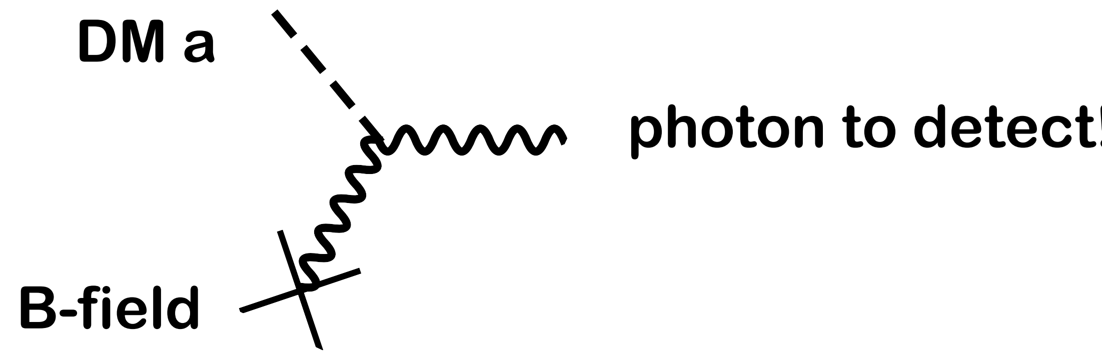
(realignment mechanism)

- Isocurvature constraints!!

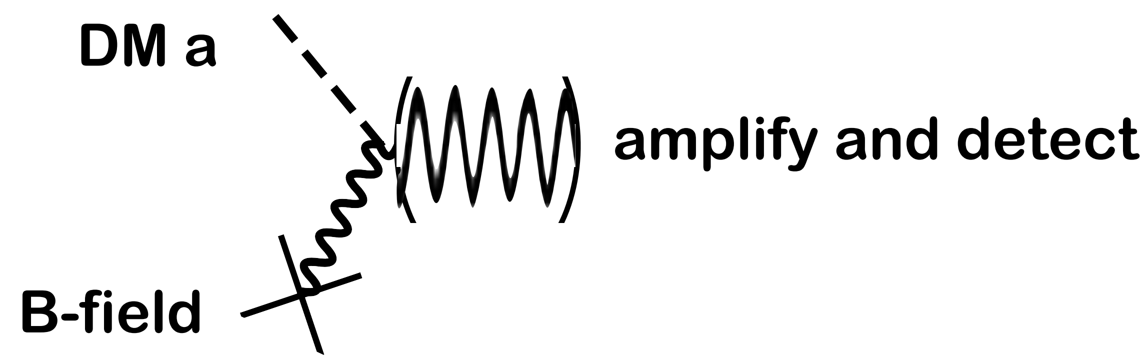


Experiments to detect axion DM

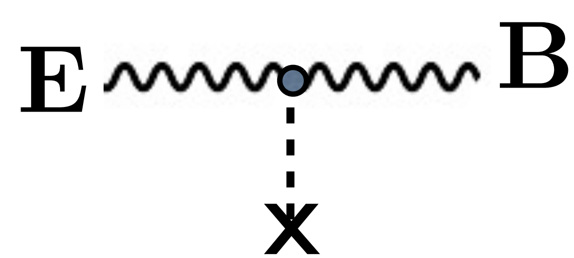
- Dish antenna



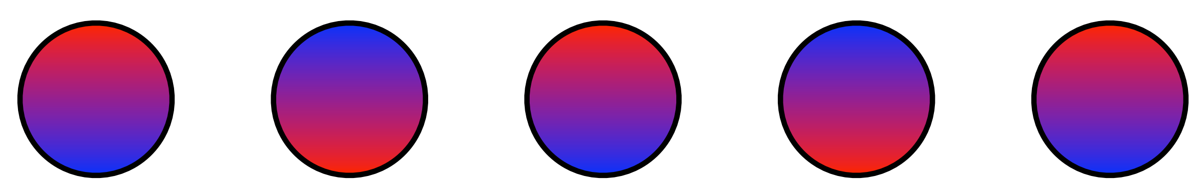
- Cavity experiments



- Light propagation



- Oscillating EDM



Wispy dark matter around

density

$$\rho_{\rm CDM} \simeq 0.3 \frac{\rm GeV}{\rm cm^3} = m_a n_a$$

velocities in the galaxy

$$v \lesssim 300 \ {\rm km/s} \sim 10^{-3} c$$

phase space density

$$\frac{n_a}{\frac{4\pi p^3}{3}} \sim 10^{29} \left(\frac{\mu{\rm eV}}{m_a}\right)^4$$

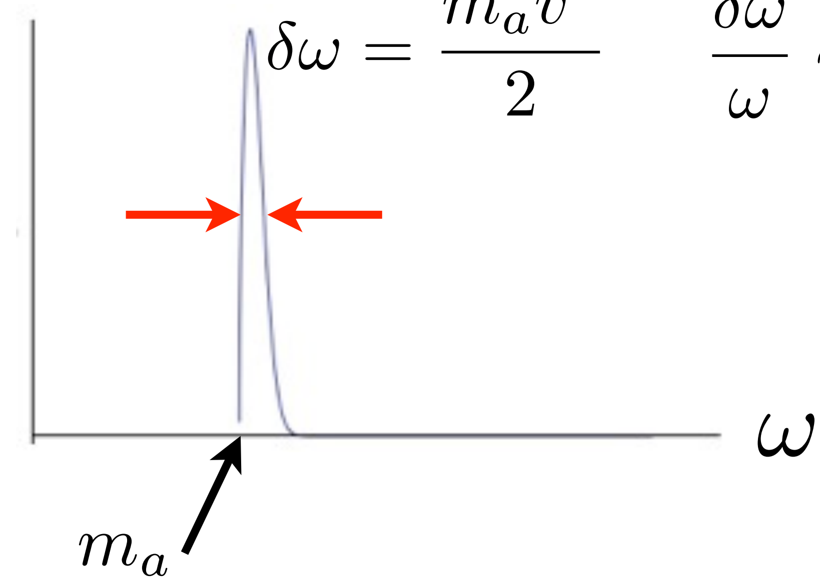
occupation number is HUGE!

→ **behaves classically**

Fourier-transform $a(x)$

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

$$\delta\omega = \frac{m_a v^2}{2} \qquad \frac{\delta\omega}{\omega} \sim 10^{-6}$$



Axion - photon mixing in a magnetic field

Raffelt, PRD'88

- In a magnetic field one photon polarization Q-mixes with the axion

$$\mathcal{L}_I = \frac{g_{a\gamma}}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} a = -g_{a\gamma} \mathbf{B} \cdot \mathbf{E}\, a$$

Not axions, nor photons are propagation eigenstates!

Axion - photon mixing in a magnetic field

Raffelt, PRD'88

- **Equations of motion for a plane wave** $\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} \exp(-i(\omega t - kz)).$

$$\left[(\omega^2 - k^2)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & -g_{a\gamma}|\mathbf{B}|\omega \\ -g_{a\gamma}|\mathbf{B}|\omega & m_a^2 \end{pmatrix}\right]\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}.$$

