

# ALP Dark Matter (...detecting)

Dec 4th 2013

Workshop: News from the Dark

Javier Redondo (LMU/MPP Munich)

# Outline

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- Summary of Axion and ALP DM
- Axion DM waves in Magnetic fields
- Dish experiment
- Understanding cavity experiments

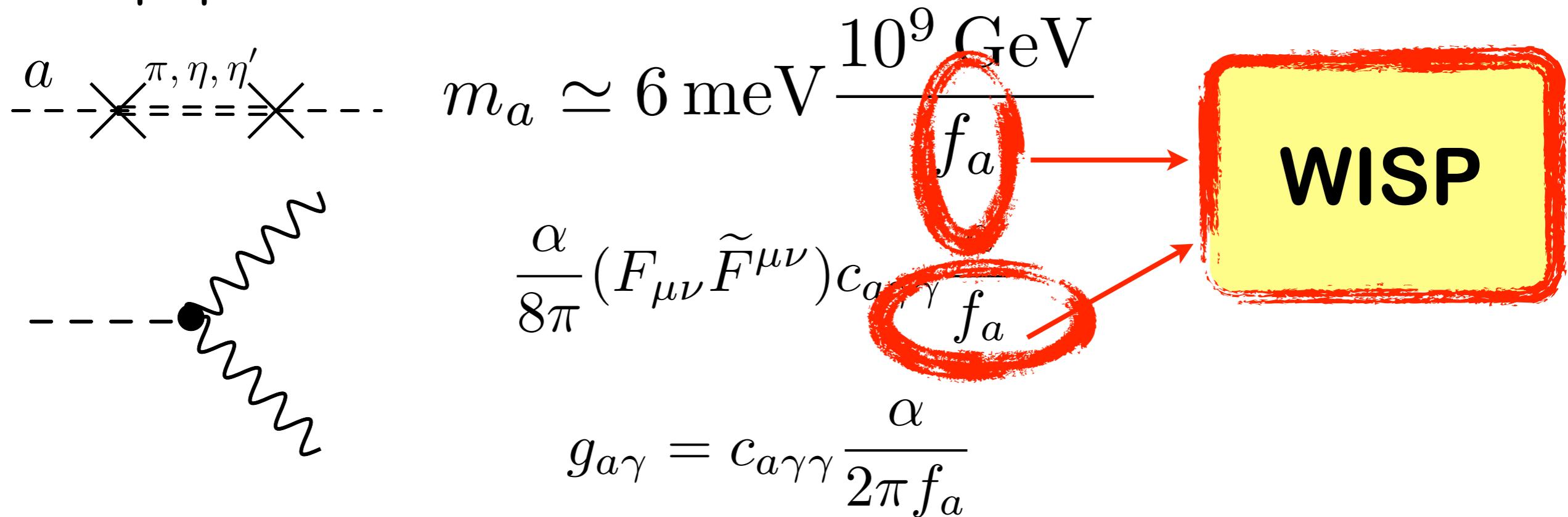
# Axions!

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

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \text{tr} \left\{ G_a^{\mu\nu} \tilde{G}_{a\mu\nu} \right\} \left( \theta + \frac{a}{f_a} \right) \quad \text{the QCD theta angle is dynamical !!}$$

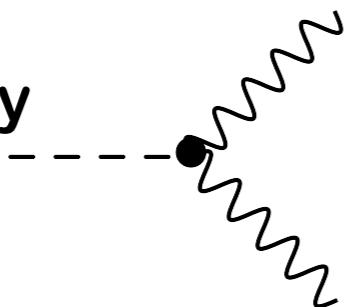
- Axions have predictable properties, which depend mostly on  $f_a$   
(Energy scale at which the U(1) is spontaneously broken)

- Axion properties



# 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

$$p_{\text{today}} \sim T_{\text{today}} \sim \text{meV}$$

~~$m_a$~~  ~~V ???~~

- NON-THERMAL

$$\rightarrow p \sim H \ll T$$

- initial conditions
- decay of cosmic strings, domain walls

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

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

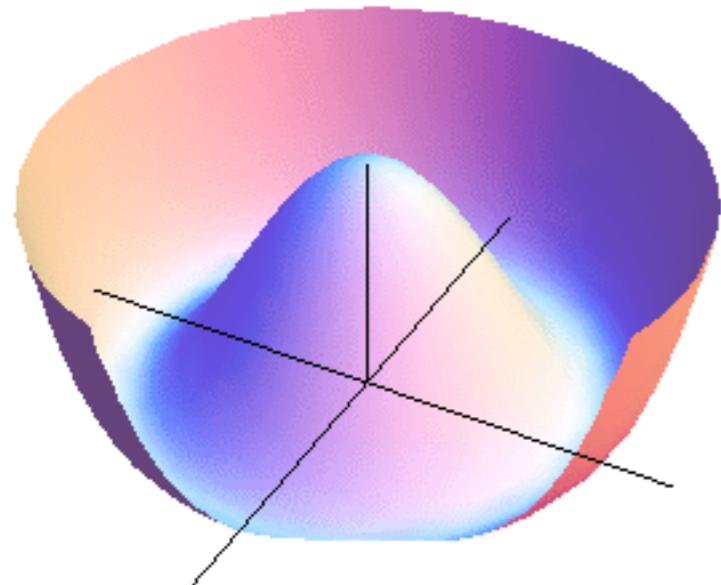
At PQ phase transition

# Axion cold dark matter I

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## Realignment mechanism

(Field space)



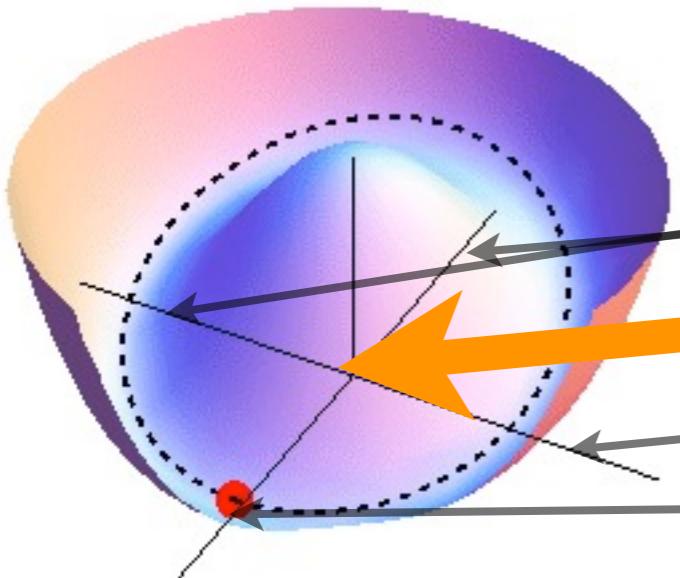
$$\Phi(x) = \rho(x) e^{i \frac{a(x)}{f_a}}$$

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

# Axion cold dark matter I

## Realignment mechanism

(Field space)



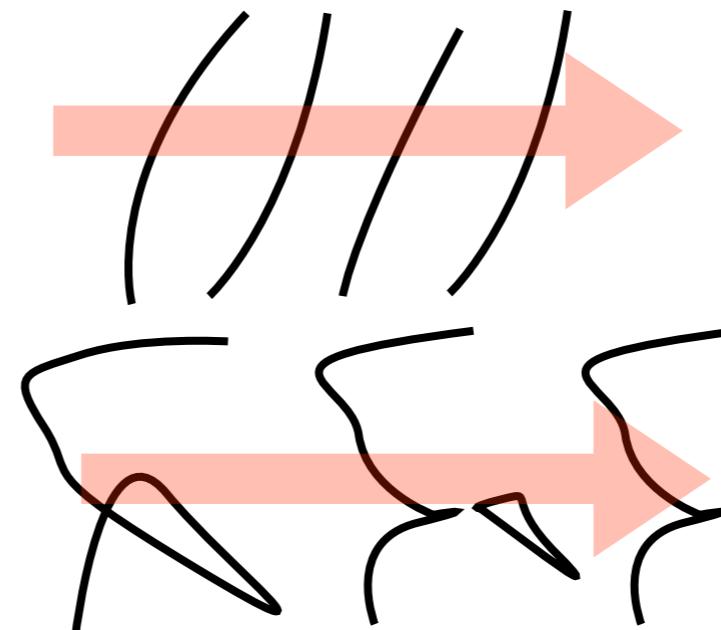
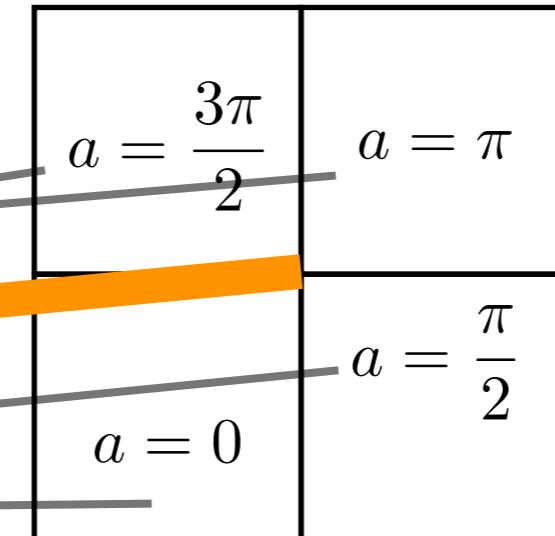
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## Cosmic Strings

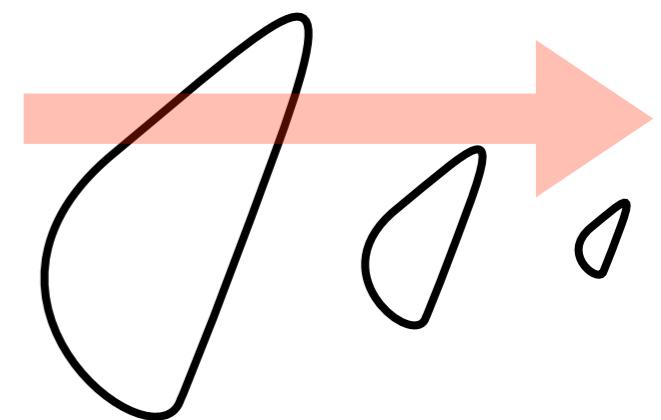
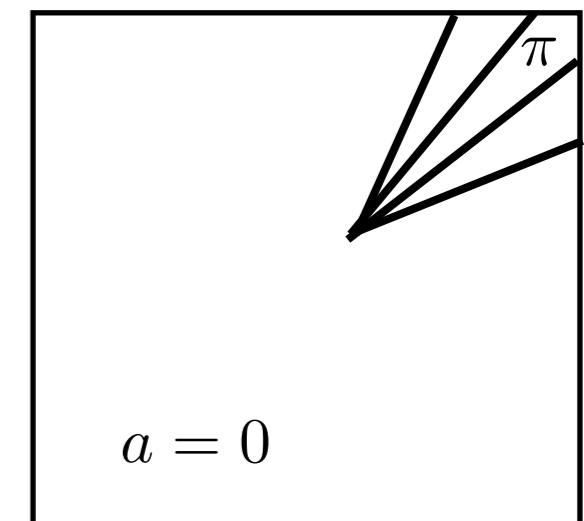
(Position space)

(T>QCD)



## Domain Walls

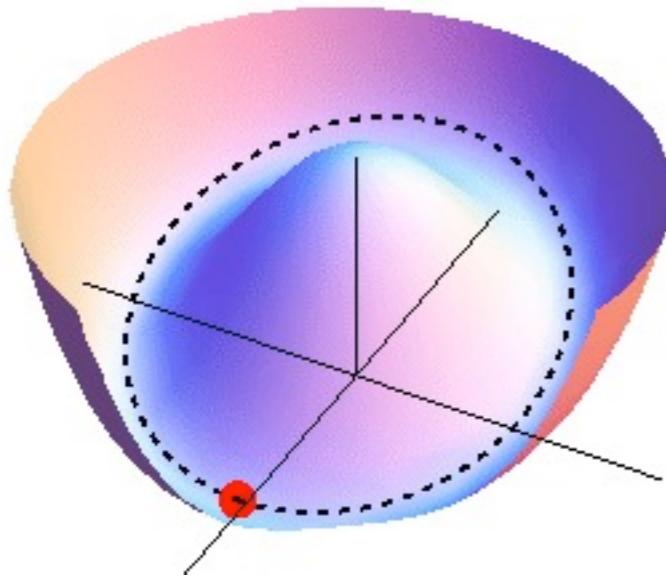
(T<QCD)



# Axion cold dark matter I

## Realignment mechanism

(Field space)



## Cosmic Strings

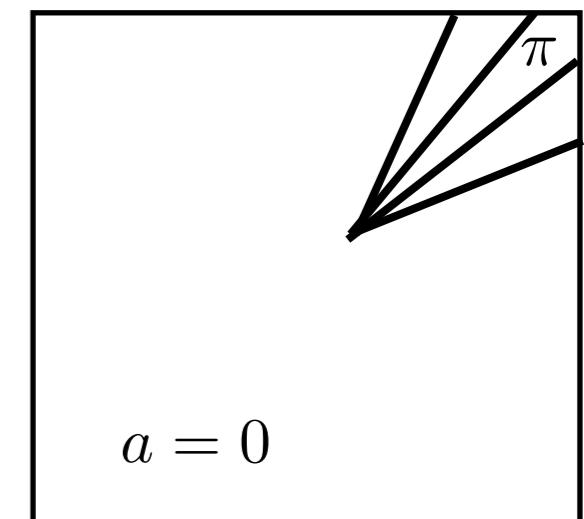
(Position space)

(T>QCD)

$a = \frac{3\pi}{2}$	$a = \pi$
$a = 0$	$a = \frac{\pi}{2}$

## Domain Walls

(T<QCD)



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

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

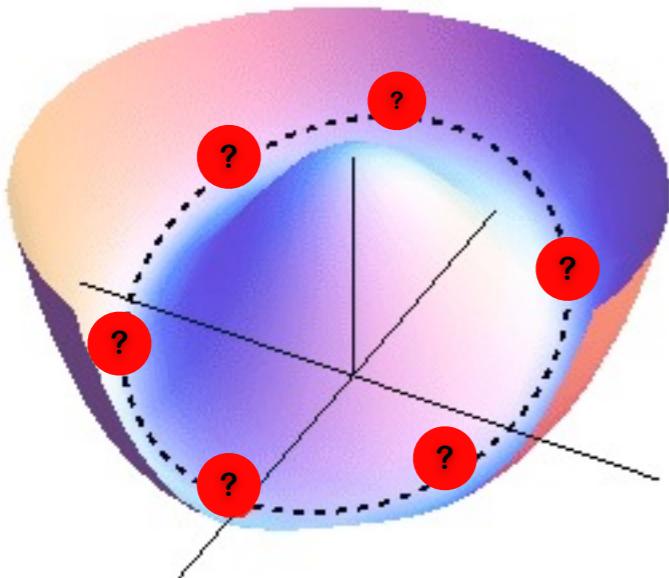
Sikivie, Harari et al.

Shellard, Davis et al.  
Kawasaki, Hiramatsu et al.

# Axion cold dark matter II (PQ before inflation)

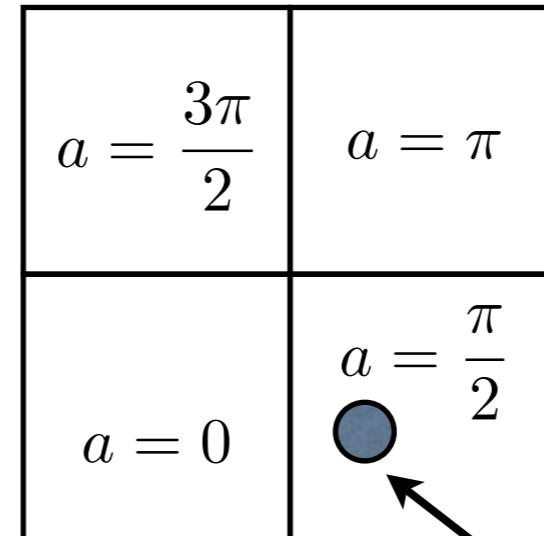
## Realignment mechanism

(Field space)



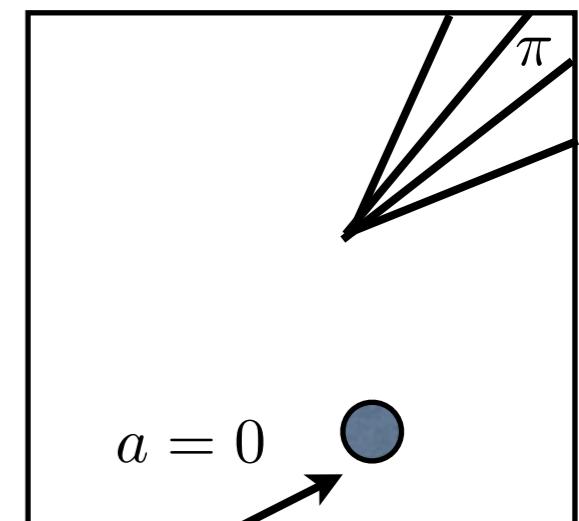
## Cosmic Strings

(Position space)  
(T>QCD)



