A new experiment to search for WISPy dark matter

Dec 13th 2013

Université Libre de Brussels

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Outline

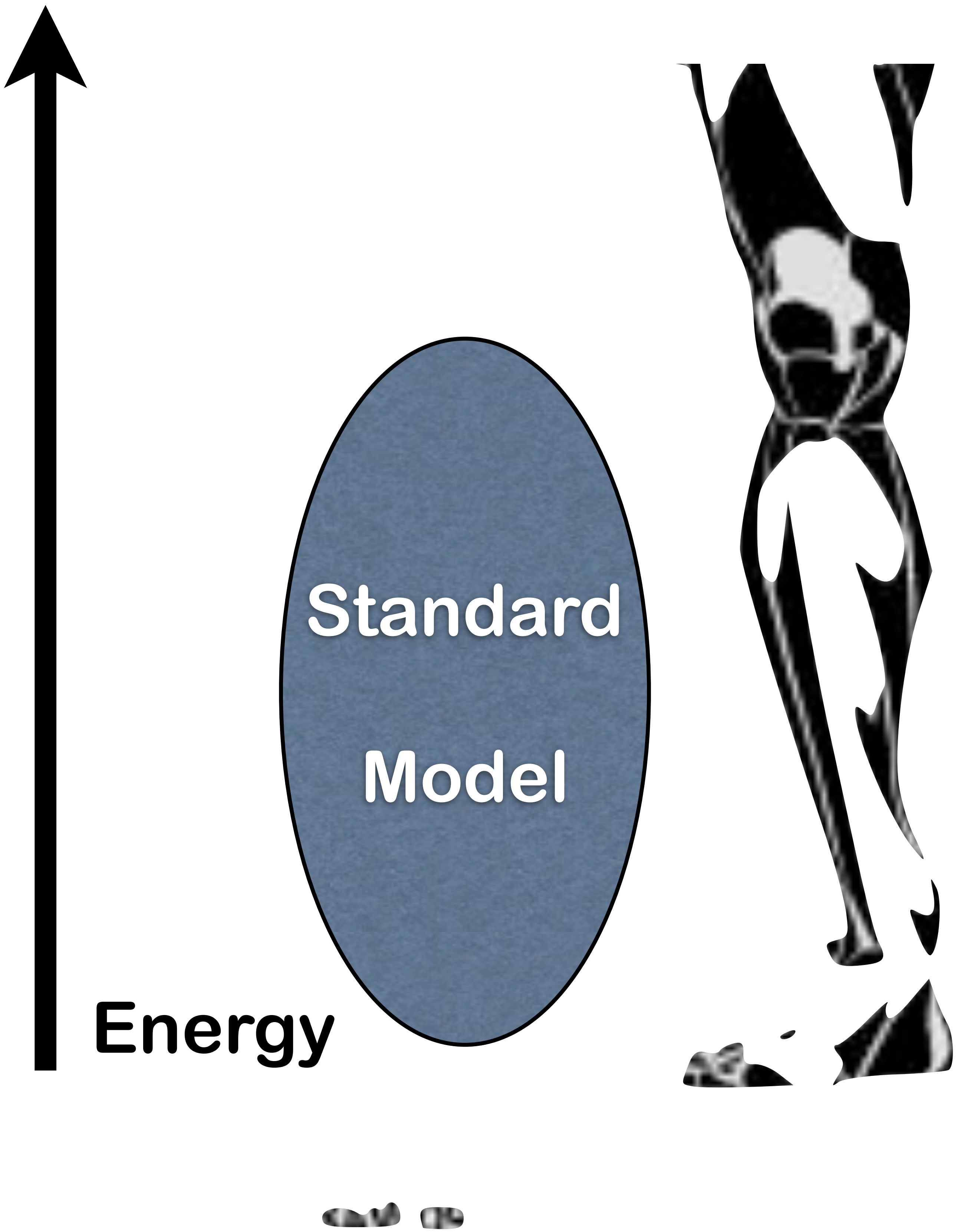
- Summary of Axion and ALP DM

- Axion DM waves in Magnetic fields

- Dish experiment

- Understanding cavity experiments

Beyond the SM ... at low energies

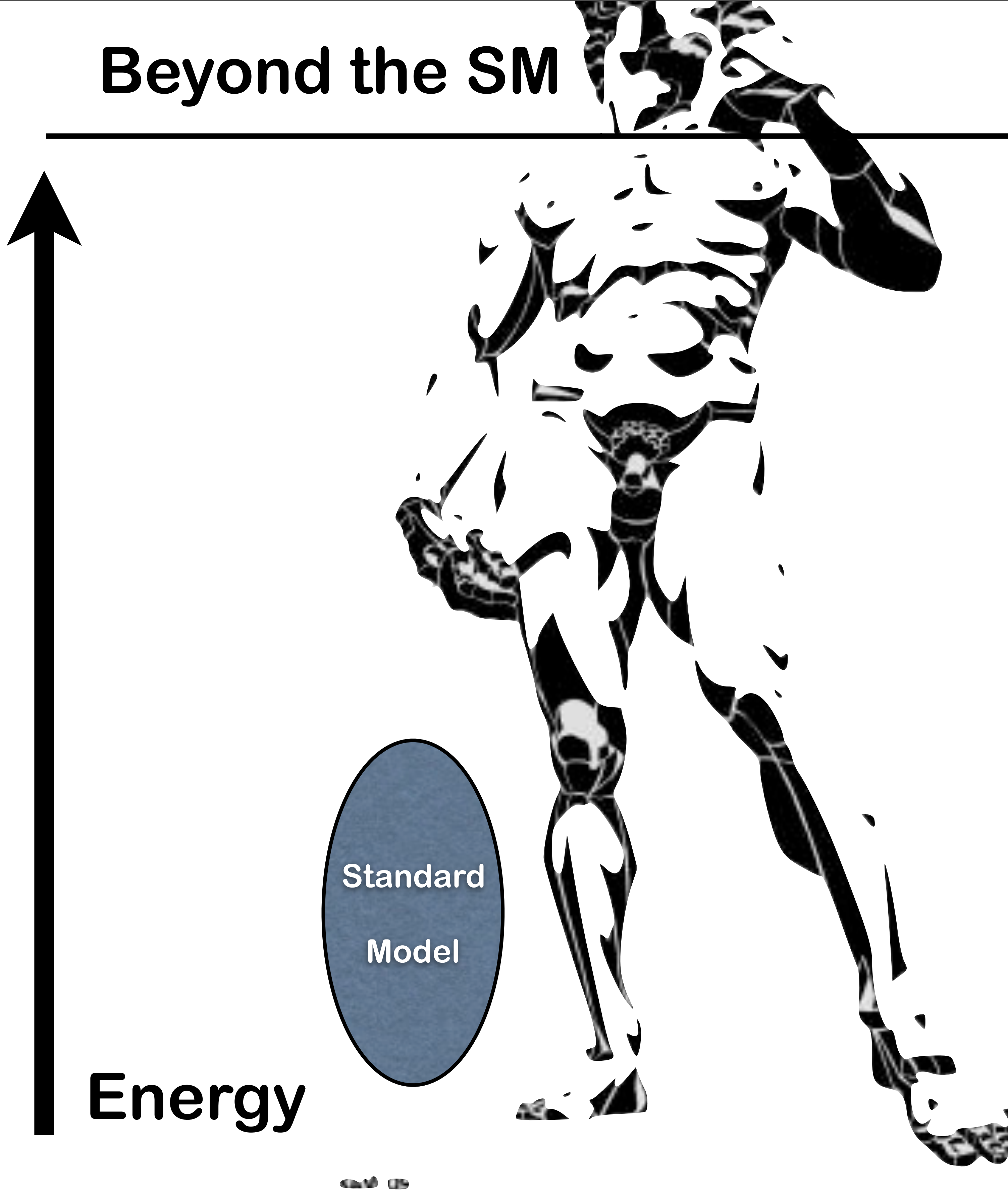


Describes extremely well fundamental physics (at low energies)

but feels certainly

INCOMPLETE

Beyond the SM ... at low energies



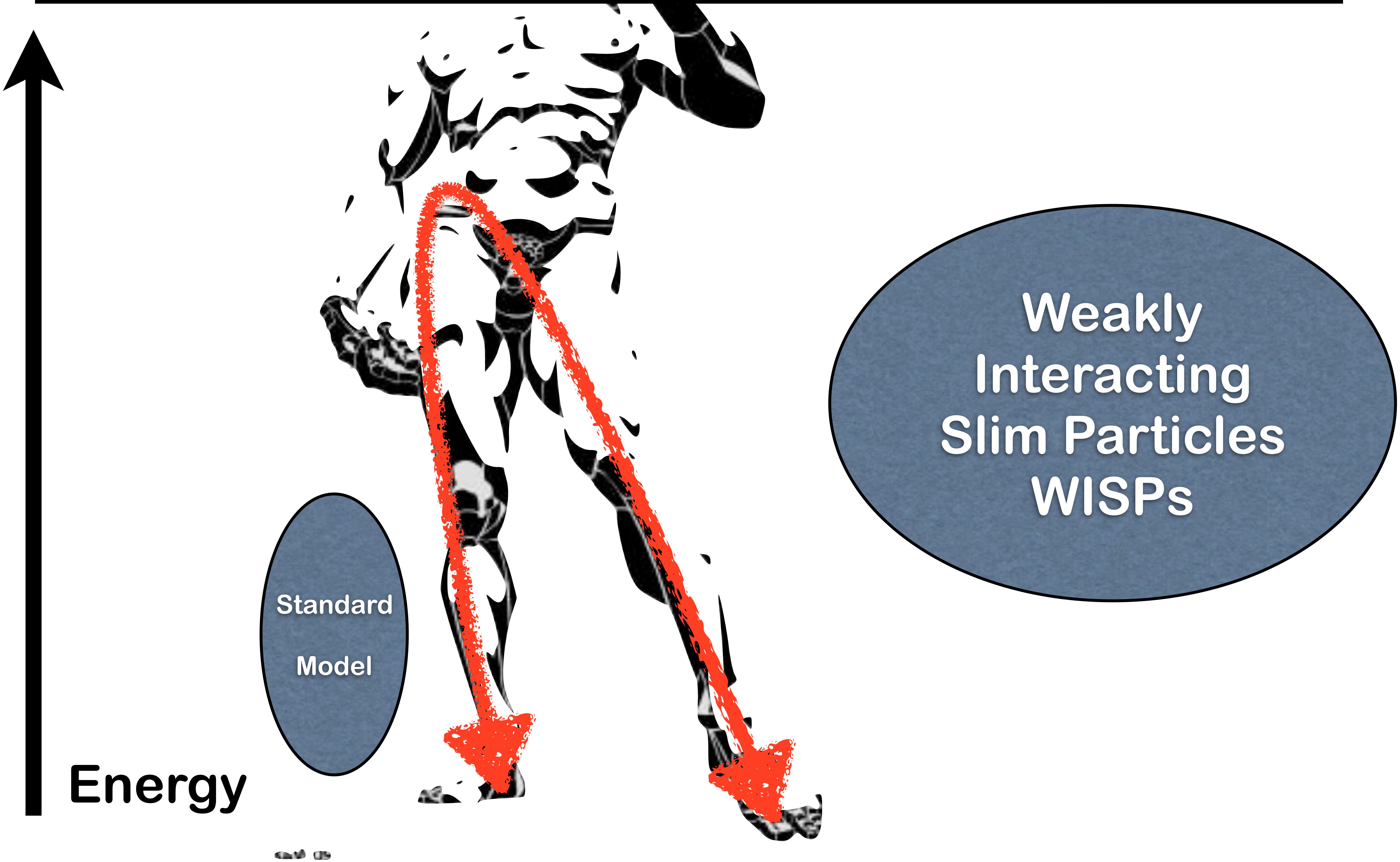
Answers are awaiting in the

high energy frontier

where more symmetric beautiful theories arise

... and can imply physics at low energies

Beyond the SM ... at low energies



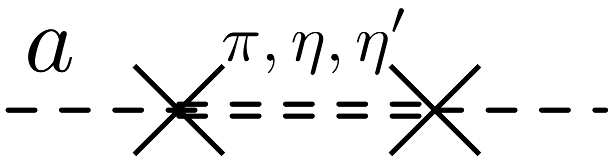
Axions!

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

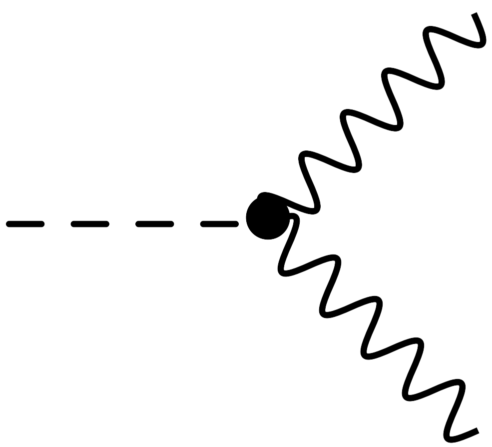
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\mathrm{tr}\left\{G_a^{\mu\nu}\widetilde{G}_{a\mu\nu}\right\}\left(\theta + \frac{a}{f_a}\right)$$ **the QCD theta angle is dynamical !!**

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

- **Axion properties**



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



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

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

Axions!

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

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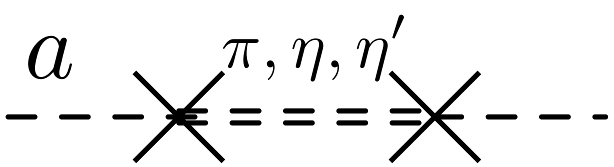

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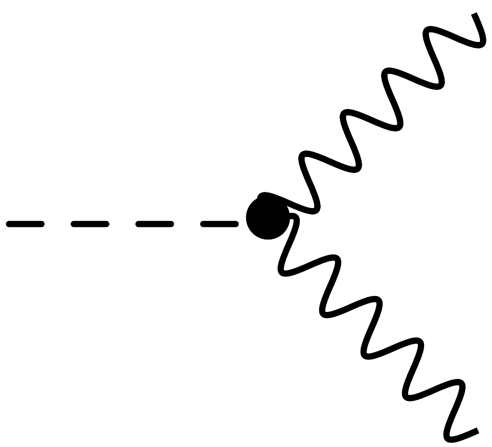


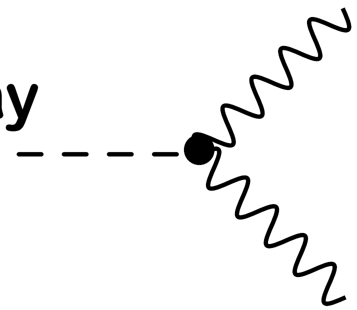
$$\frac{\alpha}{8\pi}(F_{\mu\nu}\widetilde{F}^{\mu\nu})c_{a\gamma\gamma}\frac{a}{f_a}$$

WISP

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

Axion cold dark matter

- **Axions decay**



$$\tau \sim \frac{1}{g_{a\gamma}^2 m_a^3} \propto \frac{1}{m_a^5}$$

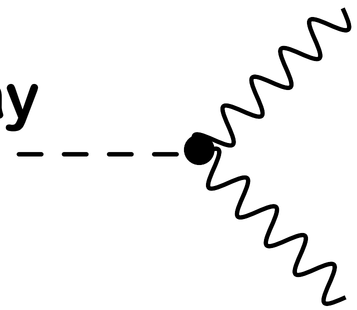
only low mass axions can be DM!

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

$$m_a > {\rm meV???}$$

Axion cold dark matter

- Axions decay



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only low mass axions can be DM!

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

~~m_a … V ???~~

- 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

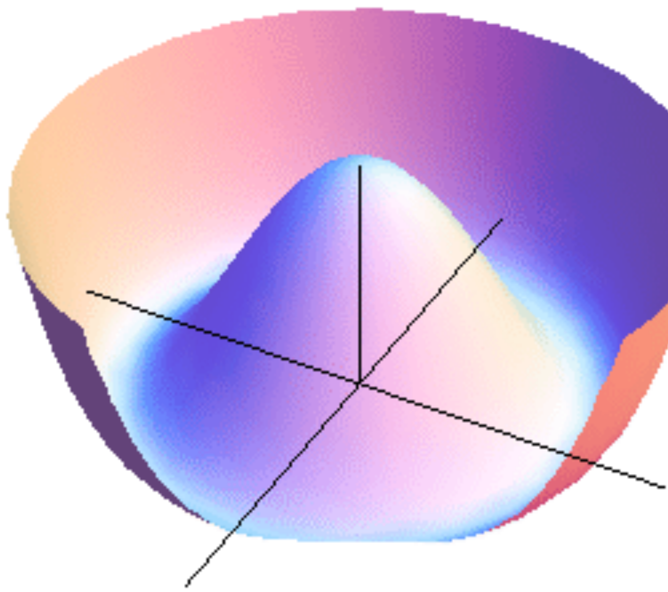
$$\frac{a(t_0)}{f_a} \in (-\pi, \pi)$$

At PQ phase transition

Axion cold dark matter I

Realignment mechanism

(Field space)



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

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

Axion cold dark matter I

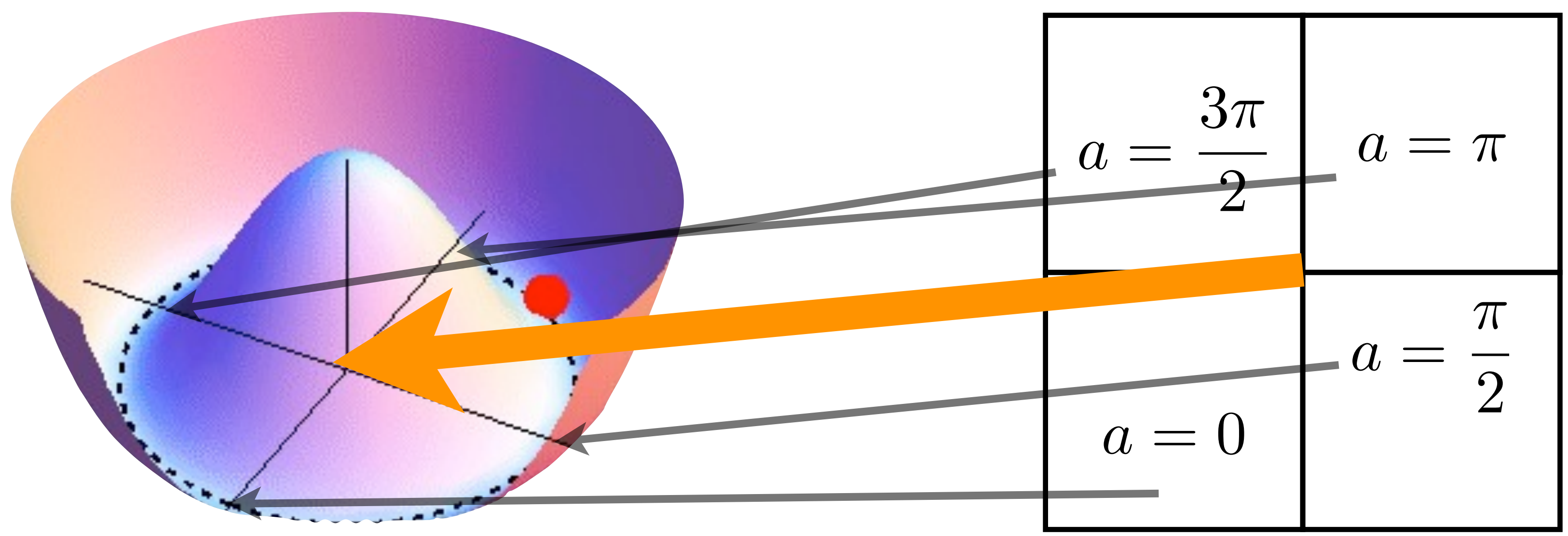
Realignment mechanism

Cosmic Strings

(Field space)

(Position space)

(T>QCD)



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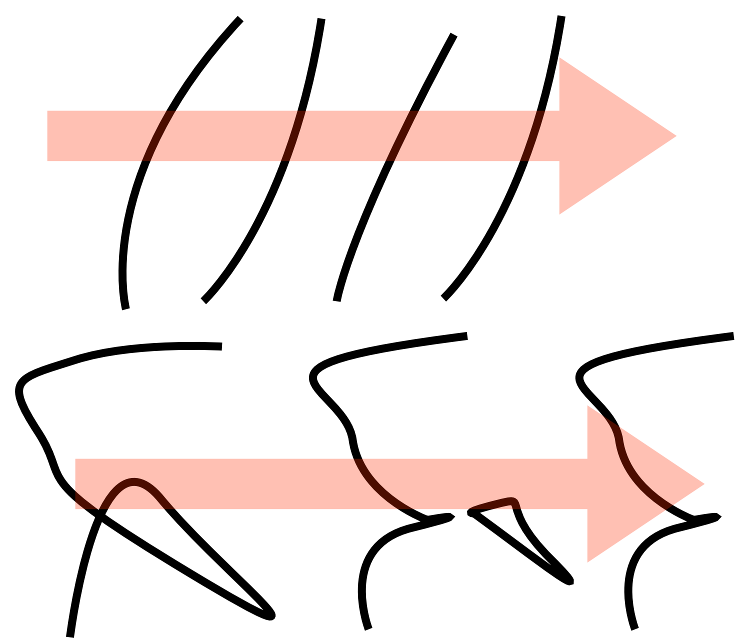

