Axion Dark Matter Detection

Axions in Canfranc 2014

Javier Redondo (LMU/MPP Munich)

Outline

- Axion DM
- Axion DM waves in Magnetic fields
- Dish experiment
- Understanding cavity experiments

Axions!

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

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

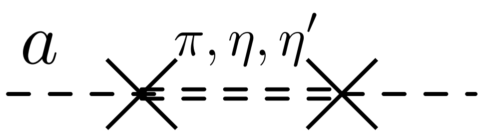
the QCD theta angle is dynamical !!

$$\frac{a(\mathbf{x},t)}{f_a} \equiv \theta(\mathbf{x},t)$$

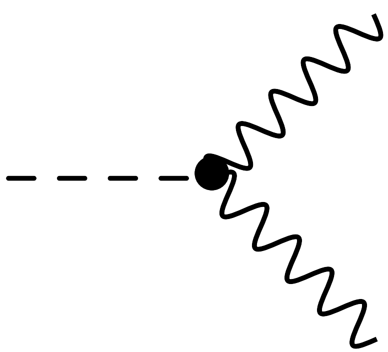
- Axions have predictable properties, which depend mostly on f_a

(Energy scale at which the U(1) is spontaneously broken)

- Axion properties



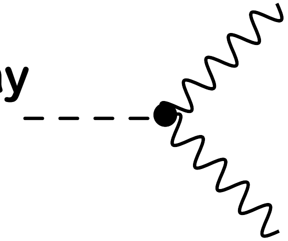
$$m_a \simeq 6\,\mathrm{meV}\frac{10^9\,\mathrm{GeV}}{f_a}$$



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

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

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

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

- **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

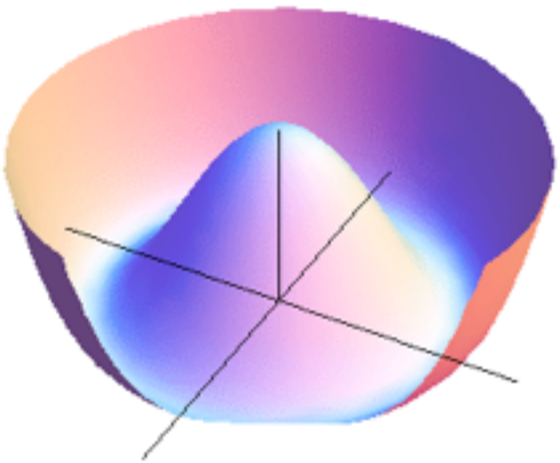
$$\frac{a(t_0)}{f_a} \in (-\pi, \pi)$$

At PQ phase transition

Axion cold dark matter I

Realignment mechanism

(Field space)



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

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

Axion cold dark matter I

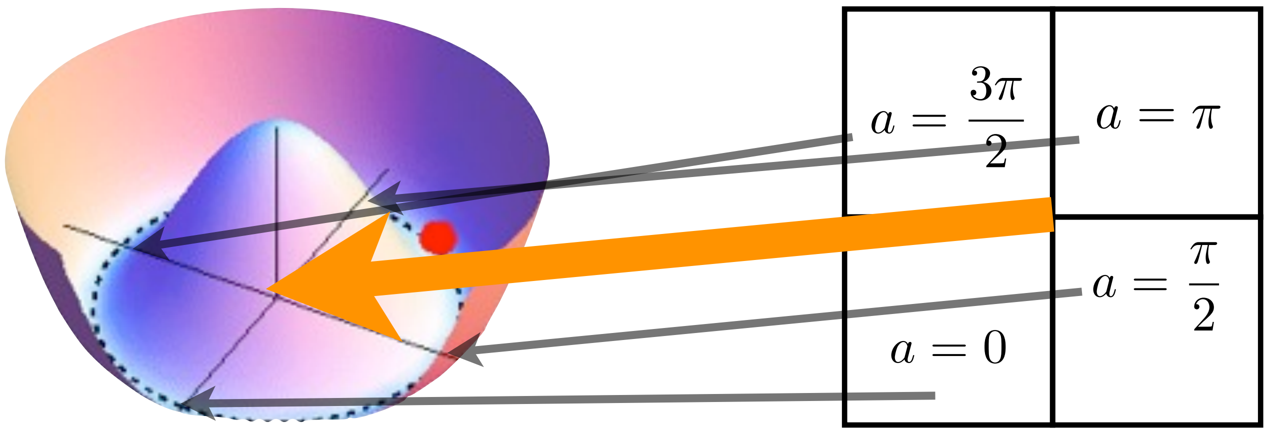
Realignment mechanism

(Field space)

Cosmic Strings

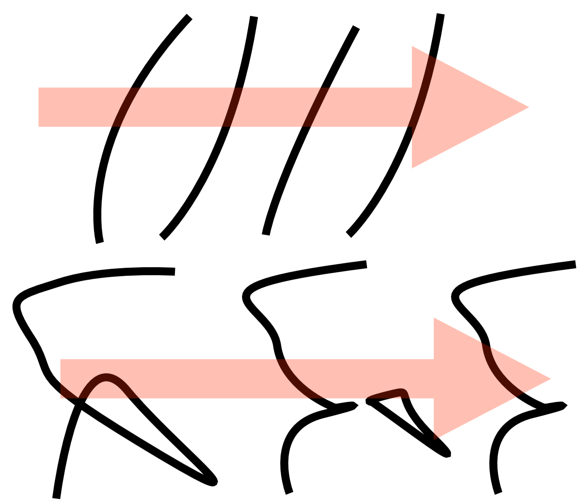
(Position space)

(T>QCD)



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

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



Axion cold dark matter I

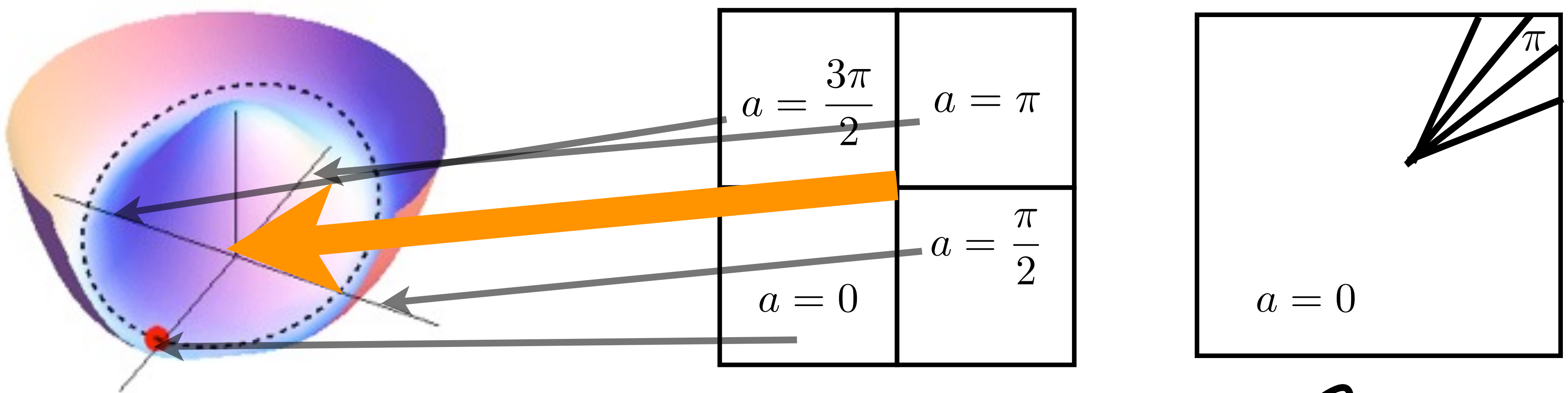
Realignment mechanism | Cosmic Strings | Domain Walls

(Field space)

(Position space)