## Domain Walls

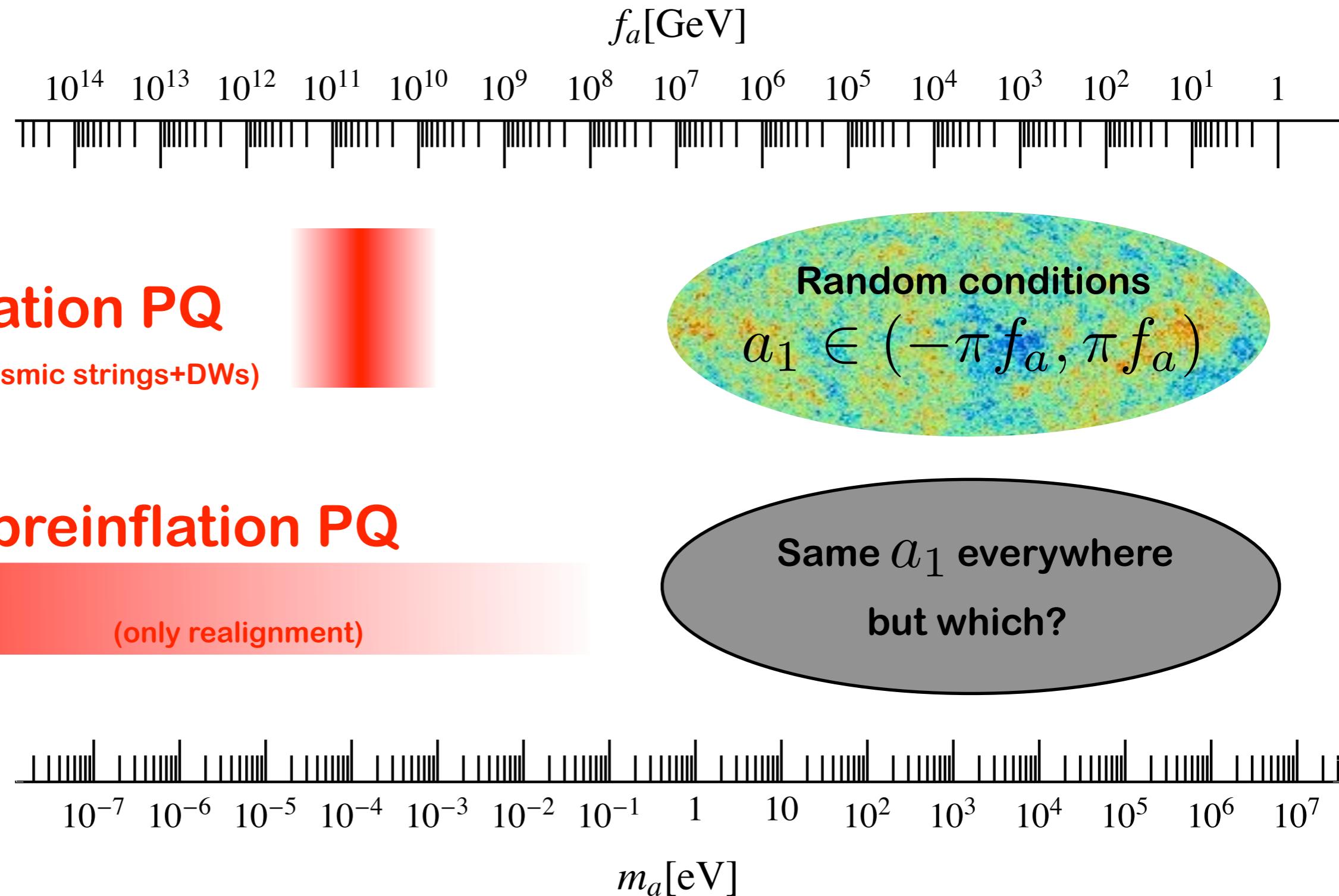
(T<QCD)



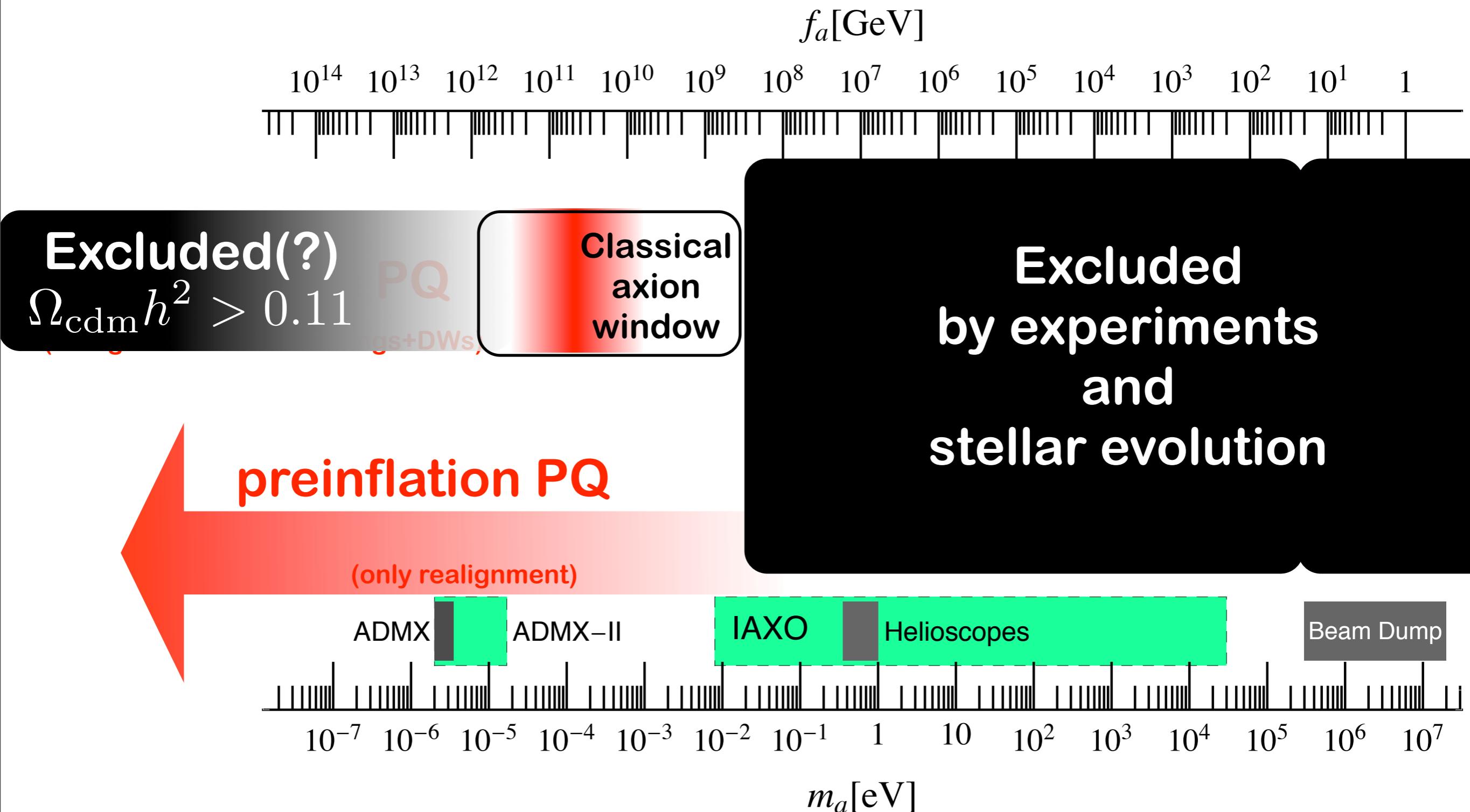
$$\frac{\Omega_{a,VR}}{\Omega_{obs}} \sim \left( \frac{40 \mu eV}{m_a} \right)^{1.184}$$

**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

# QCD axion cold dark matter (two scenarios)



# + Bounds on axions (and prospects)



# Bounds and prospects in more detail

**coupling to two photons**

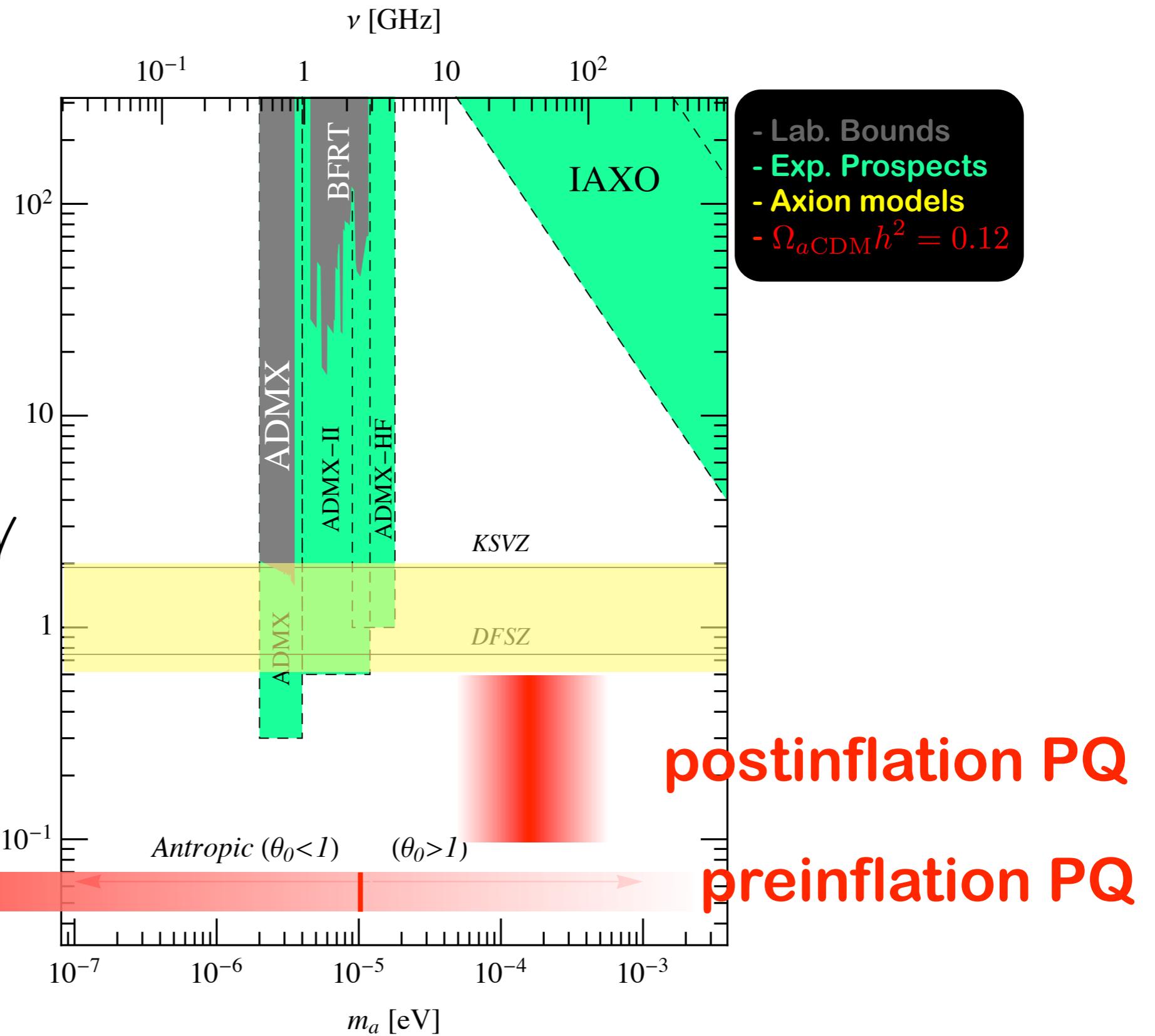
$$g_{a\gamma} = c_\gamma \frac{\alpha}{2\pi f_a}$$

$$m_a = m_a(f_a)$$

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

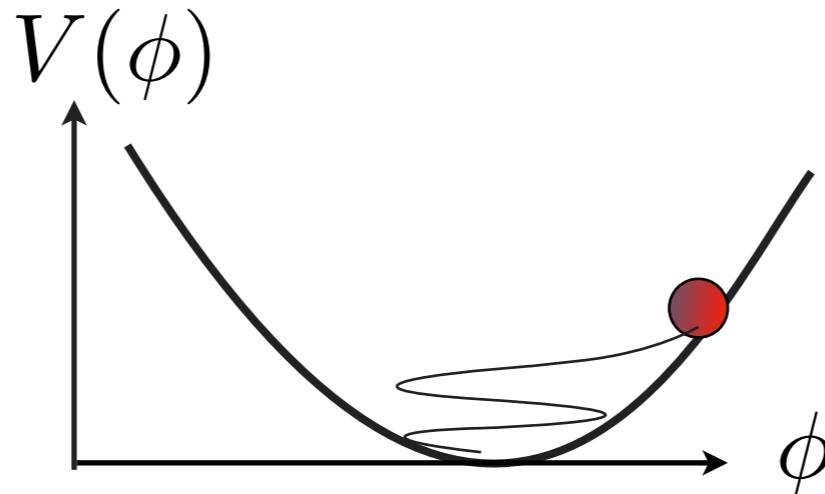


$c_\gamma$



# Relic abundance of WISPy Dark matter (realignment)

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

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

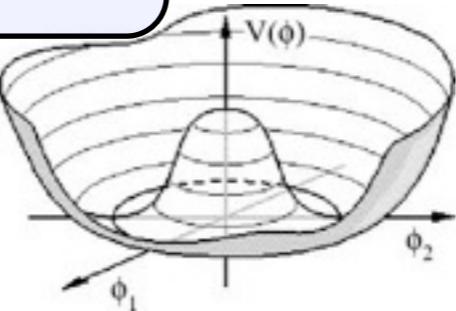
- Initial amplitude, physics at very high energies
- WISPy DM opens a window to HEP

# Weakly interacting slim particles

## Axion-like particles (ALPs) $0^-$

pseudo Goldstone bosons

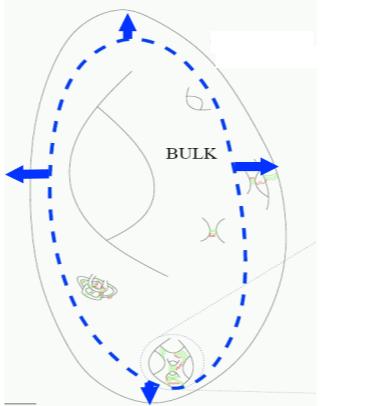
Global continuous symmetry spontaneously broken at high energy scale  $f$



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

String ‘axions’

Sizes and deformations of extra dimensions, gauge couplings

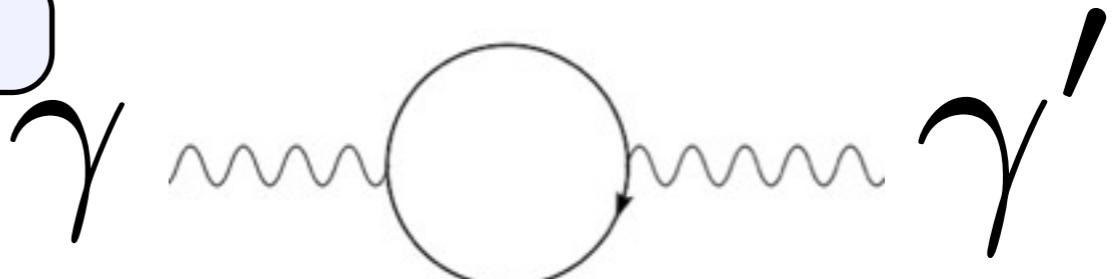


DILATONS RADION  
MODULI

## Hidden gauge bosons

Hidden (Dark) Photons, paraphotons

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



# General Axion-like particles (ALPs)

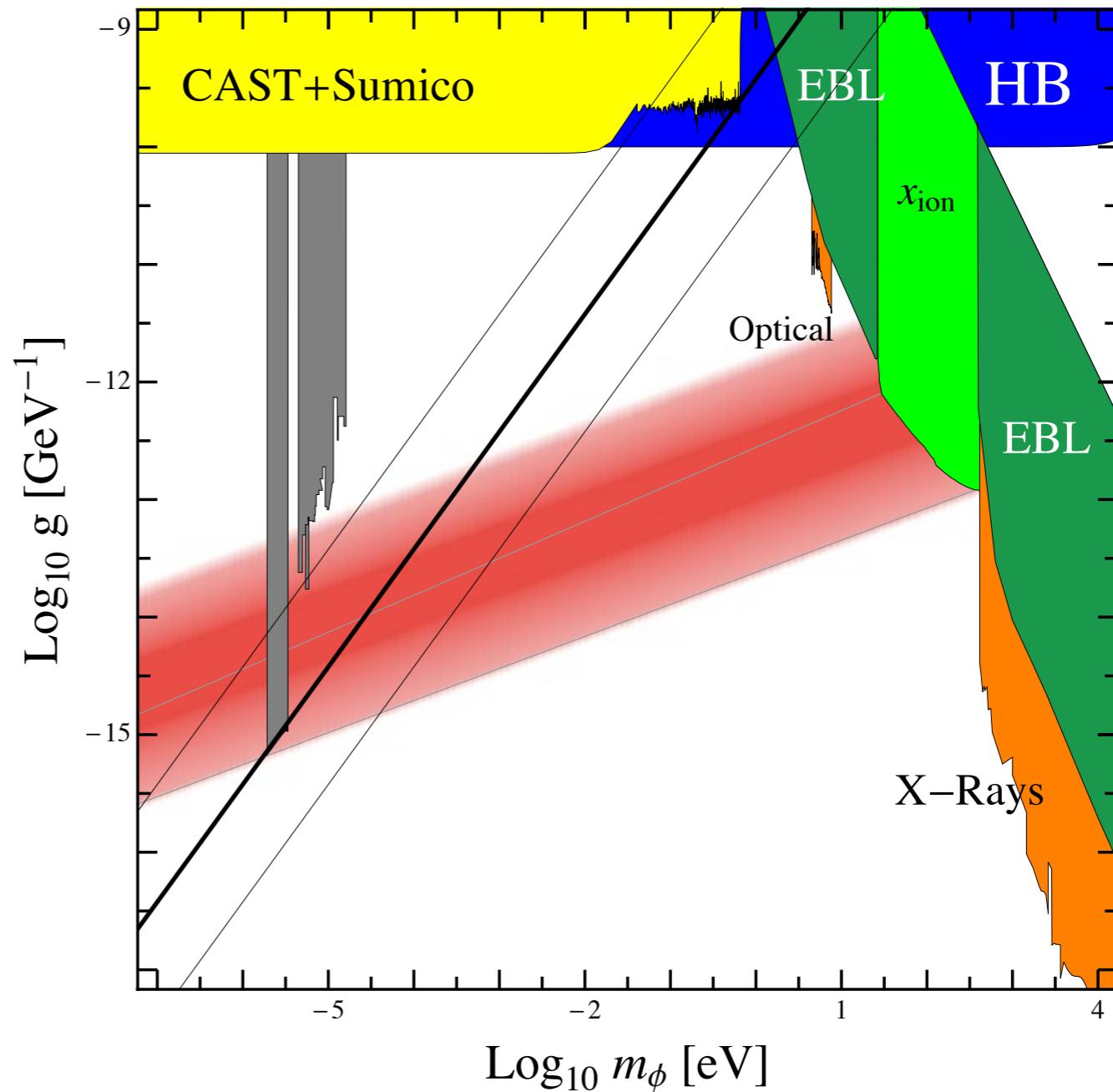
- Mass and coupling unrelated

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

- Scenario 1

$$f_a < H_I$$

(realignment+cosmic strings, DWs..)