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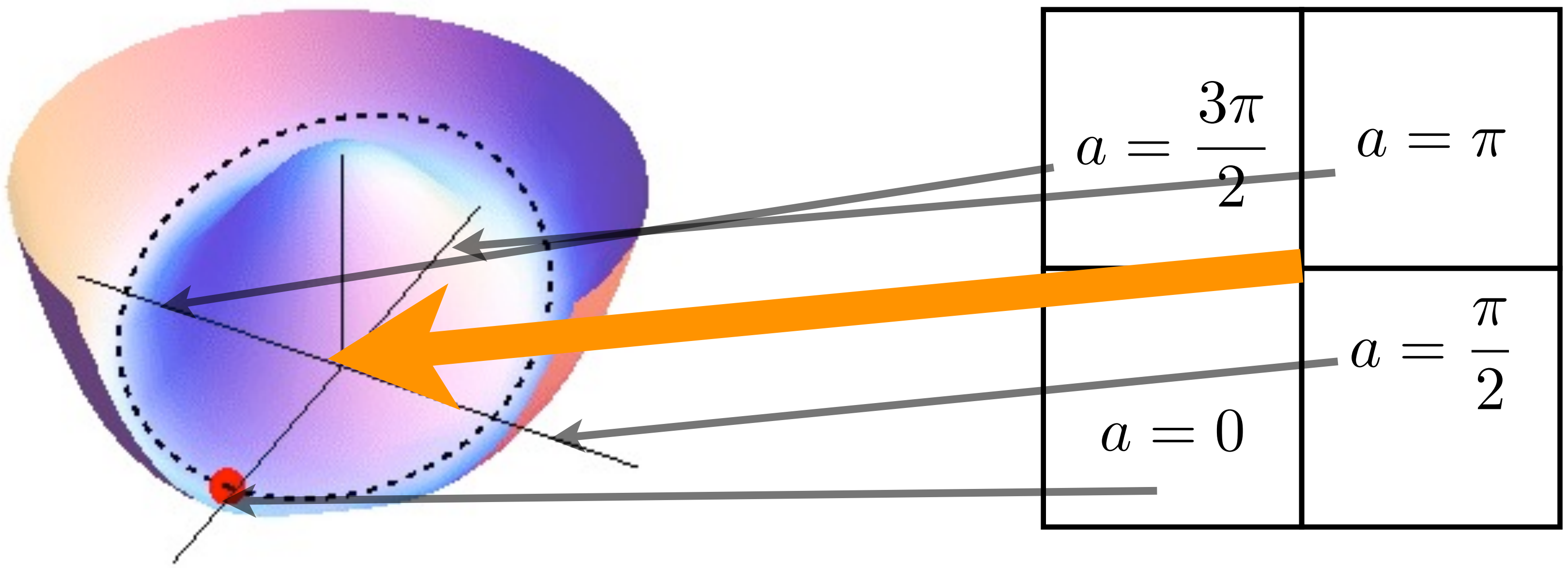

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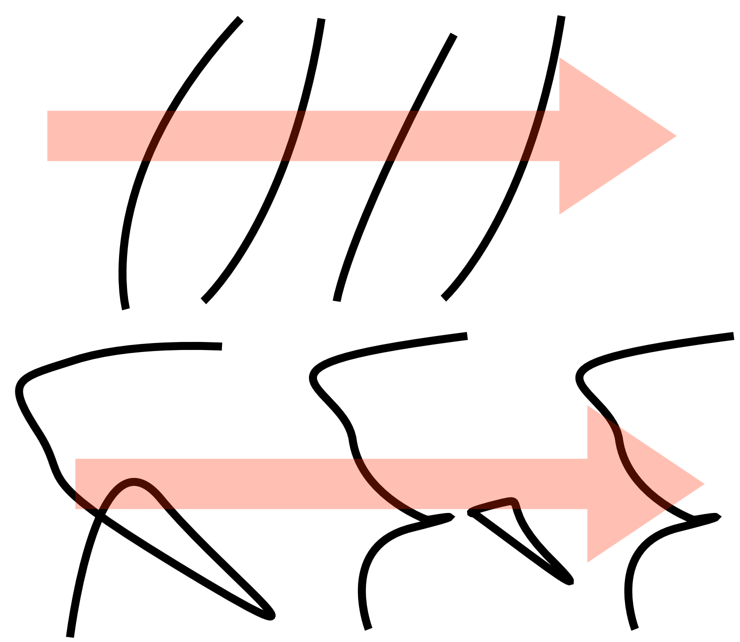
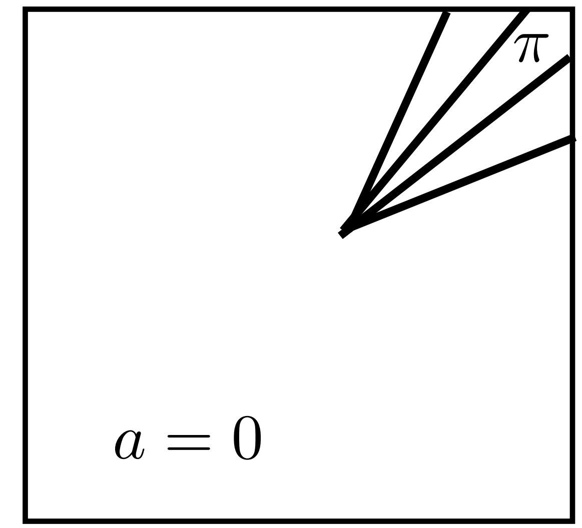
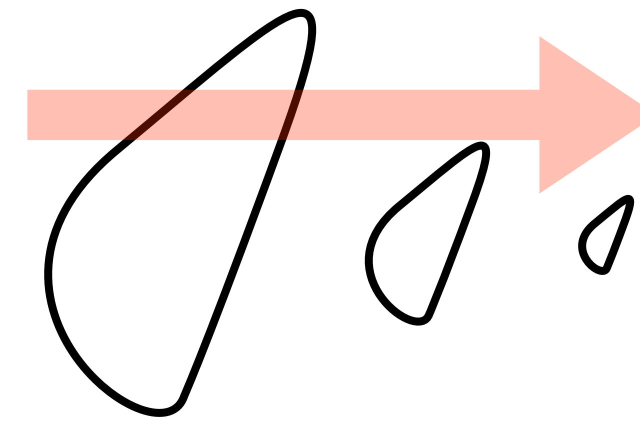


Domain Walls

(T<QCD)





Axion cold dark matter I

Realignment mechanism

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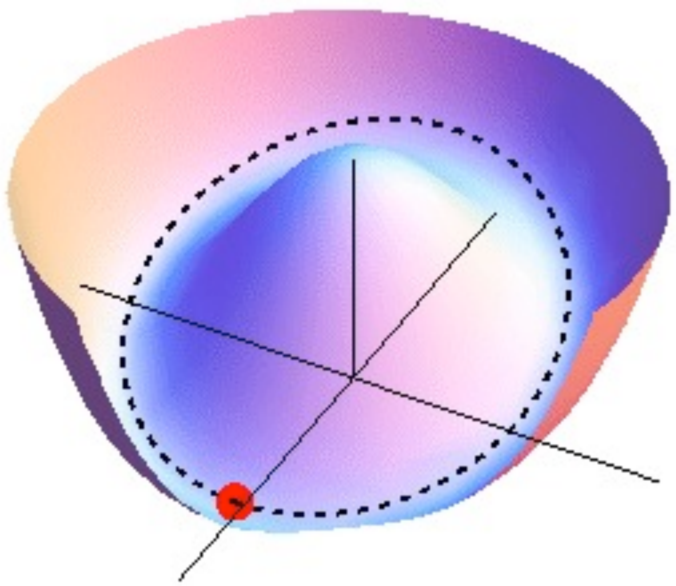
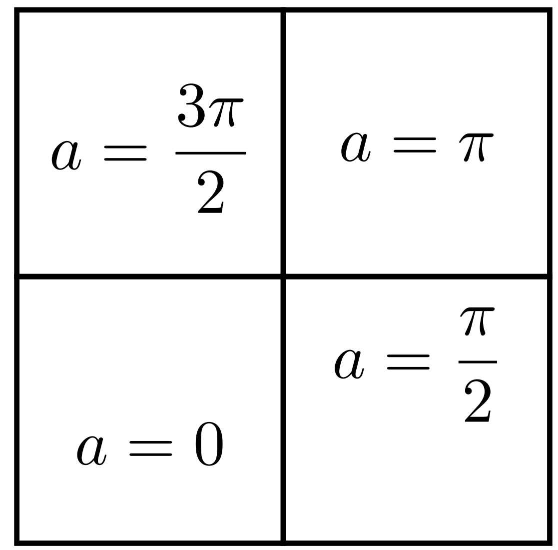


Cosmic Strings

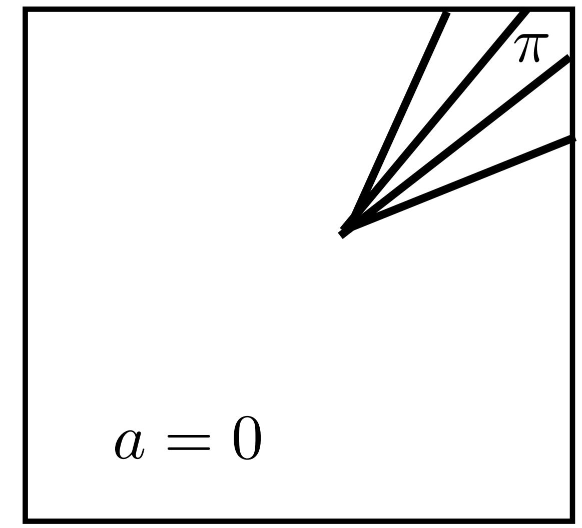
(Position space)

(T>QCD)



Domain Walls

(T<QCD)



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

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

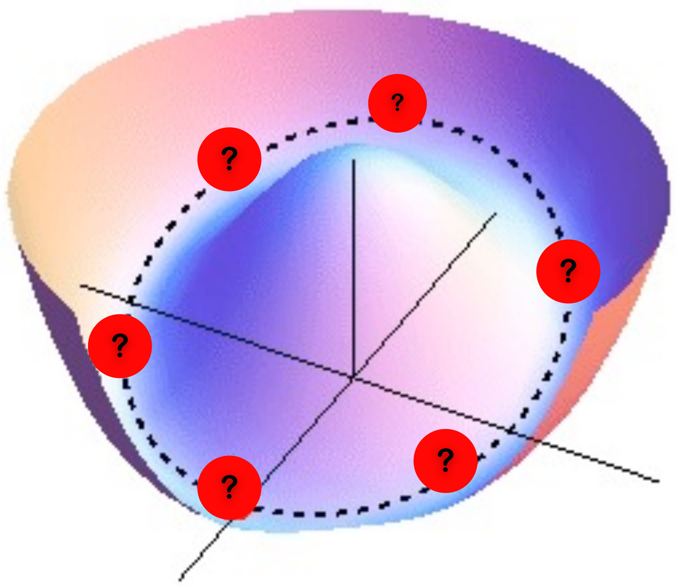
Sikivie, Harari et at.

Shellard, Davis et at.
Kawasaki, Hiramatsu et at

Axion cold dark matter II (PQ before inflation)

Realignment mechanism

(Field space)



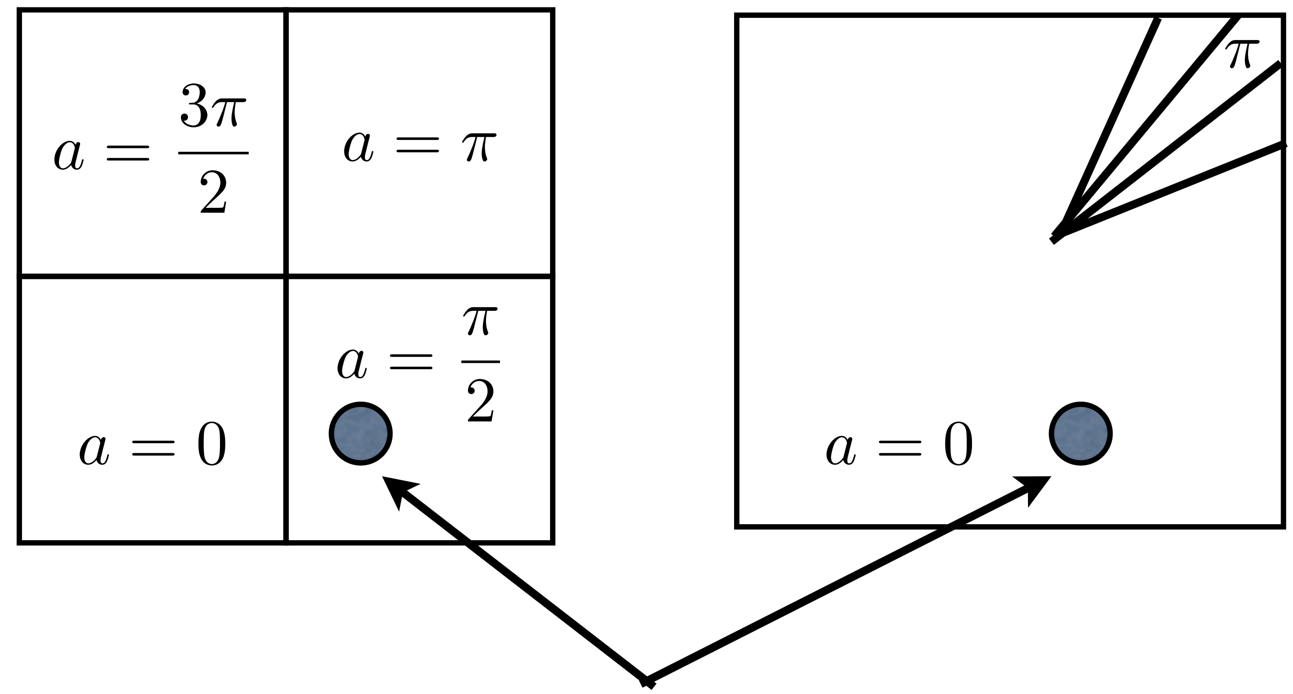
Cosmic Strings

(Position space)

(T>QCD)

Domain Walls

(T<QCD)



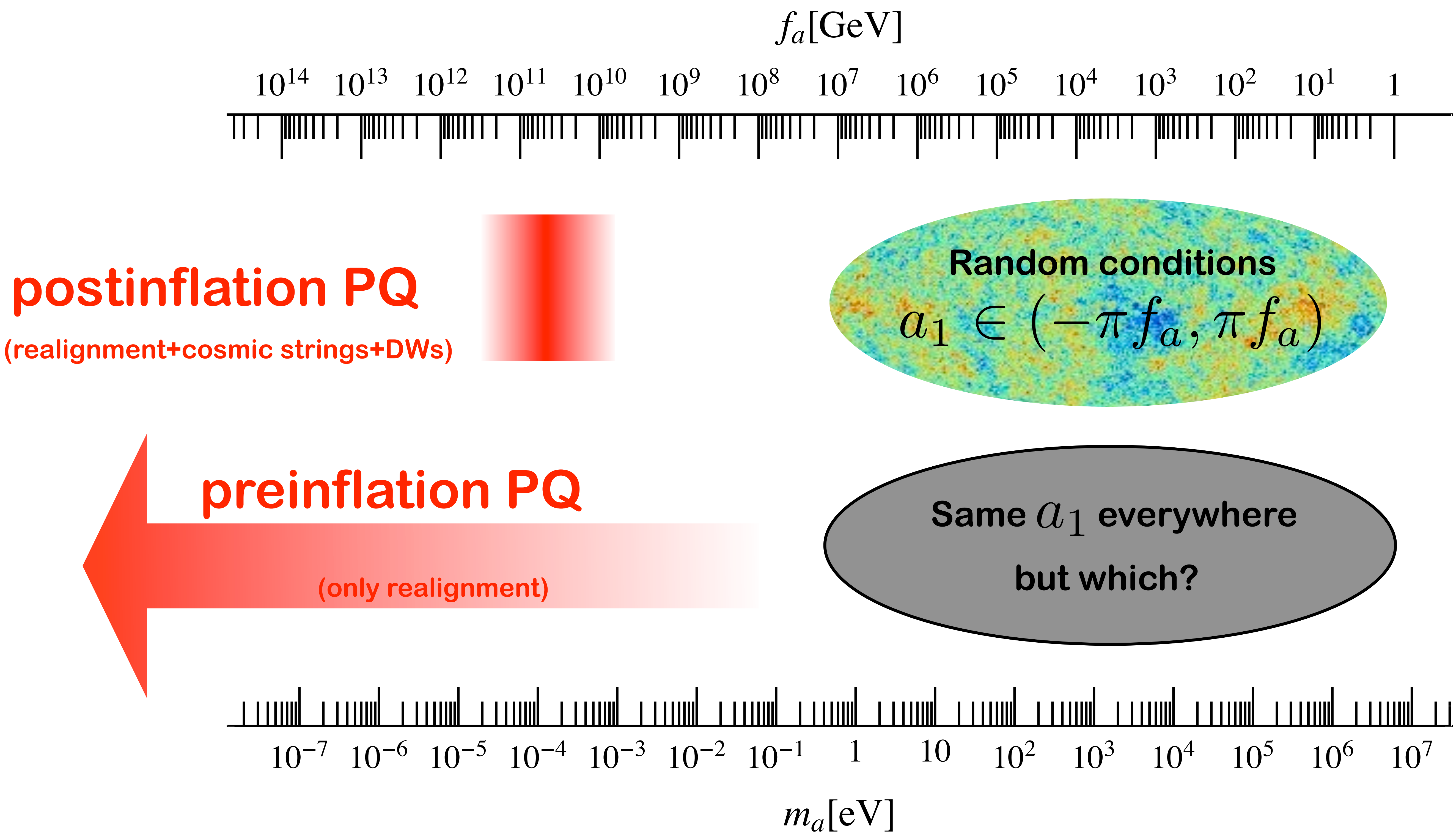
Size of our universe after inflation fits inside one of these domains

- CSs and DWs are diluted by expansion

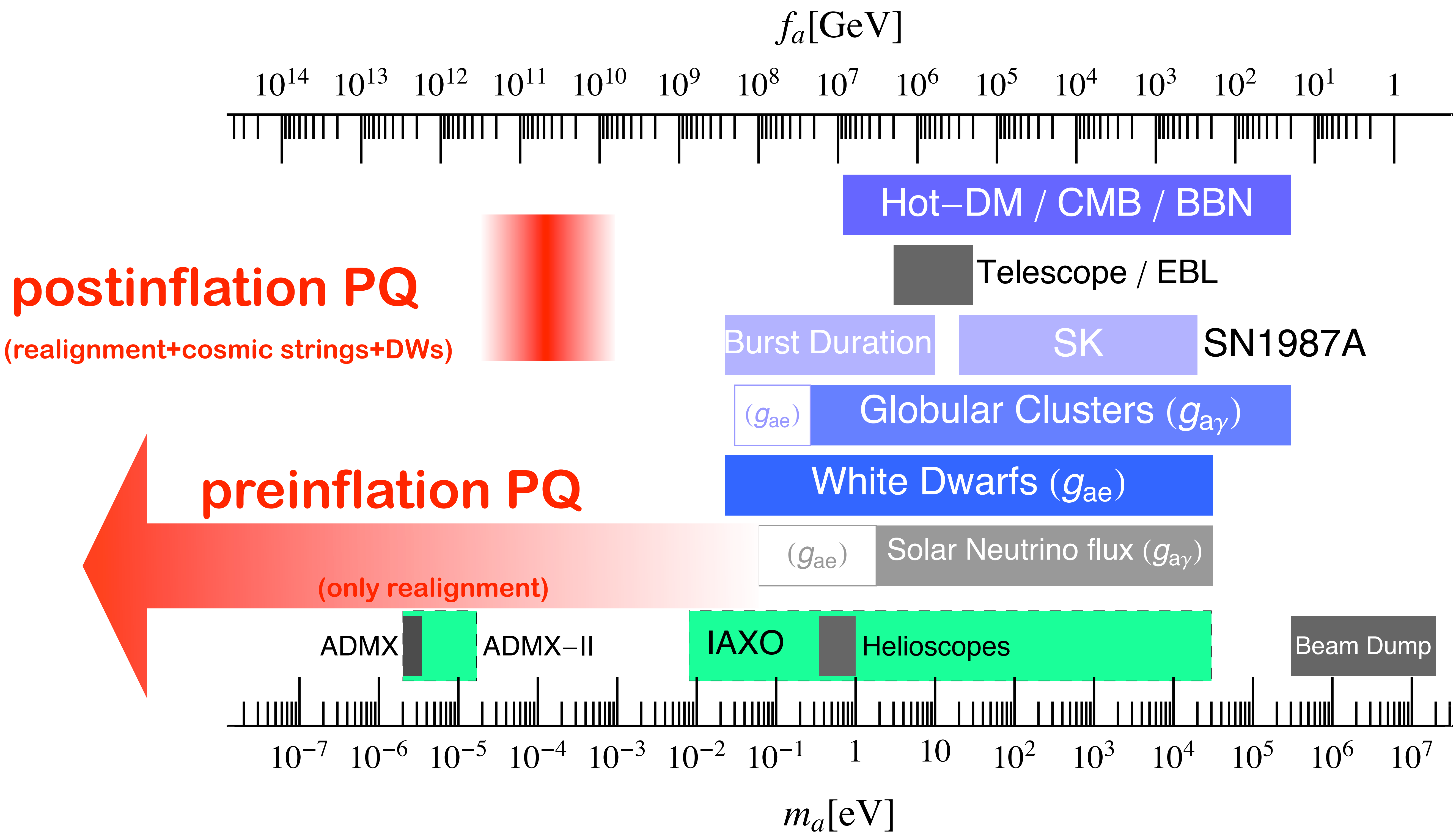
- Whole universe has 1 initial value for a

$$\frac{\Omega_{a,VR}}{\Omega_{\rm obs}} \sim \left(\frac{a_0}{f_a}\right)^2 \left(\frac{10\mu{\rm eV}}{m_a}\right)^{1.184}$$

QCD axion cold dark matter (two scenarios)



+ Bounds on axions (and prospects)