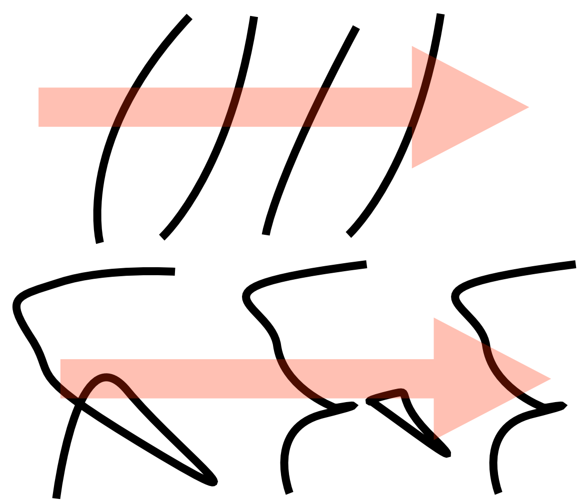
(T>QCD)

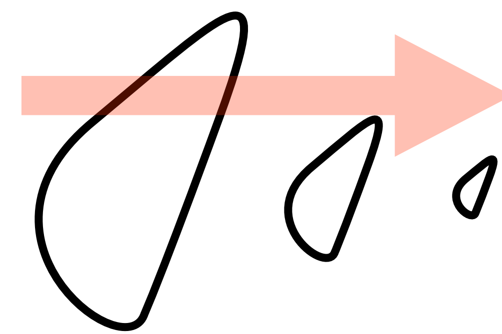
(T<QCD)



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

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

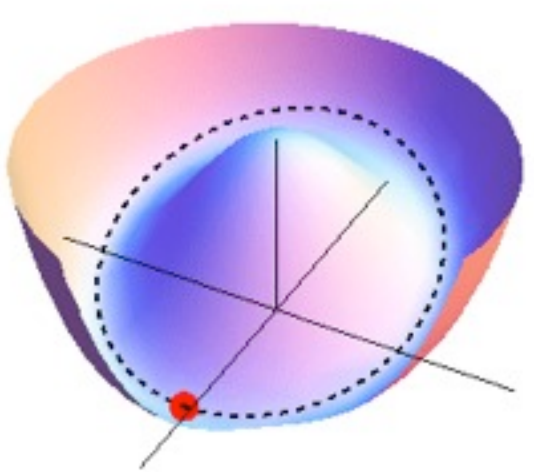




Axion cold dark matter I

Realignment mechanism

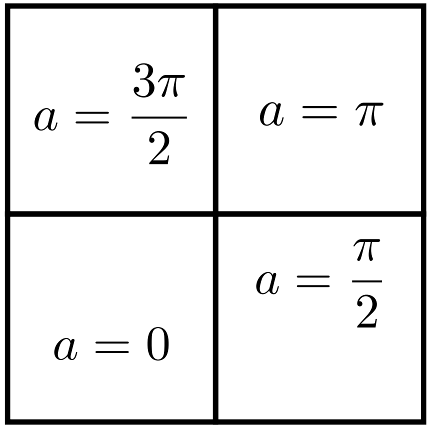
(Field space)



Cosmic Strings

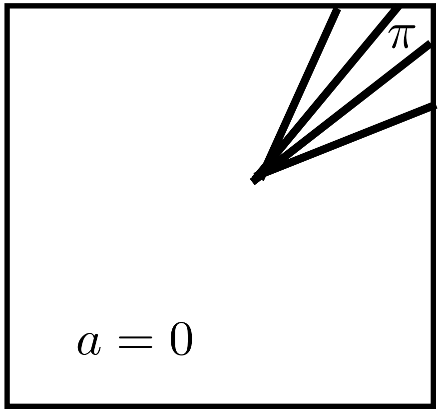
(Position space)

(T>QCD)



Domain Walls

(T<QCD)



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

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

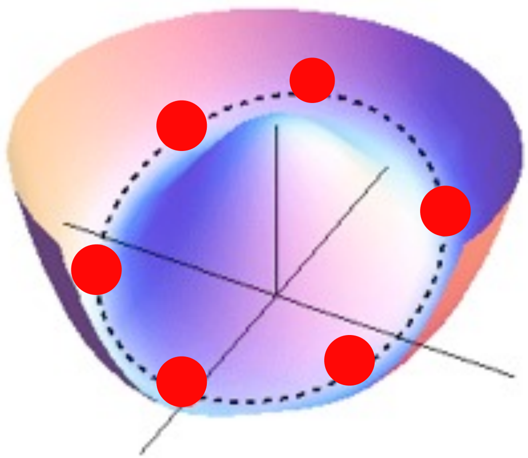
Sikivie, Harari et at.

Shellard, Davis et at.
Kawasaki, Hiramatsu et at

Axion cold dark matter II (PQ before inflation)

Realignment mechanism

(Field space)



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

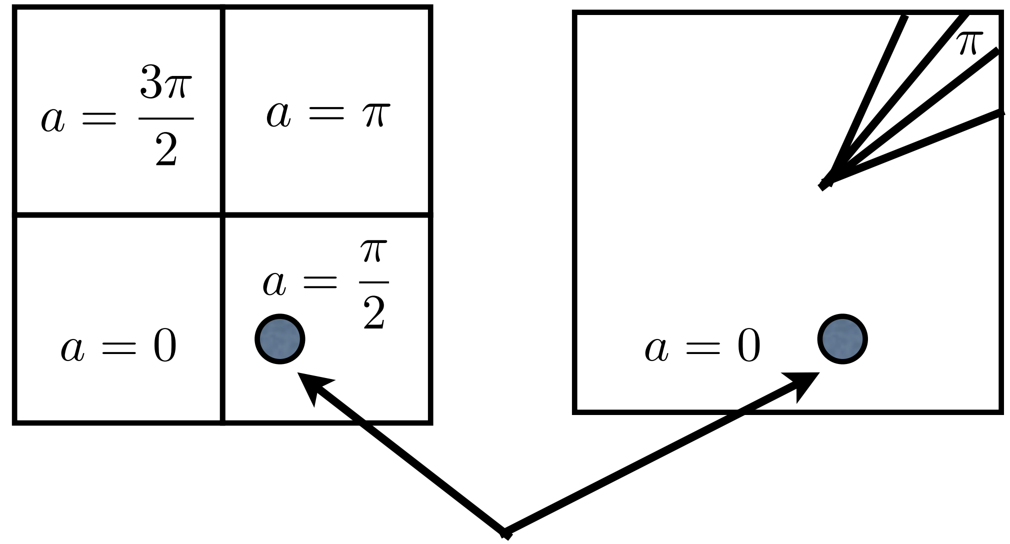
Cosmic Strings

Domain Walls

(Position space)

(T>QCD)

(T<QCD)