# General Axion-like particles (ALPs)

- Mass and coupling unrelated

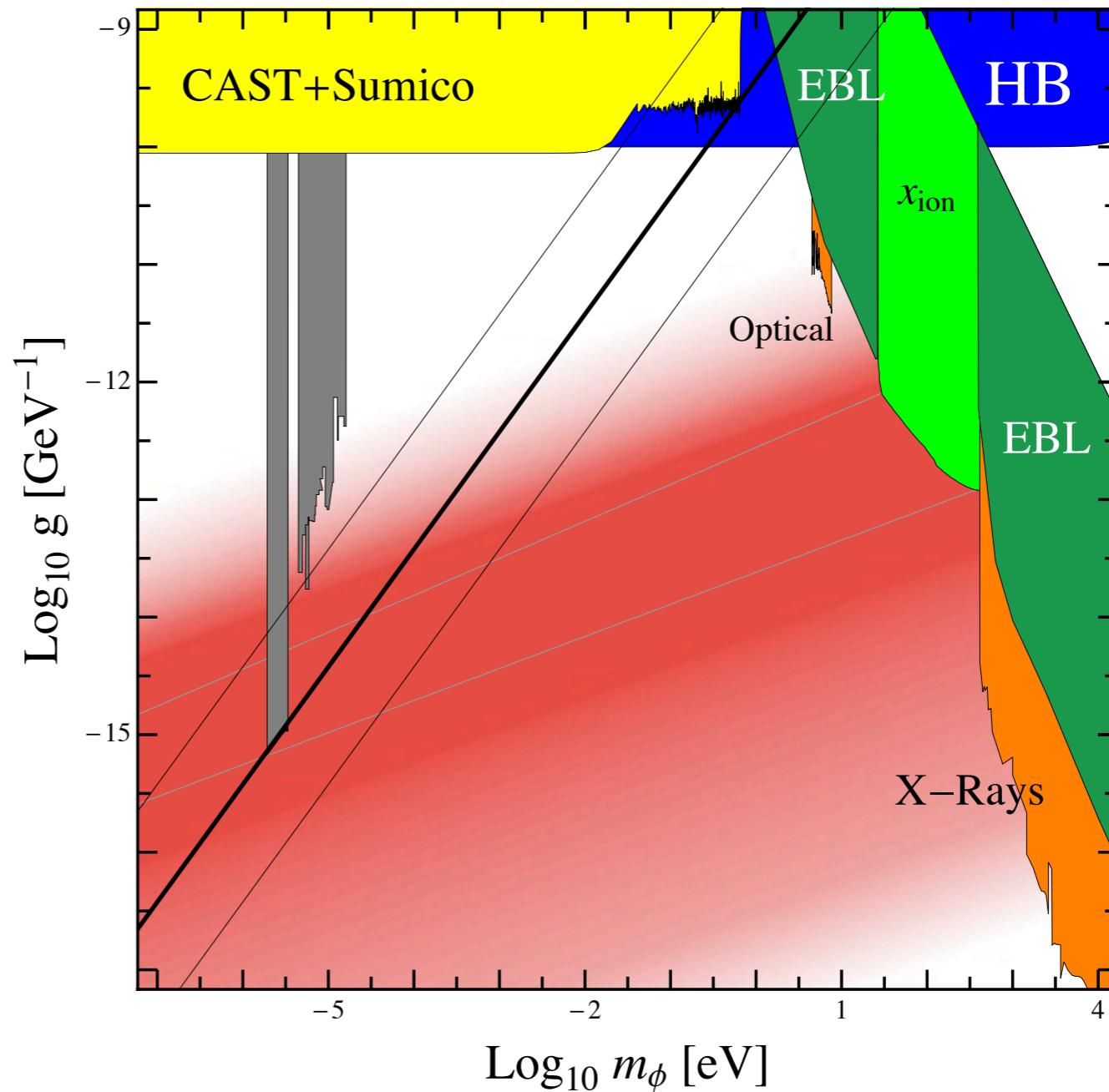
$$g = \frac{\alpha}{2\pi f_a} \times O(1)$$

- Scenario 2 (anthropic)

$$f_a > H_I$$

(realignment mechanism)

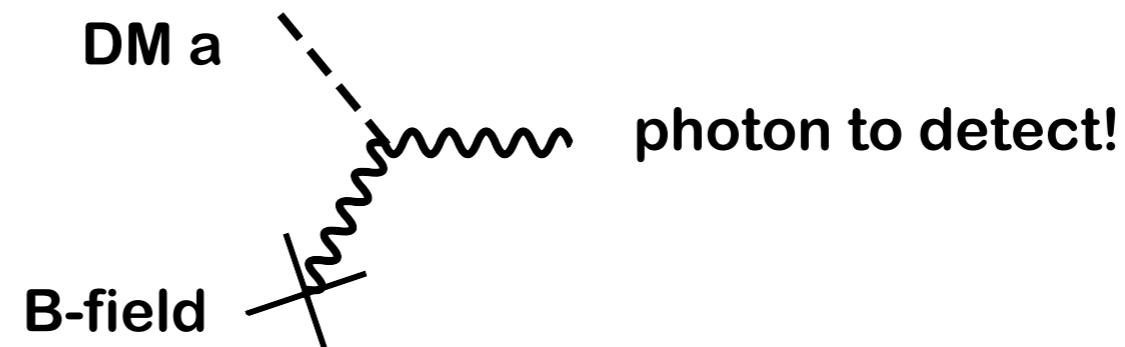
- Isocurvature constraints!!



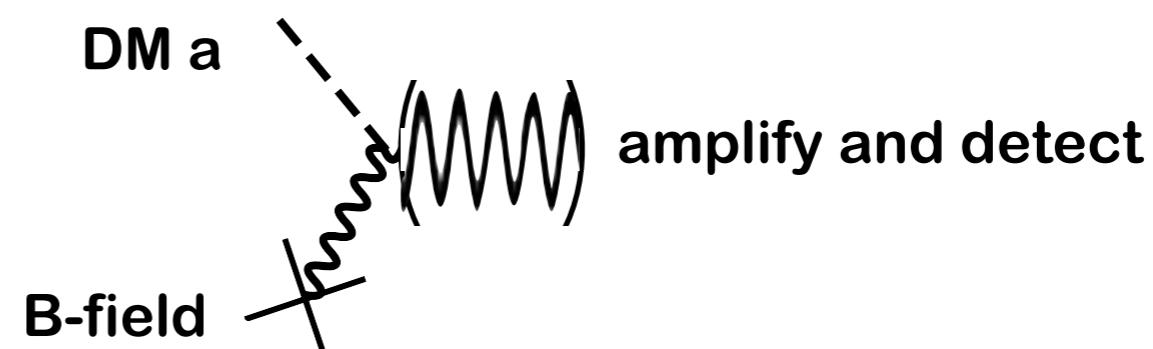
# Experiments to detect axion DM

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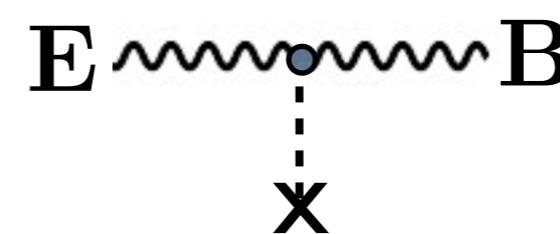
- Dish antenna



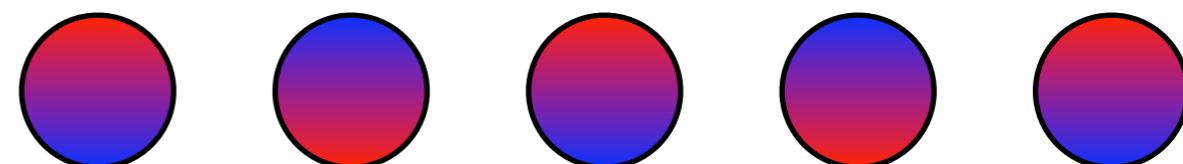
- Cavity experiments



- Light propagation



- Oscillating EDM



# DM around us

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

velocities in the galaxy

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

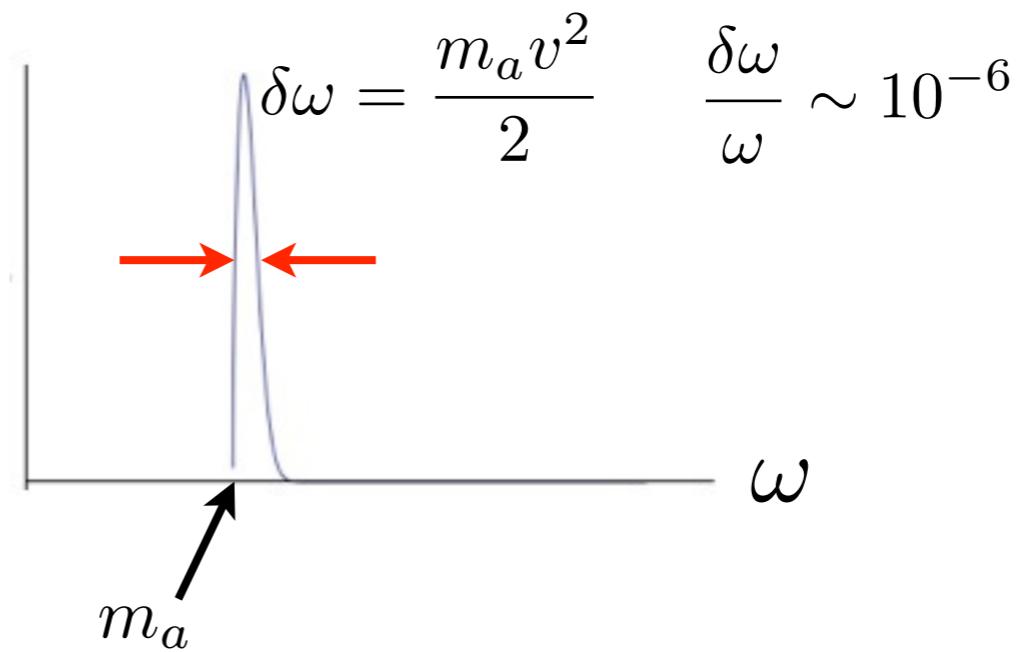
phase space density

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

occupation number is HUGE!  $\longrightarrow$  behaves like a classical NR field!

Fourier-transform  $a(x)$

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



# Axion - photon mixing in a magnetic field

Raffelt, PRD'88

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

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

Not axions, nor photons are propagation eigenstates!

Axion-photon oscillations in a magnetic field, basis for

- light shining through walls (LSW): ALPS @ DESY, GammeV,...
- Helioscopes as CAST and SUMICO
- Astrophysical anomalies? TeV transparency ...

and ...

- Haloscope DM detection

# 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  $v = \frac{k}{\omega}$  ;  $\omega \simeq m_a(1 + v^2/2 + \dots)$

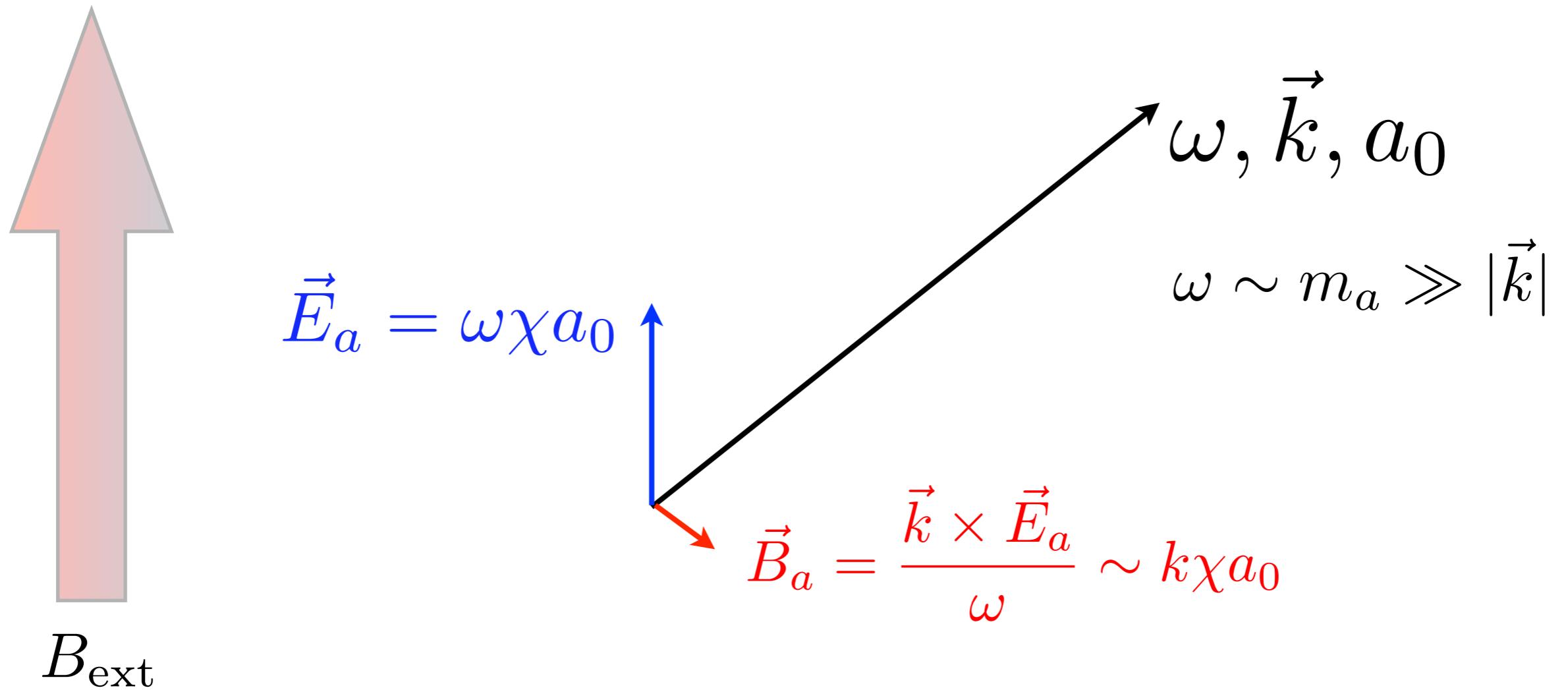
$$\left. \begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix} \right|_{\text{DM}} \propto \begin{pmatrix} -\chi_a \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

It has a small E field!