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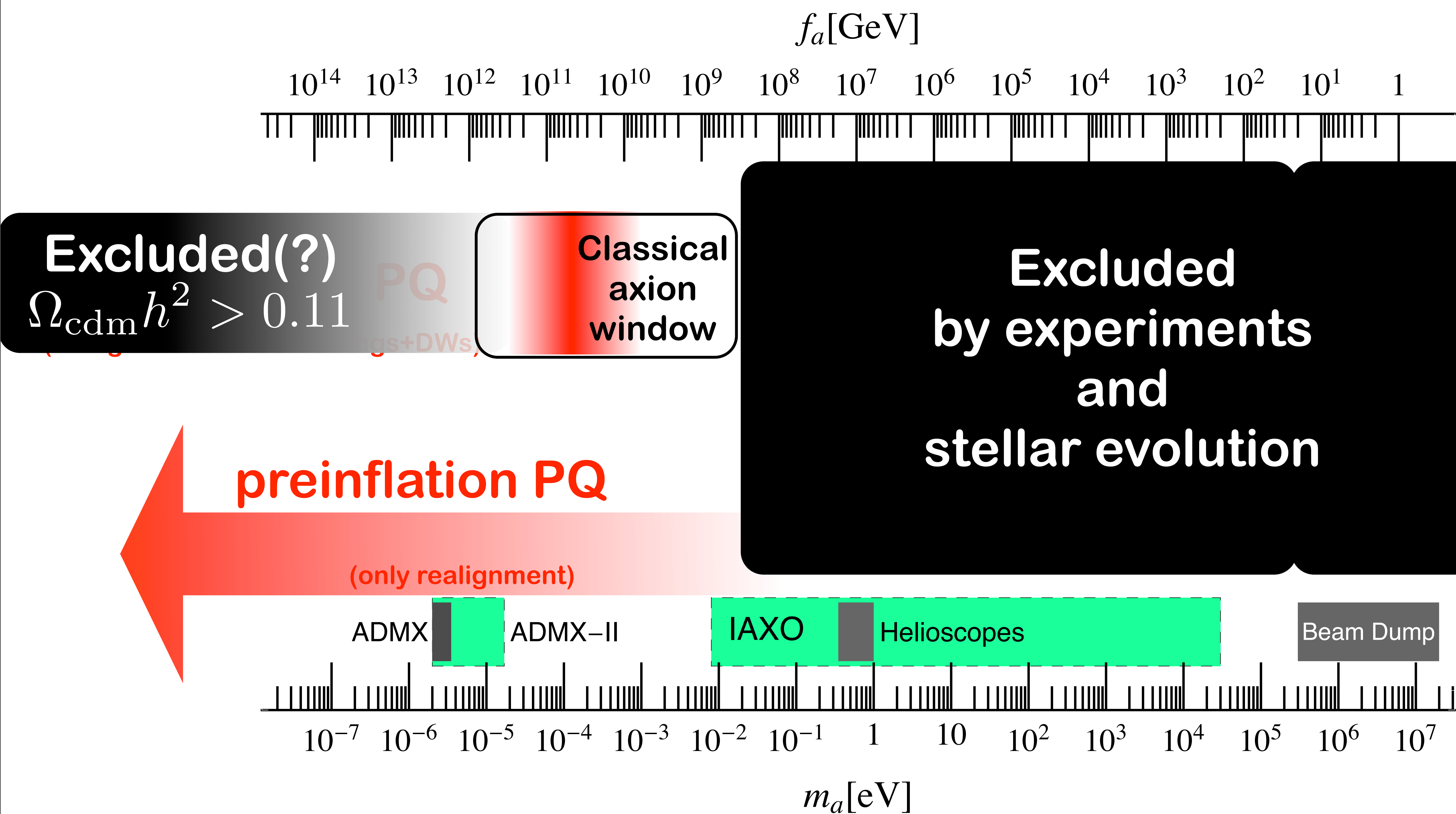


Bounds and prospects in more detail

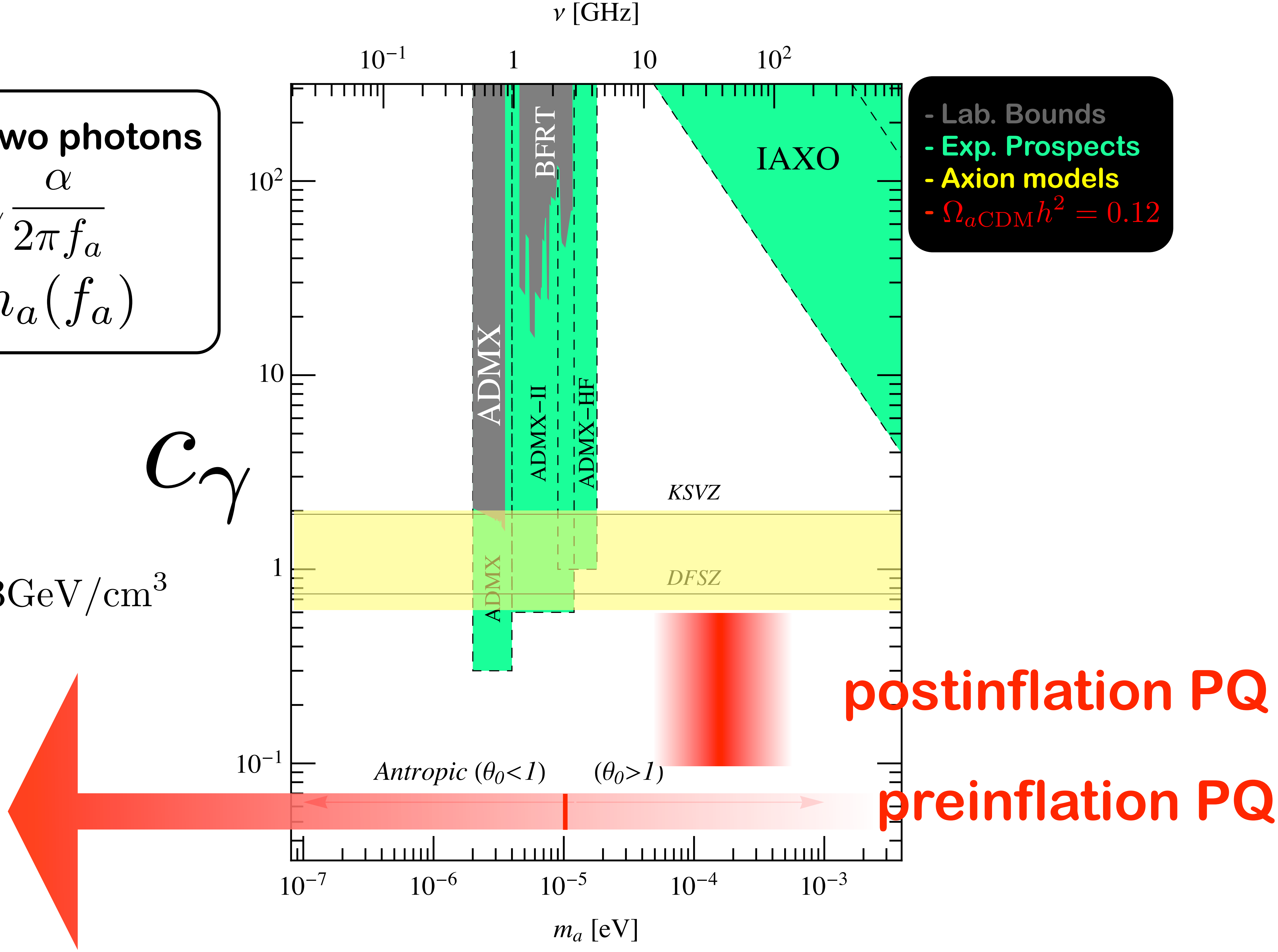
coupling to two photons

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

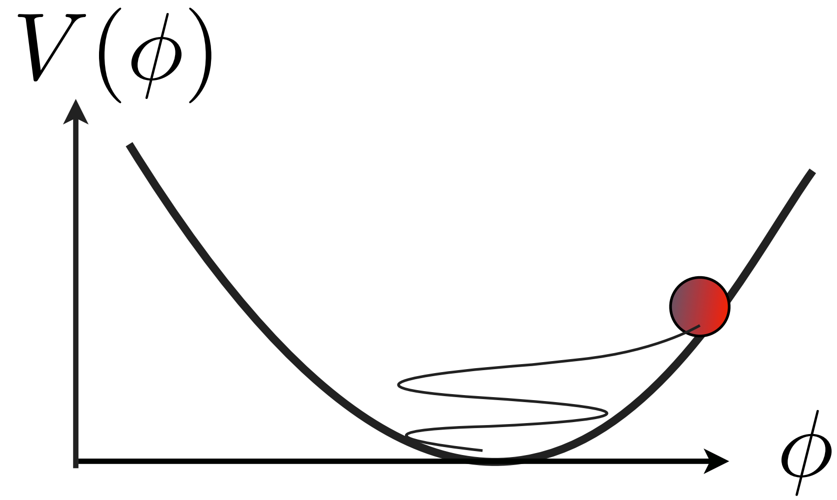
$$m_a = m_a(f_a)$$

$$c_\gamma$$

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



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

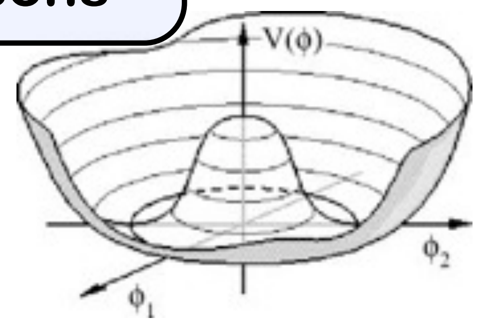
- Initial amplitude, physics at <u>very high energies</u>
- WISPy DM opens a window to HEP

Weakly interacting slim particles

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

pseudo Goldstone bosons

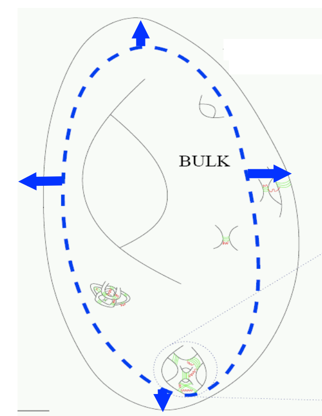
Global continuous symmetry spontaneously broken at high energy scale f



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

String 'axions'

Sizes and deformations of extra dimensions, gauge couplings

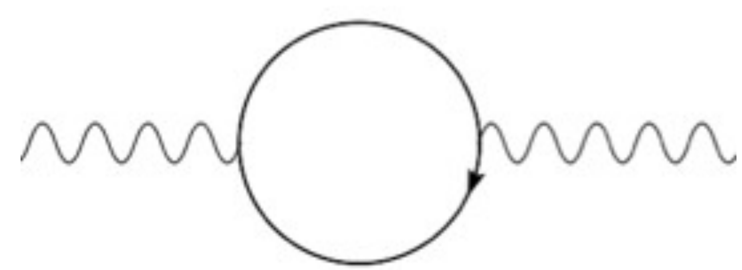


DILATONS RADION MODULI

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'

General Axion-like particles (ALPs)

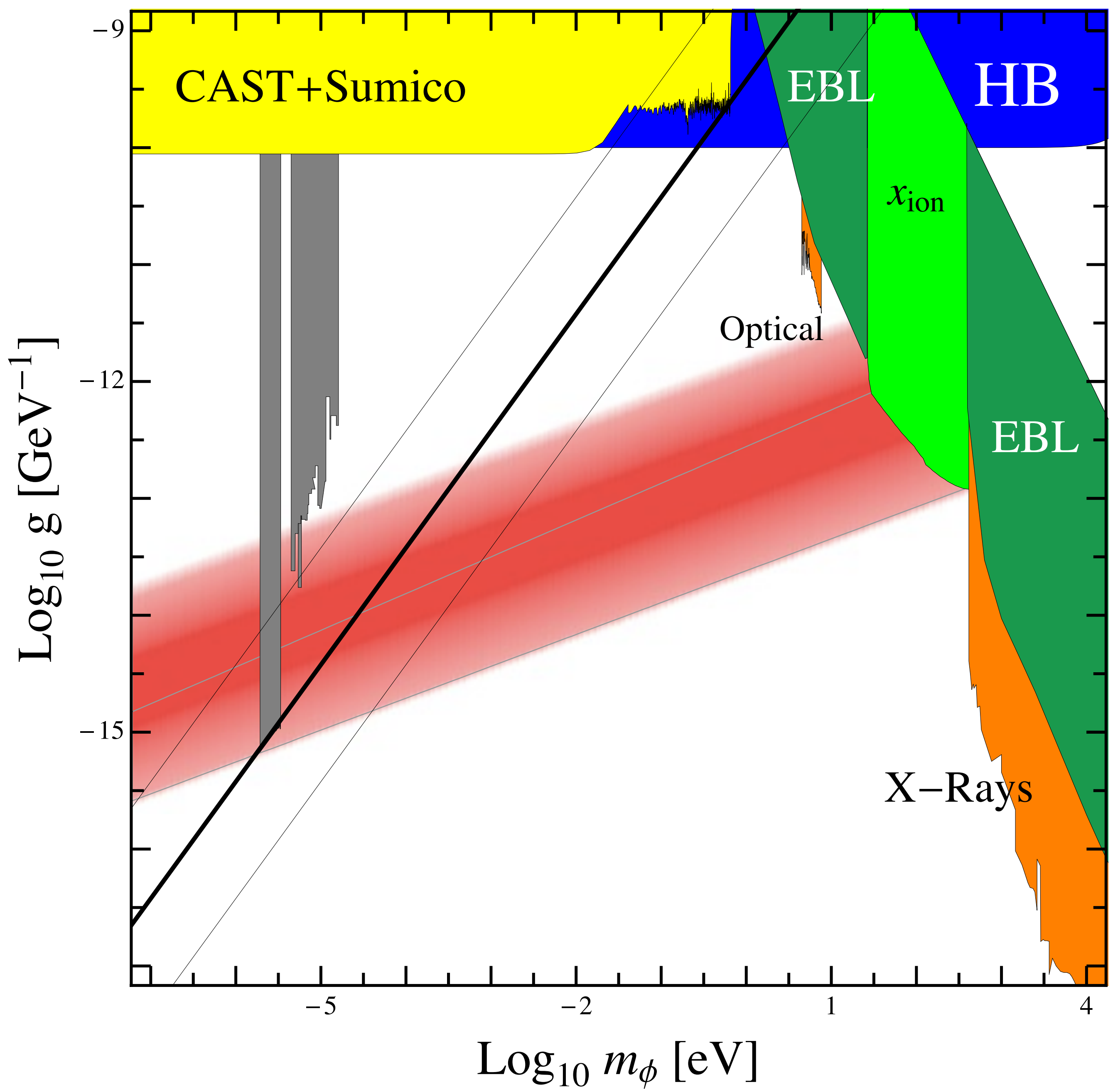
- **Mass and coupling unrelated**

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

- **Scenario 1**

$$f_a < H_I$$

(realignment+cosmic strings, DWs..)



General Axion-like particles (ALPs)

- Mass and coupling unrelated

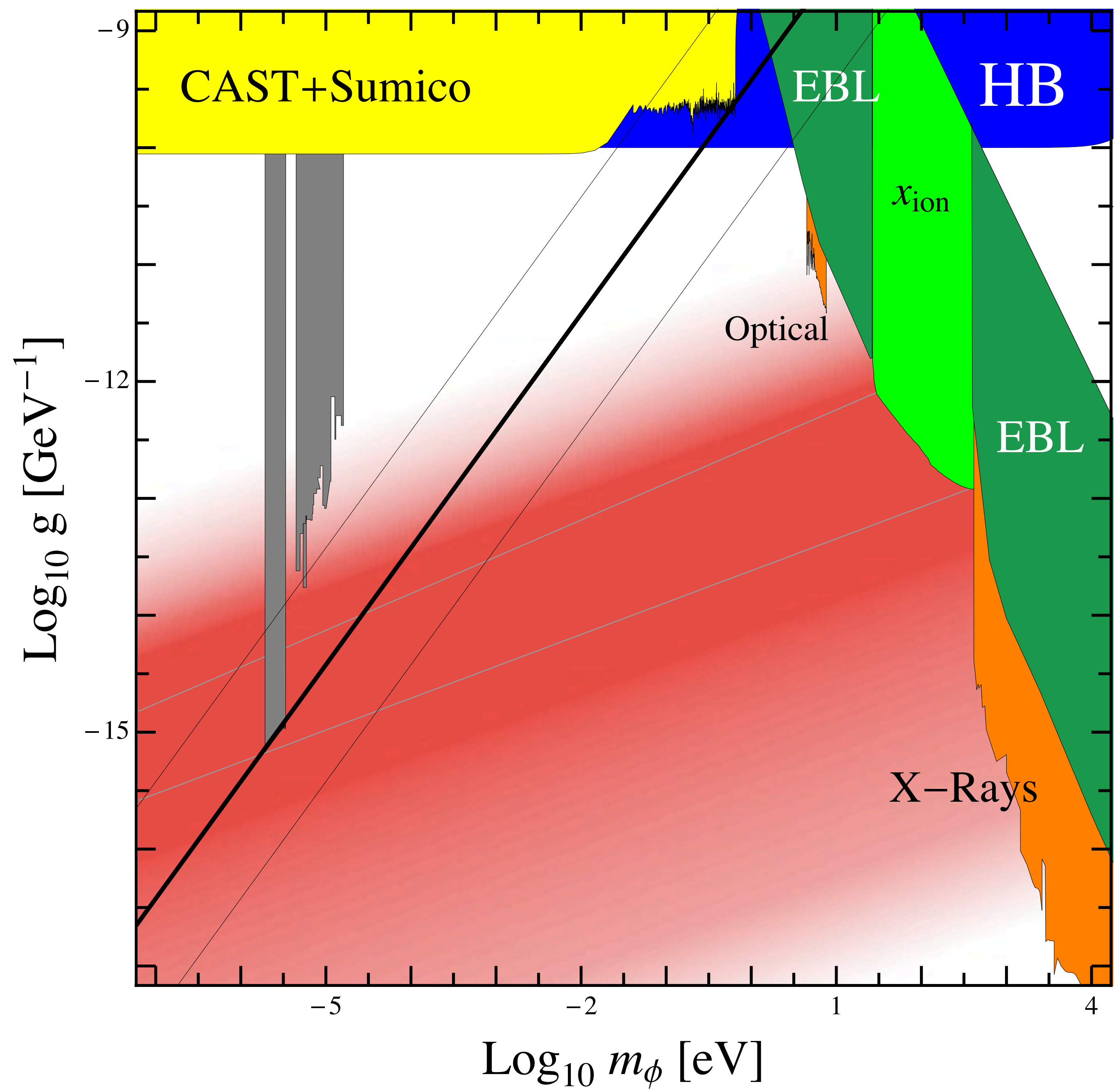
$$g = \frac{\alpha}{2\pi f_a} \times O(1)$$

- Scenario 2 (anthropic)

$$f_a > H_I$$

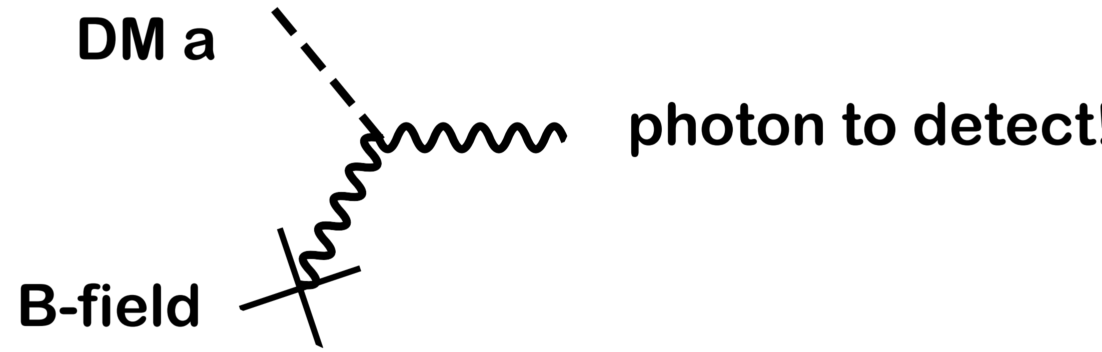
(realignment mechanism)

- Isocurvature constraints!!

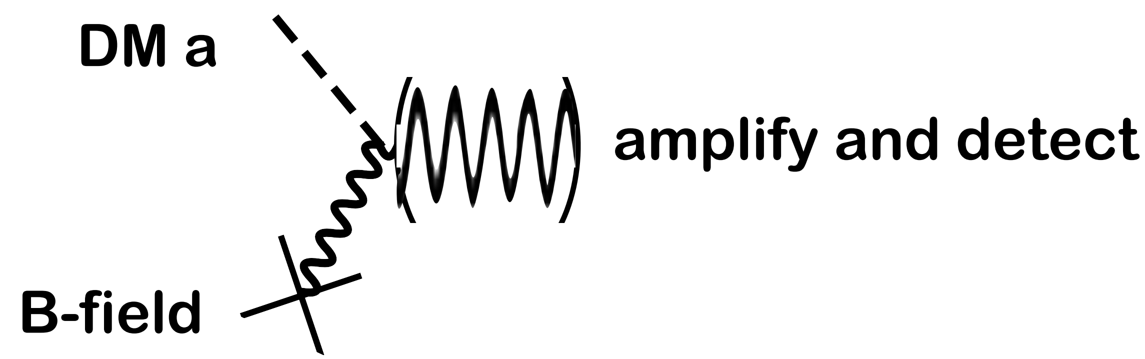


Experiments to detect axion DM

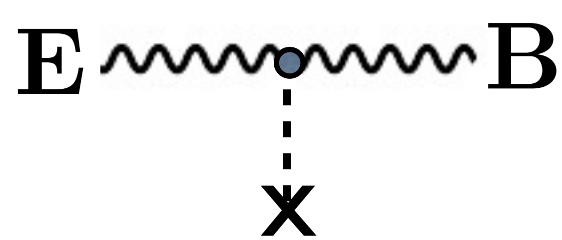
- Dish antenna



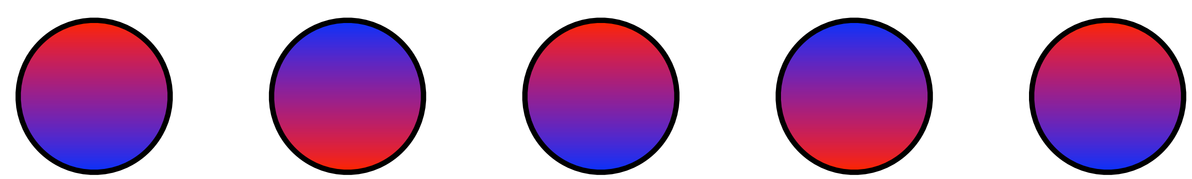
- Cavity experiments



- Light propagation



- Oscillating EDM



DM around us

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

velocities in the galaxy $v \lesssim 300\ \mathrm{km/s} \sim 10^{-3} c$

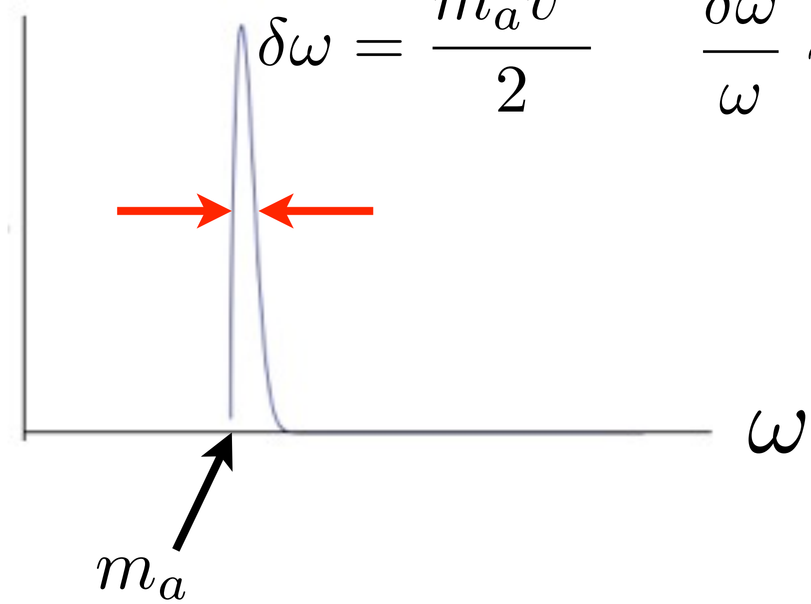
phase space density $\frac{n_a}{\frac{4\pi p^3}{3}} \sim 10^{29} \left(\frac{\mu\mathrm{eV}}{m_a}\right)^4$