axion mixes with A-component PARALLEL to the external B-field

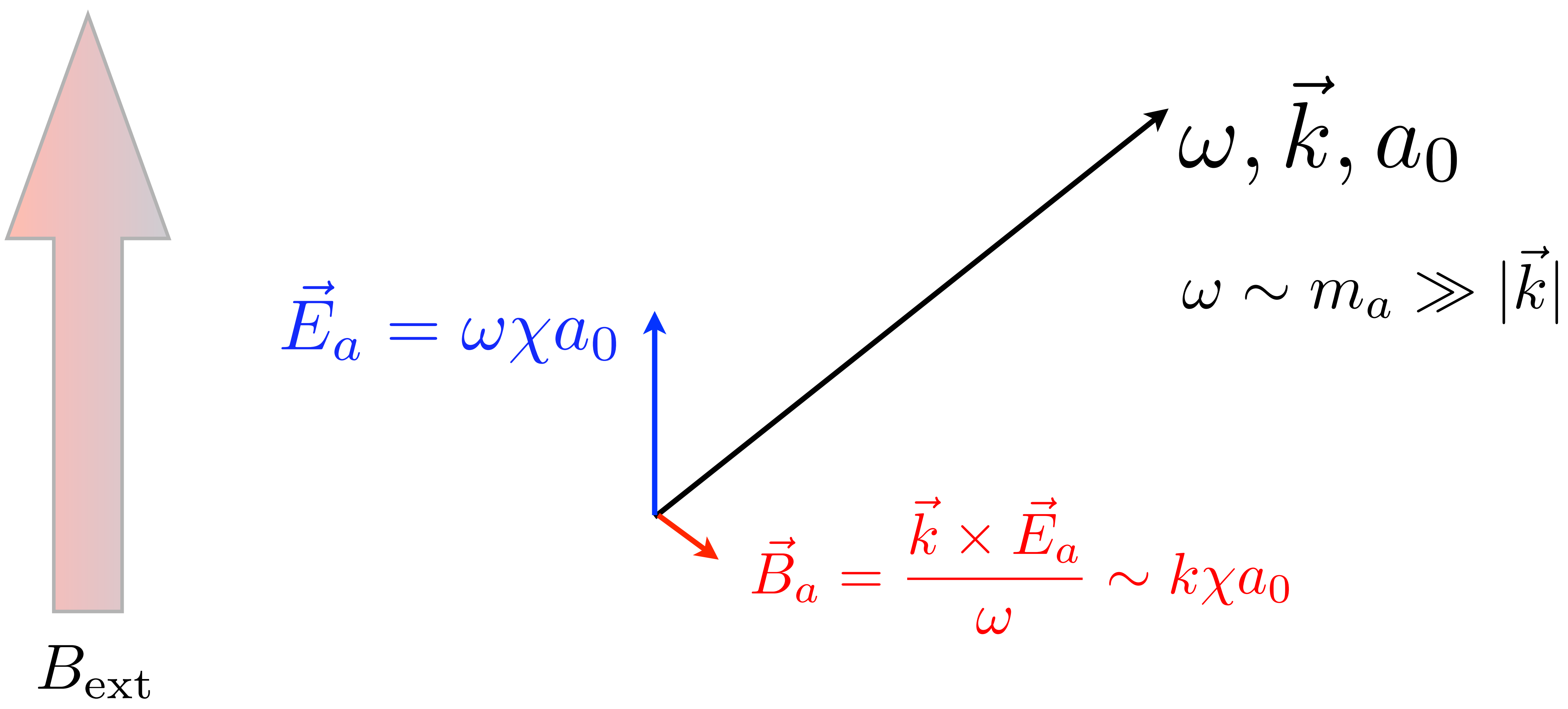
- **"Dark matter" solution** $v = \frac{k}{\omega} \quad ; \quad \omega \simeq m_a(1 + v^2/2 + ...)$

$$\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix}\Bigg|_{\rm DM} \propto \begin{pmatrix} -\chi_a \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

It has a small E field!

$$\chi_a \sim \frac{g_{a\gamma}|\mathbf{B}|}{m_a}$$

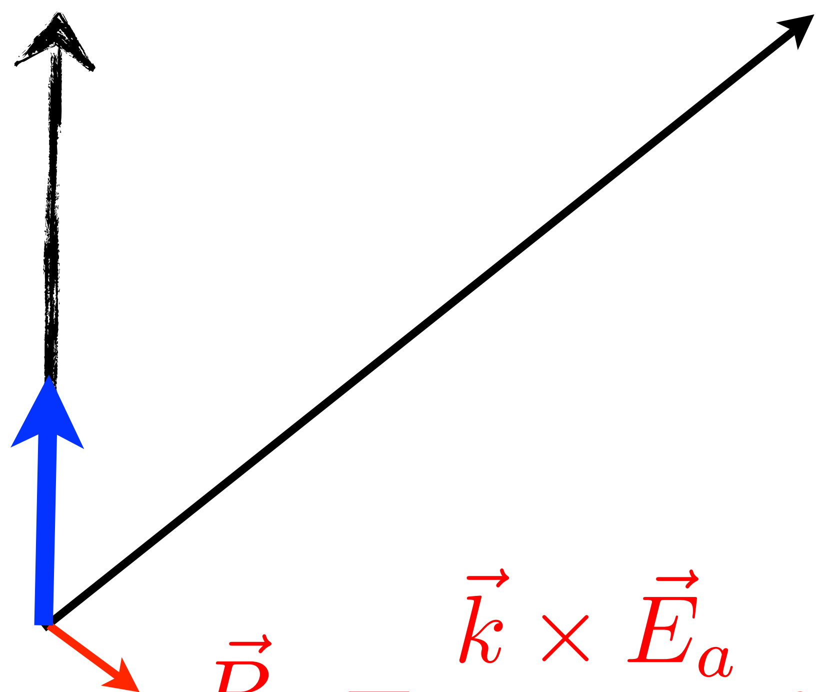
DM axions in a magnetic field



hidden photons ~~in a magnetic field~~

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

$\vec{E}' = \omega\vec{A}'$



$\omega, \vec{k}, \vec{A}'$

$\omega \sim m_a \gg |\vec{k}|$

$\vec{E}_a = \omega\chi\vec{A}'$

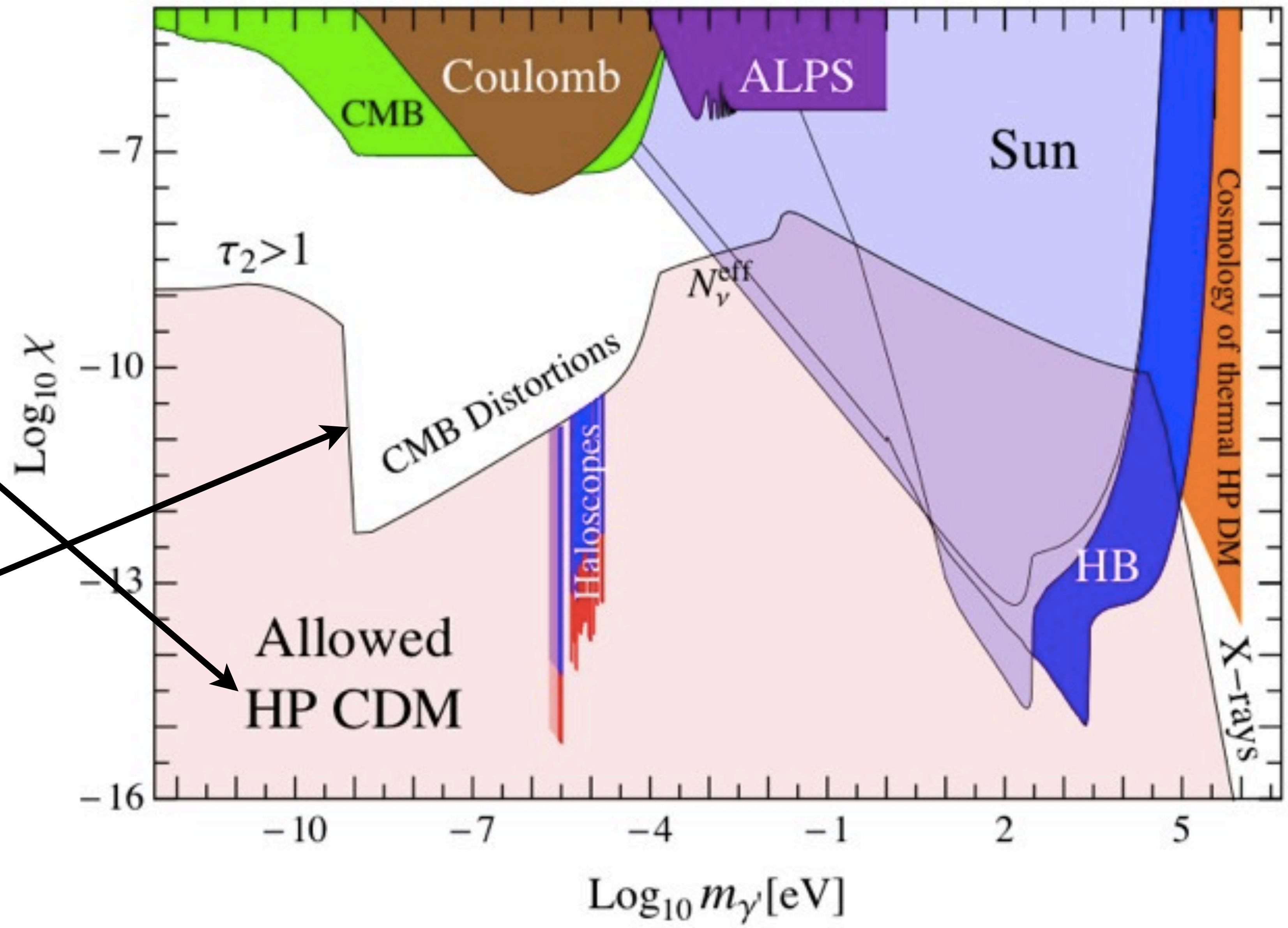
$$\vec{B}_a = \frac{\vec{k}\times\vec{E}_a}{\omega} \sim \mathcal{O}(k\chi A')$$