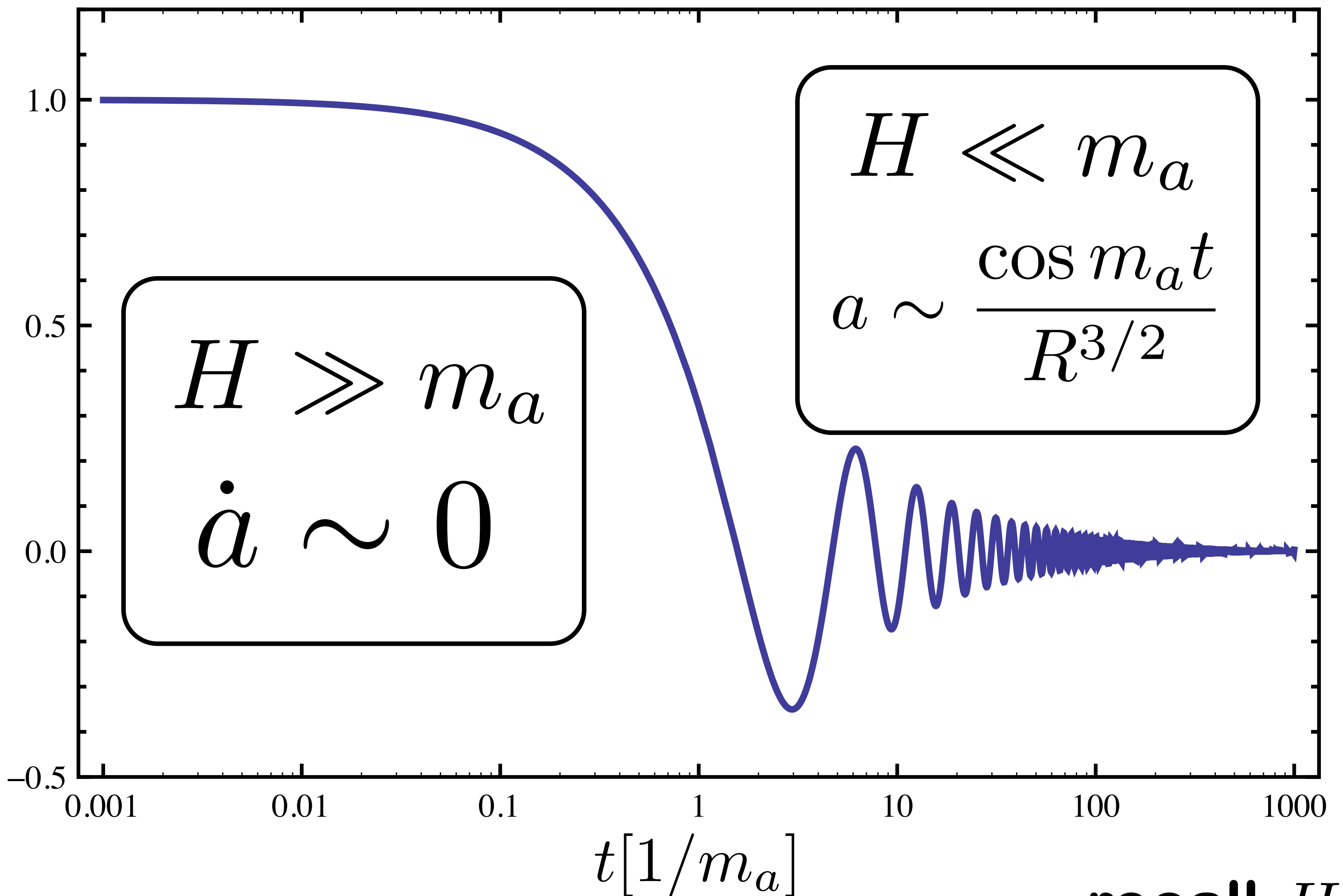
Size of our universe after inflation fits inside one of these domains

- CSs and DWs are diluted by expansion

- Whole universe has 1 initial value for a

... calculation ...

E.o.m. for zero mode $\ddot{a} + 3H\dot{a} + m_a^2 a = \ldots \sim 0$



recall $H \sim 1/t$

Relic abundance of WISPy Dark matter

comoving axion number conserved

$$\rho_a = \frac{1}{2}(\dot{a})^2 + \frac{1}{2}m_a^2 a^2 \longrightarrow N = \frac{\rho_a R^3}{m_a} = \text{ct.} = \frac{1}{2} m_a R_1^3 a_1^2$$

$$\rho_a(t_0) = m_a \frac{N}{R_0^3} = \frac{1}{2} m_a^2 a_1^2 \left(\frac{R_1}{R_0}\right)^3$$

$$\left(\frac{R_1}{R_0}\right)^3 \sim \left(\frac{T_0}{T_1}\right)^3 \sim \left(\frac{T_0}{\sqrt{H_1 m_{\rm Pl}}}\right)^3 \sim \left(\frac{T_0}{\sqrt{m_a m_{\rm Pl}}}\right)^3 \propto m_a^{-3/2}$$

$$a_1 \sim f_a \qquad f_a \propto 1/m_a$$

$$\rho_a(t_0) \propto \sqrt{m_a} f_a^2 \propto m_a^{-3/2}$$

Relic abundance of WISPy Dark matter

- Simplest scenario:

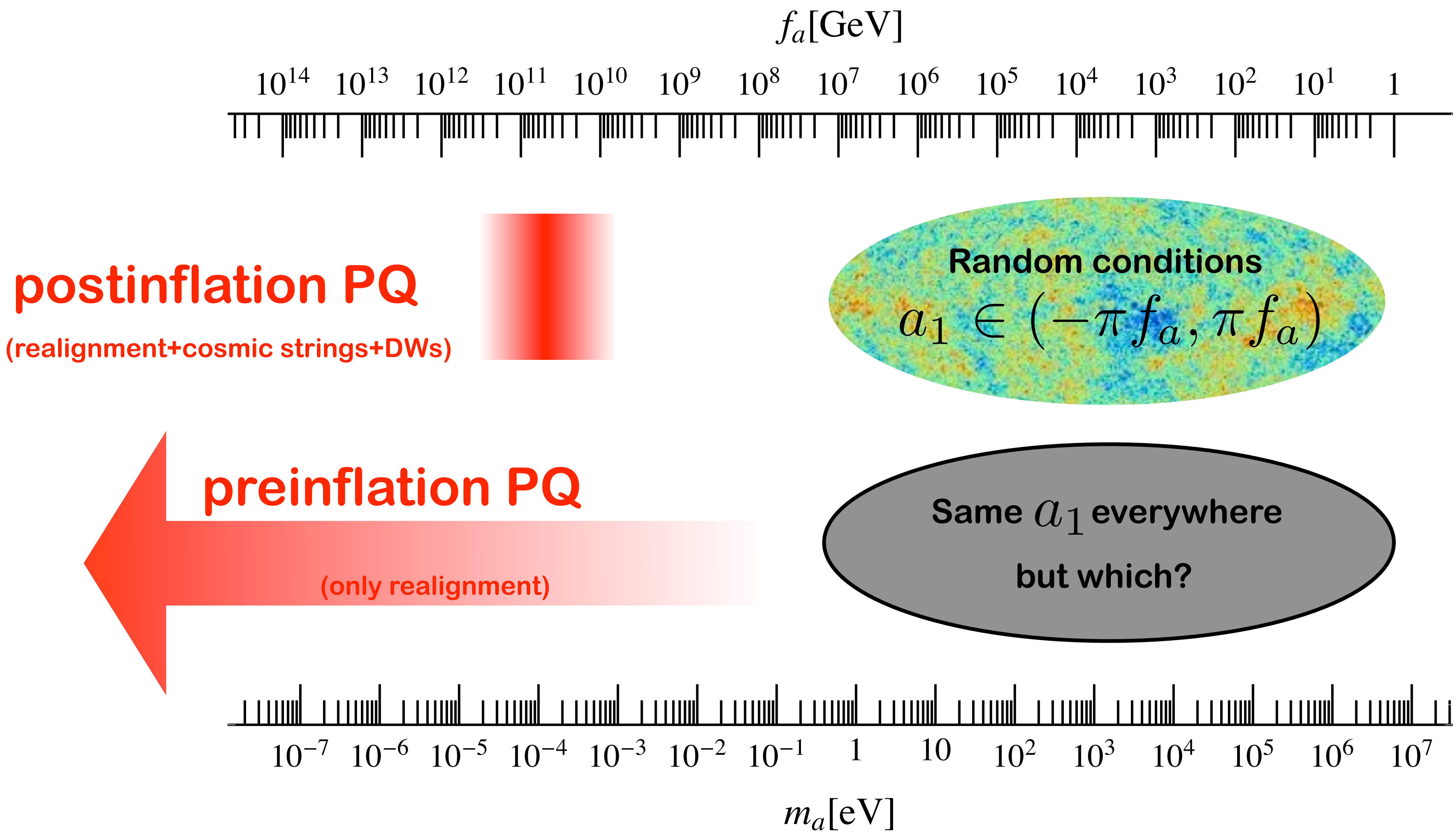
$$\rho_{a,0} \simeq 1.3\,\frac{\mathrm{keV}}{\mathrm{cm}^3} \times \sqrt{\frac{m_a}{\mathrm{eV}}}\left(\frac{a_1}{4.7\times 10^{11}\,\mathrm{GeV}}\right)^2 \mathcal{F},$$