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

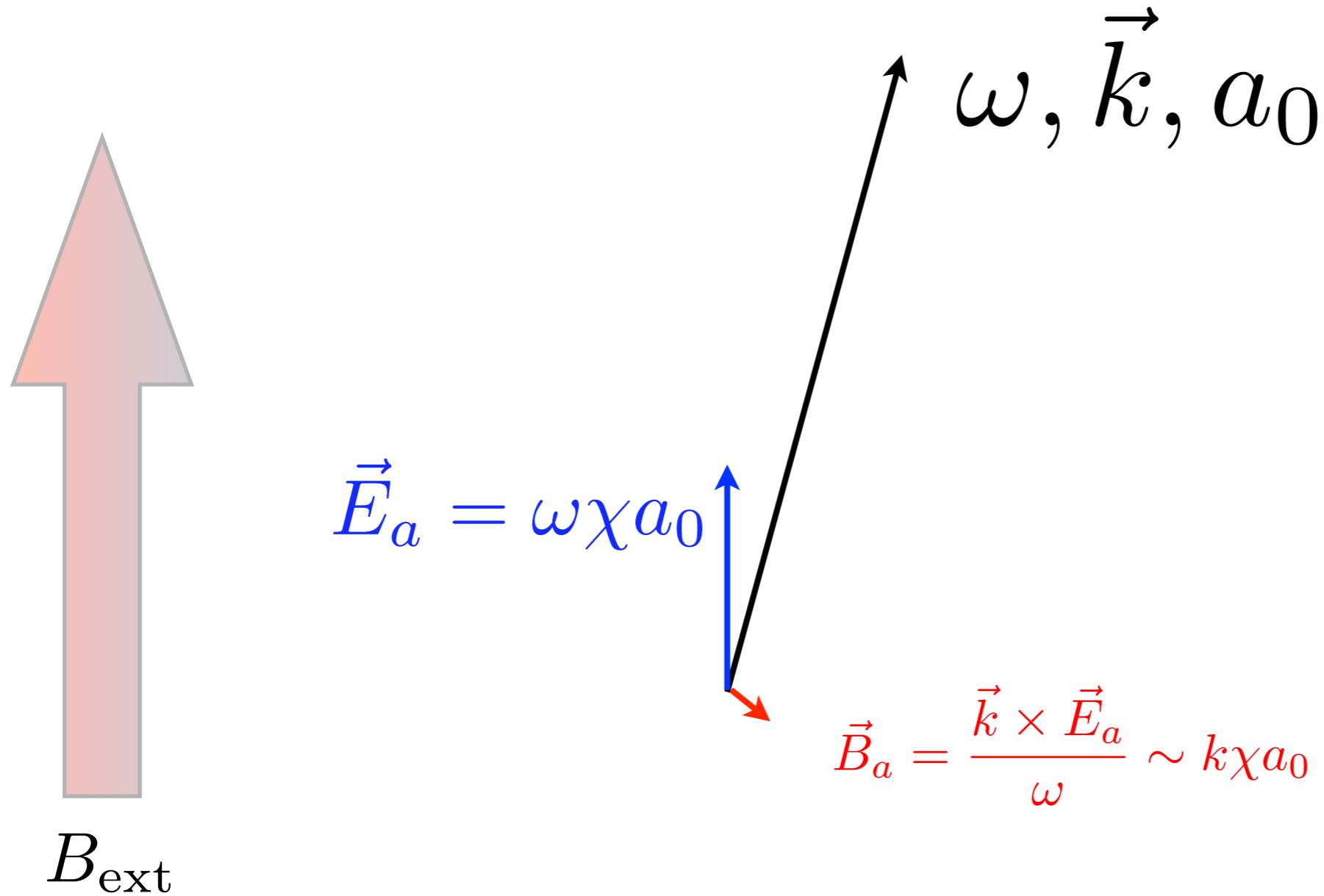
# DM axions in a magnetic field

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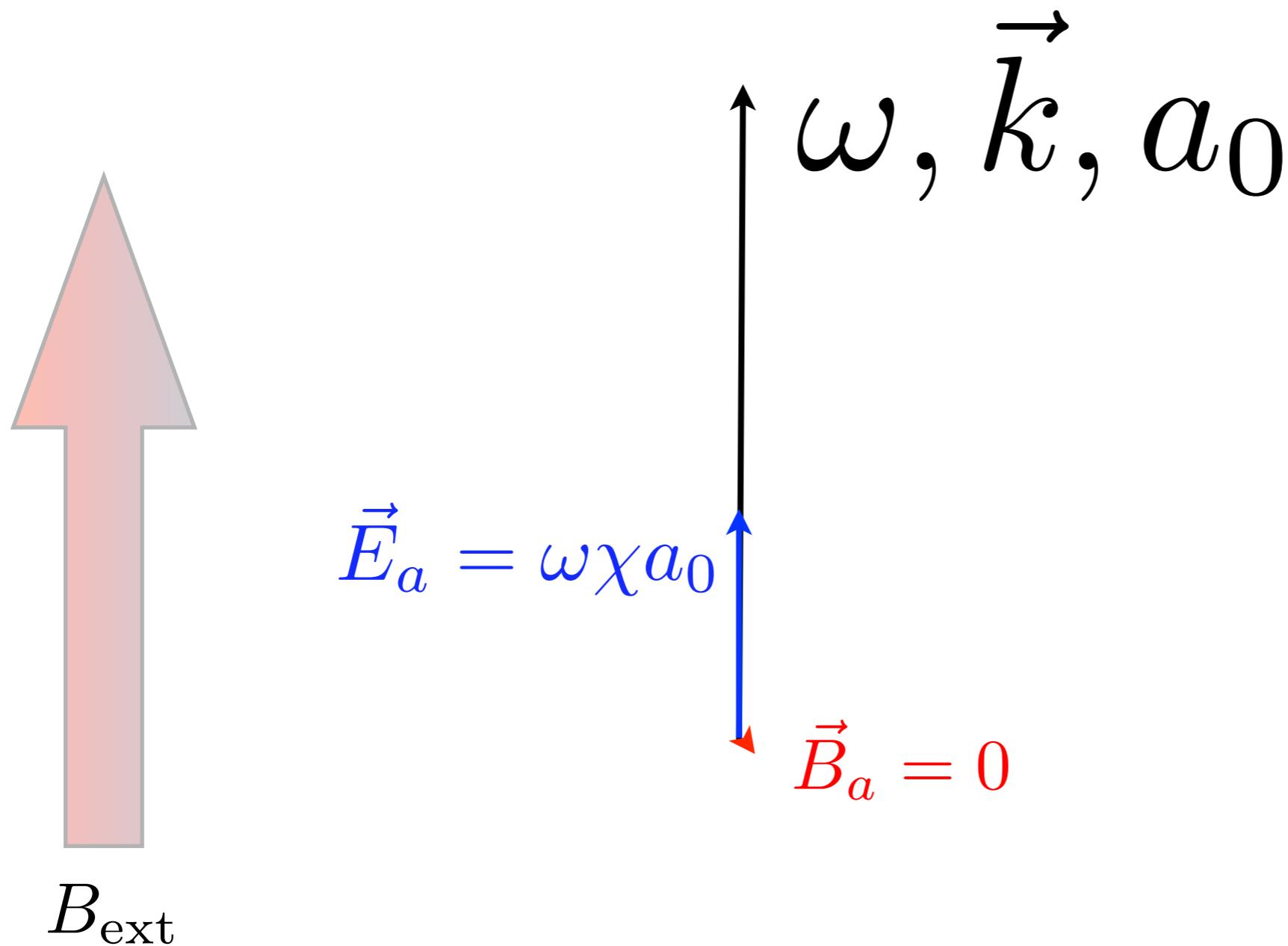
# DM axions in a magnetic field

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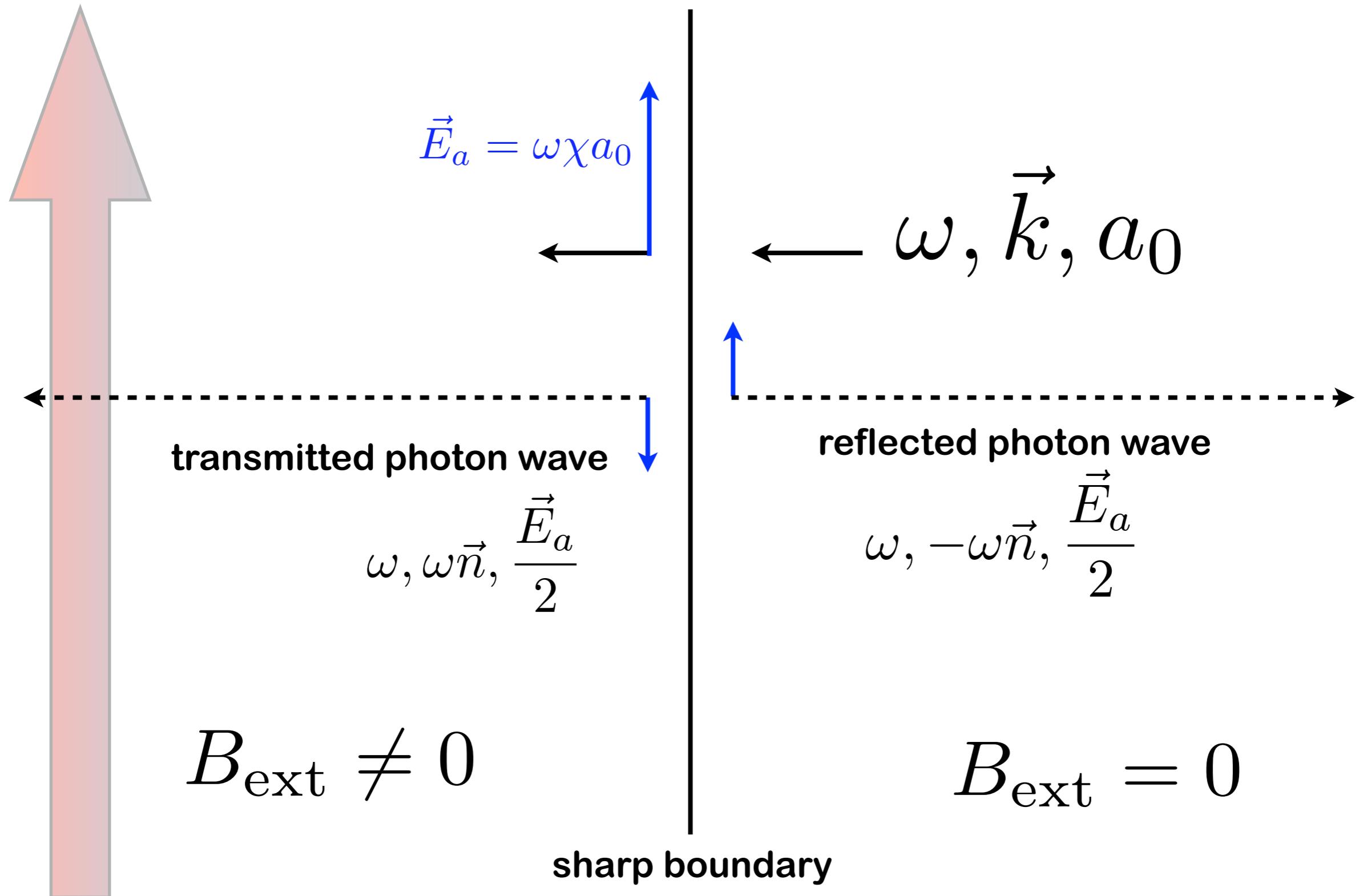


# DM axions in a magnetic field

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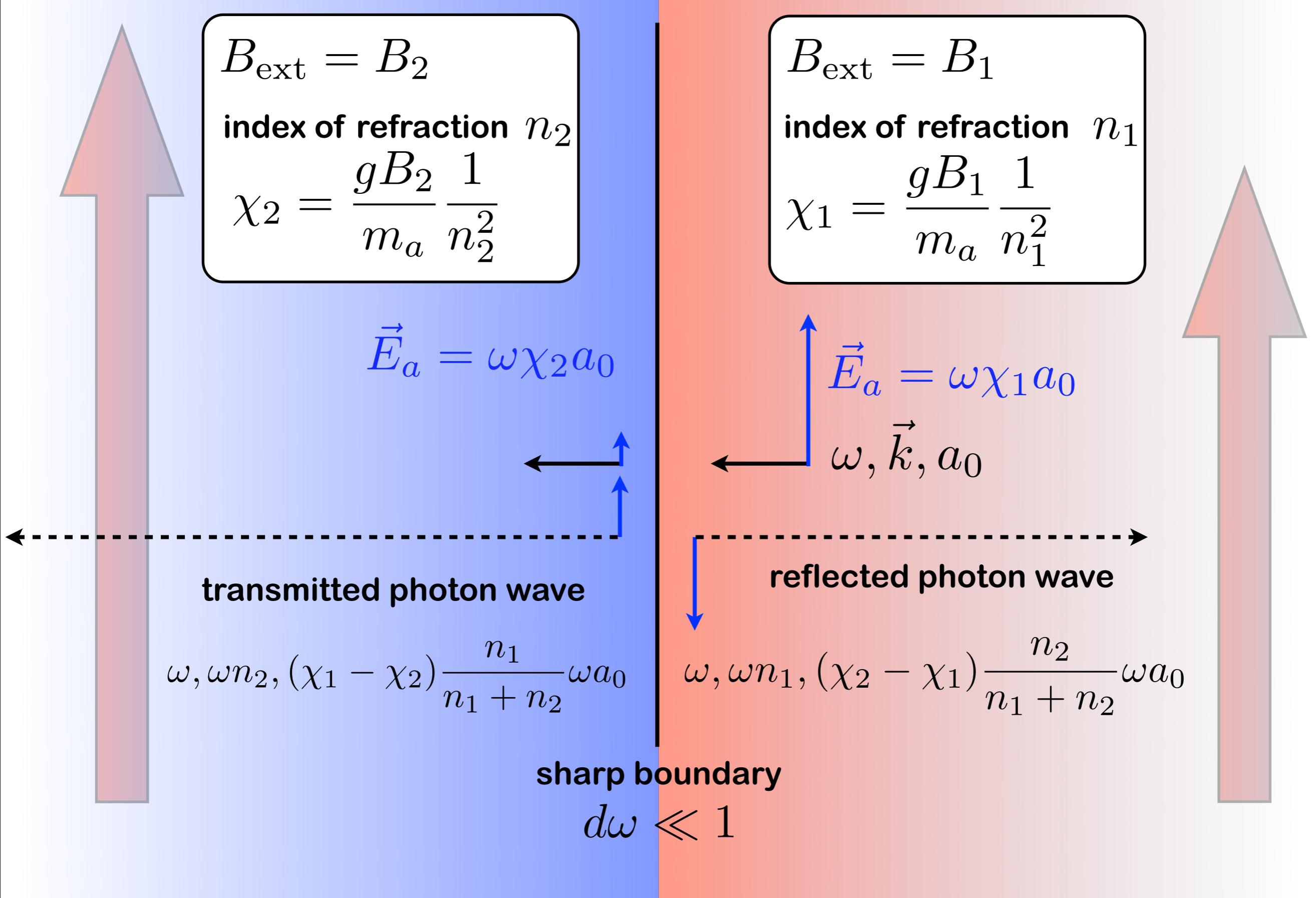


# DM axions entering a magnetic field



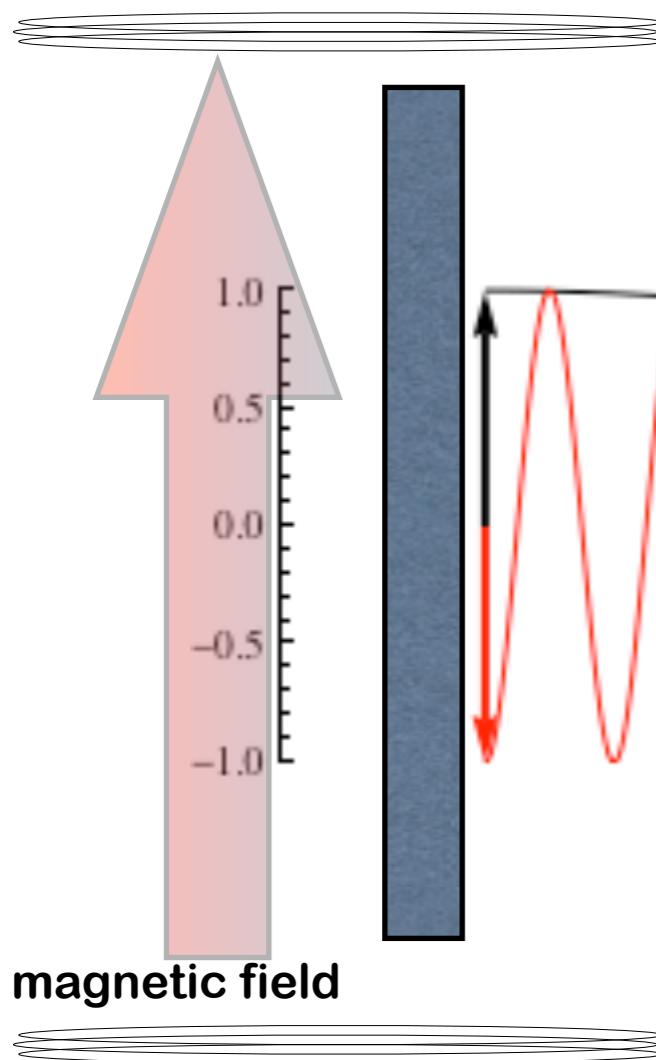
# DM axions changing medium

Jaeckel and JR, PRDxxx, arXiv:1308.1103



# Radiation from a magnetised mirror

Horns et al JCAP04(2013)016



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

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

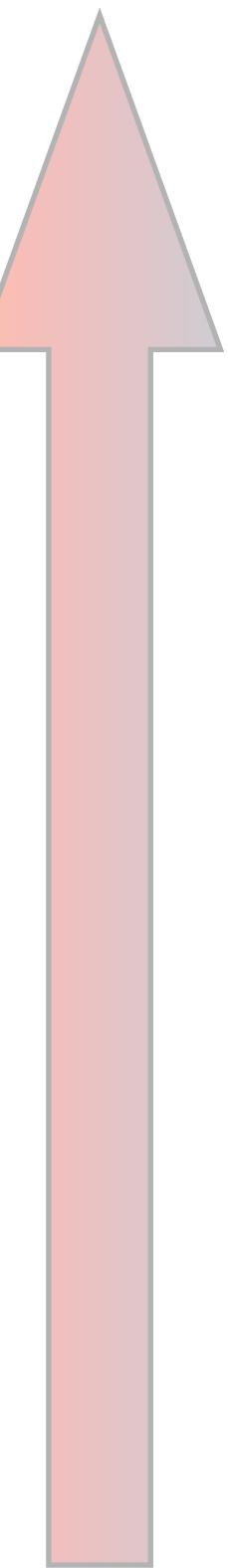
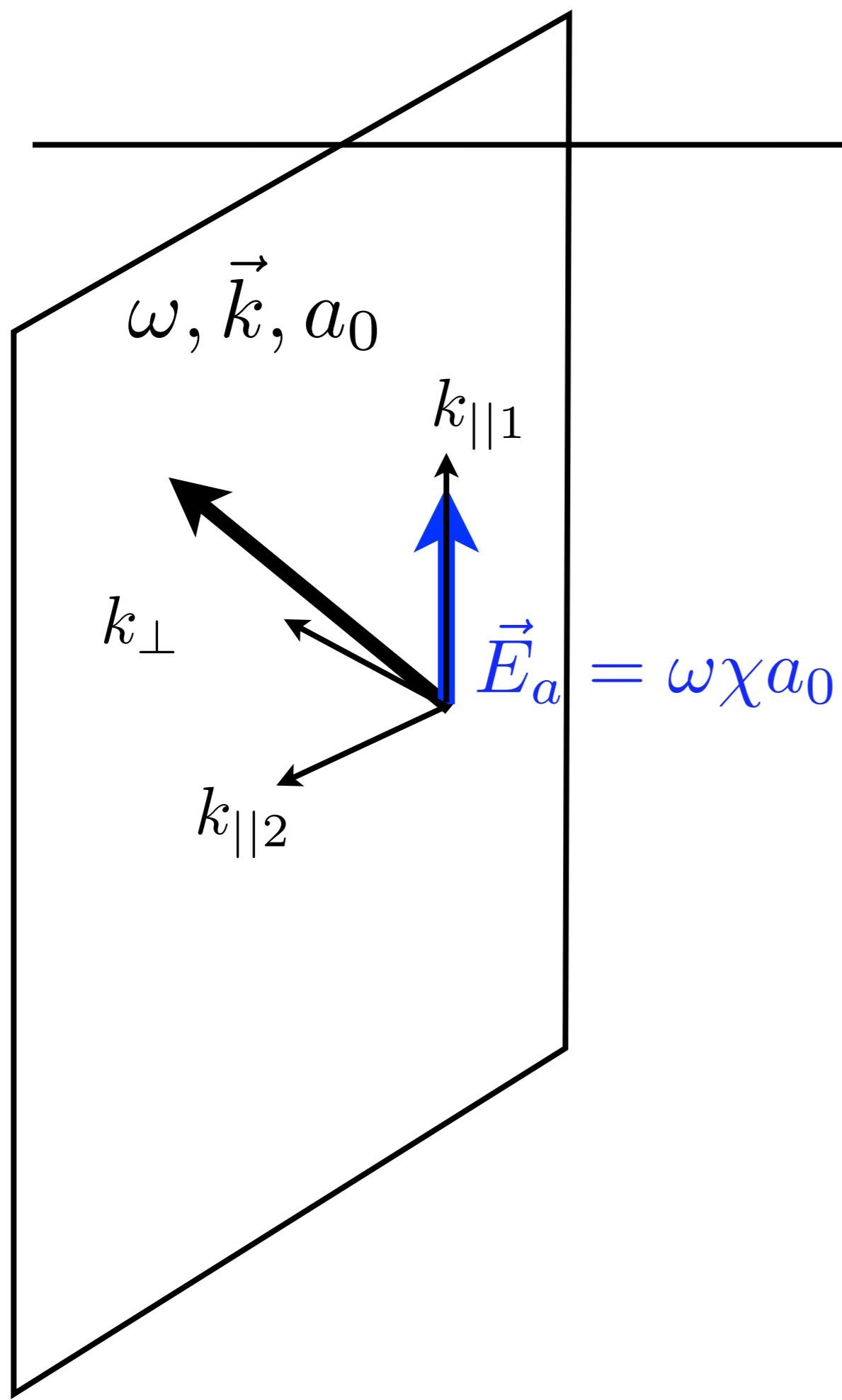
Radiated photon wave