occupation number is HUGE! ⟶ **behaves like a classical NR field!**

Fourier-transform $a(x)$

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

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



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

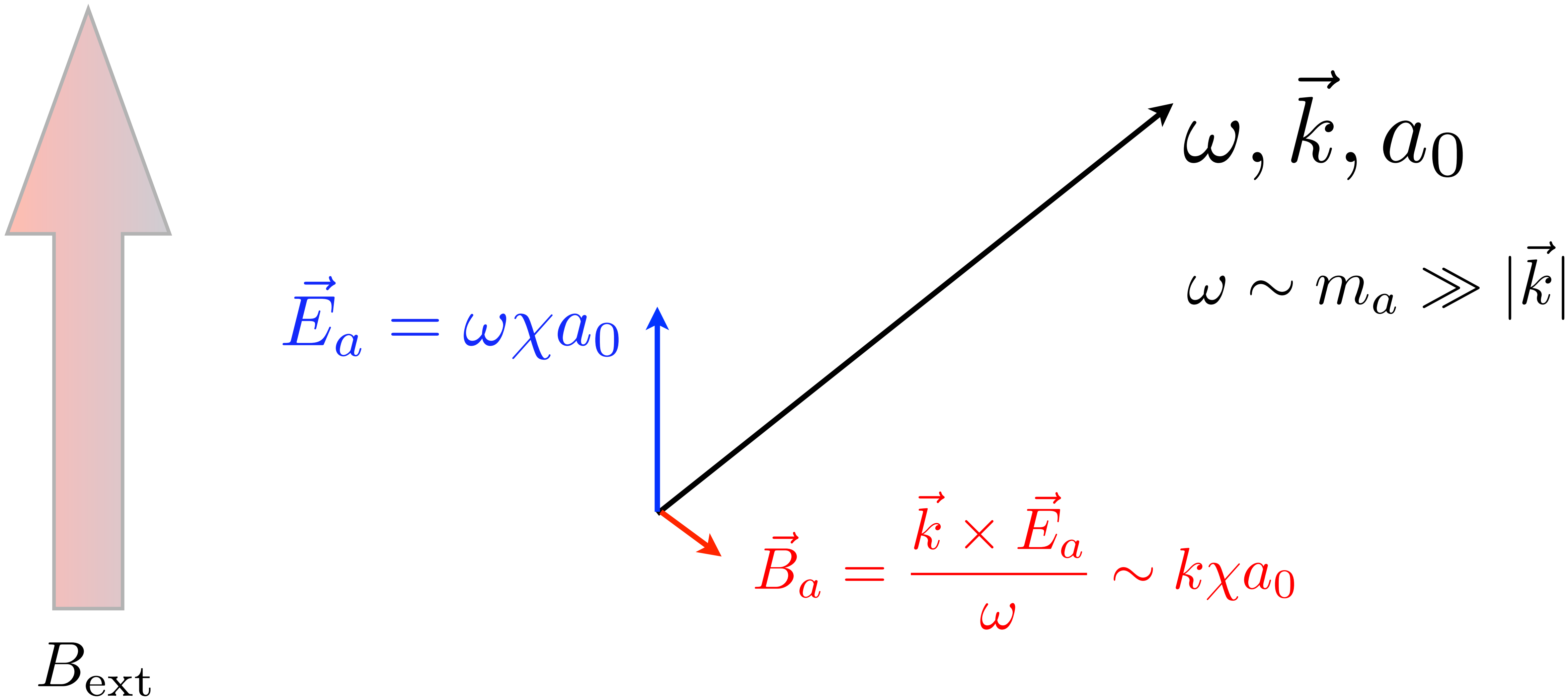
$$\left.\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix}\right|_{\mathrm{DM}} \propto \begin{pmatrix} -\chi_a \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

It has a small E field!

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

Friday, 13, December,2013

DM axions in a magnetic field



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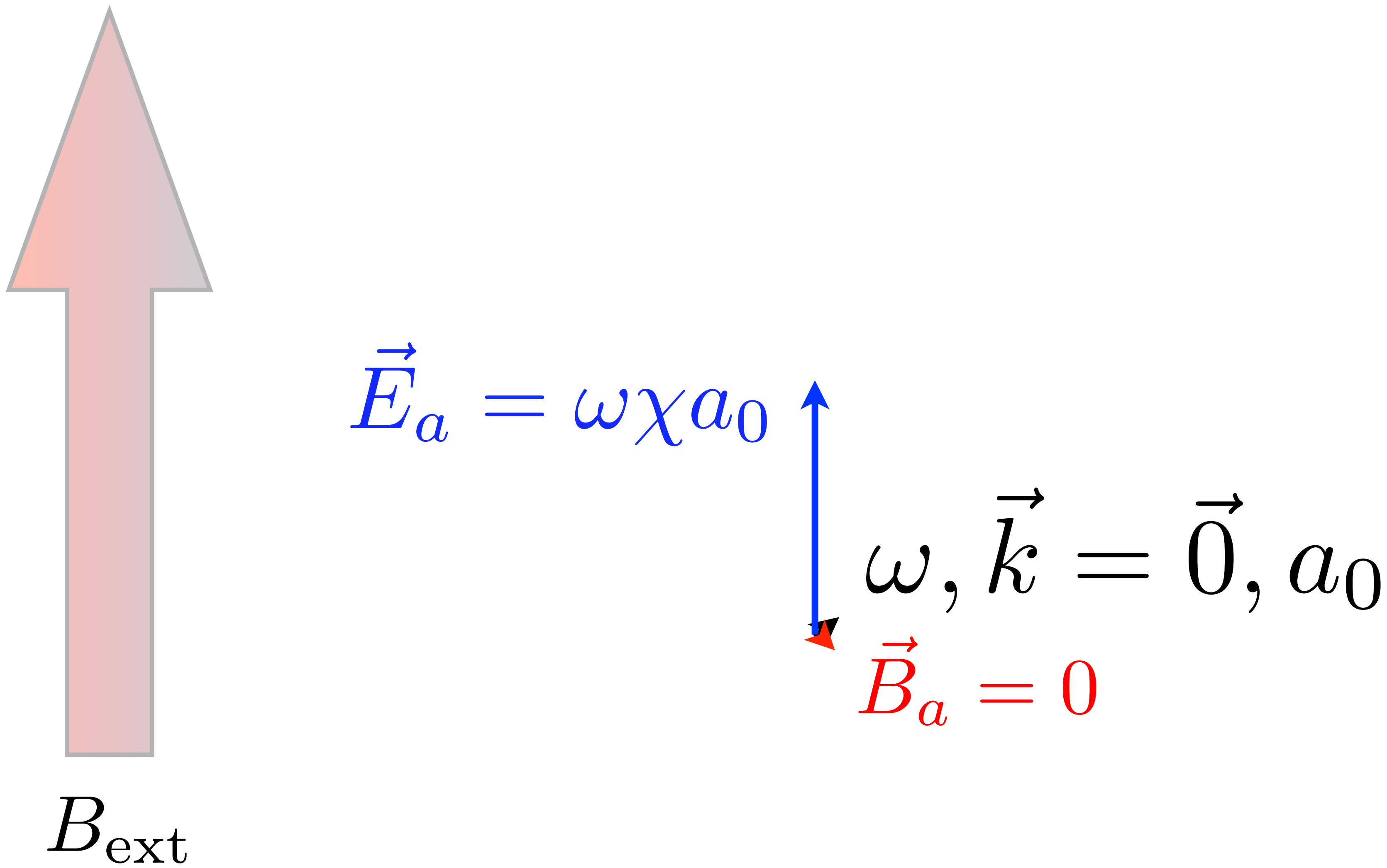
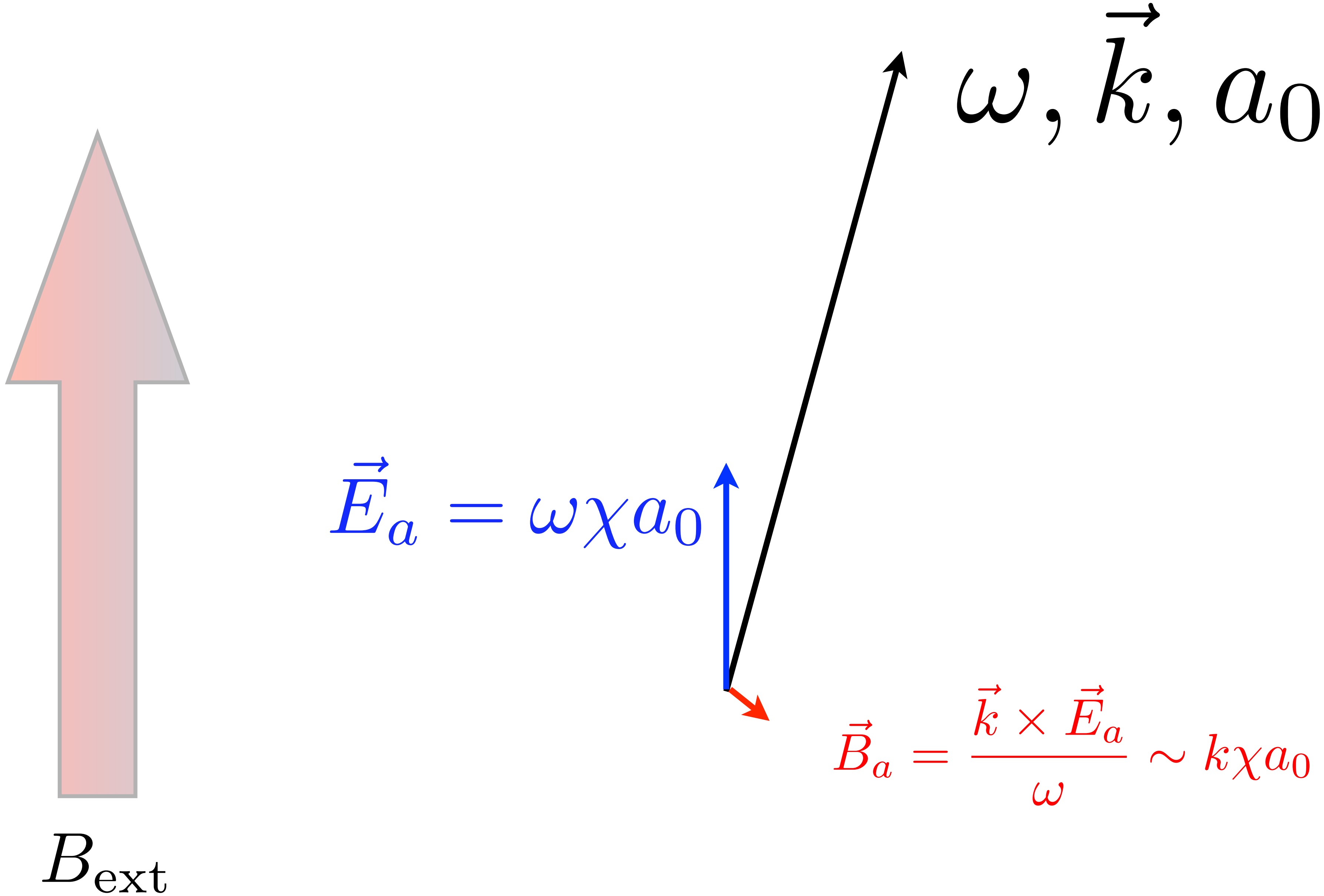
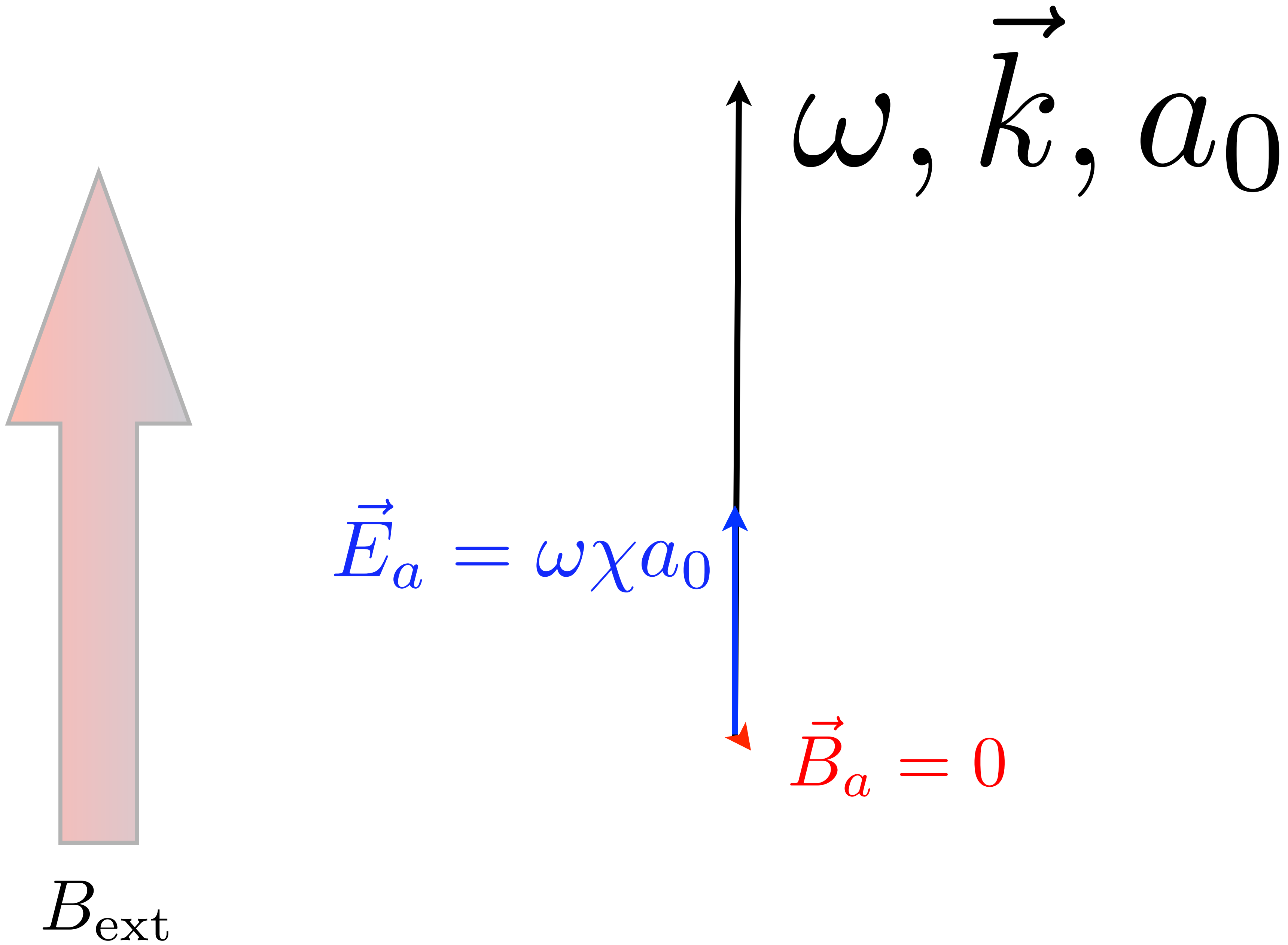