recall $\rho_{\rm CDM} \sim 1.3\frac{\mathrm{keV}}{\mathrm{cm}^3}$

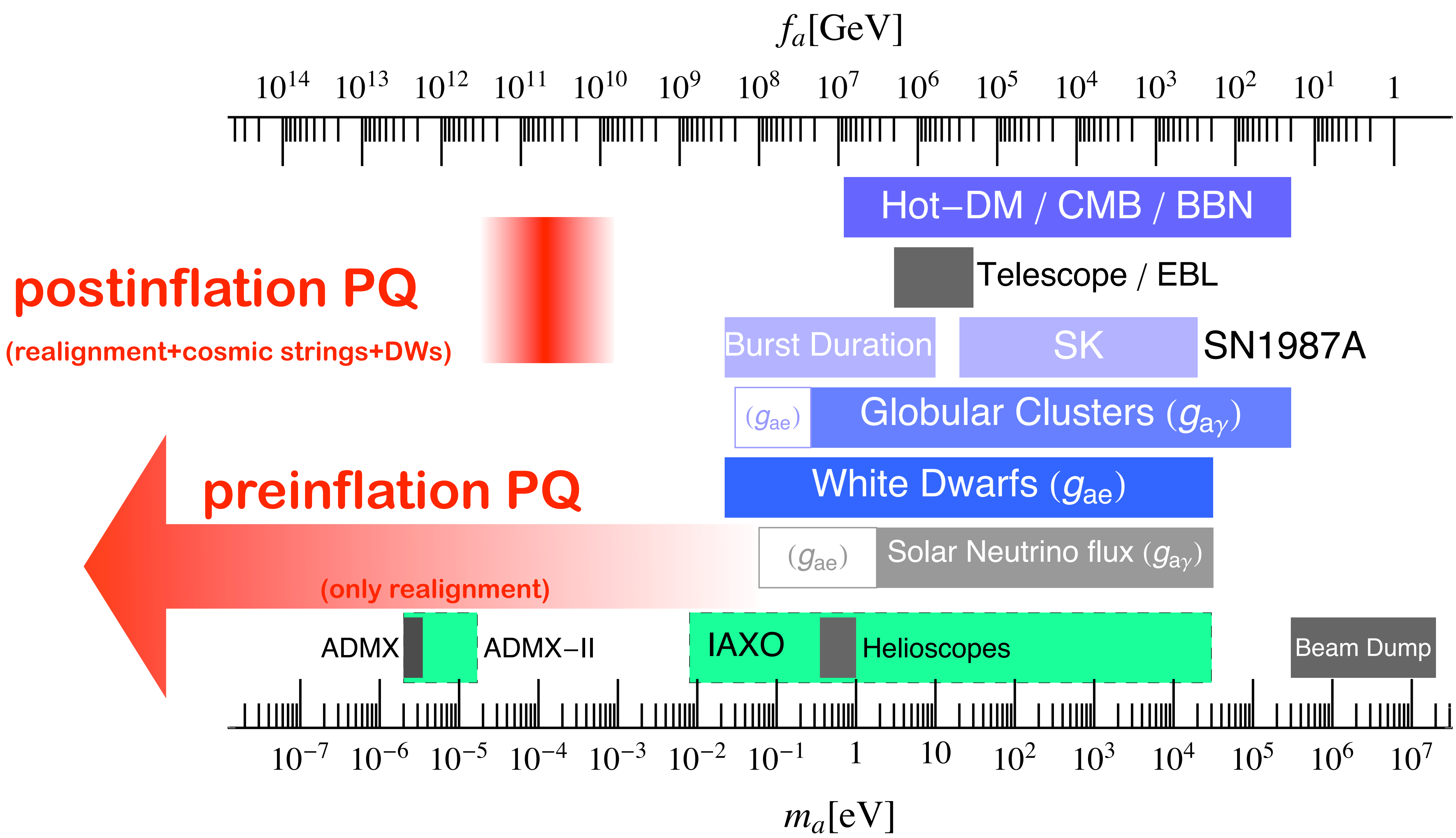
- Initial amplitude, physics at <u>very high energies</u>

- WISPy DM opens a window to HEP

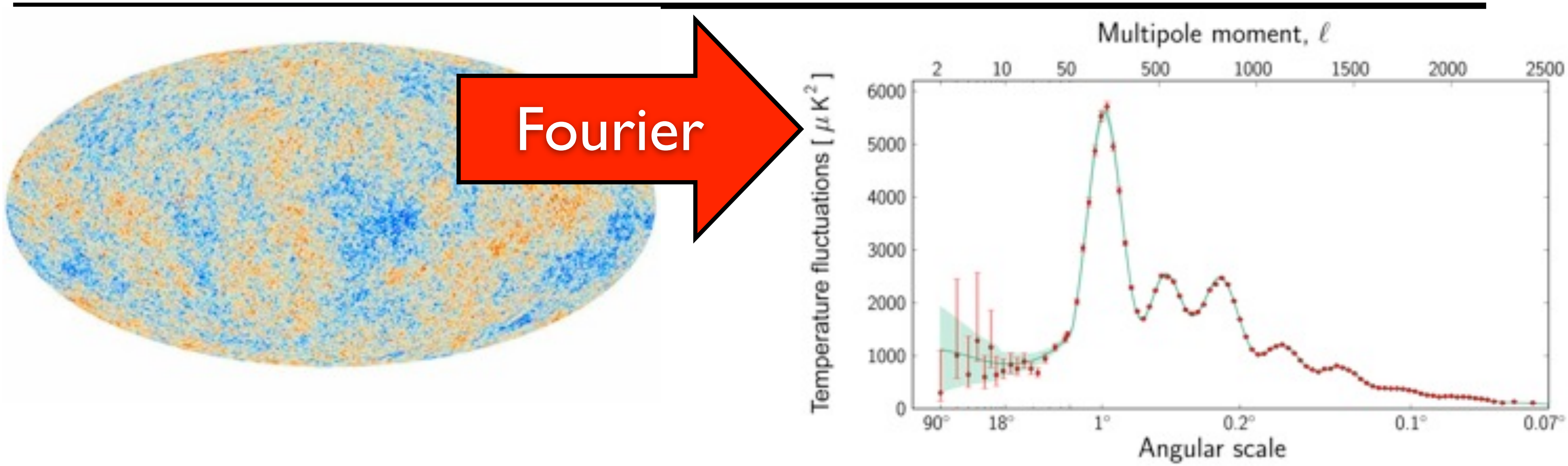
QCD axion cold dark matter (two scenarios)