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

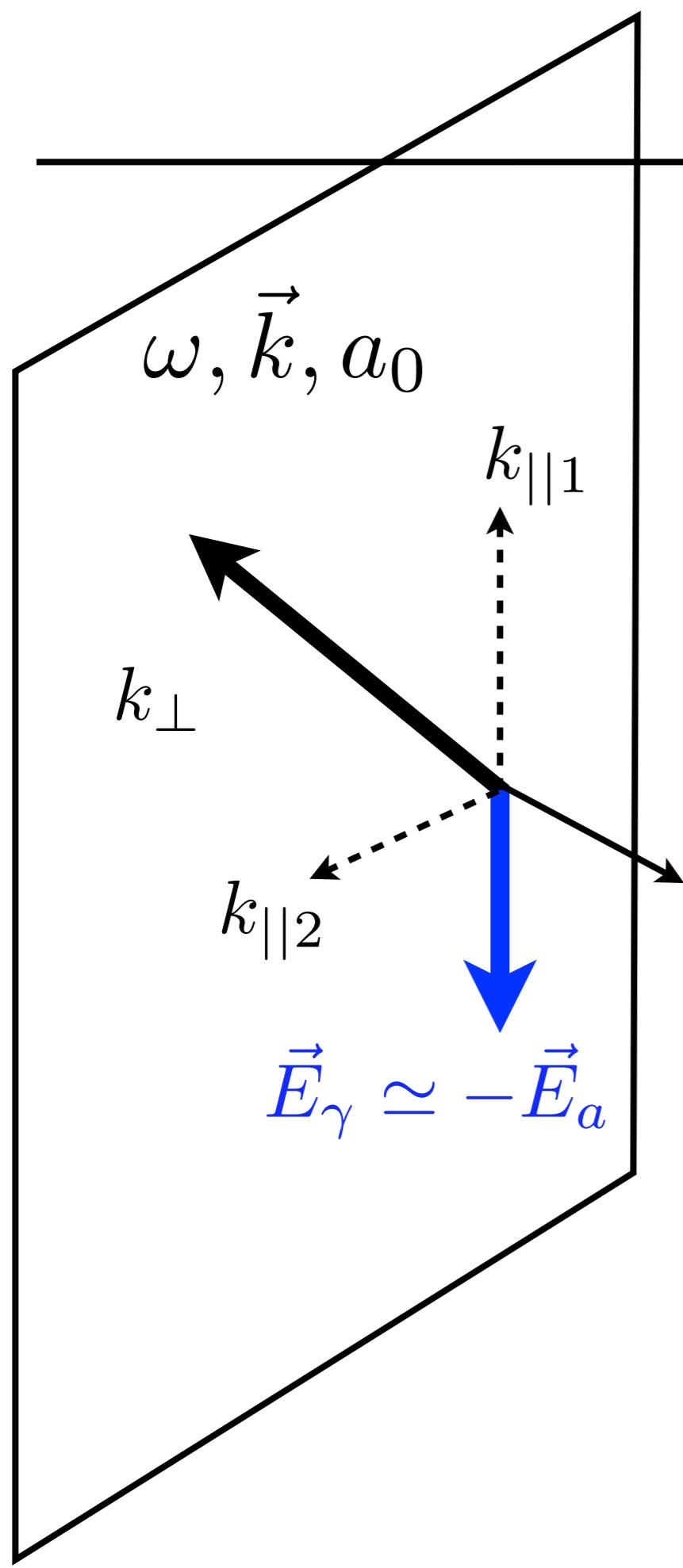
whose frequency is

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

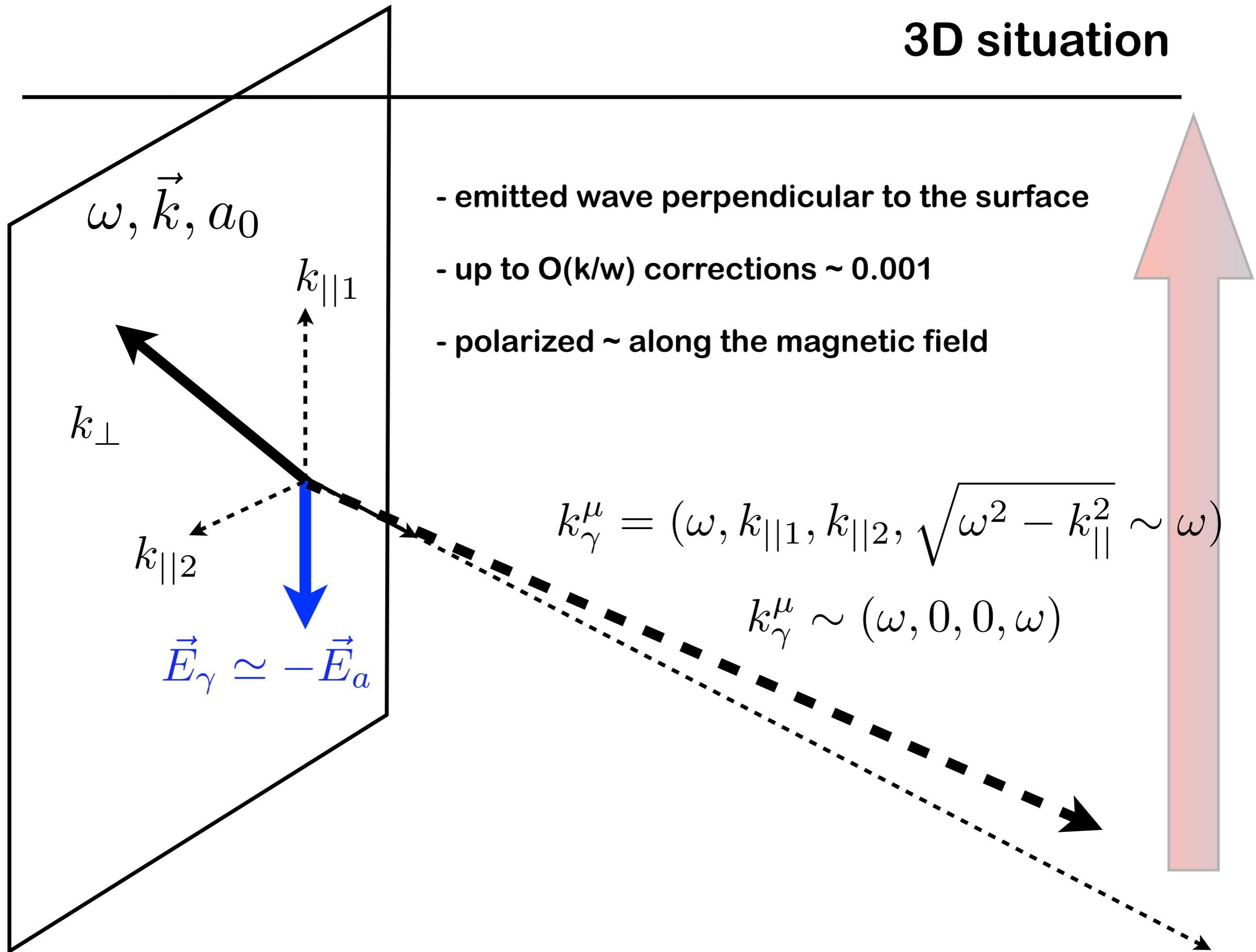
## 3D situation



# 3D situation

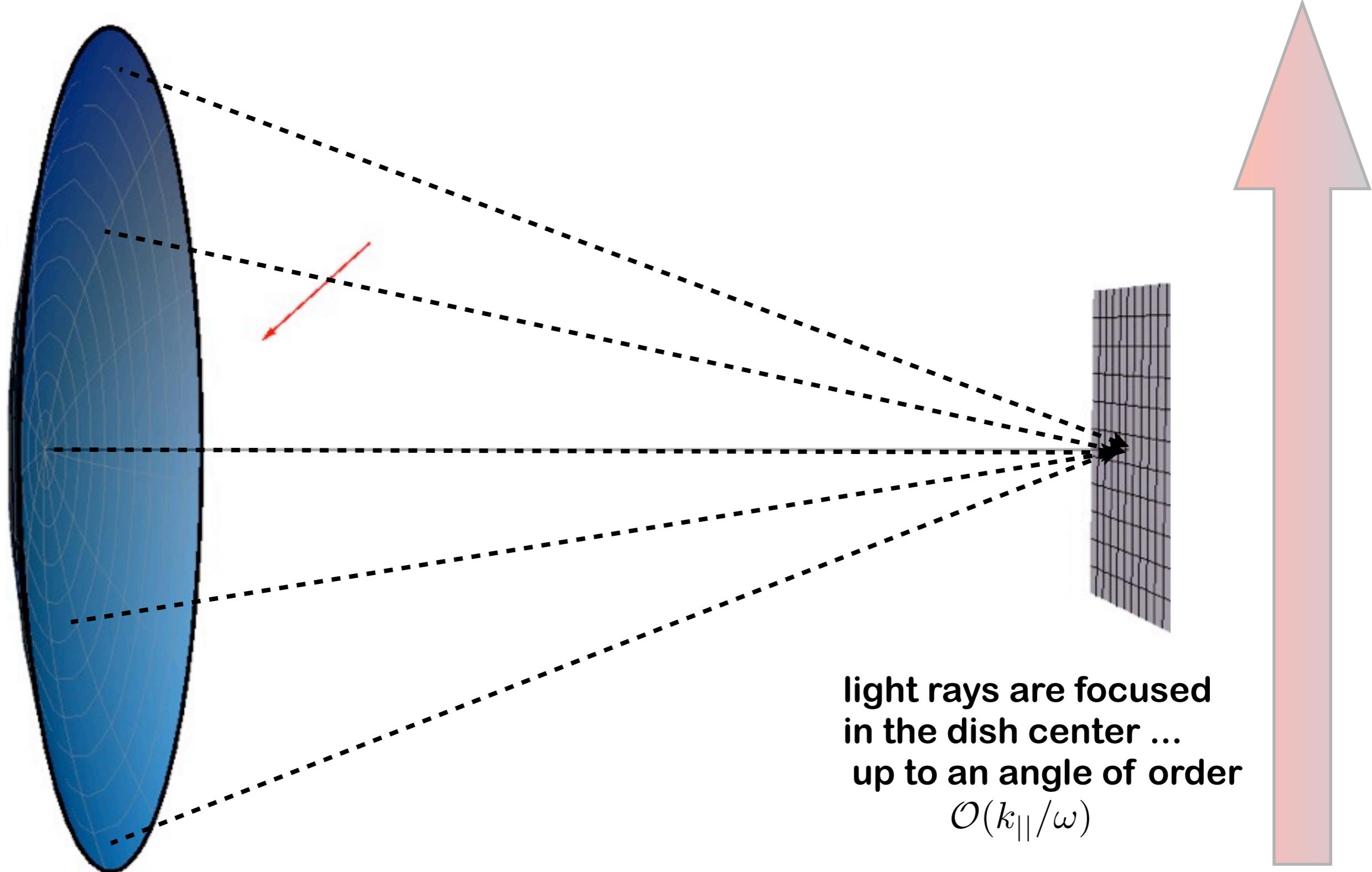


# 3D situation



# Simplest experiment

Horns et al JCAP04(2013)016



spherical reflecting dish

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

# Small electric field: how small?

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- Recall that for QCD axions  $m_a = 6 \text{ meV} (10^9 \text{ GeV}/f_a)$

$$\chi_a \sim \frac{g_{a\gamma} B}{m_a} \simeq 10^{-15} \frac{B}{10 \text{ Tesla}} \frac{c_\gamma}{2}$$

**The small component does not depend on axion mass!**

- We know the typical axion amplitude  $\rightarrow$  typical electric field

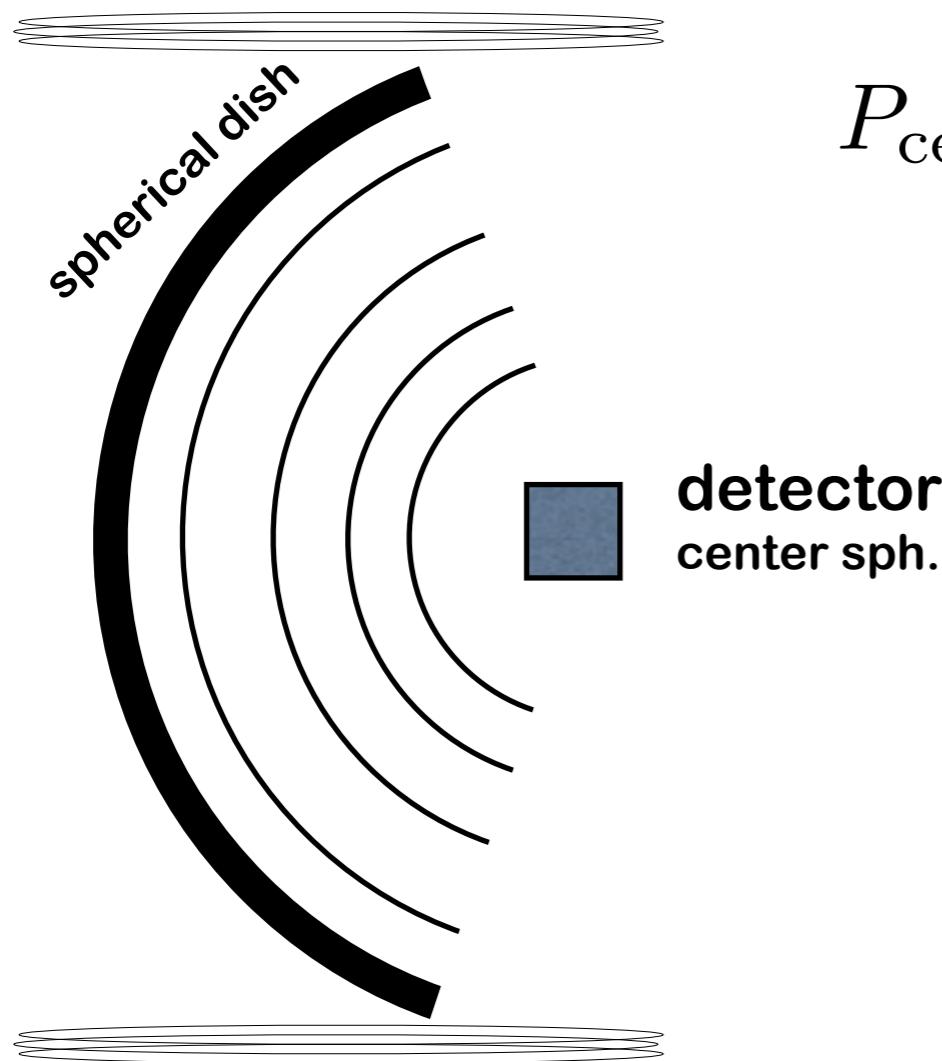
$$\rho_{\text{CDM}} = \frac{1}{2} m_a^2 a_0^2 = 0.3 \frac{\text{GeV}}{\text{cm}^3}$$

$$|\mathbf{E}|^2 \simeq |m_a \chi_a a_0|^2 \approx \chi_a^2 \rho_{\text{CDM}} = \chi_a^2 (2300 \text{ V/m})^2$$

$$|\mathbf{E}| \sim \frac{10^{-12} \text{ V}}{\text{m}} \frac{B}{5 \text{ Tesla}} \times \frac{c_\gamma}{2}$$

# Signal size

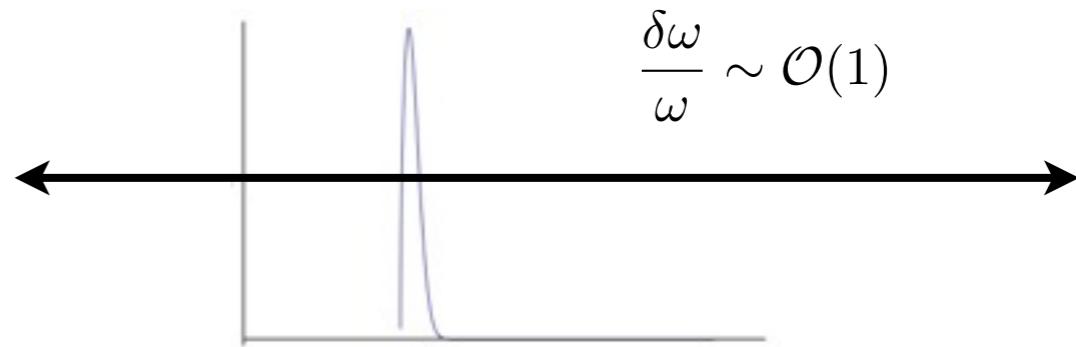
Horns et al , JCAP04(2013)016



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

**broadband!** 😊

measure 1/octave of a decade  
with the same detector at the same time



# Signal to noise

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$$\frac{S}{N} = \frac{P_{\text{signal}}}{P_{\text{noise}}} \rightarrow \frac{P_{\text{signal}}}{T_S} \sqrt{\frac{\text{time}}{\text{Bandwidth}}}$$