hidden photon parameter space

- initial condition not related with mixing

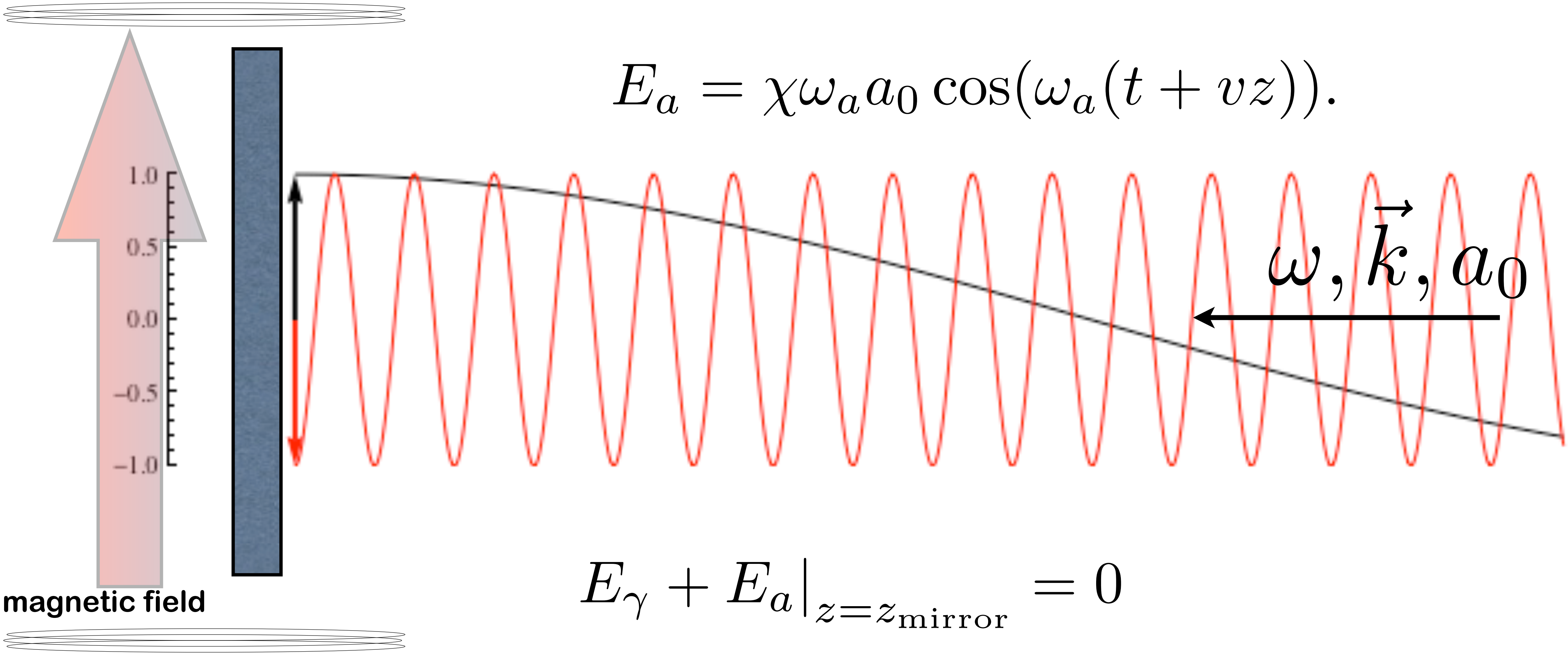
- broader parameter space

- constraints from DM oscillations into photons



Radiation from a magnetised mirror

Horns at al JCAP04(2013)016



$$E_a = \chi \omega_a a_0 \cos(\omega_a (t + vz)).$$

$$E_\gamma + E_a|_{z=z_{\mathrm{mirror}}} = 0$$

Radiated photon wave

$$E_\gamma = -\chi \omega_a a_0 \cos(\omega_\gamma (t - z)).$$

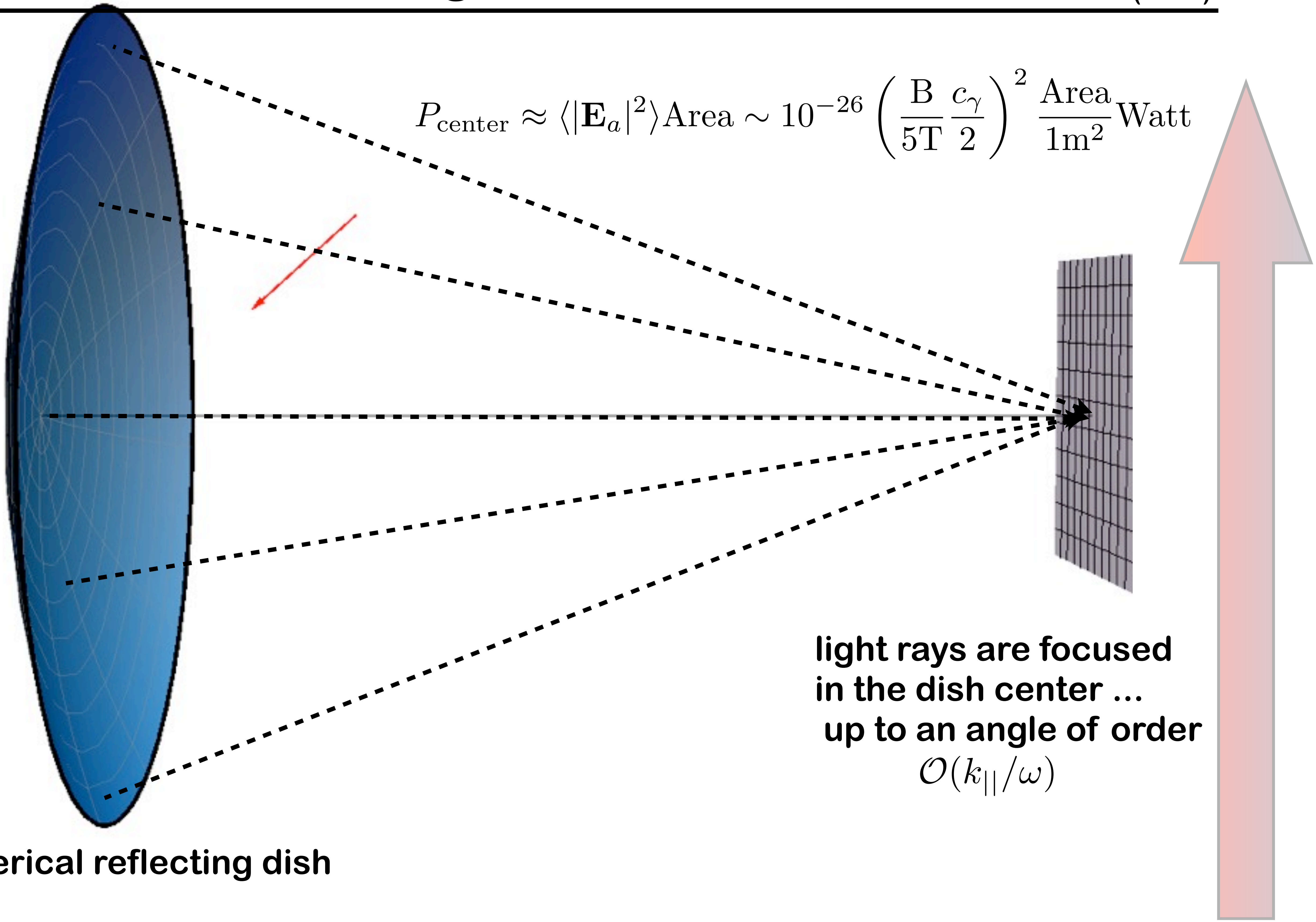
whose frequency is

$$\omega_\gamma = \omega_a = m_a(1 + v^2/2)$$

Radiation from a magnetised mirror

Horns at al JCAP04(2013)016