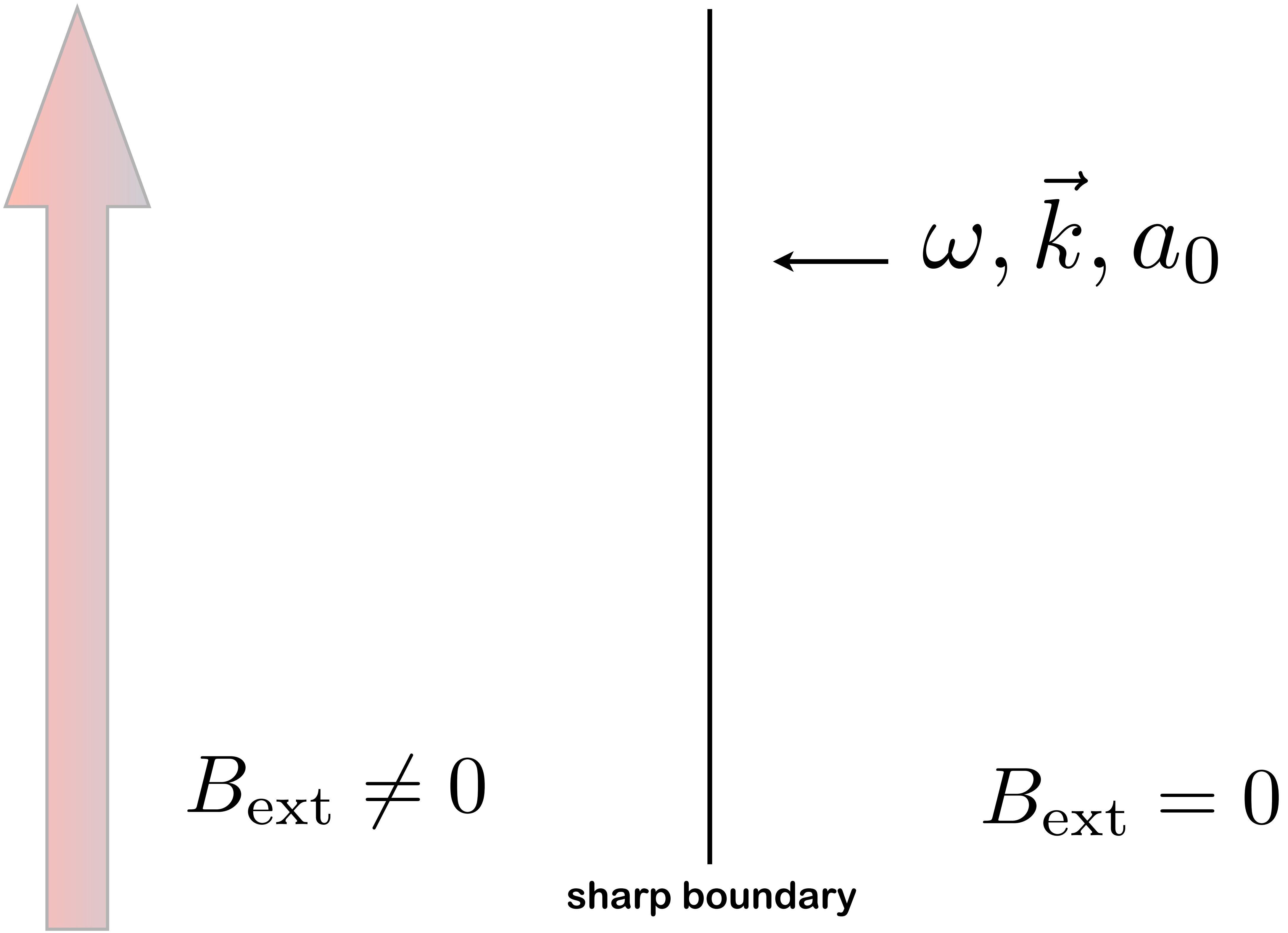
DM axions in a magnetic field



DM axions in a magnetic field



DM axions entering a magnetic field



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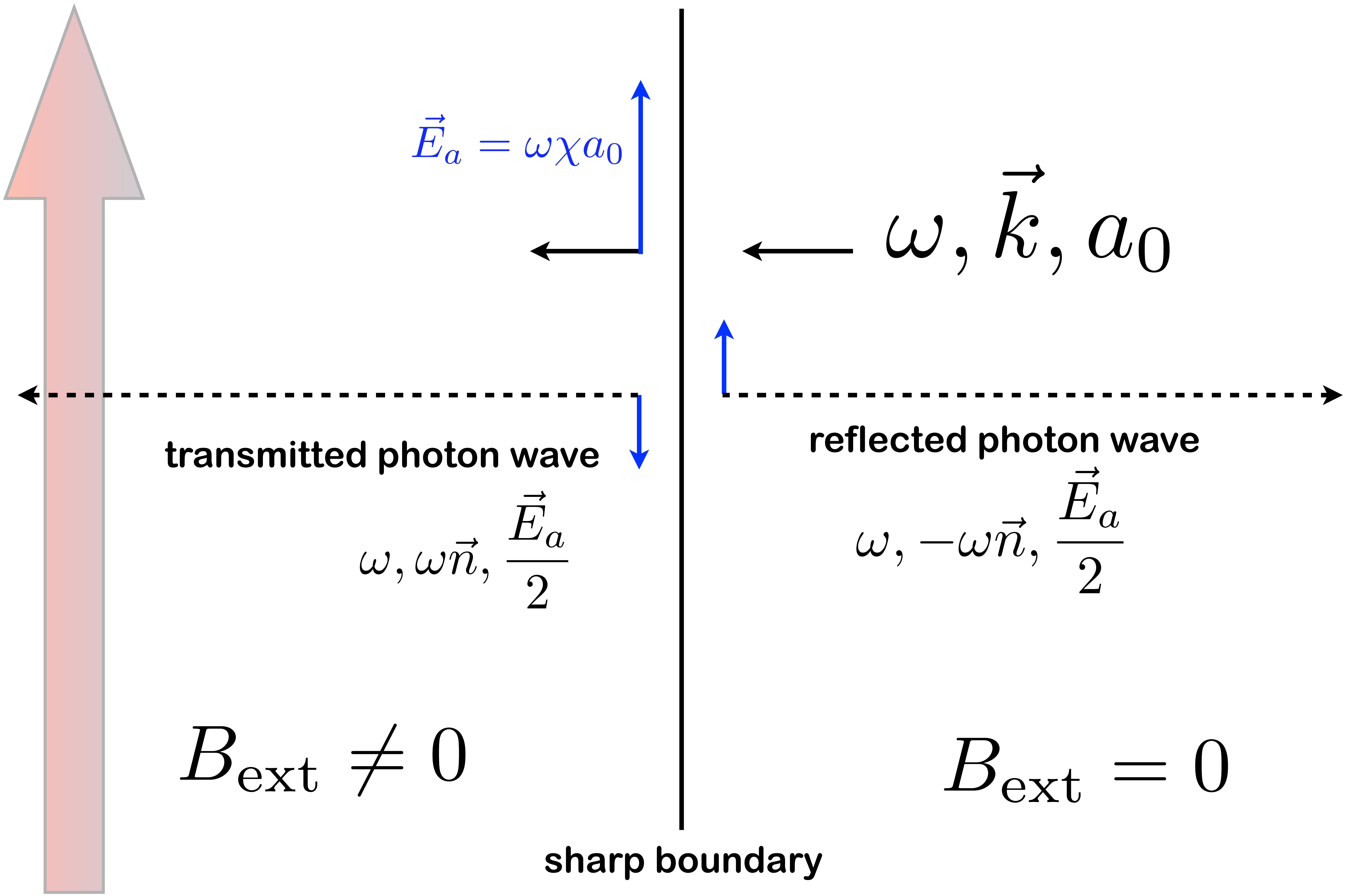
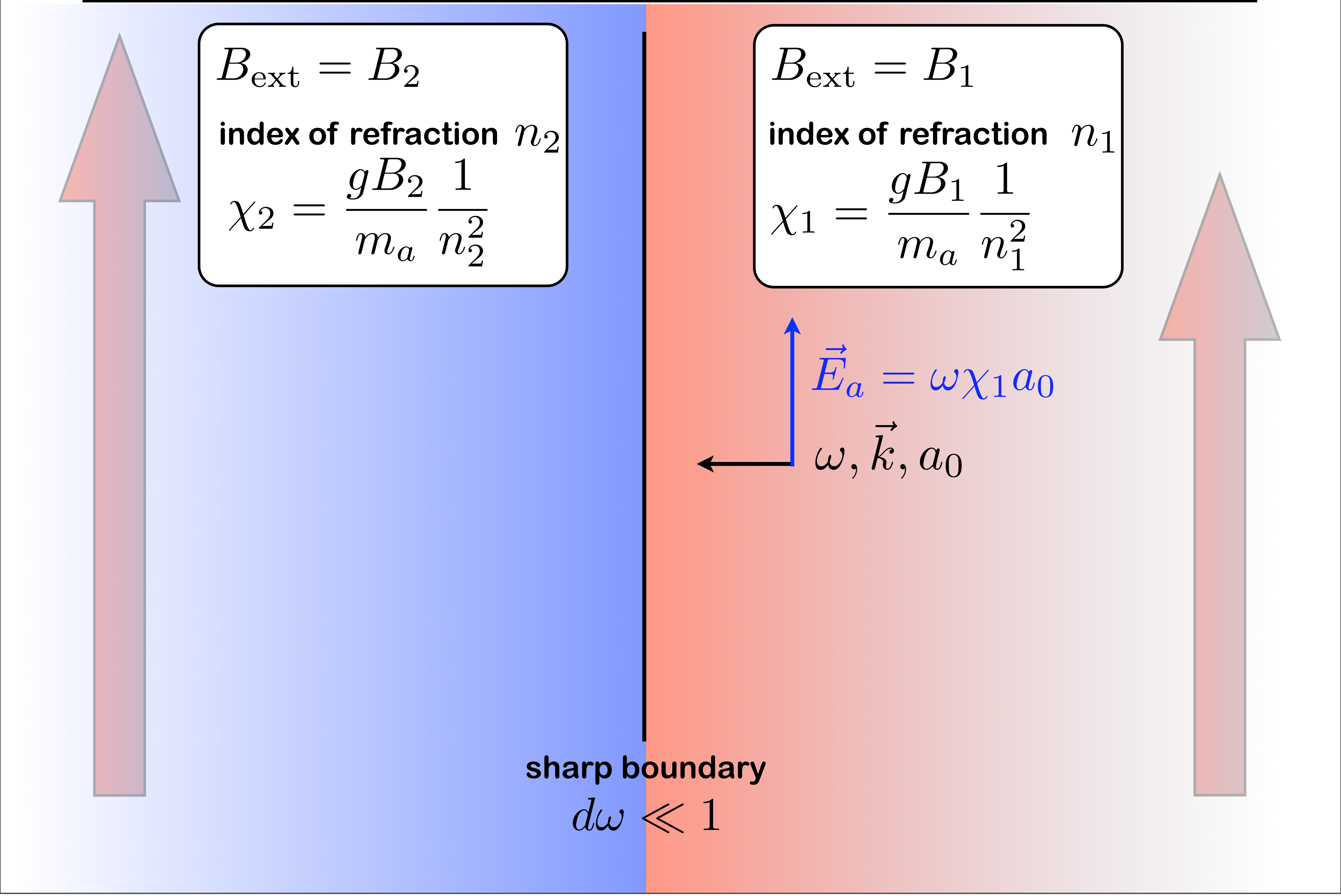


DM axions changing medium

Jaeckel and JR, PRDxxx, arXiv:1308.1103



DM axions changing medium

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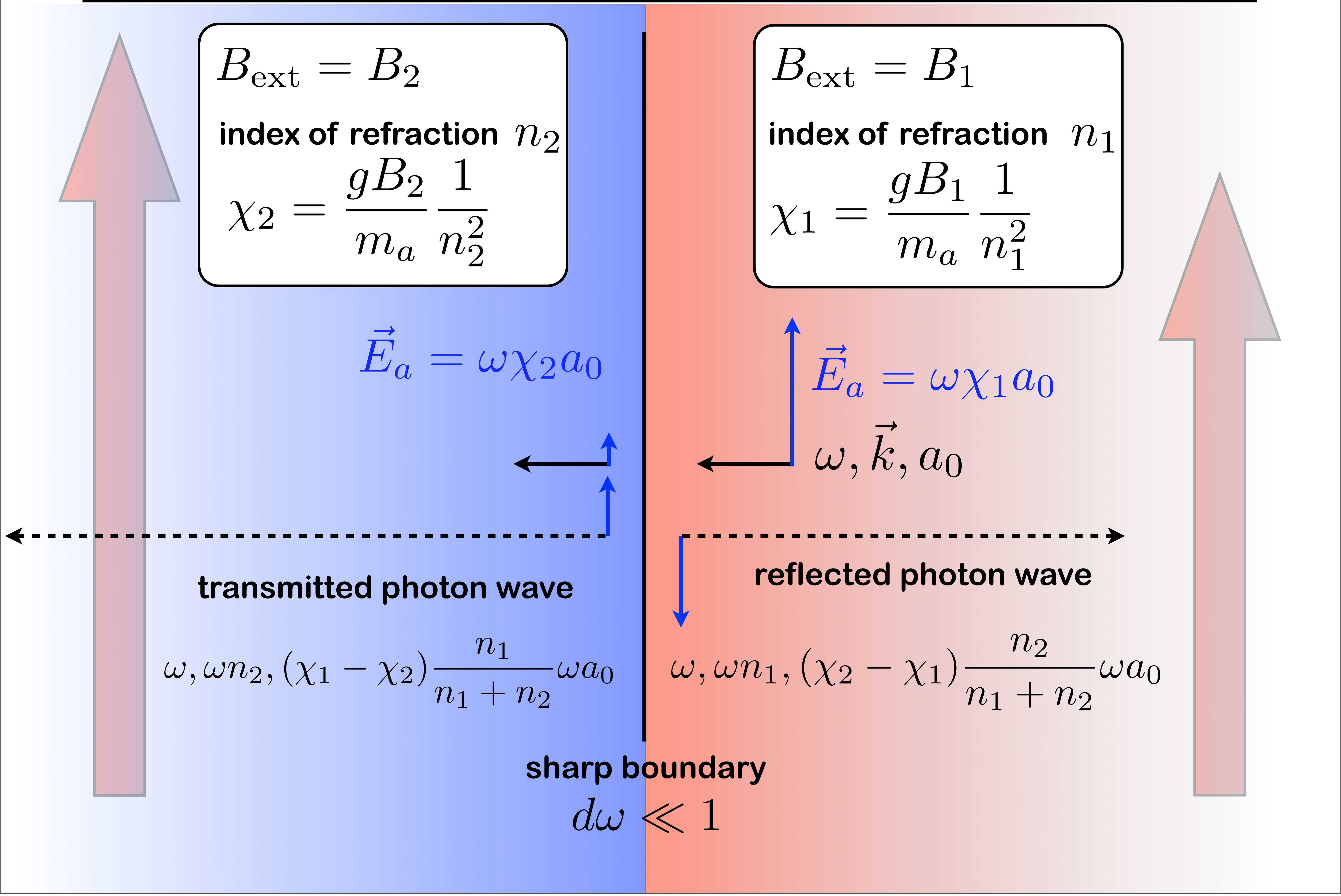
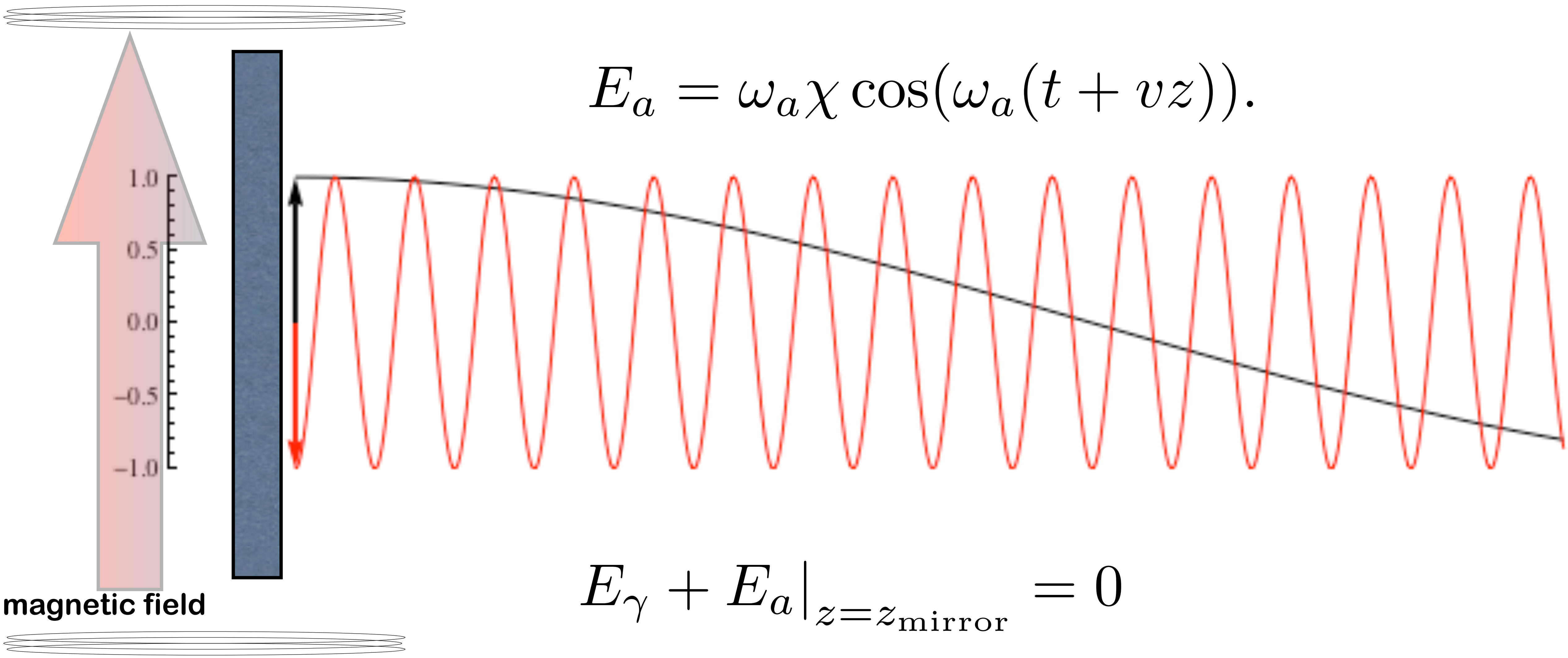


Radiation from a magnetised mirror

Horns at al JCAP04(2013)016

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



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

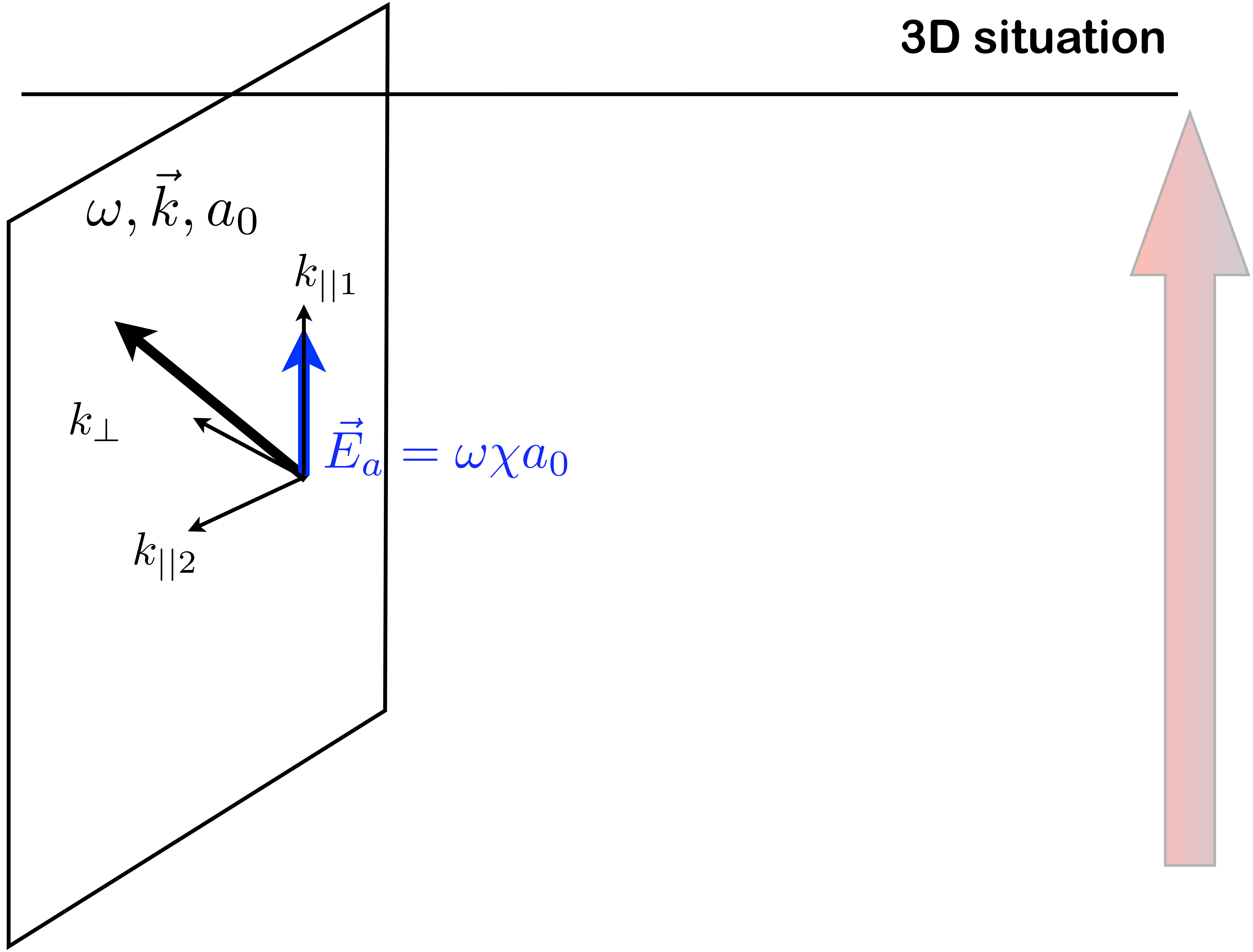
Radiated photon wave

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

whose frequency is

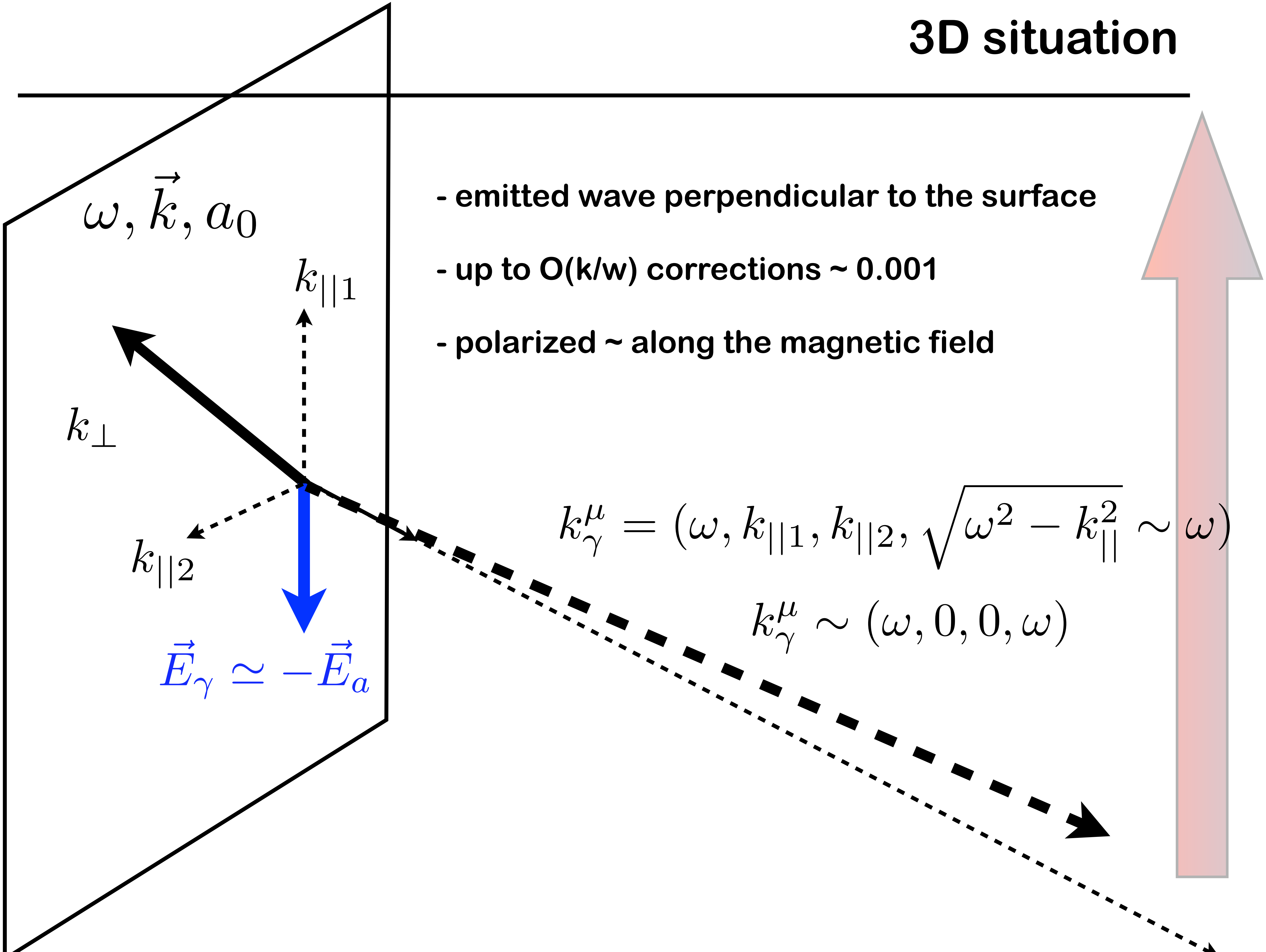
$$\omega_\gamma = \omega_a = m_a (1 + v^2/2)$$

3D situation



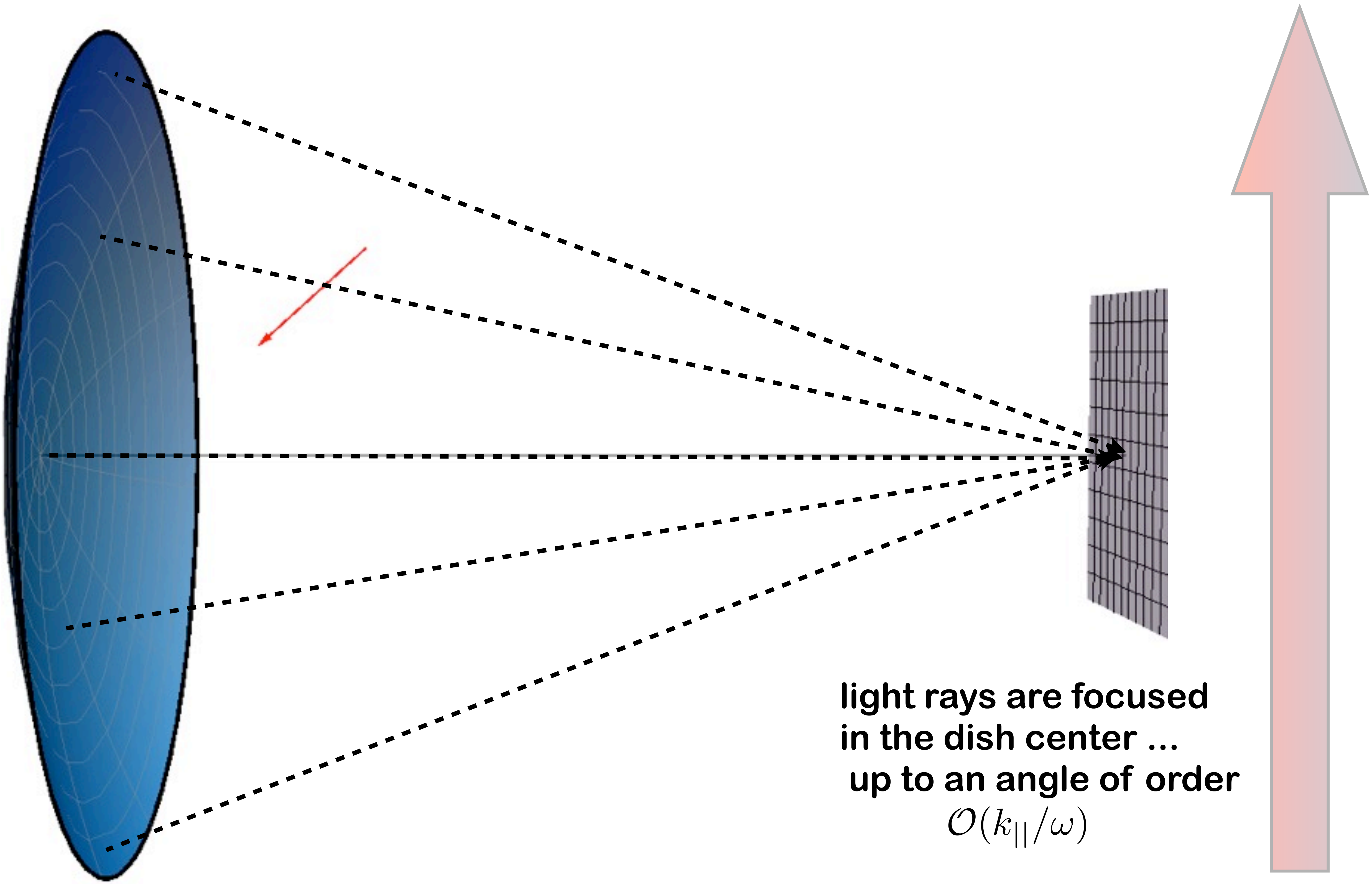
3D situation

- emitted wave perpendicular to the surface
- up to O(k/w) corrections ~ 0.001
- polarized ~ along the magnetic field



Simplest experiment

Horns at al JCAP04(2013)016



spherical reflecting dish

Small electric field: how small?