$$(P_{\text{noise}} \equiv T_S \Delta\omega)$$

measurement dominated by background

$$(T_{S\text{q.lim.}} = \omega)$$

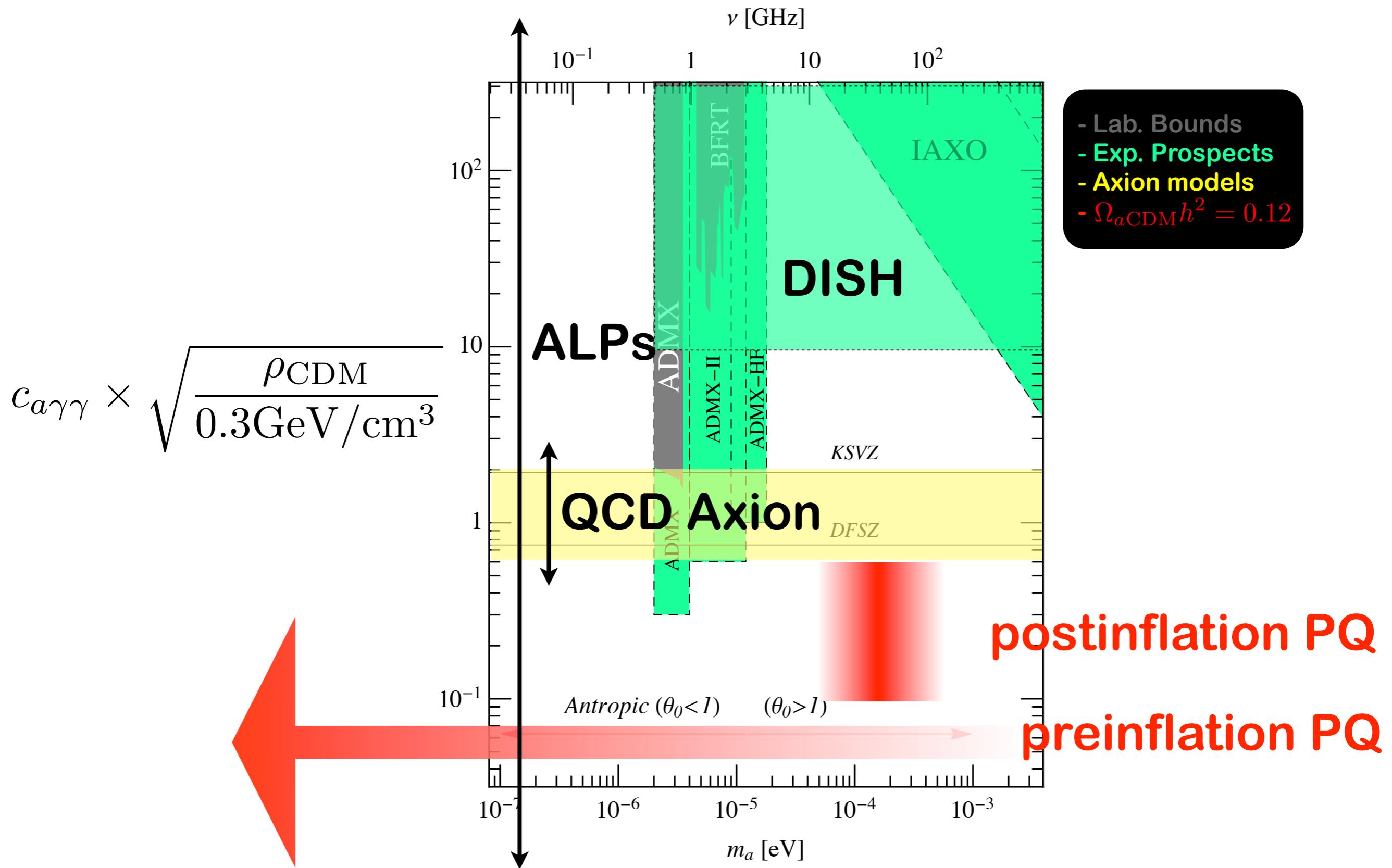
$$\frac{S}{N} = 3 \times 10^{-2} \frac{5\text{K}}{T_S} \frac{\text{Area}}{10 \text{ m}^2} \left( \frac{B}{5 \text{ T}} \frac{c_\gamma}{2} \right)^2 \sqrt{\frac{\text{time}}{1 \text{ year}} \frac{10^{-6}}{\Delta\omega/\omega} \frac{10 \mu\text{eV}}{m_a}}$$



diffraction  $m_a R \ll 1$

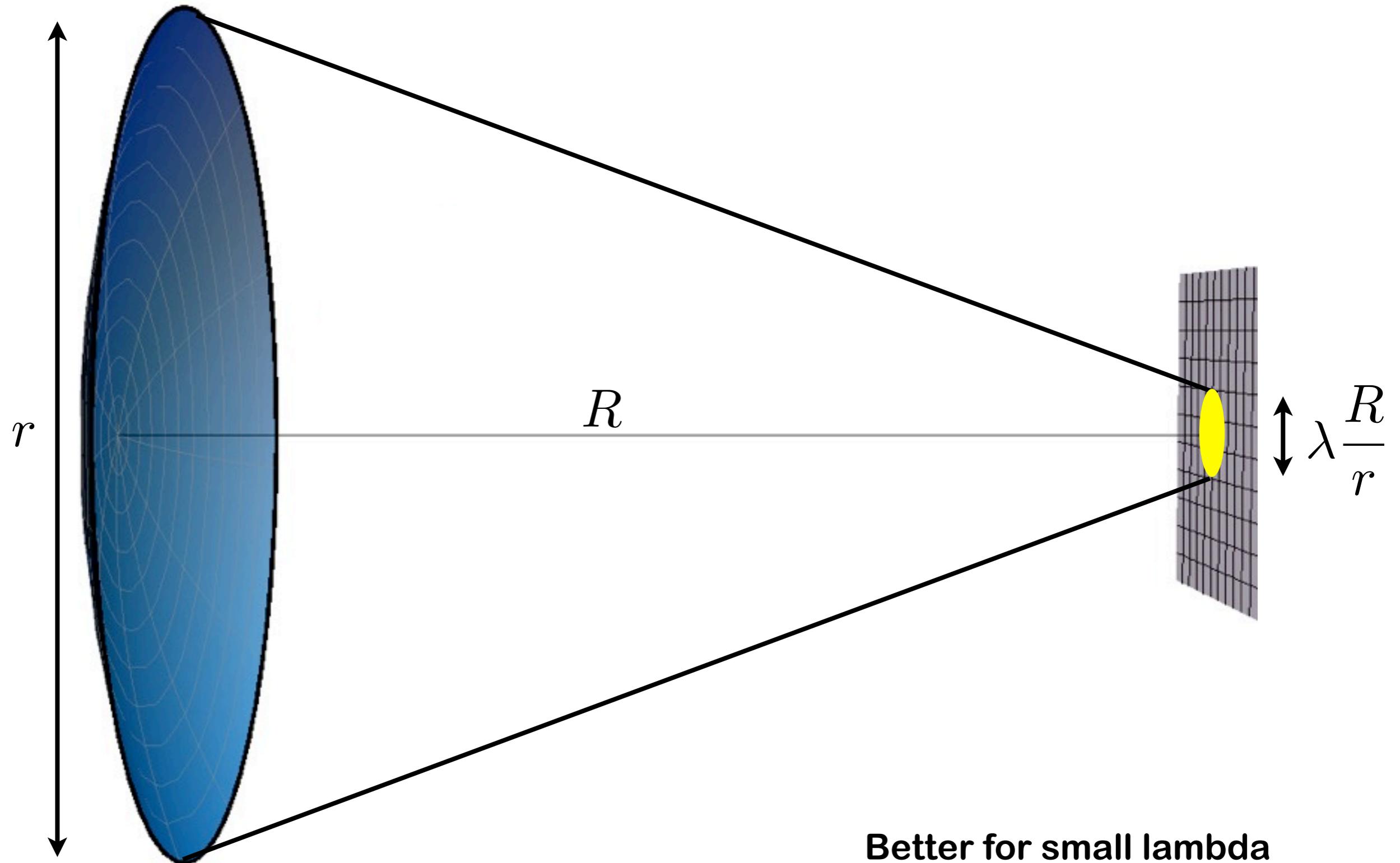
... need more area, more B, less noise, more time?  
... up-fluctuation in the DM density?

# Dish antenna reach: Axions and ALPs



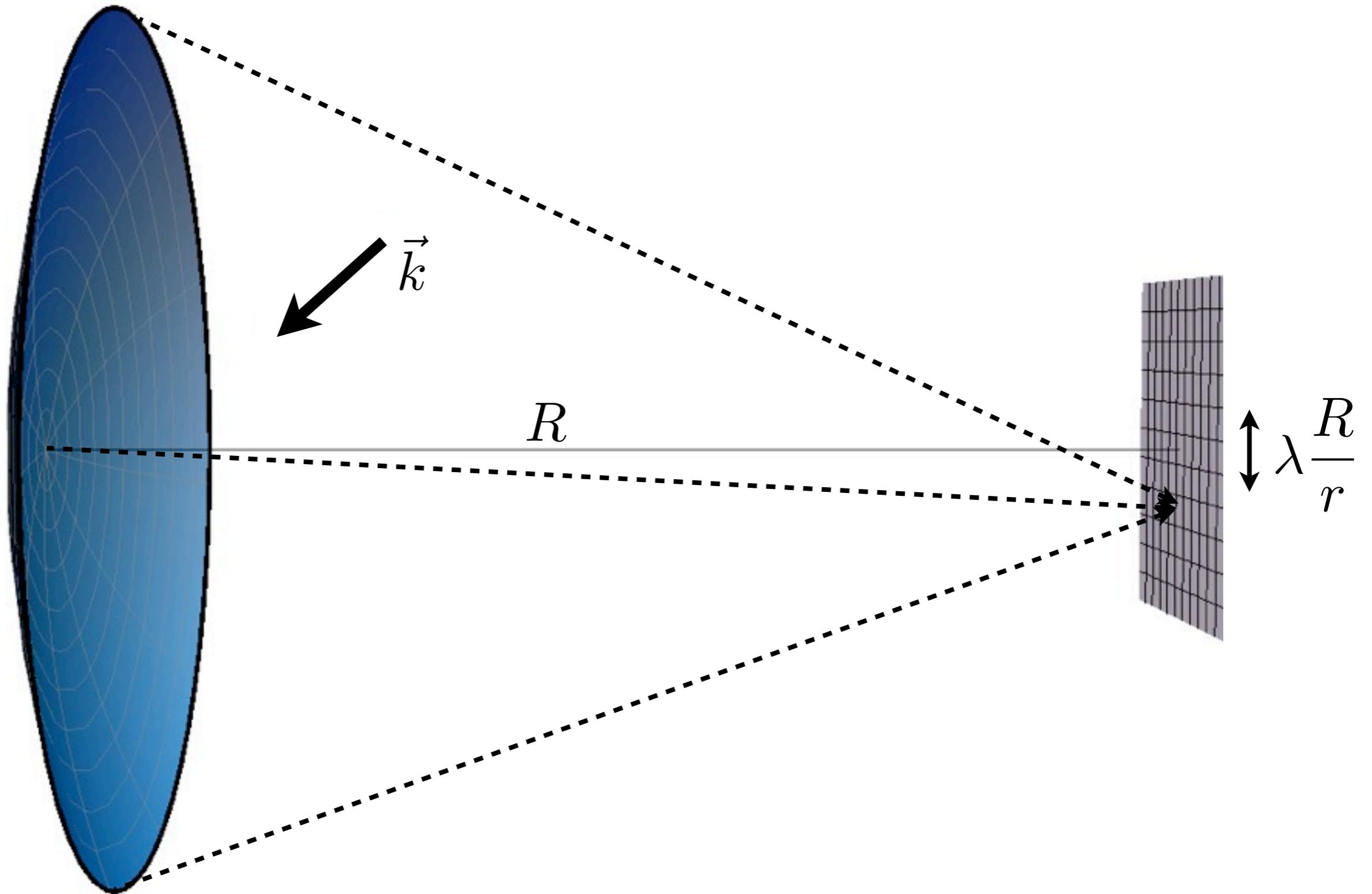
# Limitations: Diffraction

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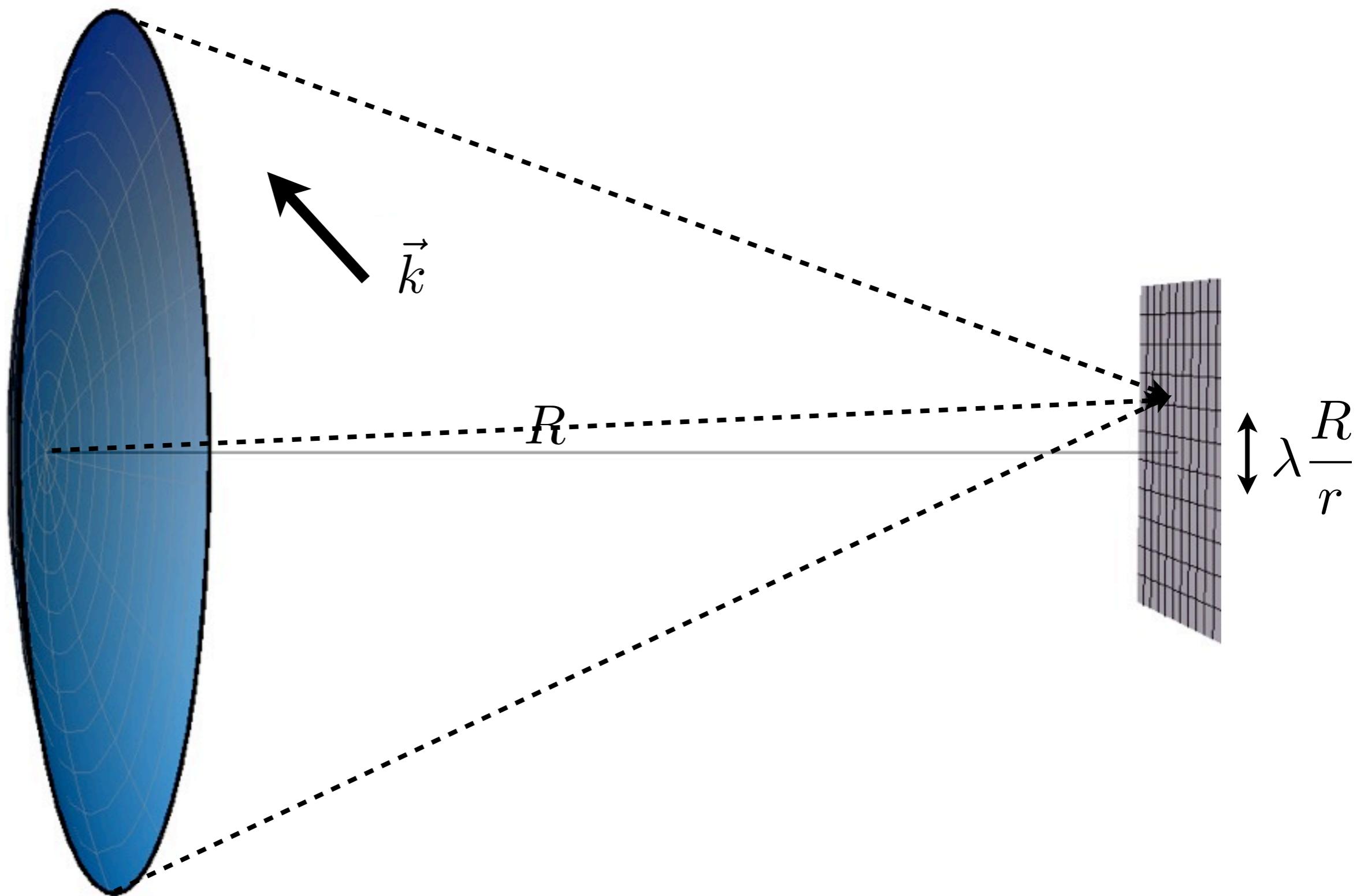
## Limitations: momentum distribution

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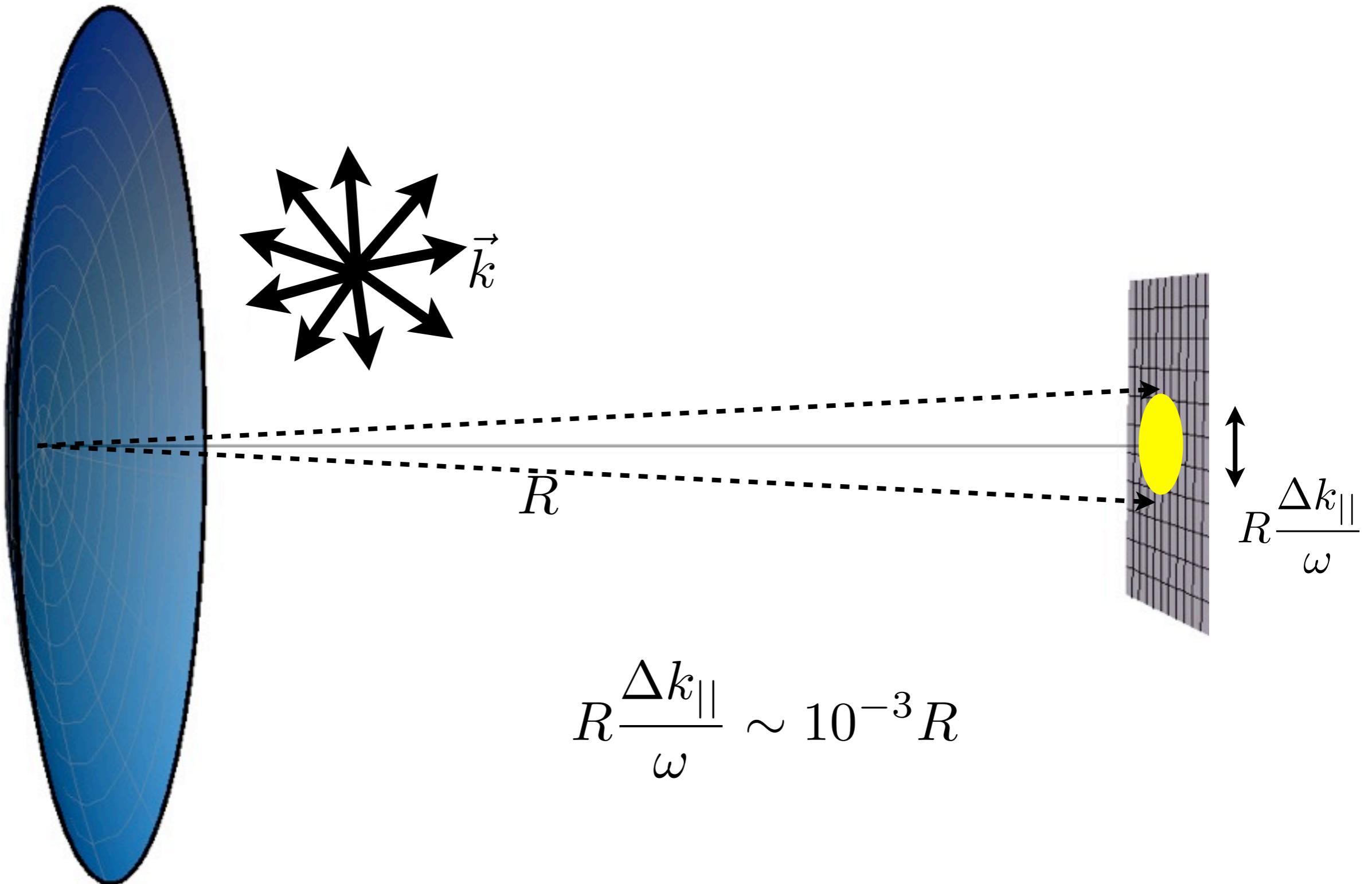
## Limitations: momentum distribution