$$P_{\text{center}} \approx \langle |\mathbf{E}_a|^2 \rangle \text{Area} \sim 10^{-26} \left(\frac{\text{B}}{5\text{T}} \frac{c_\gamma}{2} \right)^2 \frac{\text{Area}}{1\text{m}^2} \text{Watt}$$



light rays are focused in the dish center ... up to an angle of order $\mathcal{O}(k_{||}/\omega)$

spherical reflecting dish

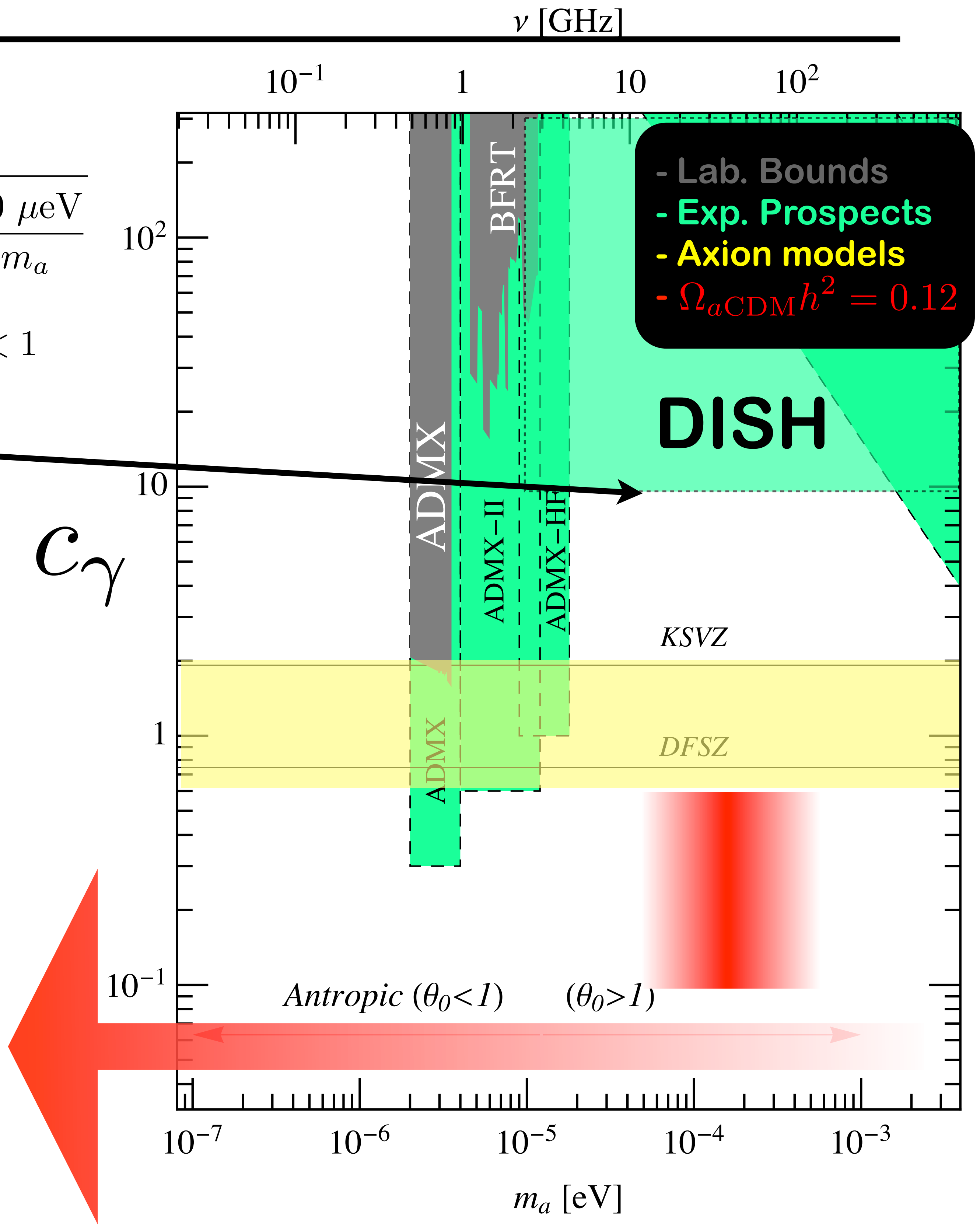
Reach

Signal to noise

$$\frac{S}{N} = 3\times 10^{-2}\,\frac{5\mathrm{K}}{T_S}\,\frac{\mathrm{Area}}{10\ \mathrm{m}^2}\left(\frac{B}{5\ \mathrm{T}}\,\frac{c_\gamma}{2}\right)^2\sqrt{\frac{\mathrm{time}}{1\ \mathrm{year}}\,\frac{10^{-6}}{\Delta\omega/\omega}\,\frac{10\ \mu\mathrm{eV}}{m_a}}$$

diffraction $m_a R \ll 1$

- **A=10 m2**
- **B=5 T**
- **T_{noise}=5K**
- **Detectors every 1/8 in frequency**