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

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

The small component does not depend on axion mass!

- We know the typical axion amplitude -> typical electric field

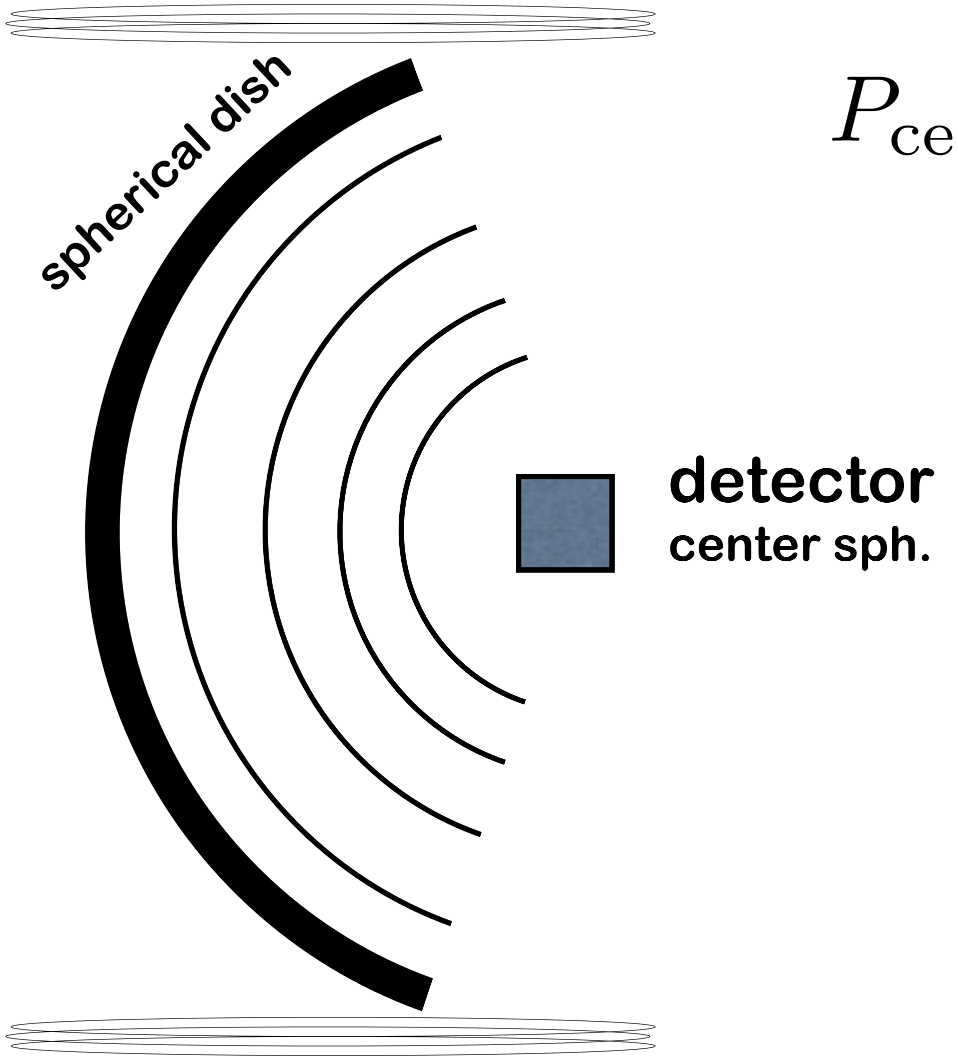
$$\rho_{\mathrm{CDM}} = \frac{1}{2}m_a^2 a_0^2 = 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

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

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

Signal size

Horns et al , JCAP04(2013)016

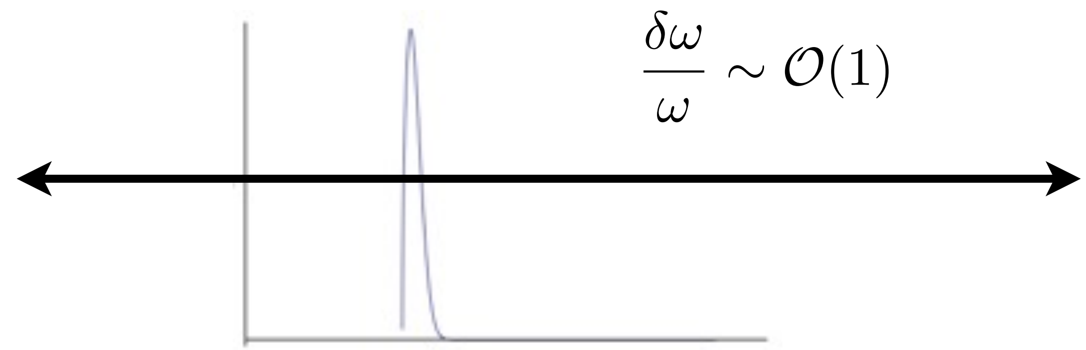


$$P_{\text{center}} \approx \langle |\mathbf{E}_a|^2 \rangle A_{\text{dish}} \sim \chi^2 \rho_{\text{CDM}} A_{\text{dish}}$$

$$\sim 10^{-26} \left(\frac{\text{B}}{5\text{T}} \frac{c_\gamma}{2} \right)^2 \frac{\text{A}}{1\text{m}^2} \text{Watt}$$

broadband! :-)

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



$$\frac{\delta\omega}{\omega} \sim \mathcal{O}(1)$$

Signal to noise

$$\frac{S}{N} = \frac{P_{\rm signal}}{P_{noise}} \to \frac{P_{\rm signal}}{T_S}\sqrt{\frac{\rm time}{\rm Bandwidth}}$$