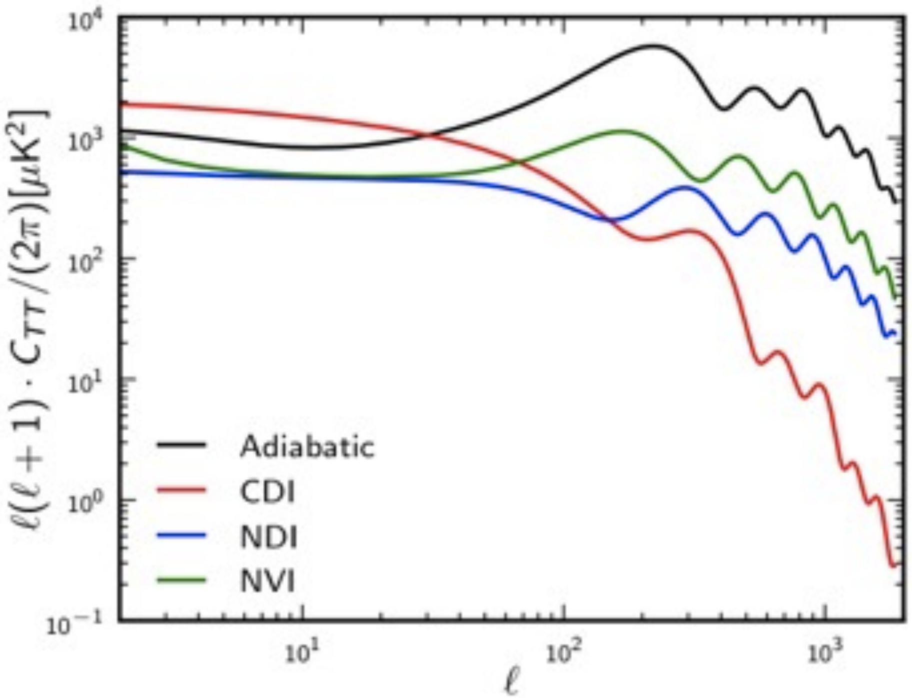


+ Bounds on axions (and prospects)



ISOCURVATURE perturbations in the CMB





fit different contributions and constraint them

$$P_{\rm iso} < 0.02\, P_s \quad (95\%\text{C.L.})$$

ISOCURVATURE perturbations in the CMB

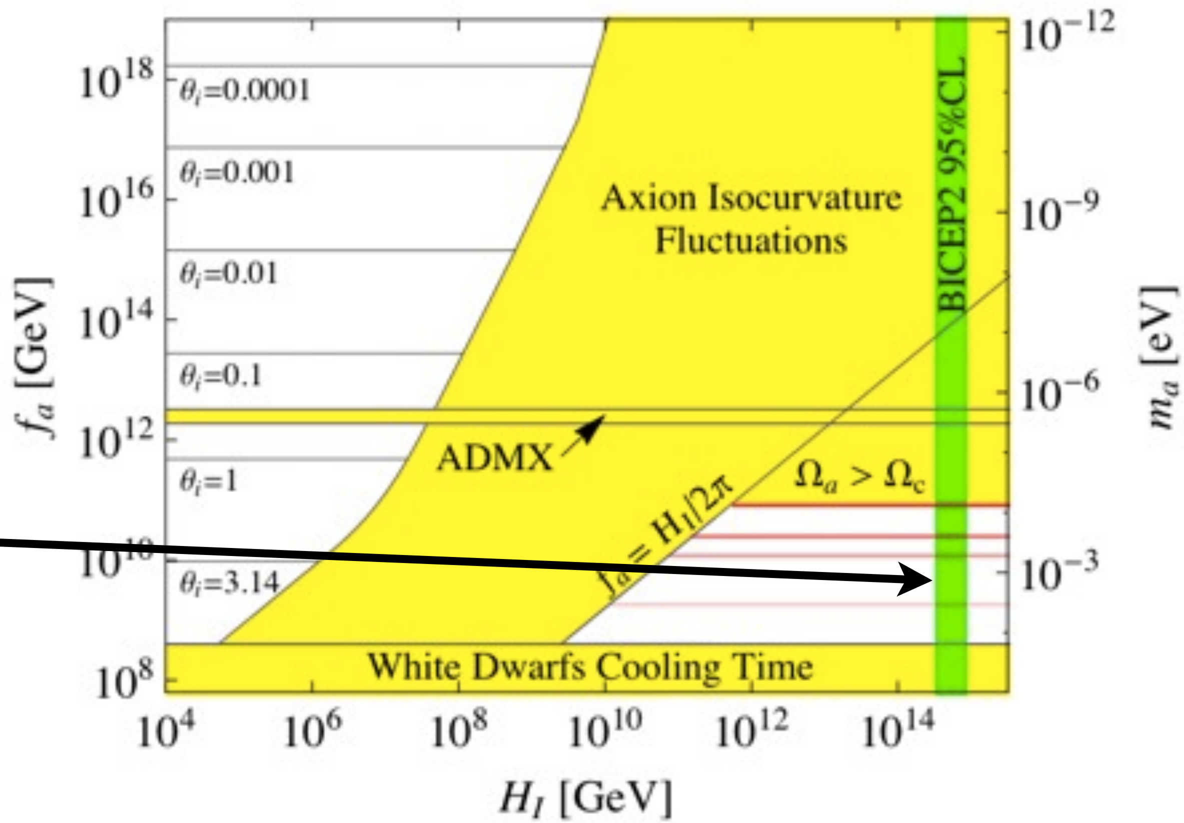
$$P_{\rm iso} = \frac{d\langle n_a\rangle}{n_a} \sim \frac{d\langle a^2\rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2}$$

insisting on axion DM $\theta_I = \theta_I(f_a)$

Planck constrains f_a

as function of H_I

Last week, BICEP2 (!!) measured indirectly H_I



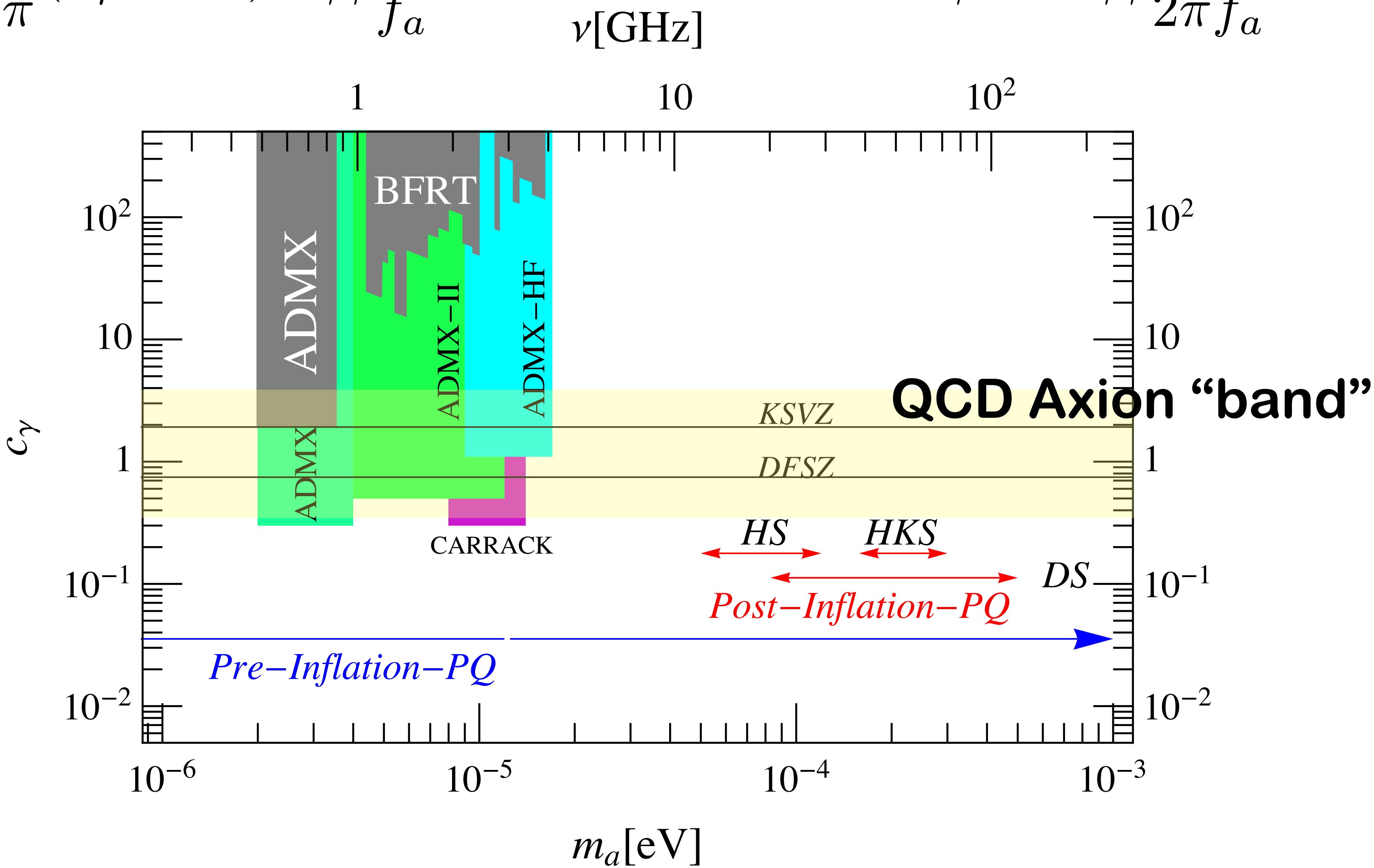
- Taken at face value Pre-Inflation-PQ is excluded