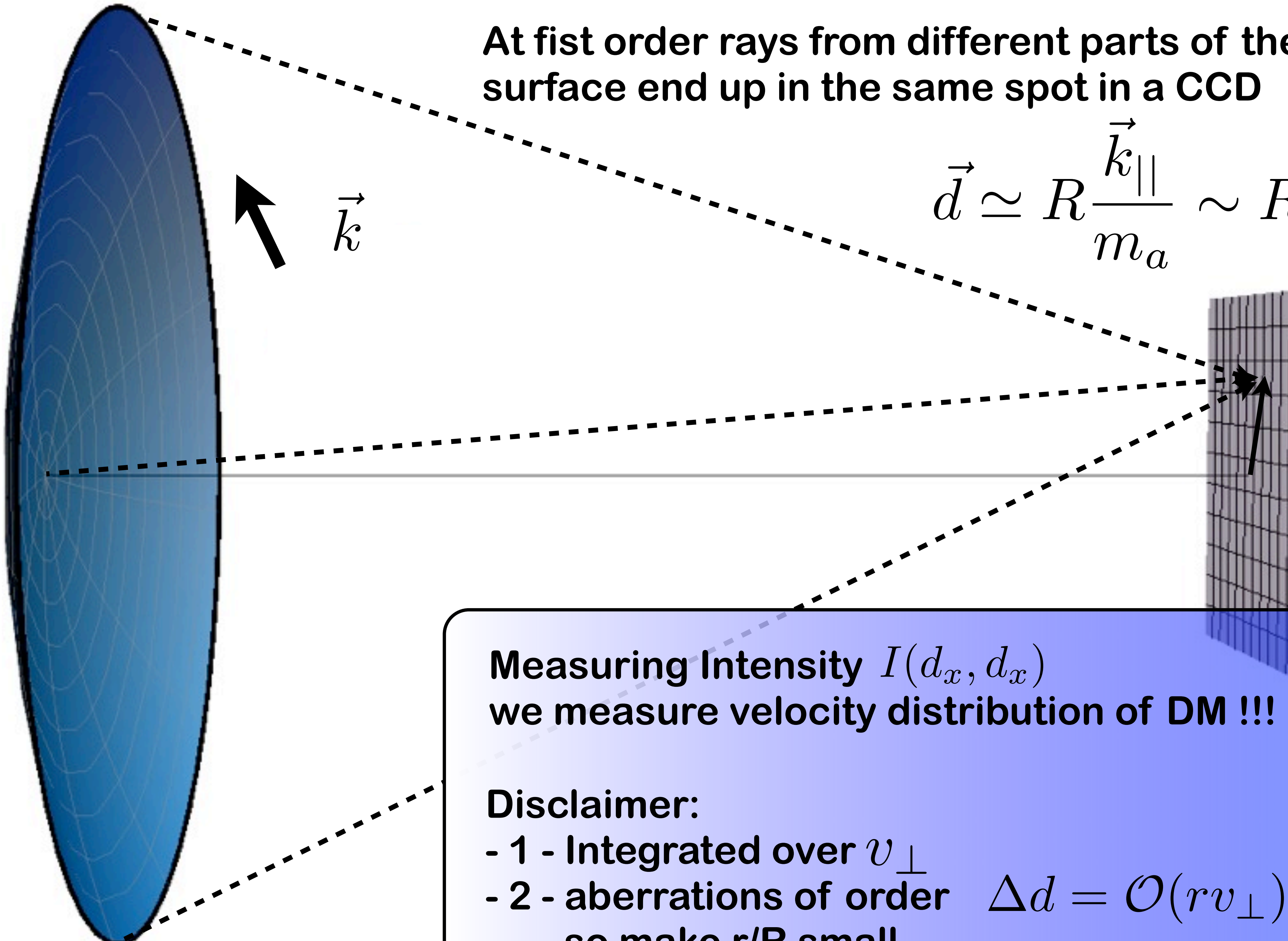
-need more area?
-more B?
-less noise?
-more time?
-up-fluctuation in the DM density?

Detecting the velocity distribution!

Jaeckel and JR, arXiv:1307.7181

At fist order rays from different parts of the surface end up in the same spot in a CCD

$$\vec{d} \simeq R\frac{\vec{k}_{||}}{m_a} \sim R\vec{v}_{||}$$

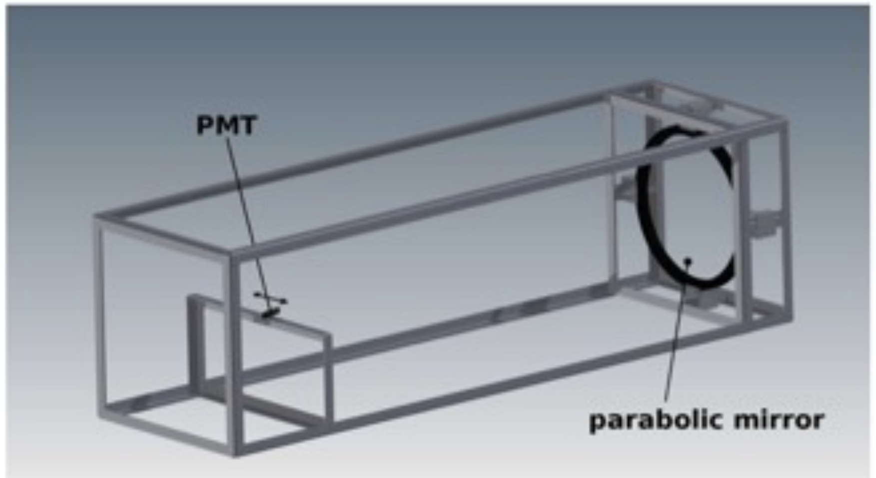


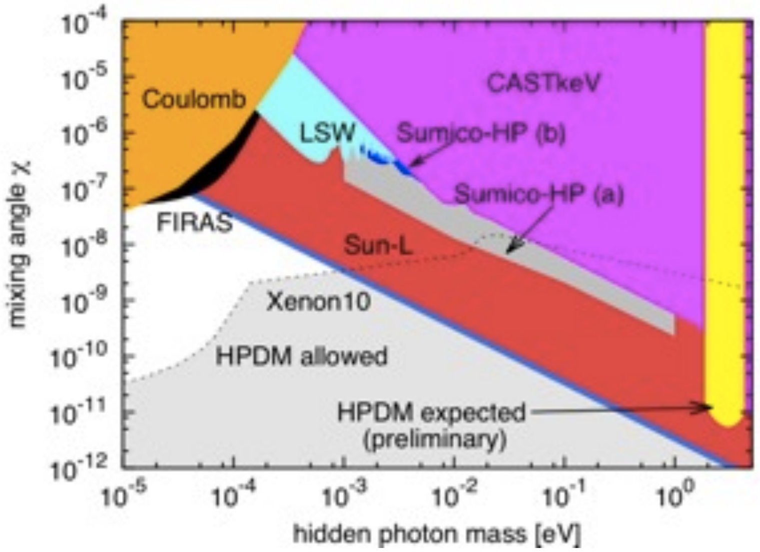
Measuring Intensity $I(d_x, d_x)$
we measure velocity distribution of DM !!!

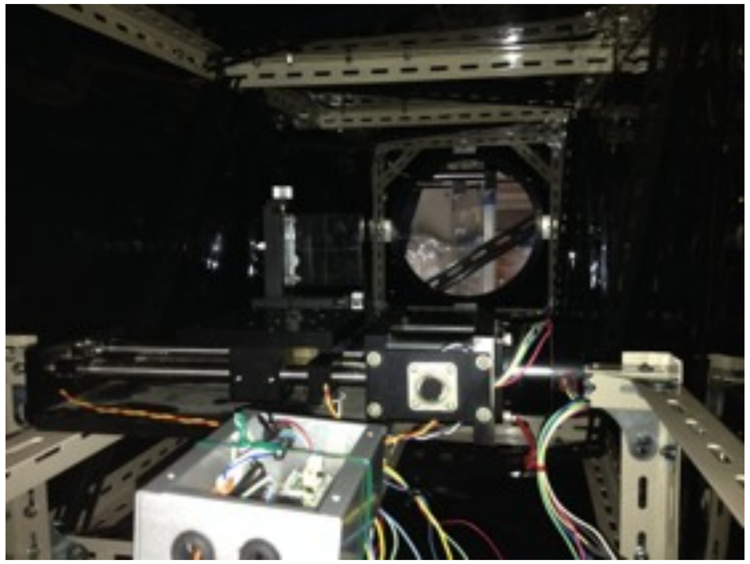
Disclaimer:
- 1 - Integrated over $v_\perp$
- 2 - aberrations of order $\Delta d = \mathcal{O}(rv_\perp)$
  so make r/R small

First moves in the visible

- Tokyo U. (moving to the MW)