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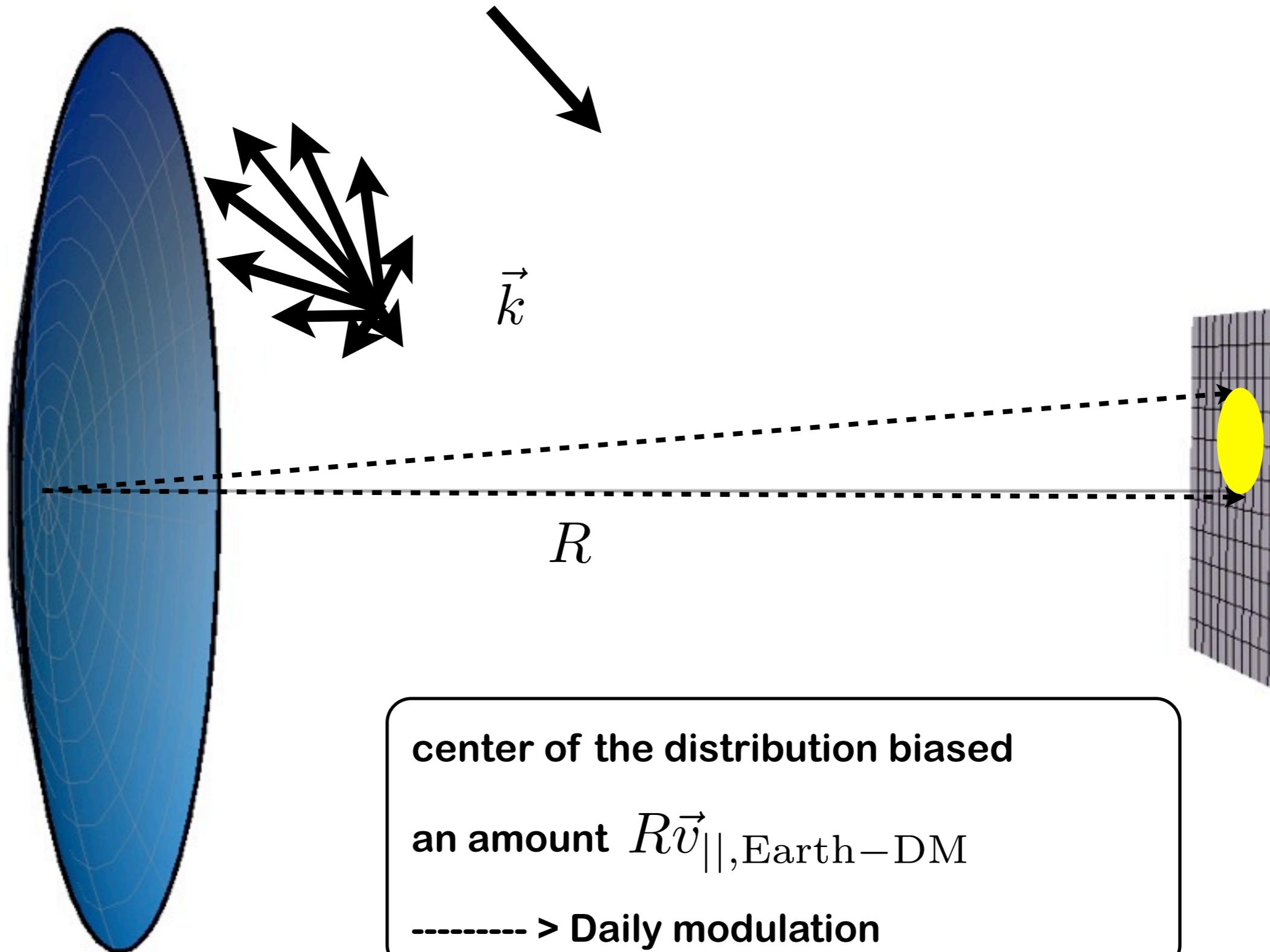


## Limitations: momentum distribution

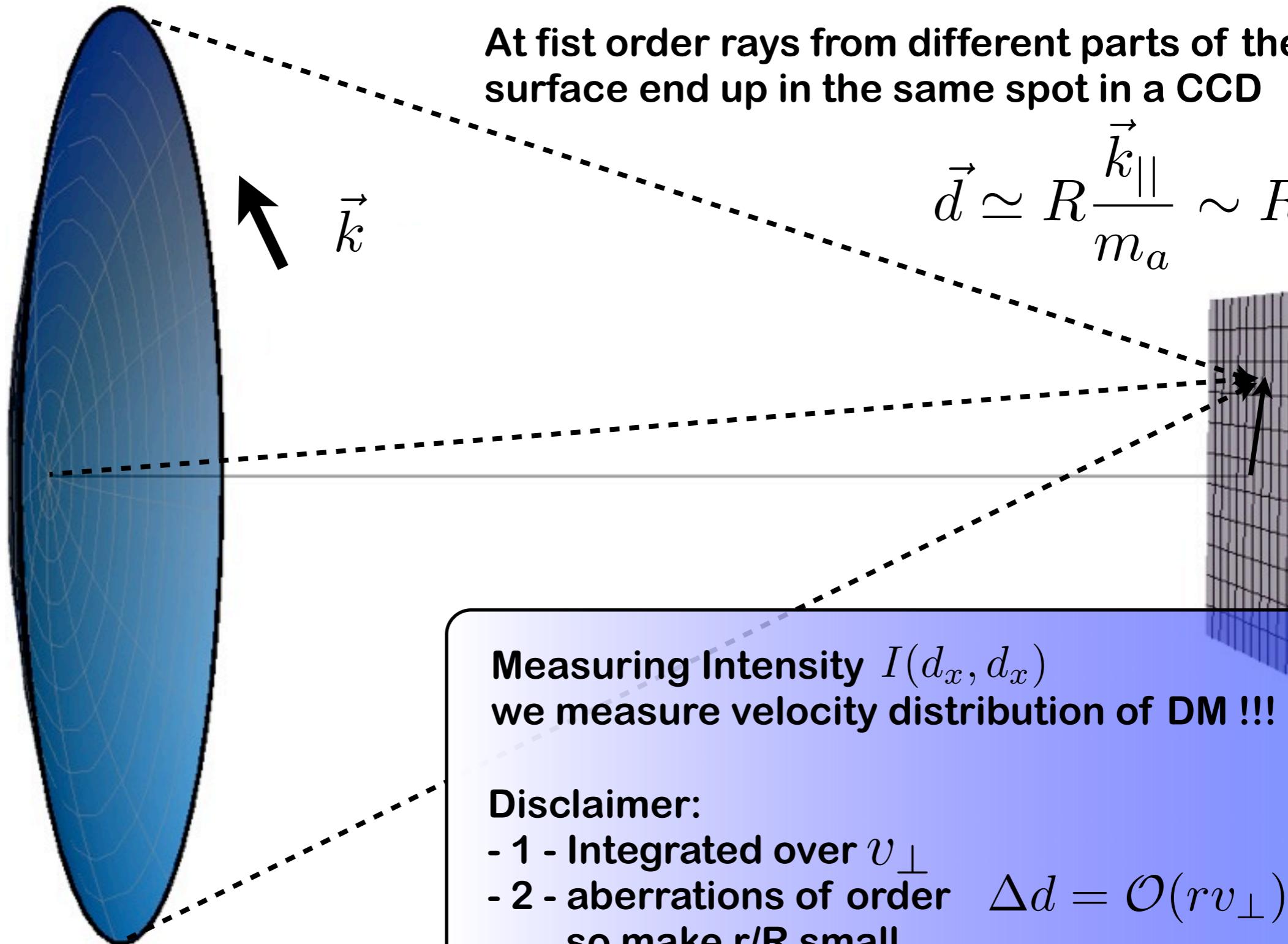
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## Limitations: momentum distribution and Earth's motion with respect to DM



# Detecting the velocity distribution of DM!



# Cavity searches (haloscopes)

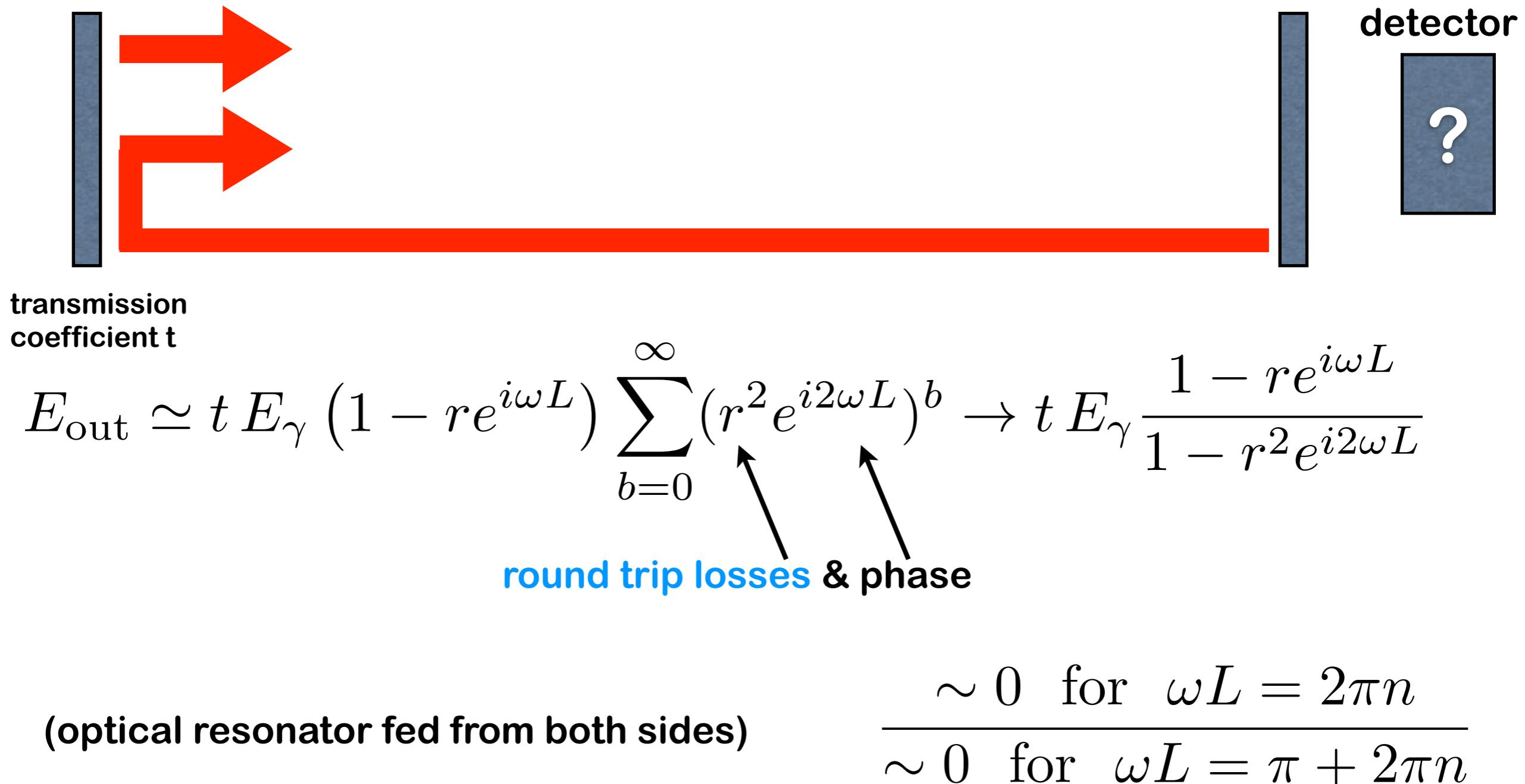
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- Different understanding of the conventional  
**HALOSCOPES**

# Cavity searches (haloscopes)

Sikivie PRL '83

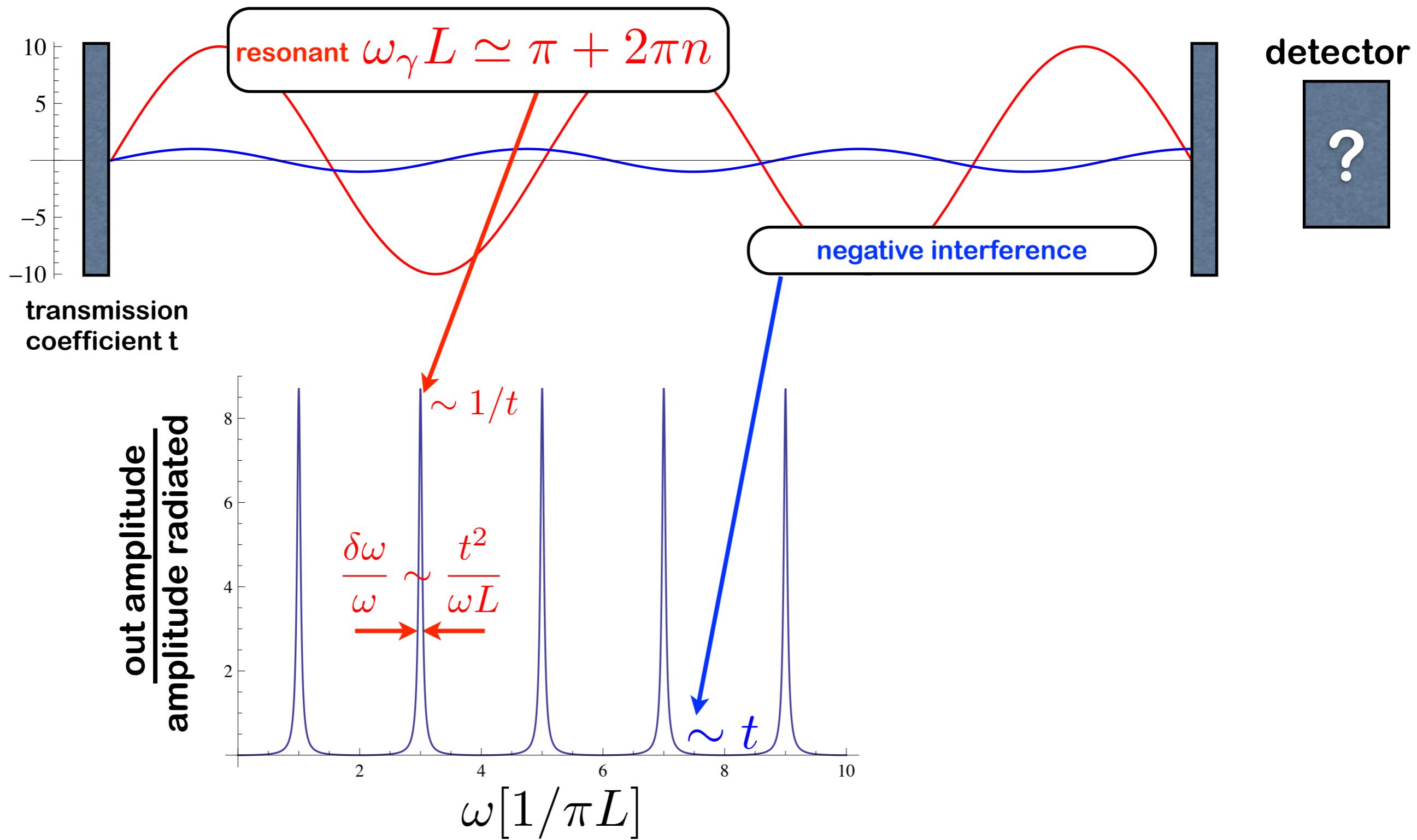
- Use two facing mirrors (simplistic resonant cavity in 1D)



# Cavity searches (haloscopes)

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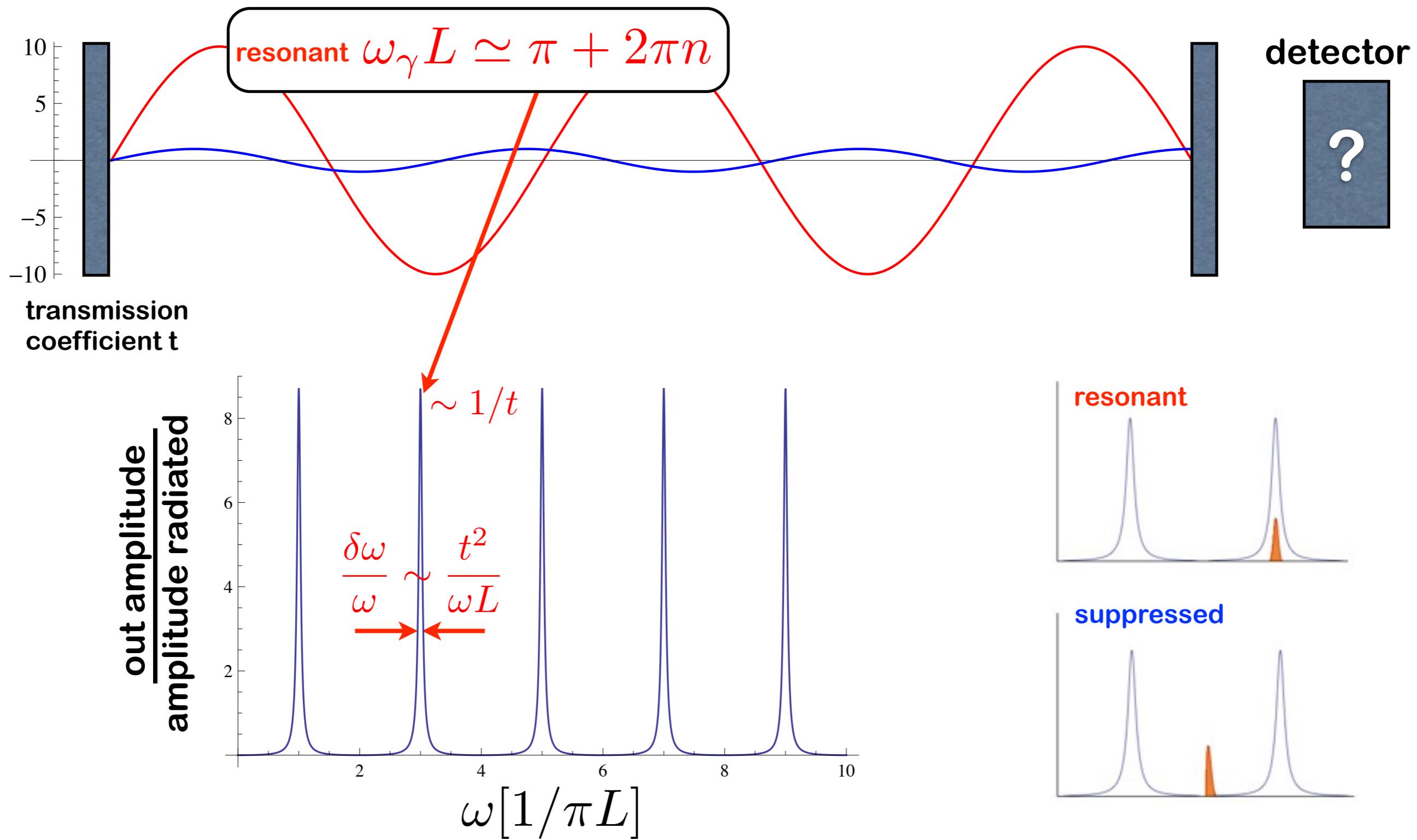
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Sikivie PRL '83