- Caveats:
    - BICEP2 needs to be confirmed
    - some models avoid isocurvature perturbations

-This does not mean that the mass range I showed is totally excluded:
    - Axions subdominant component of DM
    - Entropy production
    - ...

Laboratory

$$\frac{\alpha}{8\pi}(F_{\mu\nu}\widetilde{F}^{\mu\nu})c_{a\gamma\gamma}\frac{a}{f_a} \qquad g_{a\gamma} = c_{a\gamma\gamma}\frac{\alpha}{2\pi f_a}$$



Axion DM around us

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

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

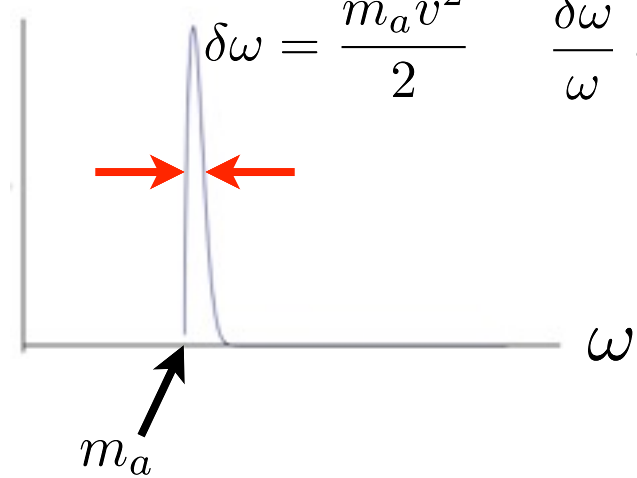
phase space density $\quad \dfrac{n_a}{\frac{4\pi p^3}{3}} \sim 10^{29} \left(\dfrac{\mu\mathrm{eV}}{m_a}\right)^4$

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

Fourier-transform $a(x)$

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

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



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 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

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Not axions, nor photons are propagation eigenstates!

Maxwell's equations with axions ... $F_{\mu\nu} = \partial_\mu A_\nu(\mathbf{x}, t) - \partial_\nu A_\mu(\mathbf{x}, t)$

$$\partial^\mu F_{\mu\nu} = g_{a\gamma} \widetilde{F}_{\mu\nu} \partial^\mu a(\mathbf{x}, t)$$

$$(\partial_t^2 - \Delta) A_\nu = g_{a\gamma} \widetilde{F}_{\mu\nu} \partial_\mu a$$

Axion - photon mixing in a magnetic field

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

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Maxwell's equations with axions ... $F_{\mu\nu} = \partial_\mu A_\nu(\mathbf{x},t) - \partial_\nu A_\mu(\mathbf{x},t)$

$$\partial^\mu F_{\mu\nu} = g_{a\gamma}\widetilde{F}_{\mu\nu}\partial^\mu a(\mathbf{x},t)$$

$$(\partial_t^2 - \Delta)A_\nu = g_{a\gamma}\widetilde{F}_{\mu\nu}\partial_\mu a$$

Axion's equation with Maxwell's

$$(\partial_t^2 - \Delta)a = -g_{a\gamma}F^{\mu\nu}\widetilde{F}_{\mu\nu}/4$$

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

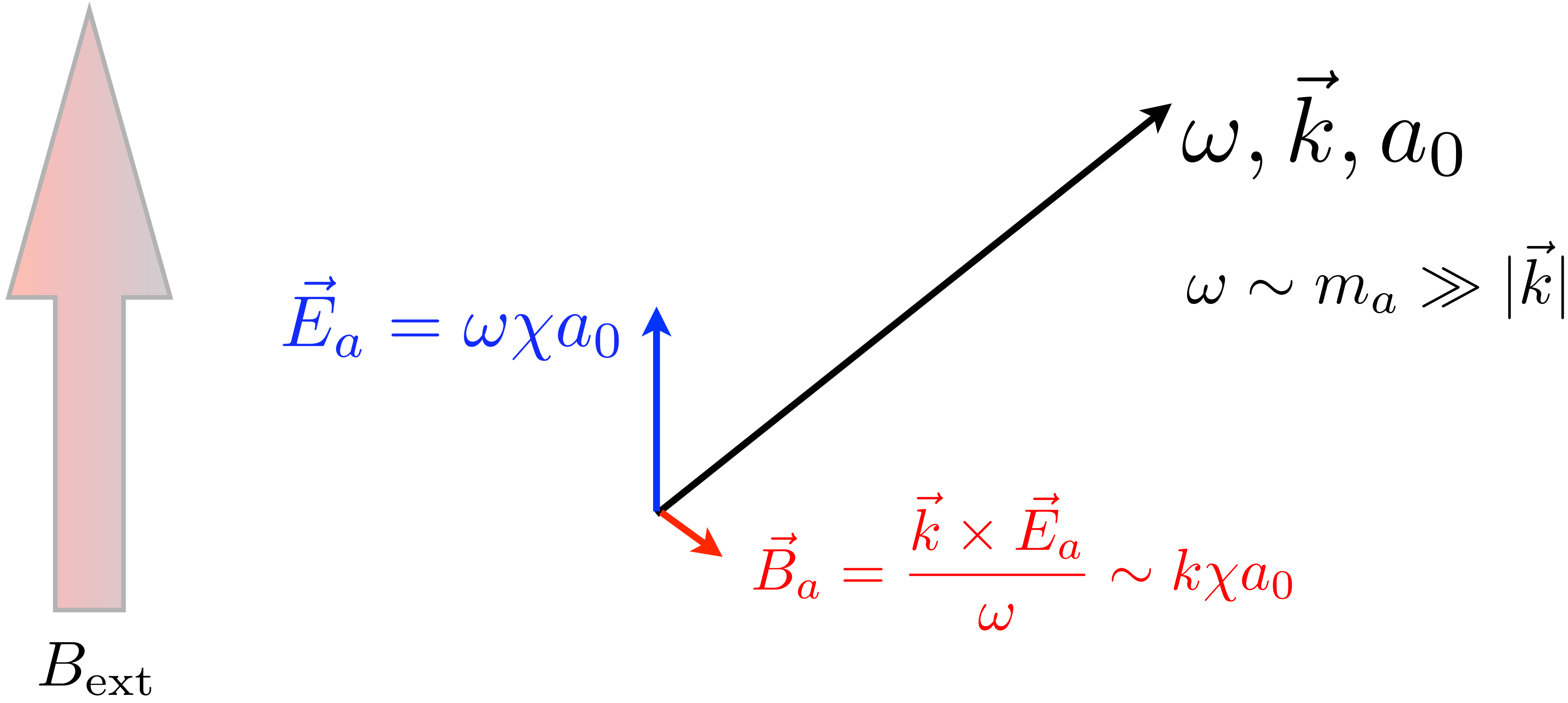
- **"Dark matter" solution** $v = \frac{k}{\omega}$; $\omega \simeq m_a(1 + v^2/2 + ...)$