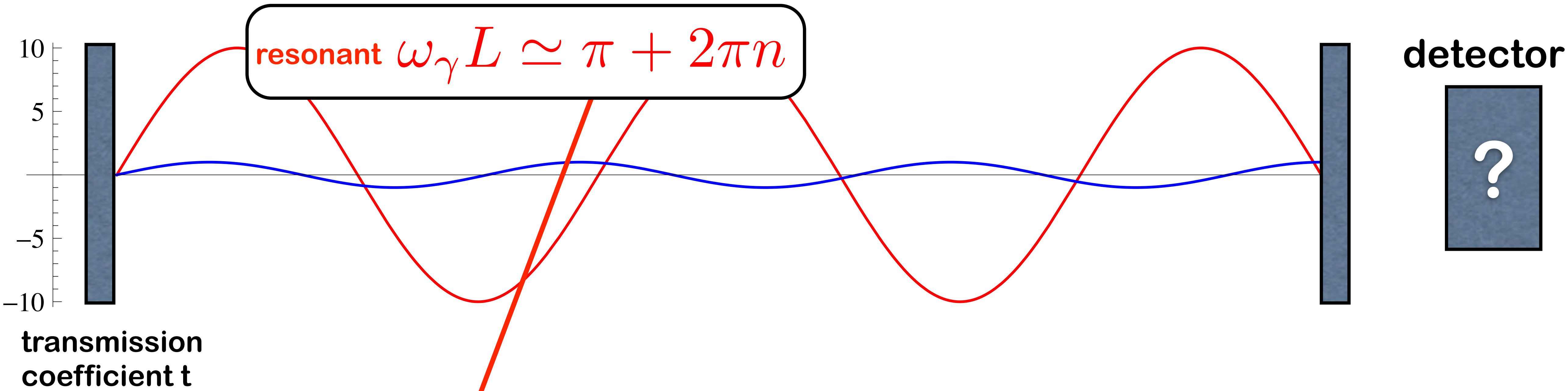


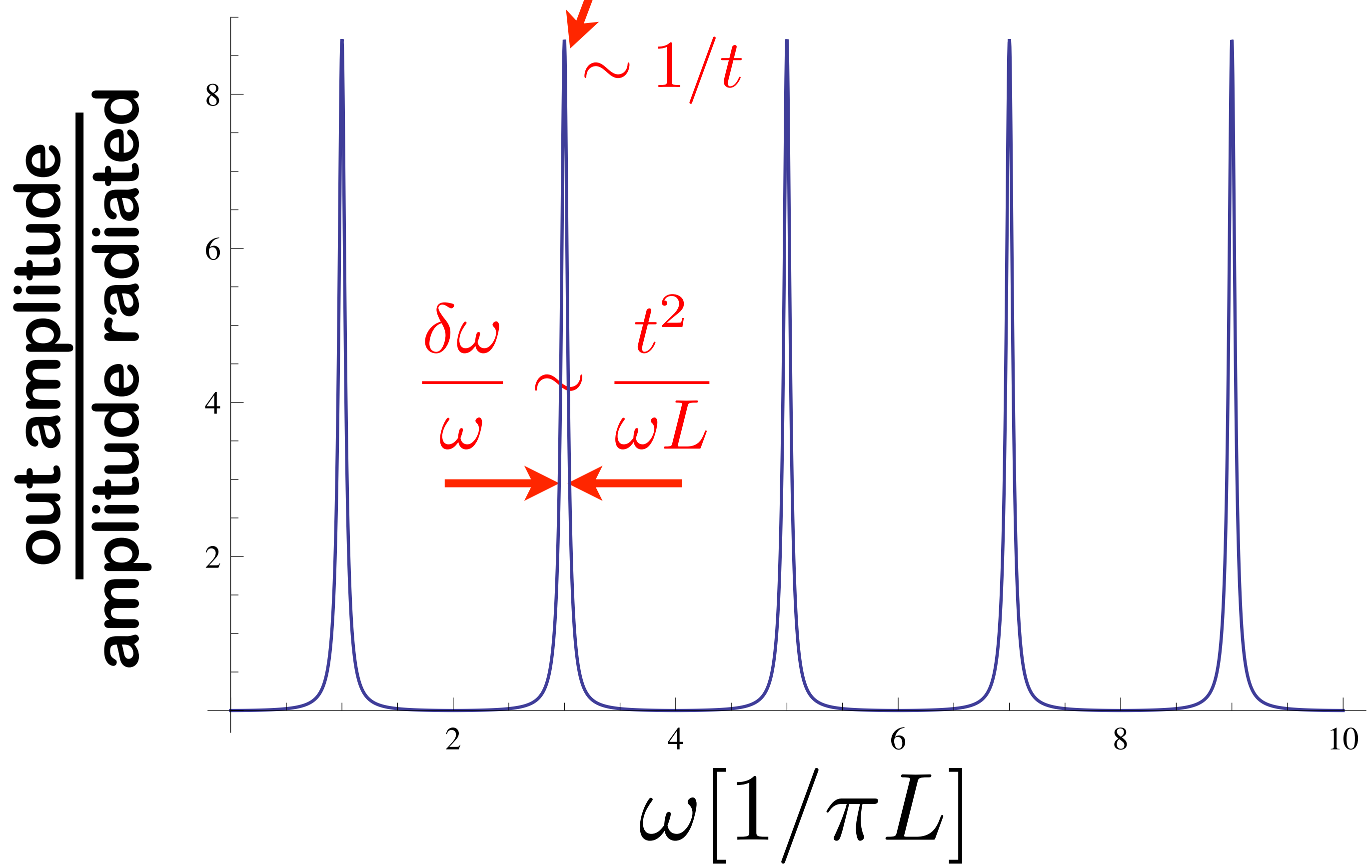
- DESY (Dark matter: a light move aftermath)

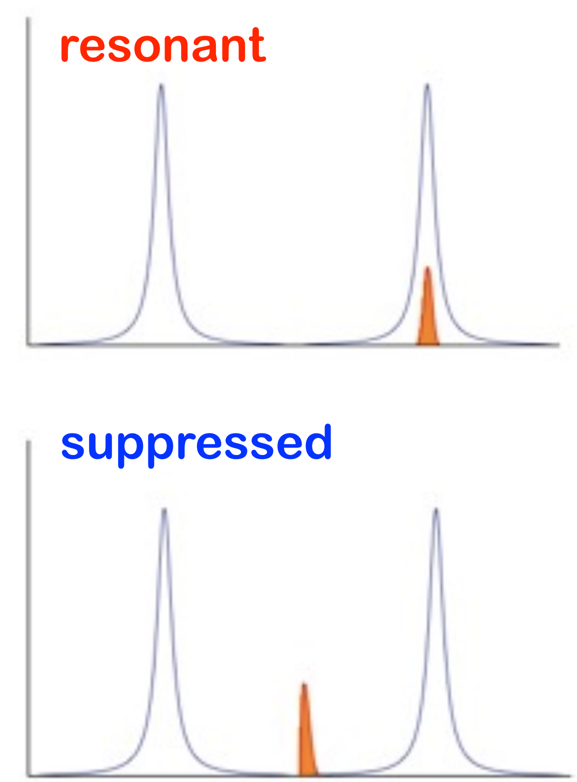
axion DM with resonant cavities

Sikivie PRL '83

- Use two facing mirrors (simplistic resonant cavity in 1D)







axion DM with resonant cavities

- same Area
- same detector

$$\left.\frac{S}{N}\right|_{\rm cavity} \simeq Q \left.\frac{S}{N}\right|_{\rm dish}$$

- quality factor $Q \sim \frac{1}{\text{number of reflections until attenuation or dephase}} \lesssim 10^{-6}$