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

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

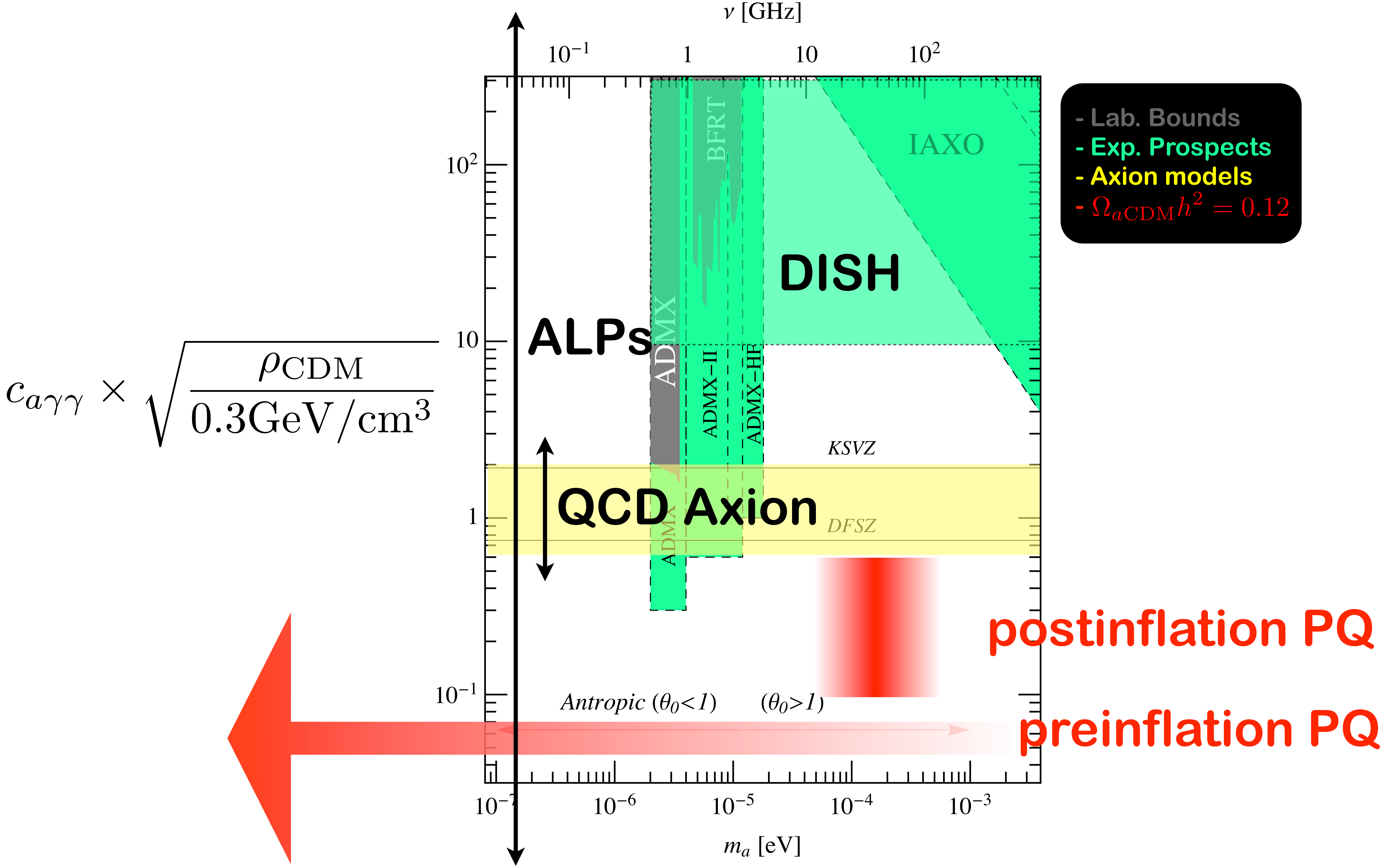
measurement dominated by background

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

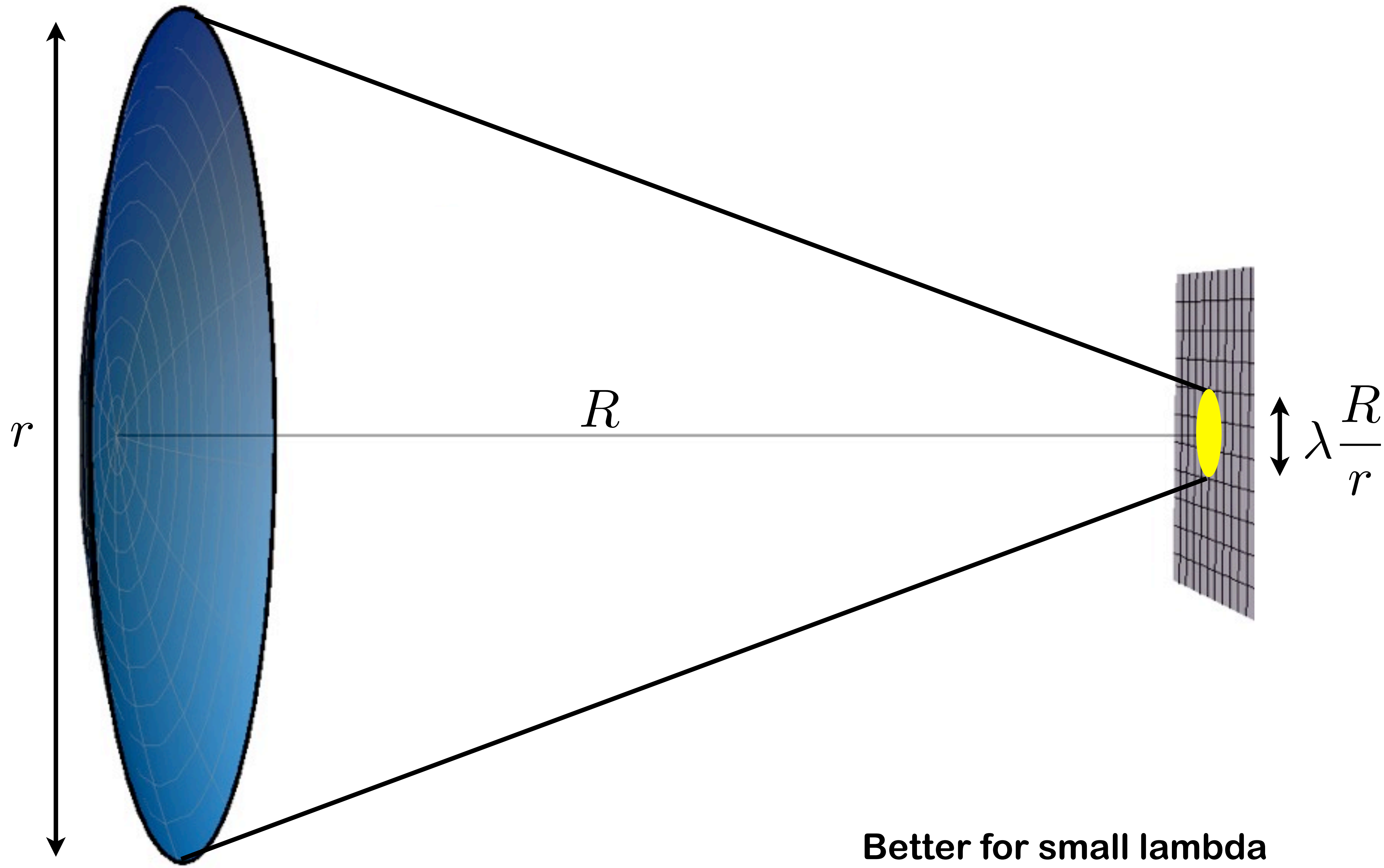
diffraction $m_a R \ll 1$

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

Dish antenna reach: Axions and ALPs

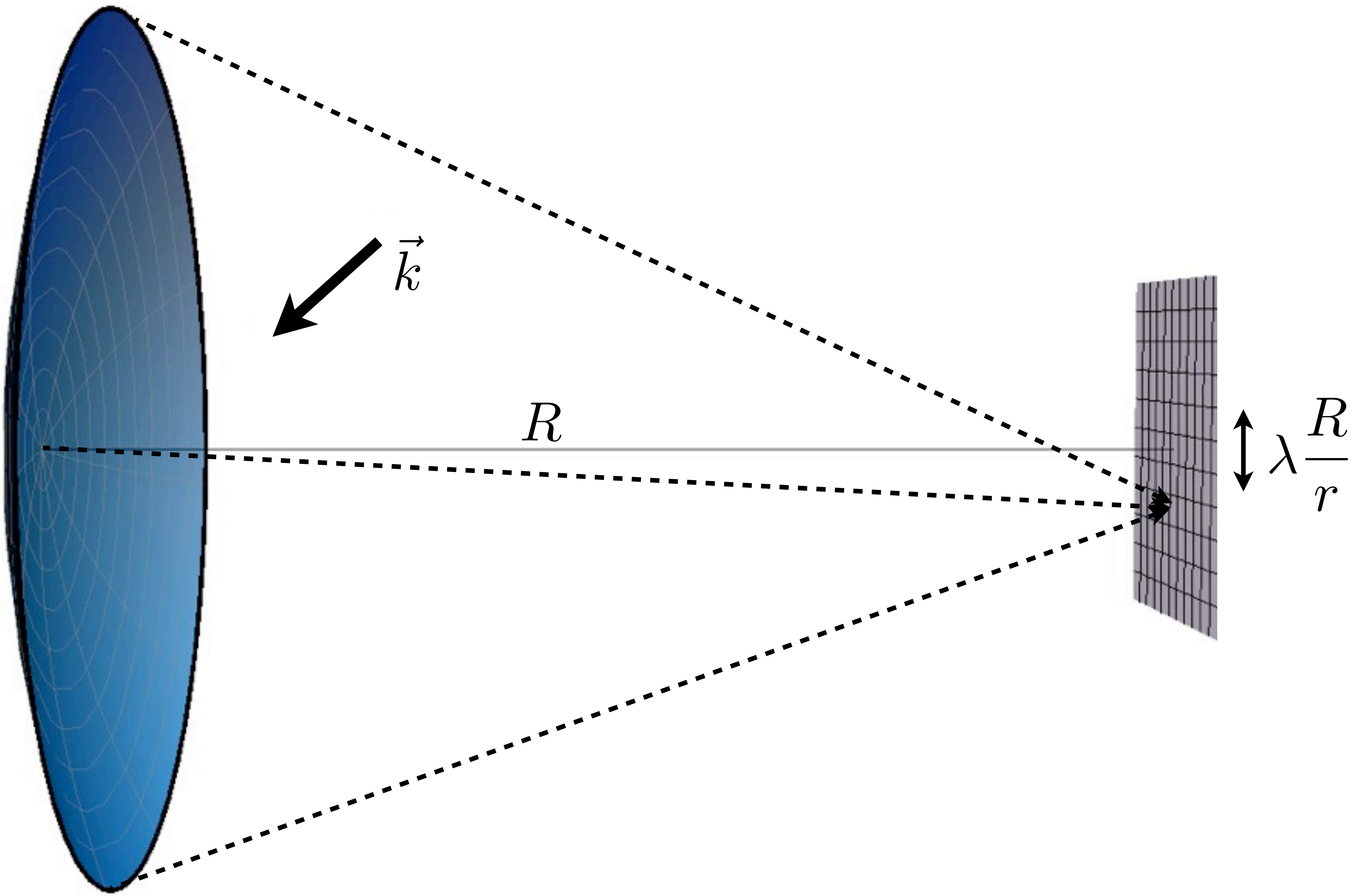


Limitations: Diffraction

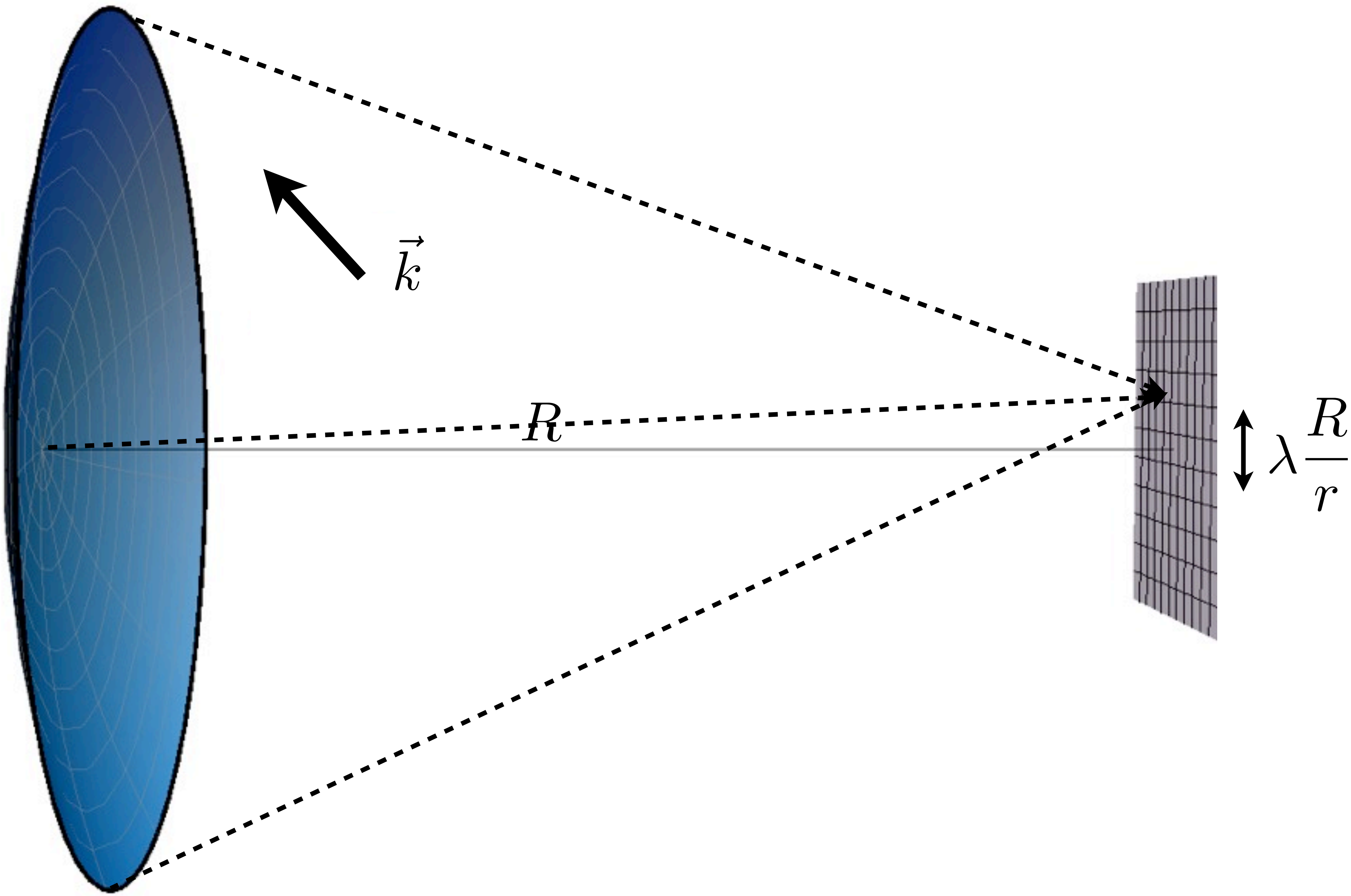


Better for small lambda

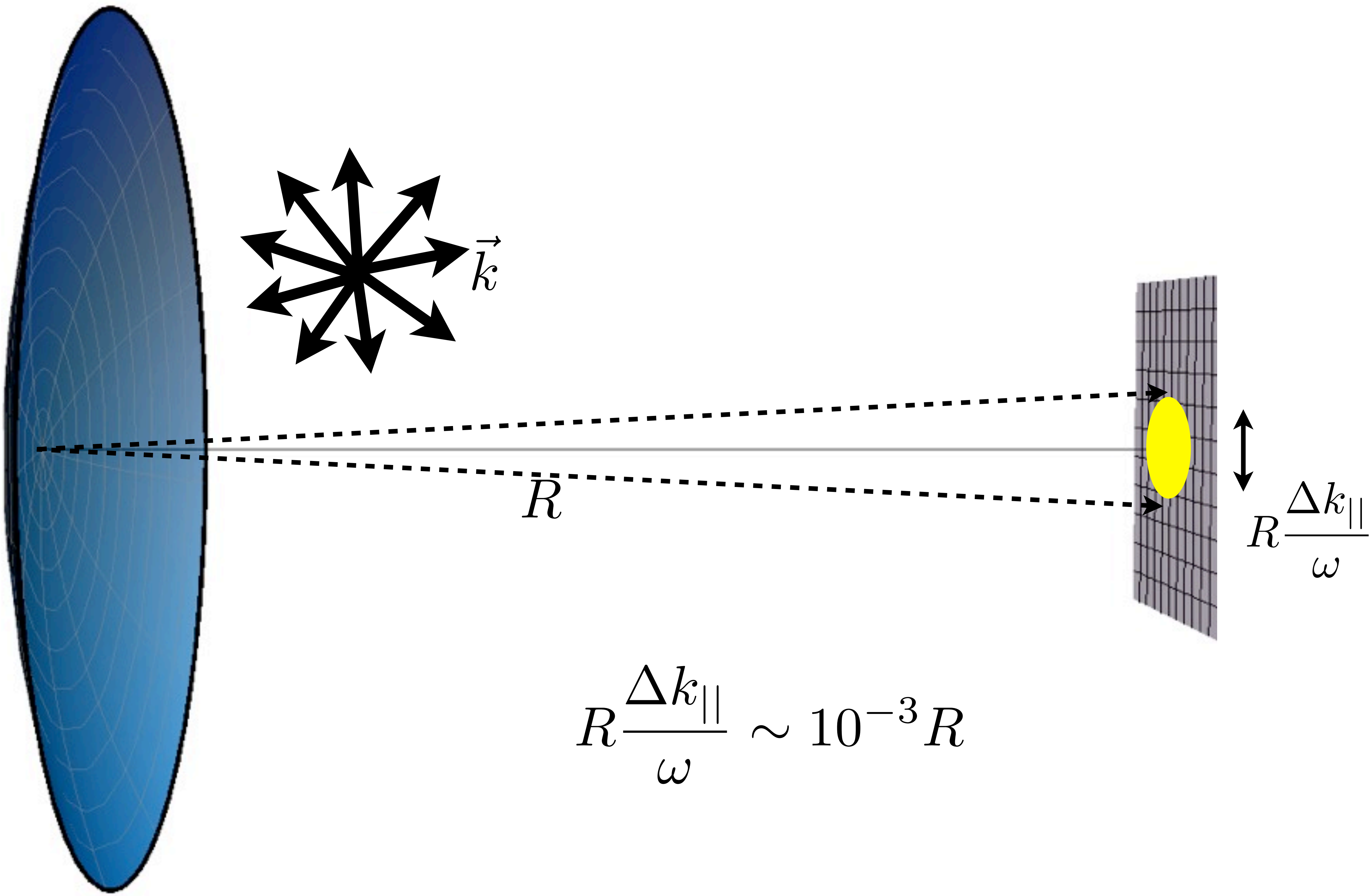
Limitations: momentum distribution



Limitations: momentum distribution

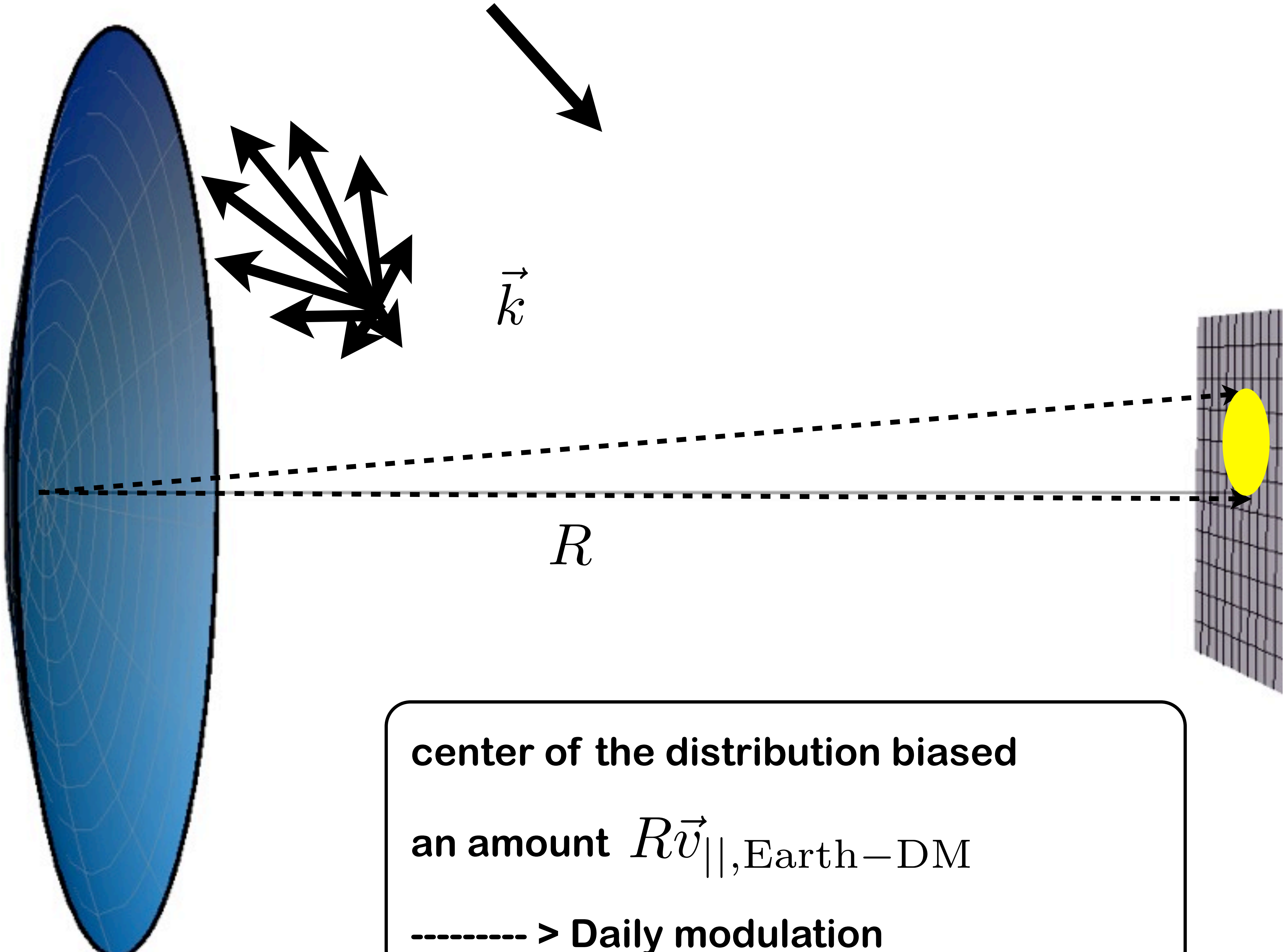


Limitations: momentum distribution



$$R\frac{\Delta k_{||}}{\omega} \sim 10^{-3}R$$

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

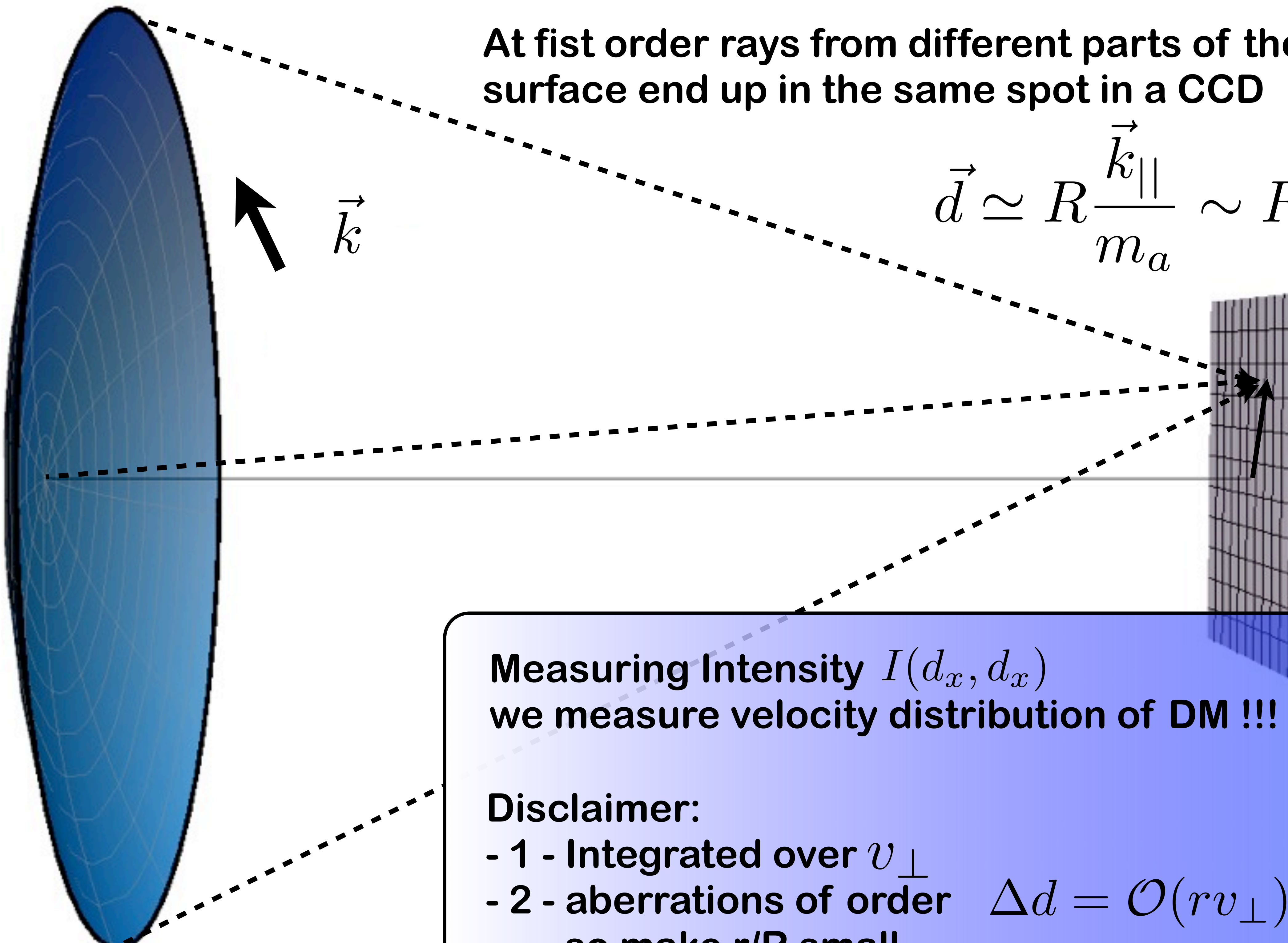


center of the distribution biased

an amount $R\vec{v}_{||,\mathrm{Earth-DM}}$

---------- > Daily modulation

Detecting the velocity distribution of DM!



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 $\Delta d = \mathcal{O}(r v_\perp)$
  so make r/R small

Cavity searches (haloscopes)

- Different understanding of the conventional

HALOSCOPES

Cavity searches (haloscopes)

Sikivie PRL '83

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

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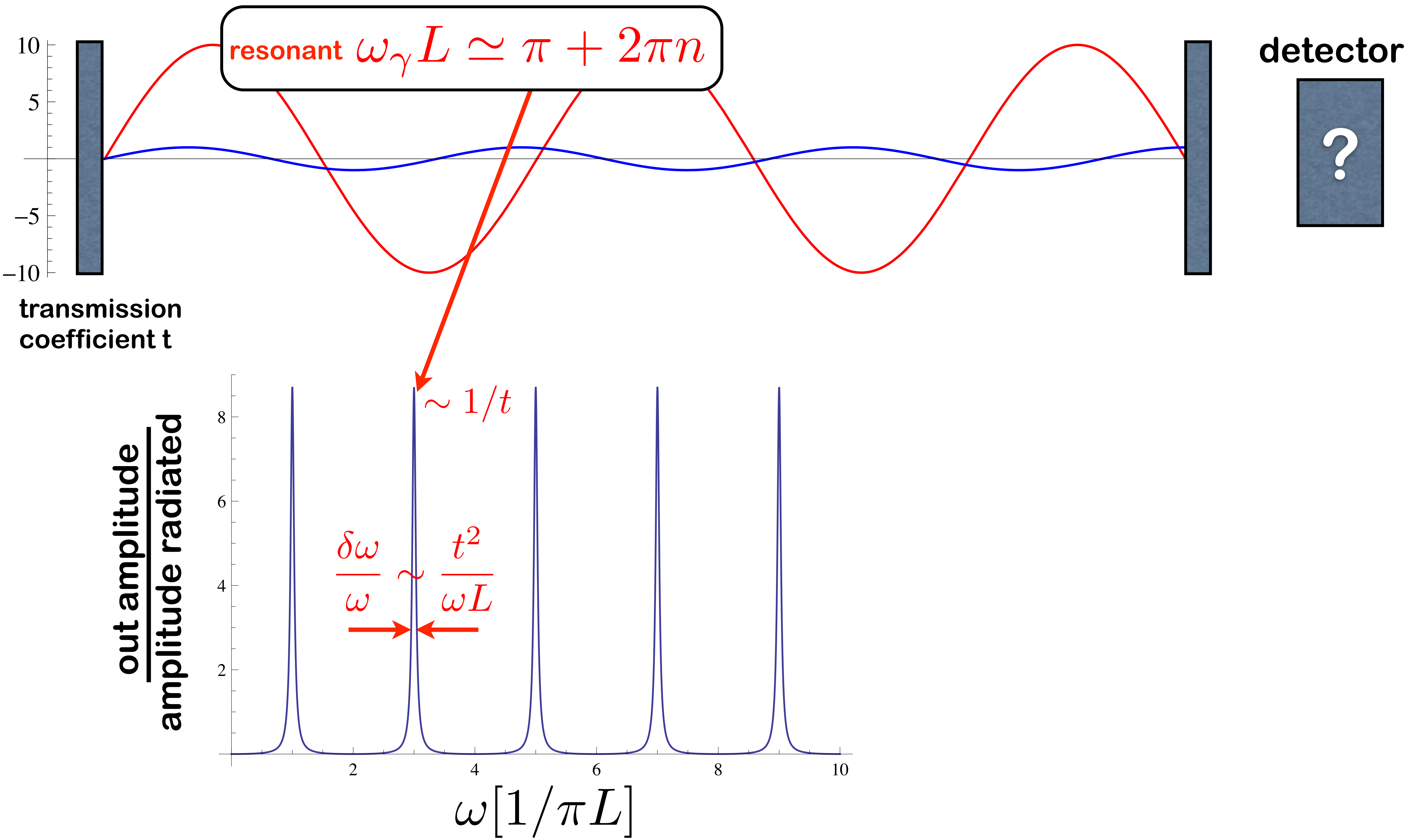

Cavity searches (haloscopes)

Sikivie PRL '83

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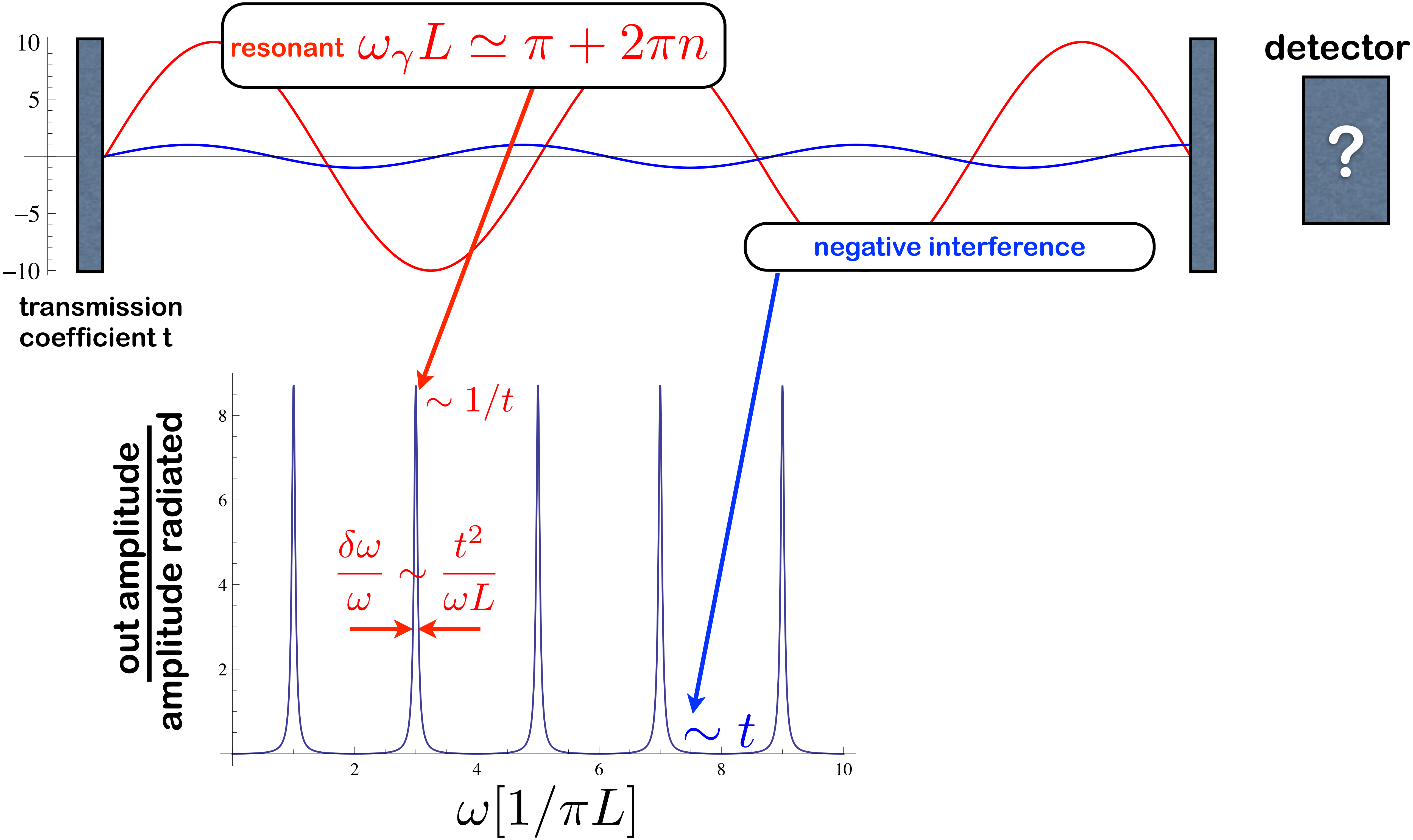

Cavity searches (haloscopes)

Sikivie PRL ‘83

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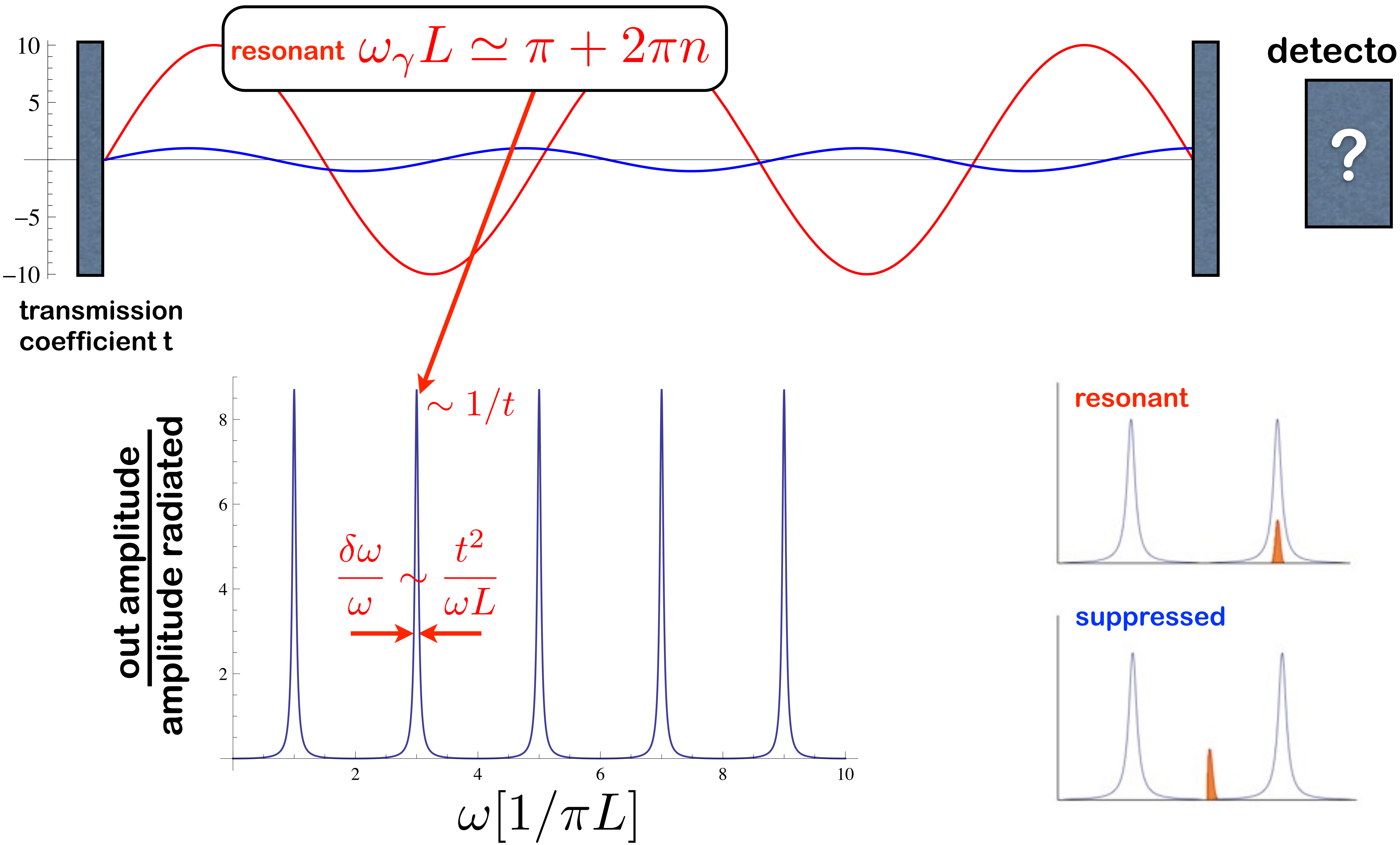


Cavity searches (haloscopes)