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

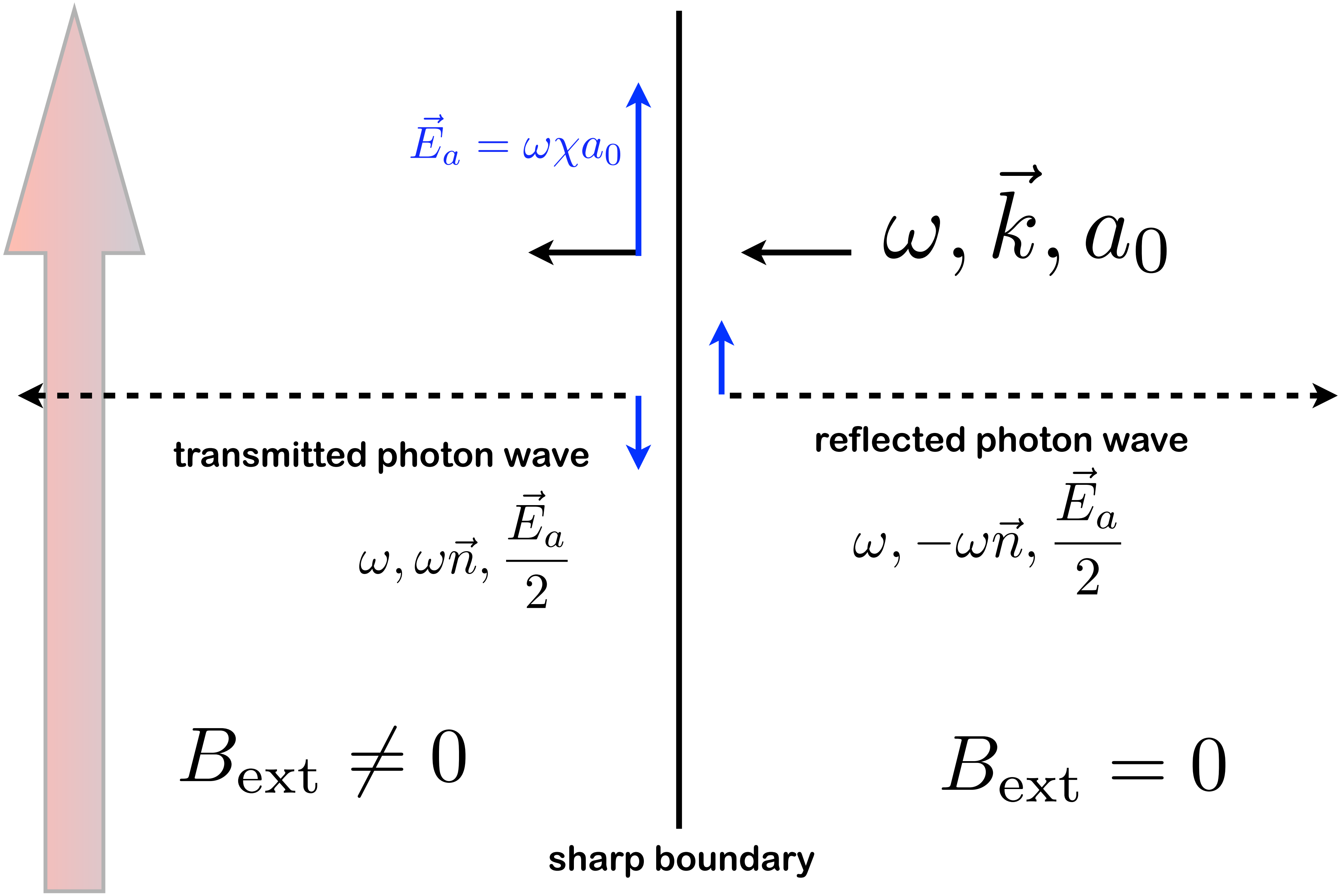
It has a small E field!