- but need to tune the cavity to m_a with a precision m_a/Q

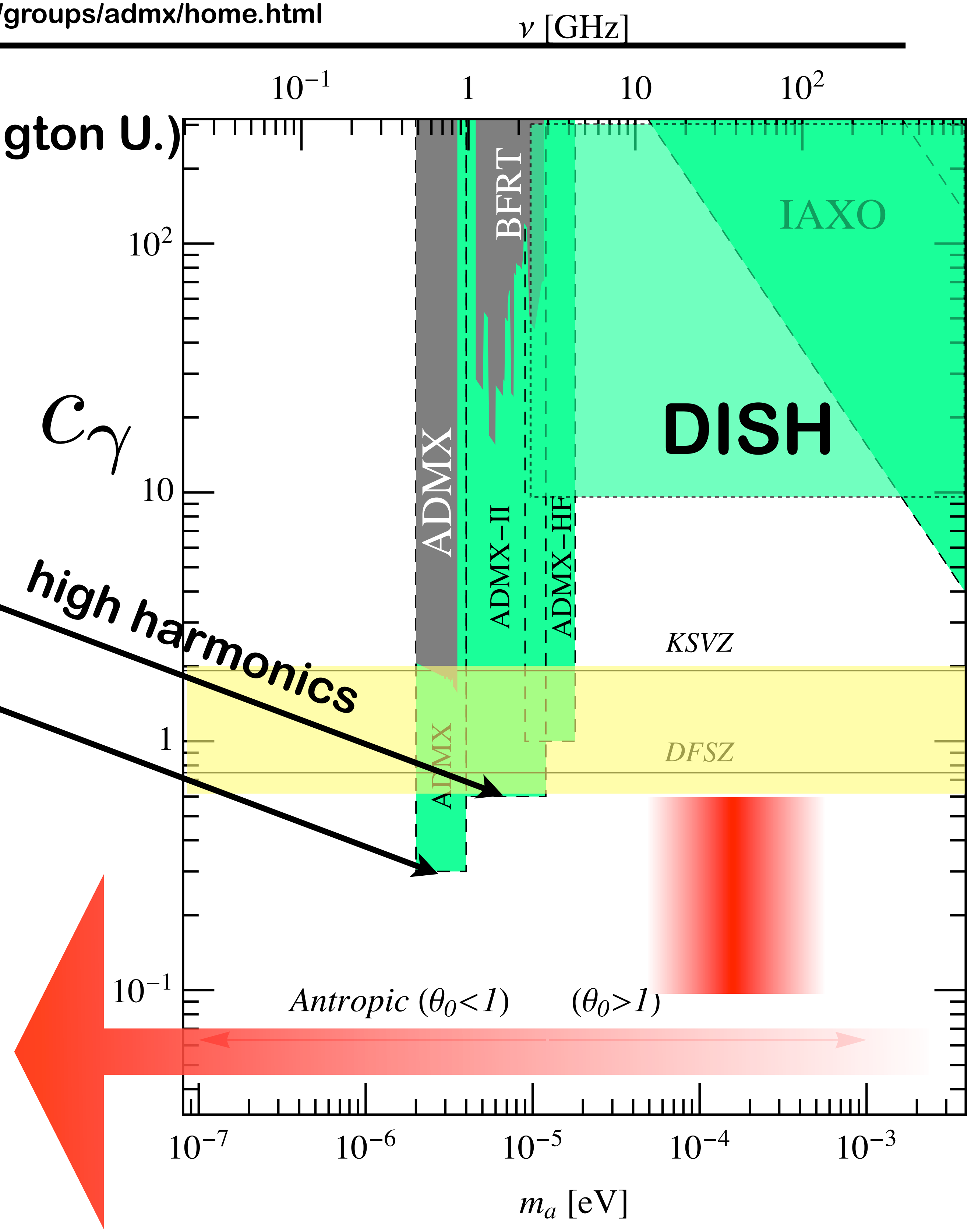
slow scan over different resonant frequencies

$$\frac{S}{N} = 4\kappa\mathcal{G}\frac{5\text{ K}}{T_S}\frac{Q}{10^5}\left(\frac{B}{5\text{ T}}\frac{c_\gamma}{2}\right)^2\sqrt{\frac{\text{time}}{10\text{ min}}\frac{10^{-5}}{\Delta\omega/\omega}}\left(\frac{1\ \mu\text{eV}}{m_a}\right)^{5/2}\frac{V}{(\pi/m_a)^3}$$

ADMX

http://www.phys.washington.edu/groups/admx/home.html

- **Axion DM eXperiment ADMX (Washington U.)**



8T field, H =1 m, D =0.42m

$$m_a > 2\mu\mathrm{eV}$$

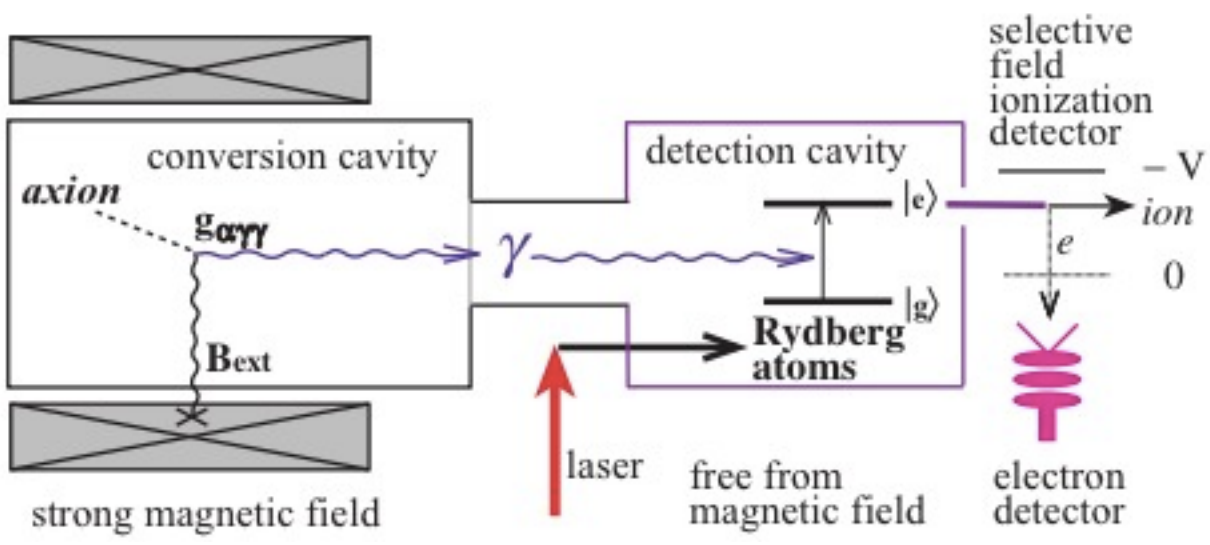
Liquid He
SQUID detector (Q-limited)