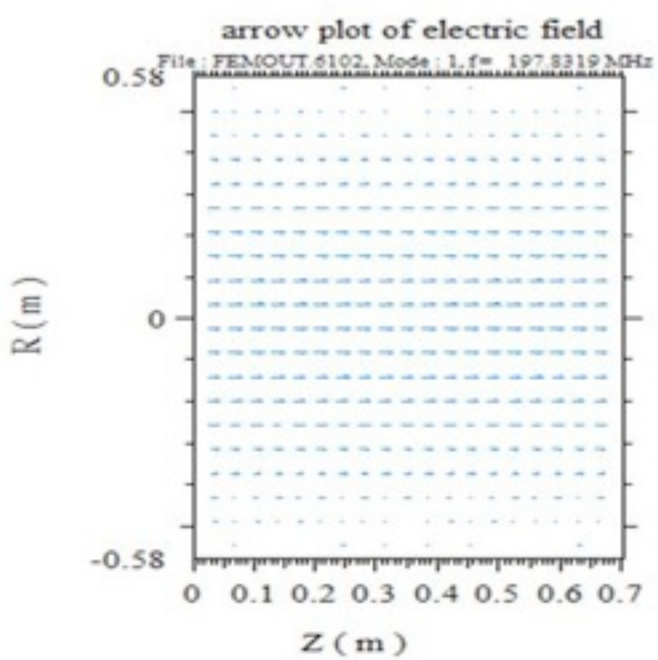
- **Power Loss (cavity tuned!!); putting an pickup we can ideally extract the same**

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

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

- **Usual 3-D formula is**

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



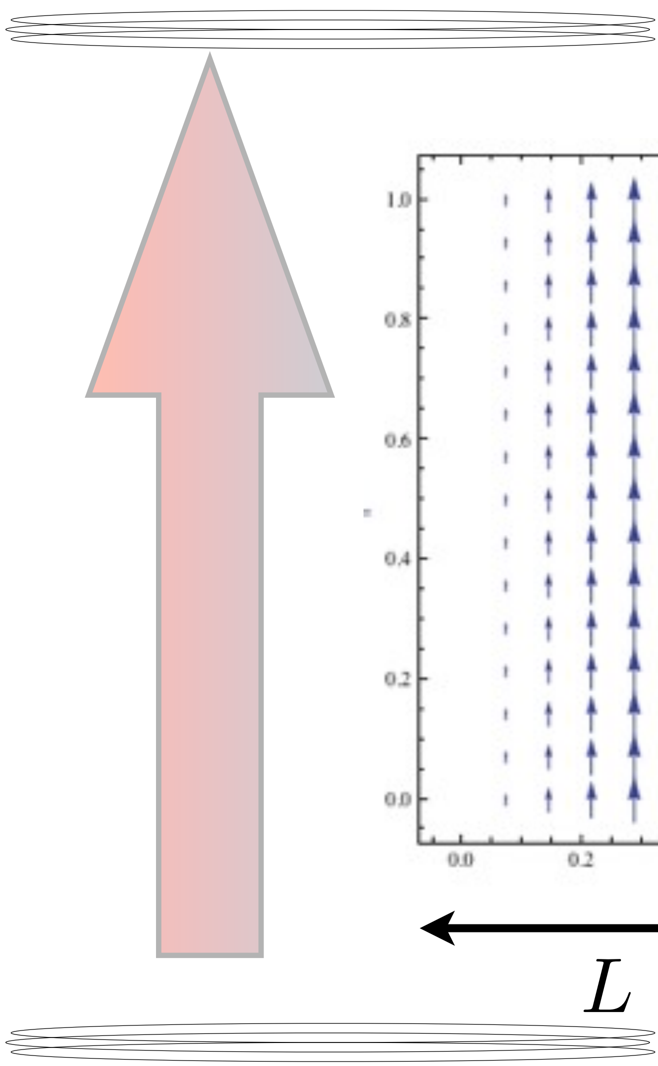
Q **quality factor**

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

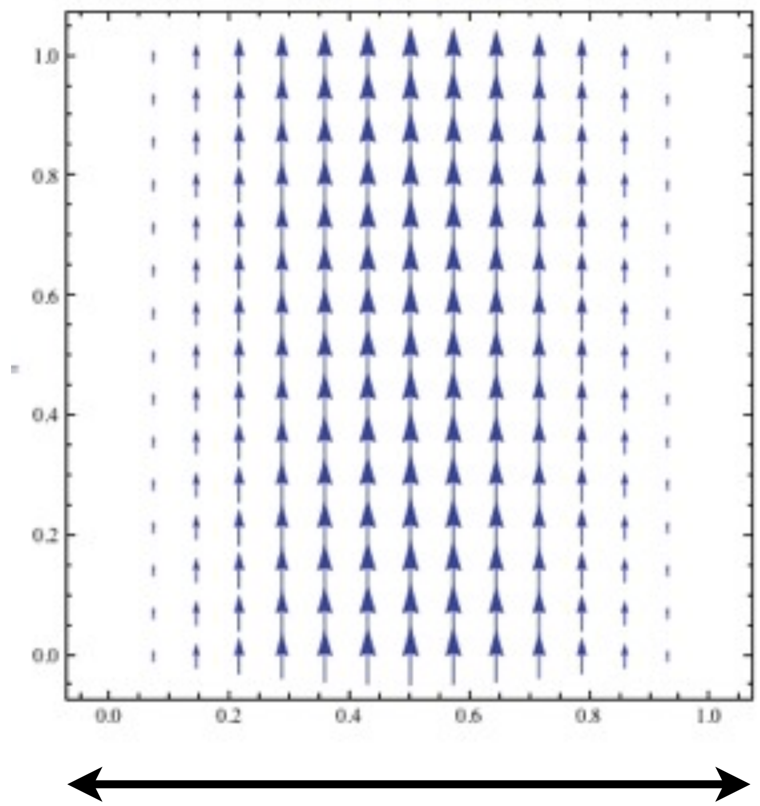
κ **coupling**

Cavity searches (haloscopes)

- Pillbox cavity

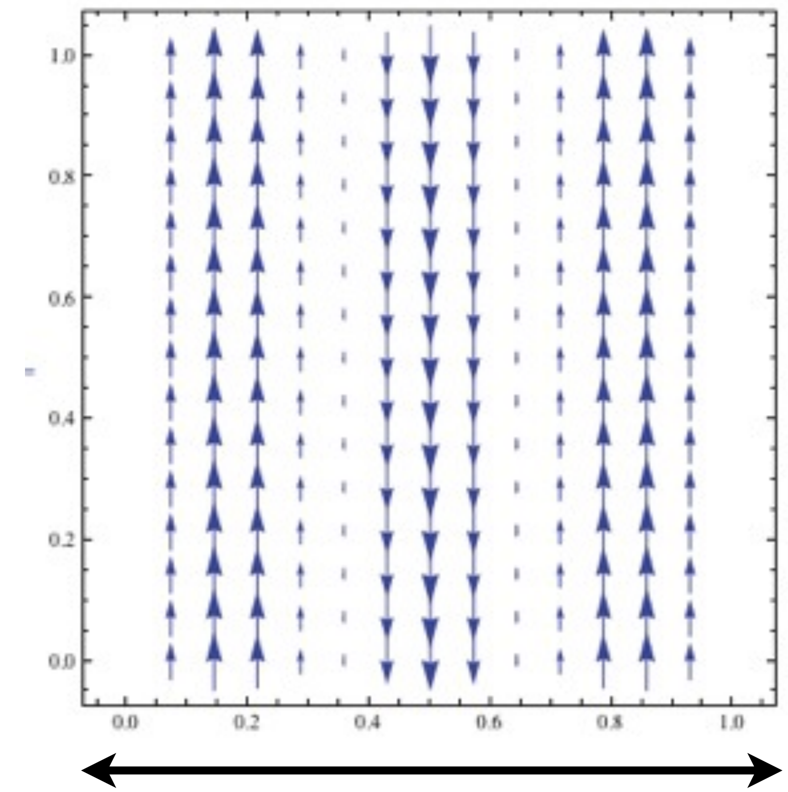


TE10



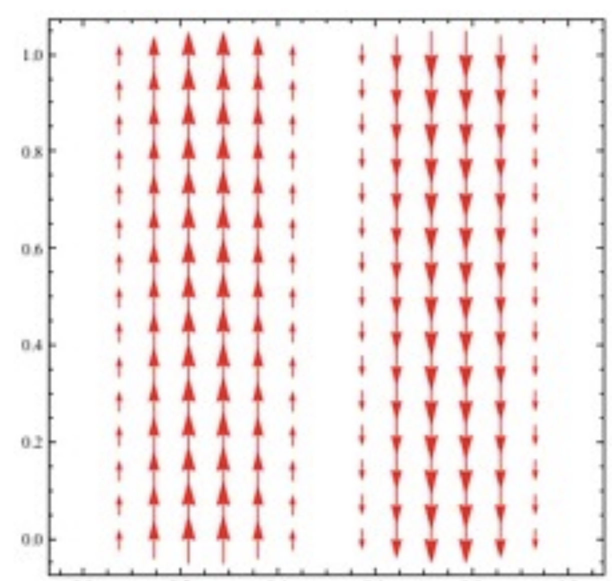
$$L = \pi/m_a$$

TE30



$$L = 3\pi/m_a$$

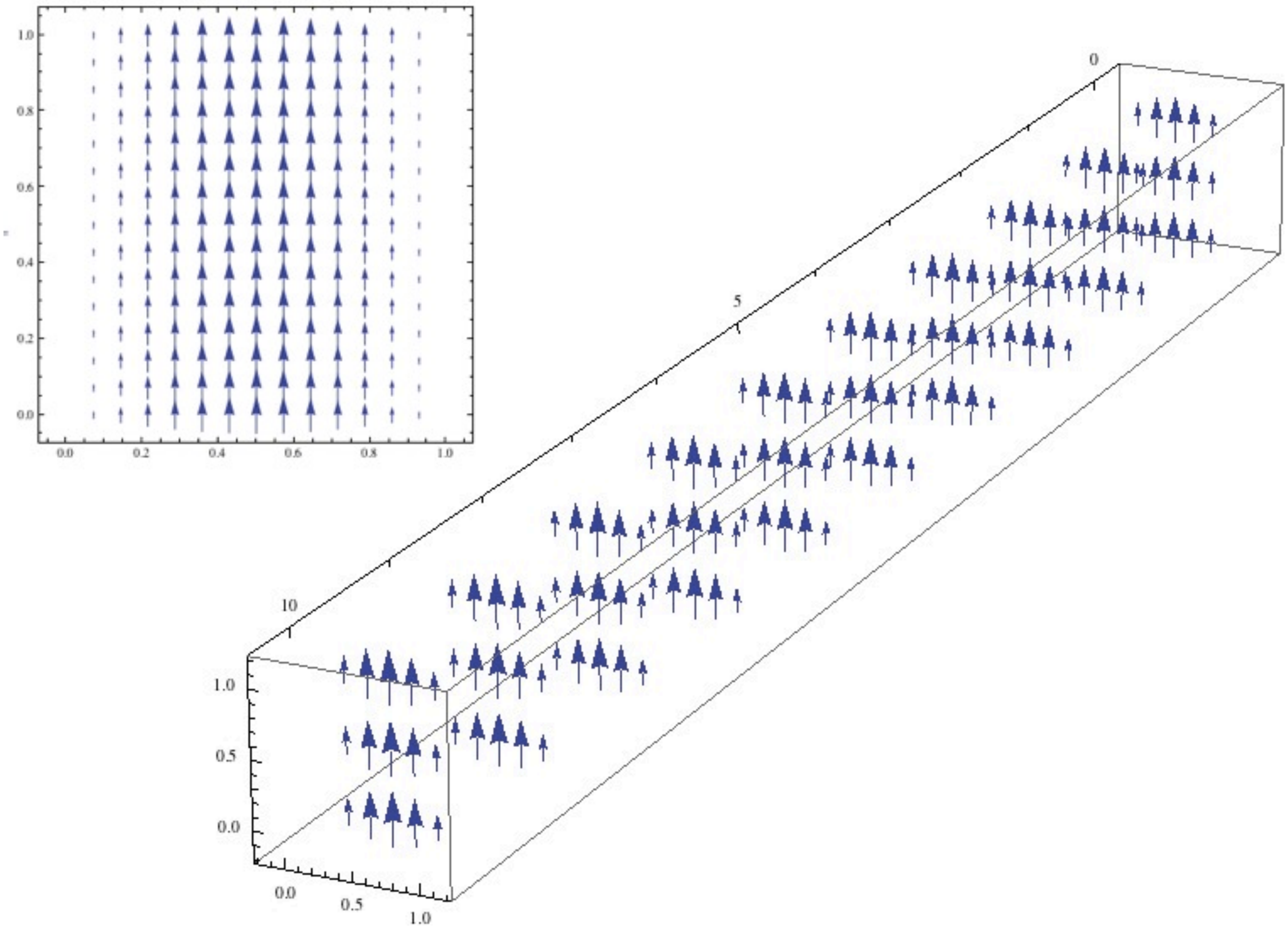
TE20



$$\mathcal{G} = 0$$

Cavity searches (haloscopes)

- **Pillbox cavity**



Cavity searches (haloscopes)

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

$$L_{x,y,z} = 0.6\ \mathrm{m} \times \mathrm{n}_{\mathrm{x,y,z}}$$

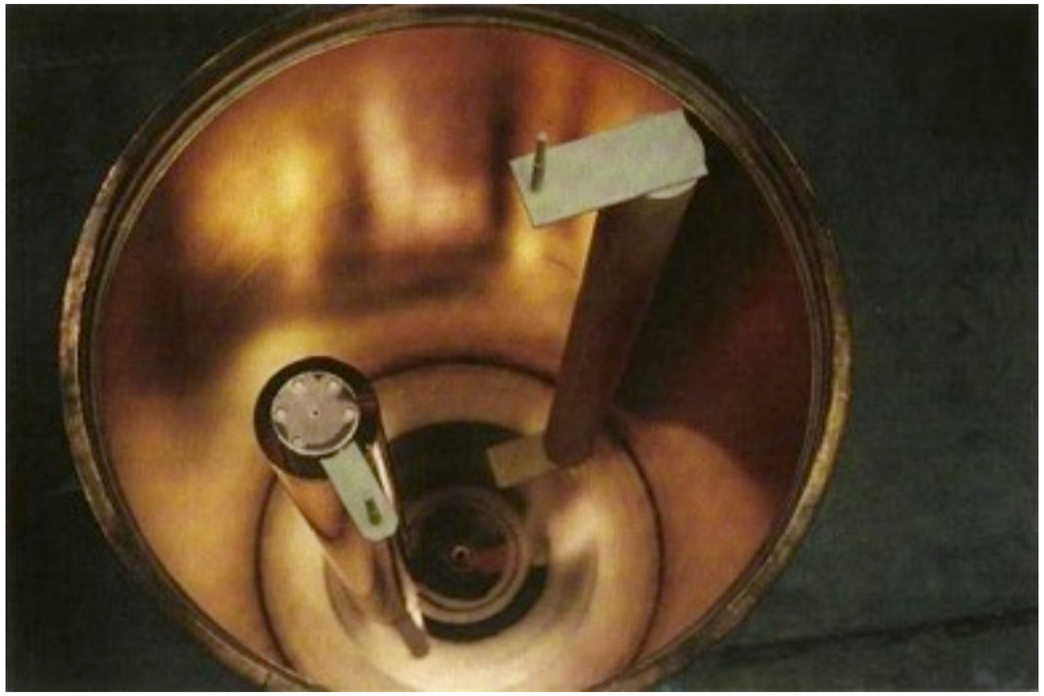
- Problem: we don't know the axion mass -> scan over resonant freqs.

- 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

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

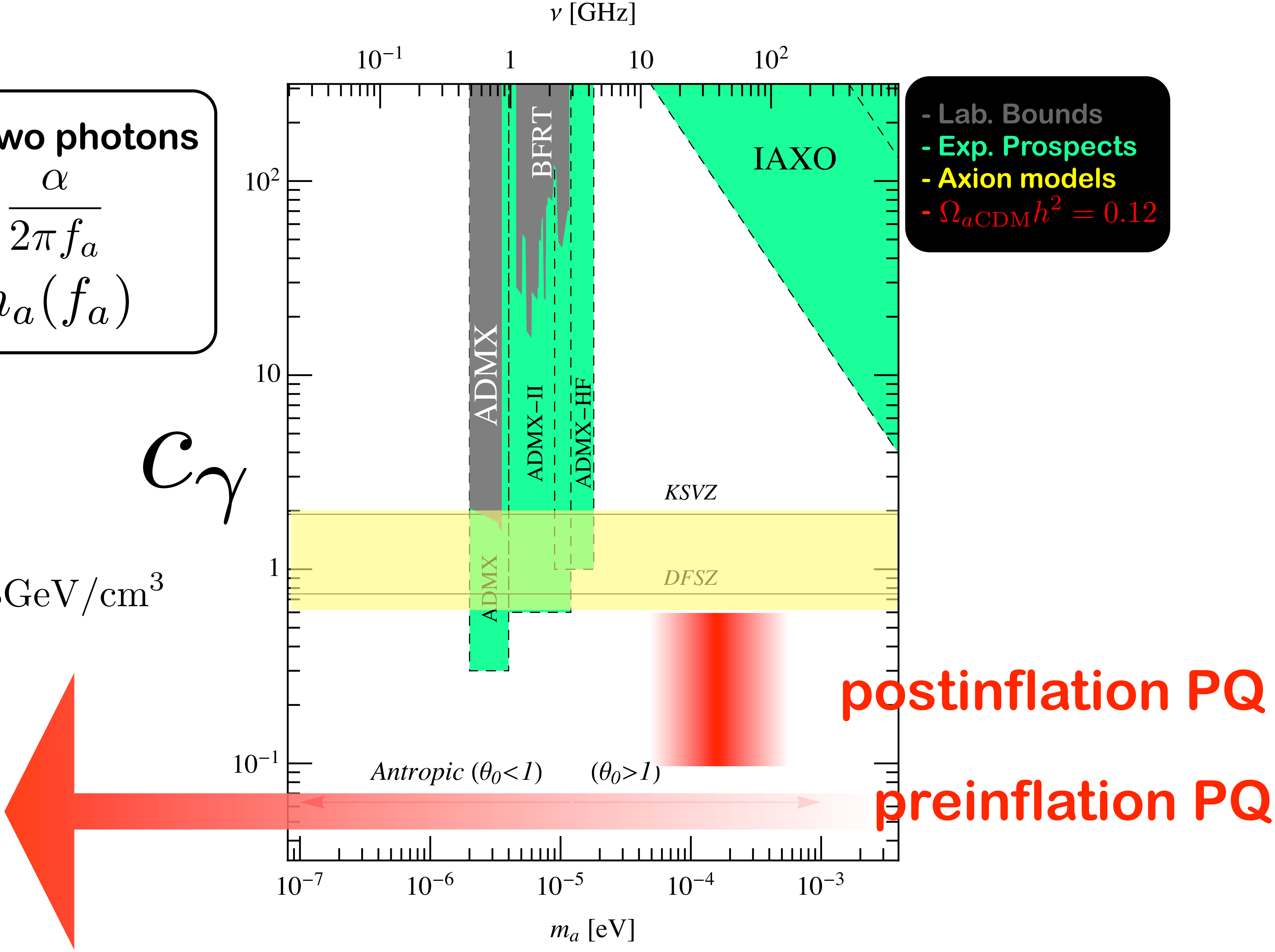
coupling to two photons

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

$$m_a = m_a(f_a)$$

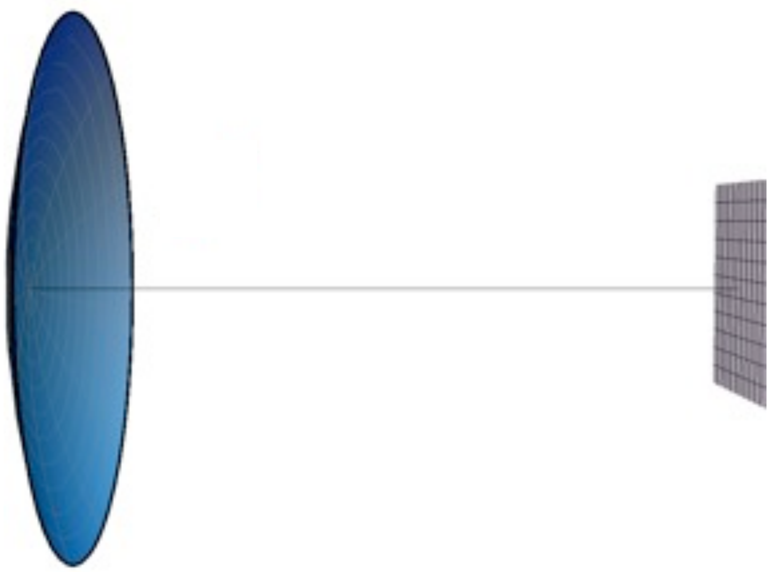
$$c_\gamma$$

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

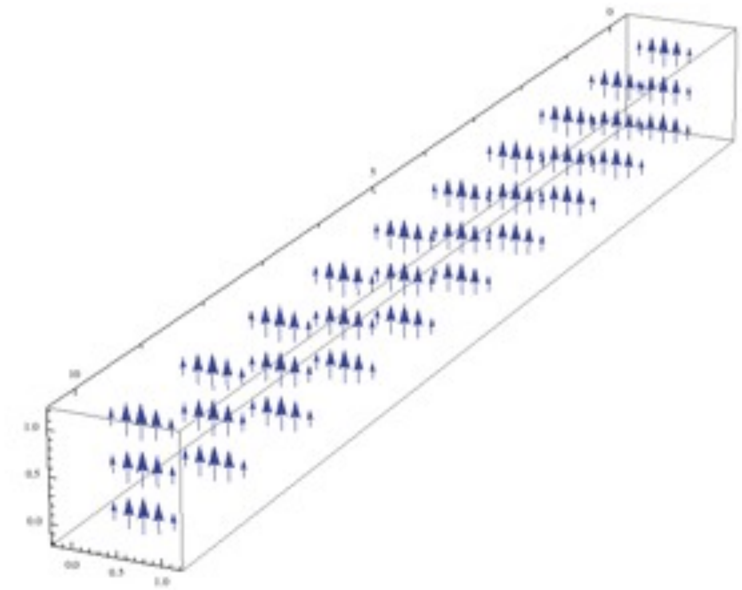


Friday, 13, December,2013

Comparison



vs



$$L = \pi/m_a$$

- broadband
- quite insens. to mass

- needs tune
- very sens. to mass

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

- better at large mass

- better at small mass

Conclusions

- 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

- 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