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



# Cavity searches (haloscopes)

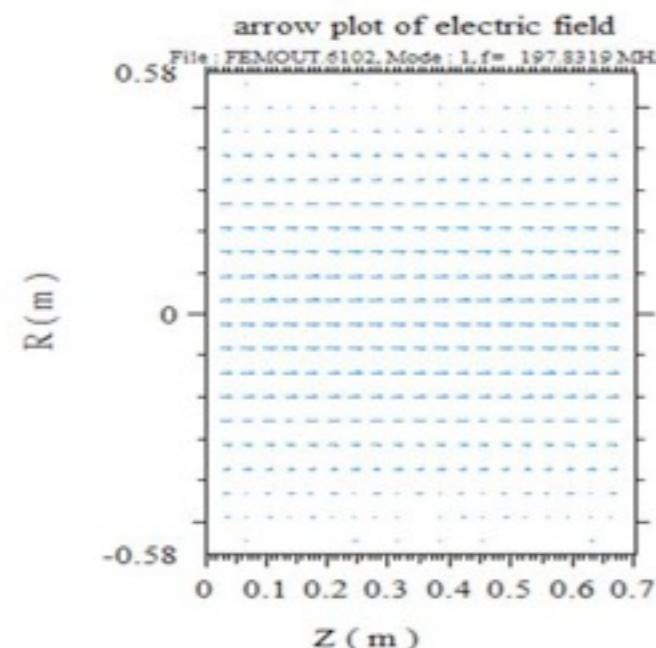
- Power Loss (cavity tuned!!); putting an pickup we can ideally extract the same

$$P_{\text{loss}} = \frac{1}{t^2} \chi^2 \rho_{\text{CDM}} \text{Area}$$

$$P_{\text{out}} \sim 10^{-20} \frac{\text{W}}{\text{m}^2} \left( \frac{B}{10T} \frac{c_\gamma}{2} \right)^2 \frac{\text{Area}}{1 \text{ m}^2}$$

- Usual 3-D formula is

$$P_{\text{out}} = \kappa Q \chi^2 \rho_{\text{CDM}} (m_a V) \mathcal{G}$$



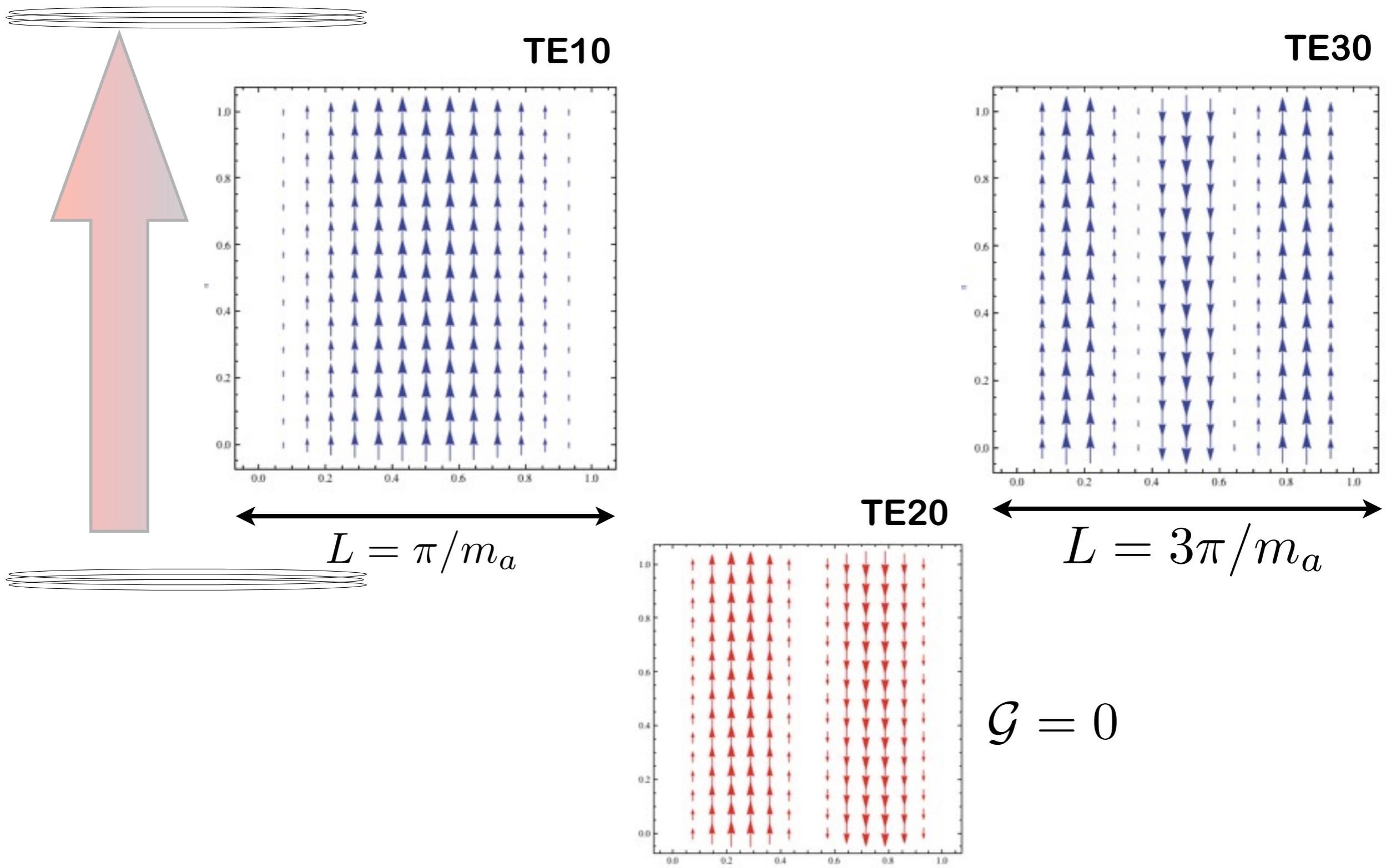
$Q$  quality factor

$$\mathcal{G} = \frac{\left( \int dV \mathbf{E}_{\text{mode}} \cdot \mathbf{B} \right)^2}{|\mathbf{B}|^2 V \int dV |\mathbf{E}_{\text{mode}}|^2}$$

$\kappa$  coupling

# Cavity searches (haloscopes)

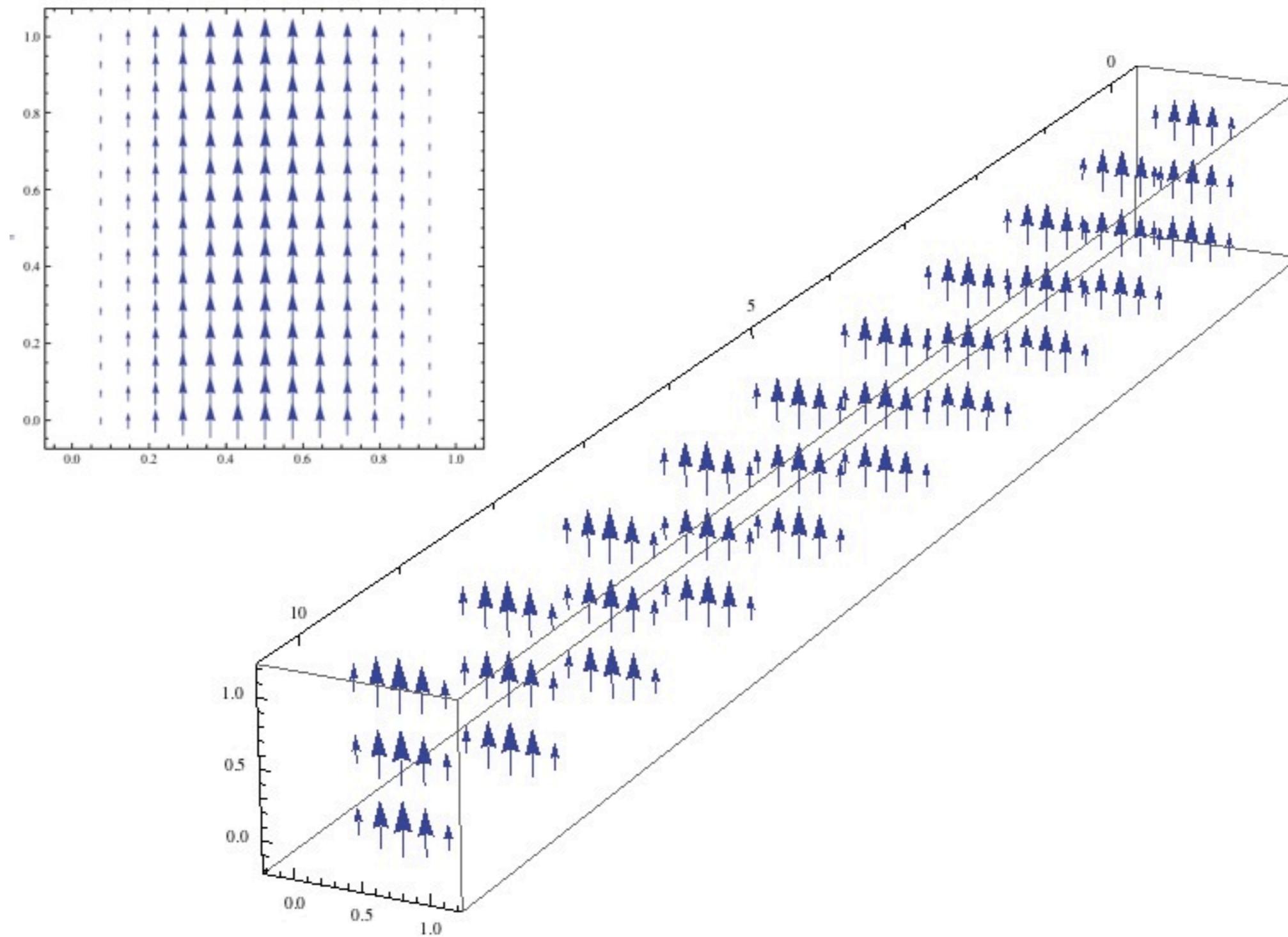
- Pillbox cavity



# Cavity searches (haloscopes)

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## - Pillbox cavity



# Cavity searches (haloscopes)

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

$$L_{x,y,z} = 0.6 \text{ m} \times n_{x,y,z}$$

- Problem: we don't know the axion mass -> scan over resonant freqs.

- Explore resonant frequencies (not many suitable, factor of a few)
- change L\_s? (feasible?)
- Set of plugs? (typically small range)
- Massive tuning rods/whatevers?
- Different cavities?

# ADMX

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

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



Liquid He

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

Scan much faster!

$$1\text{year} = 5 \times 10^5 \text{min}$$

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

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

## - ADMX-HF

Higher the mass; (smaller cavity...), larger bandwidth, QL higher  
typically smaller signal; larger background -> less sensitive

# Cavity searches II: ADMX and relatives

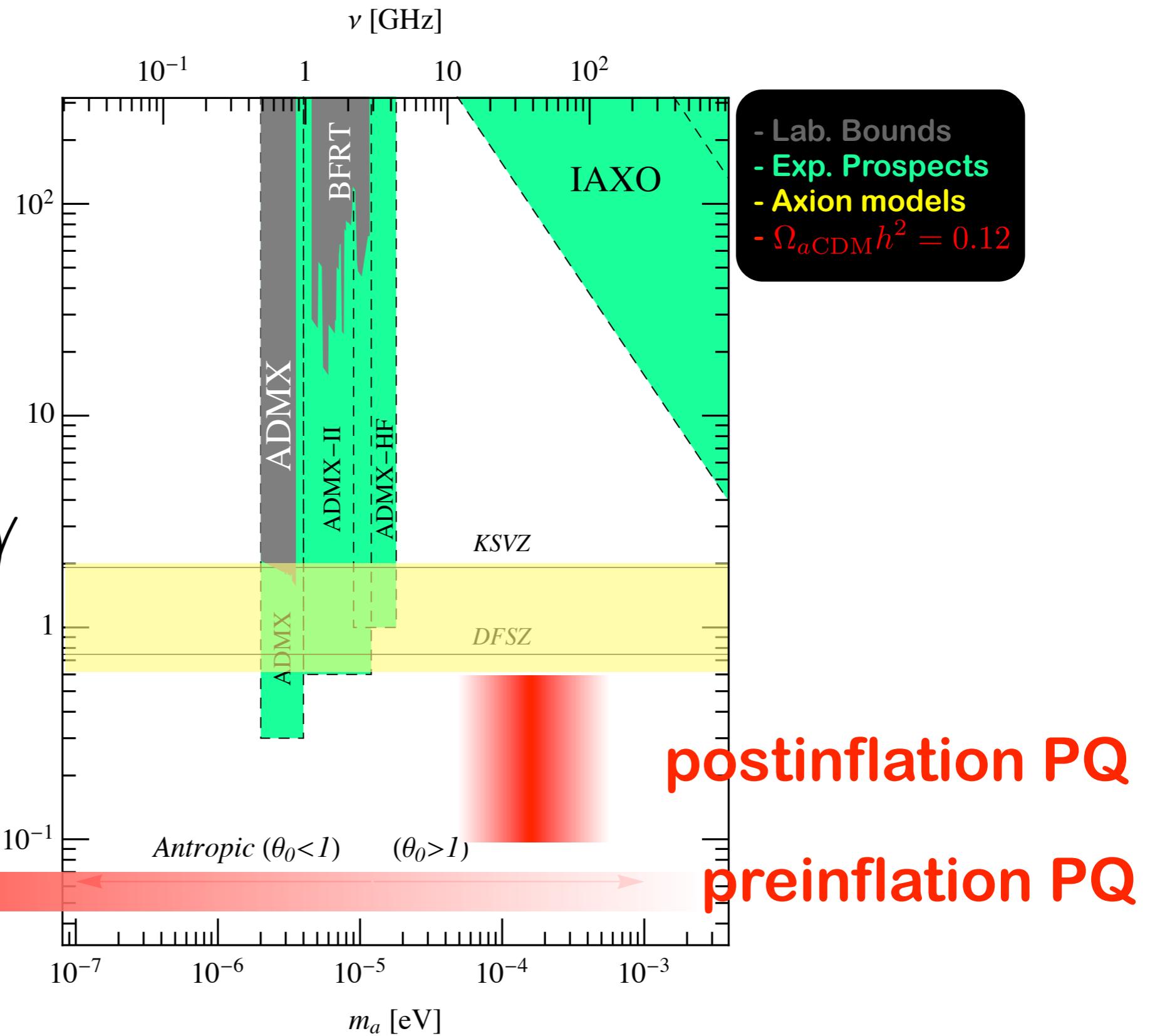
**coupling to two photons**

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

$$m_a = m_a(f_a)$$

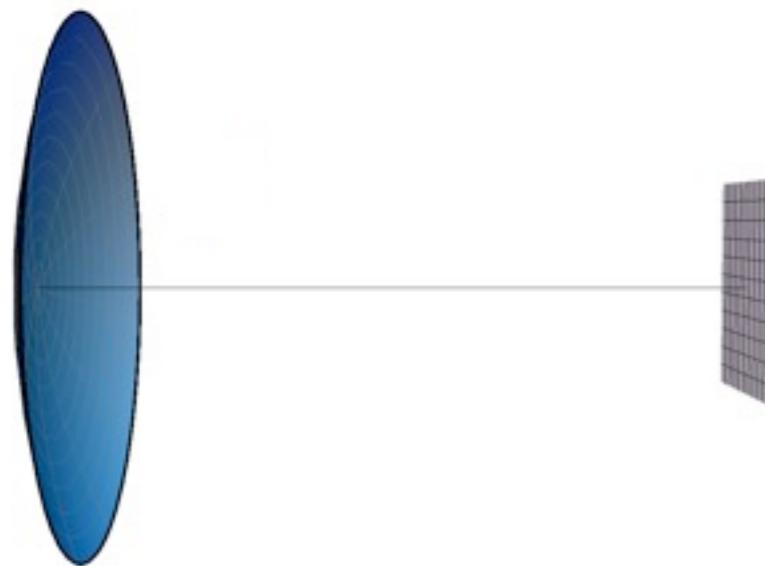
$$c_\gamma$$

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

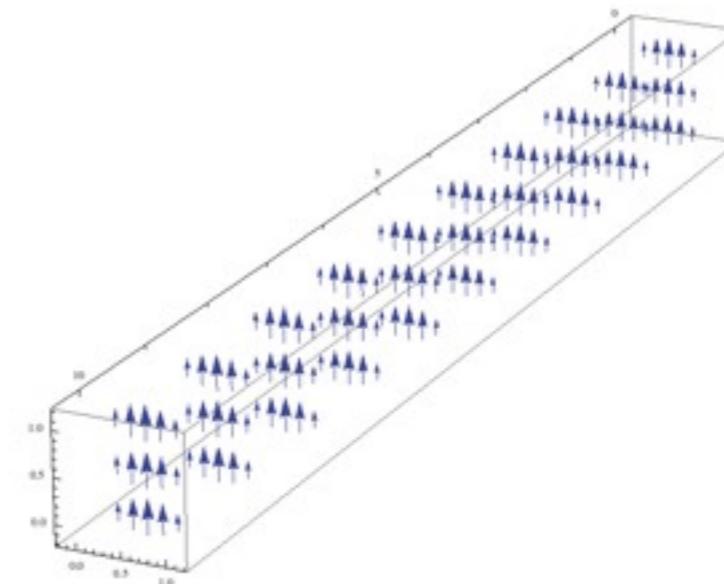


# Comparison

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vs



$$L = \pi/m_a$$

- broadband
- quite insens. to mass

- needs tune
- very sens. to mass

$$\frac{P_{\text{dish}}}{P_{\text{cavity}}} \sim \frac{A_{\text{dish}} m_a^2}{Q_{\text{cavity}}} \sim \frac{A_{\text{dish}} m_a^2}{10^5 - 10^6}$$

- better at large mass

- better at small mass

# Conclusions

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- Axion DM - well motivated
  - underrepresented (getting better)
  - testable
  - key targets not covered
- 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!

# Getting better

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- New IBS (Institute of Basic Science) Center for Axion and Precision Physics (CAPP) KAIST campus, Daejeon/Korea
- + in US, Yale developing ADMX-HF
- Europe getting involved (DESY, CERN, Unizar)

## - International Axion Observatory

main goal:  
solar axions  
but also DM