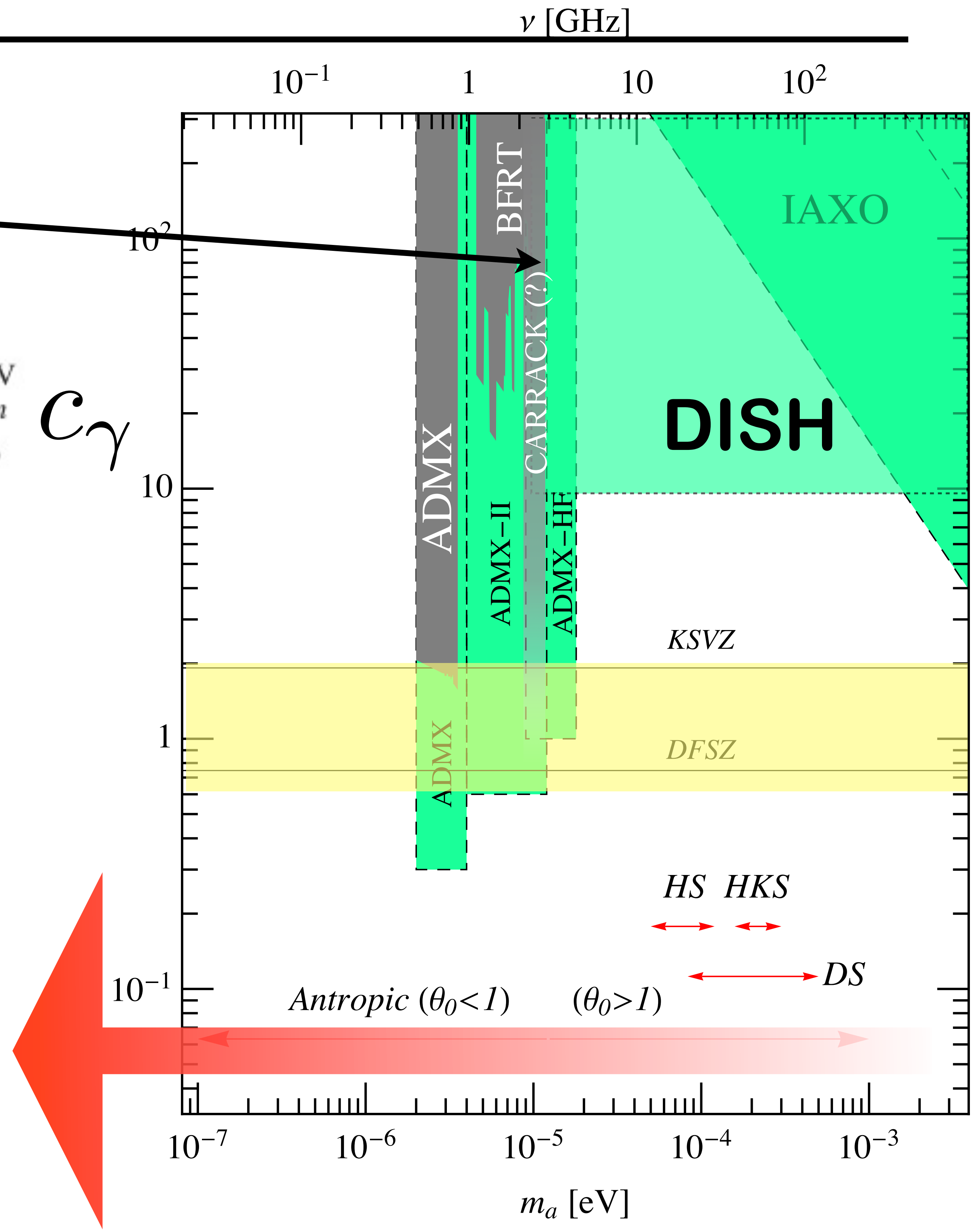
$$T_S \sim 0.5\ \mathrm{K}$$

Scan much faster!

CARRACKs

- Kyoto U.





7T field, D ~0.1m

$$m_a \sim 10\mu\text{eV}$$

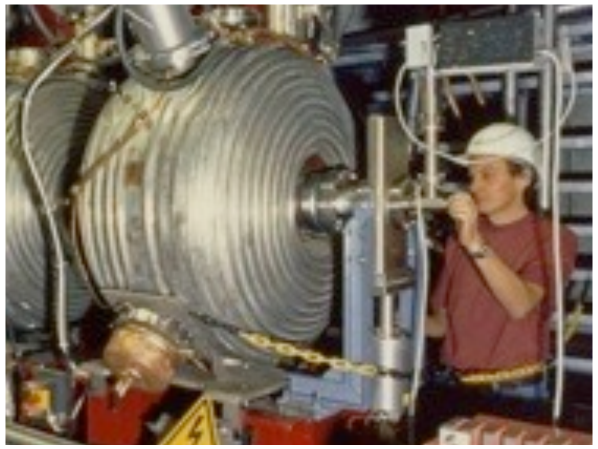
Rydberg atom detection

$$T_S \sim 0.05\ \text{K}$$

Scan much faster!

WISPDMX

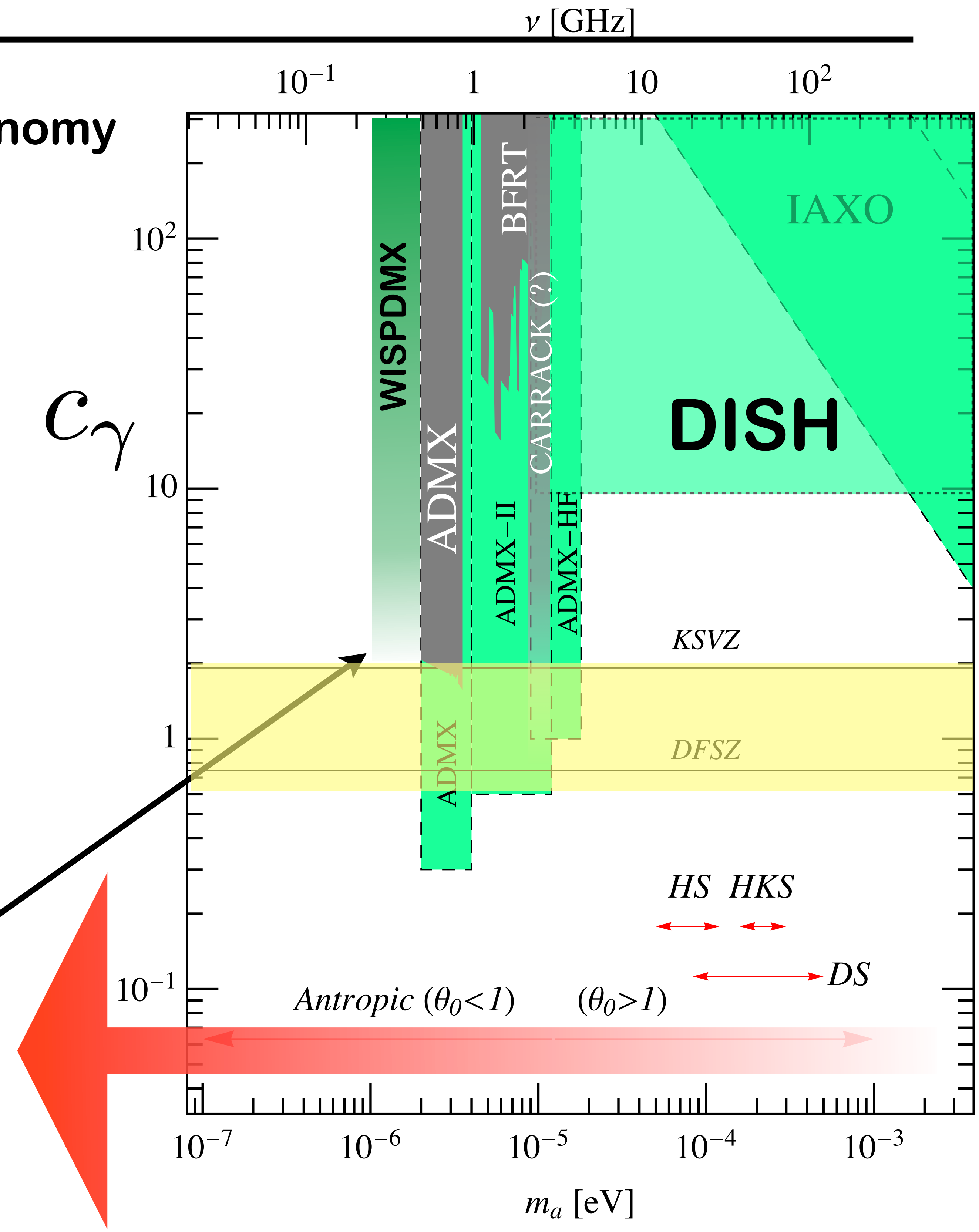
- DESY and Max Planck for radioastronomy



- Frequencies and Q-factors

Mode	ν [MHz]	Q_0	Mode	ν [MHz]	Q_0
TM_{010}	199	53360	TM_{014}	579	122500
TM_{011}	295	44830	TM_{015}	707	60950
TM_{012}	433	47450	TM_{016}	765	105070
TM_{013}	524	47710	TM_{017}	832	102230

- No B-field (hidden photons)
- 2-3 T existing in DESY



Concluding

- Axion DM - well motivated
  - underrepresented (getting better)
  - testable
  - key targets not covered
  - experiments are sensitive to ALPs and HPs

- New experiment: dish antenna
  - a little short for axions (ALPs,WISPs!)
  - directional detection

- New understanding of the old experiments

- More experiments needed!, some on the go!
  - ADMX-II, HF
  - New efforts in EU, stay in tune!