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

DM axions in a magnetic field

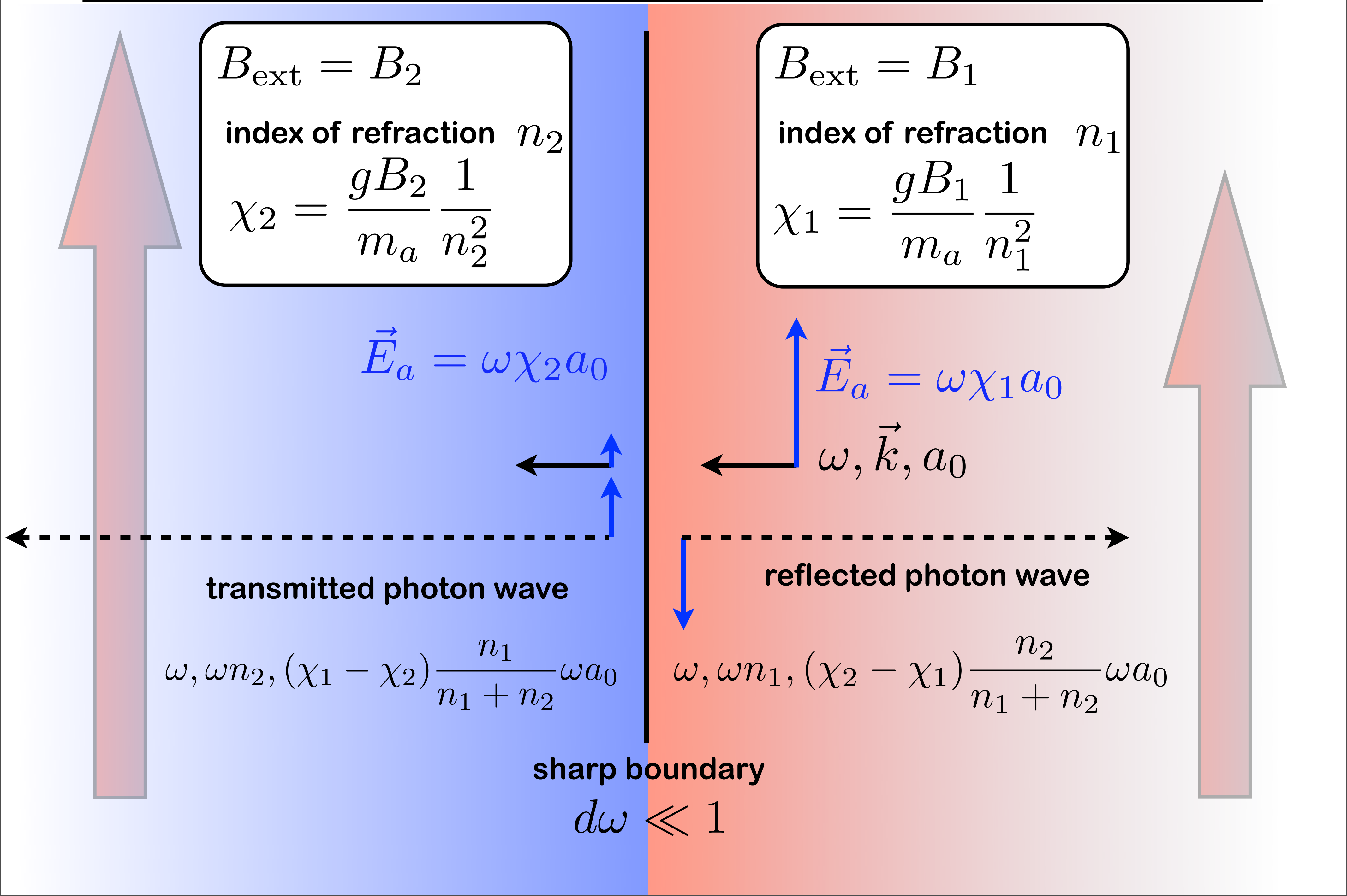


DM axions entering a magnetic field



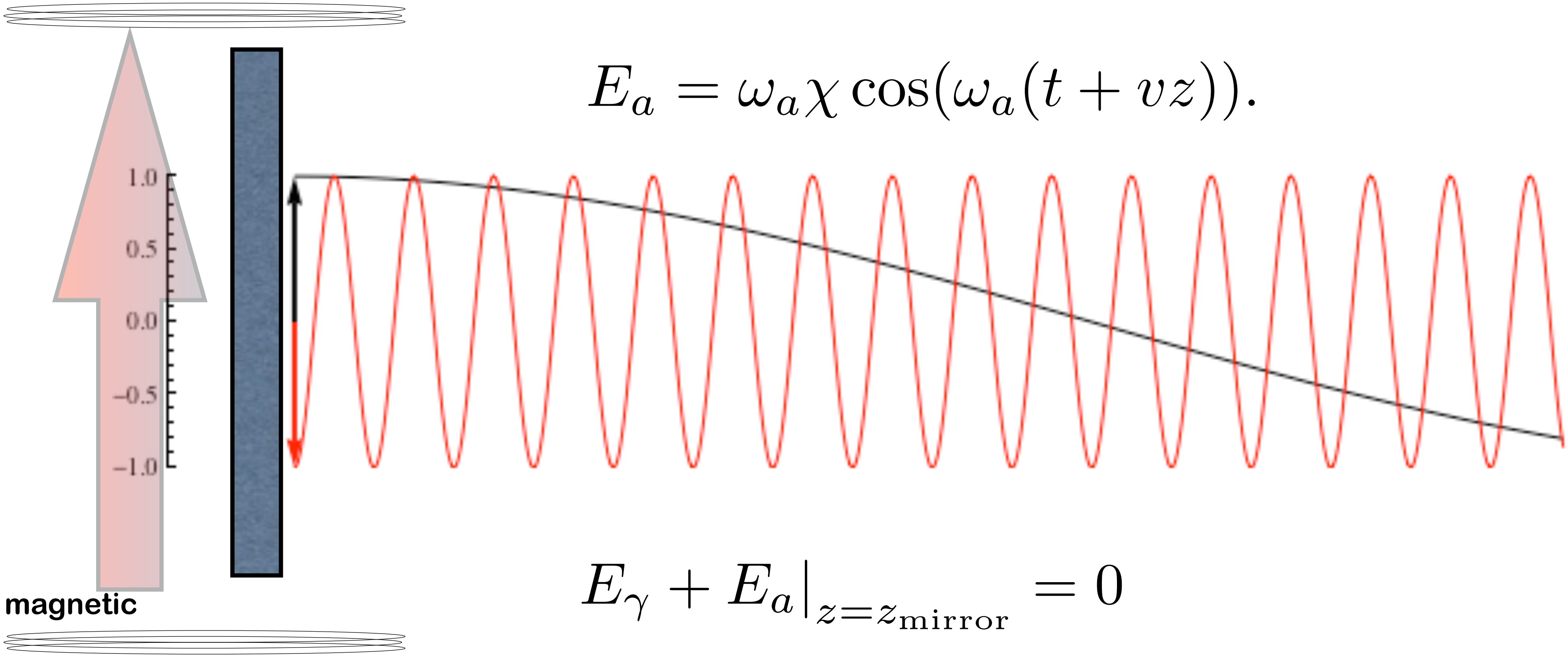
DM axions changing medium

Jaeckel and JR, PRDxxx, arXiv:1308.1103



Radiation from a magnetised mirror

Horns at al JCAP04(2013)016



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

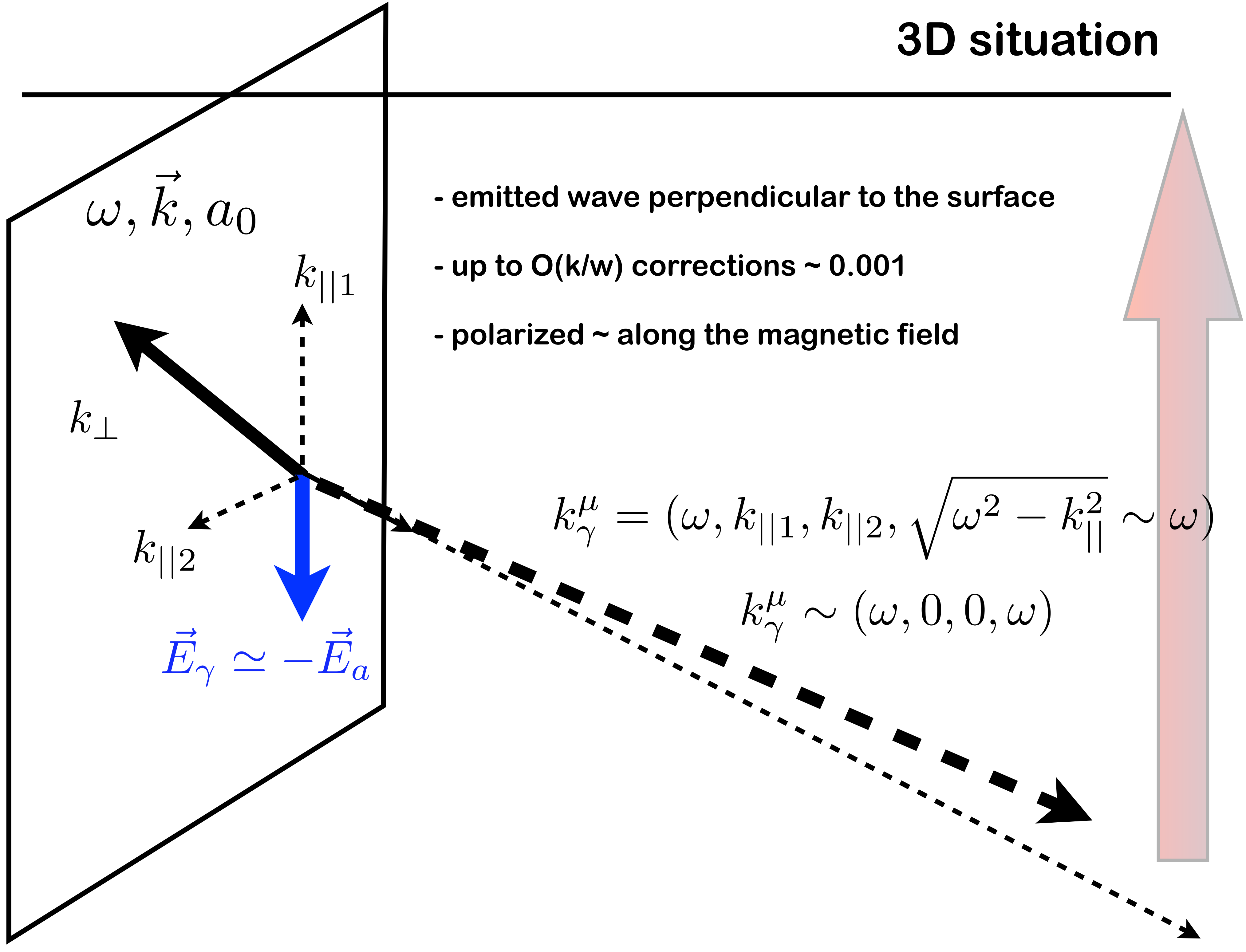
$$E_\gamma + E_a|_{z=z_{\rm mirror}} = 0$$

Radiated photon wave

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

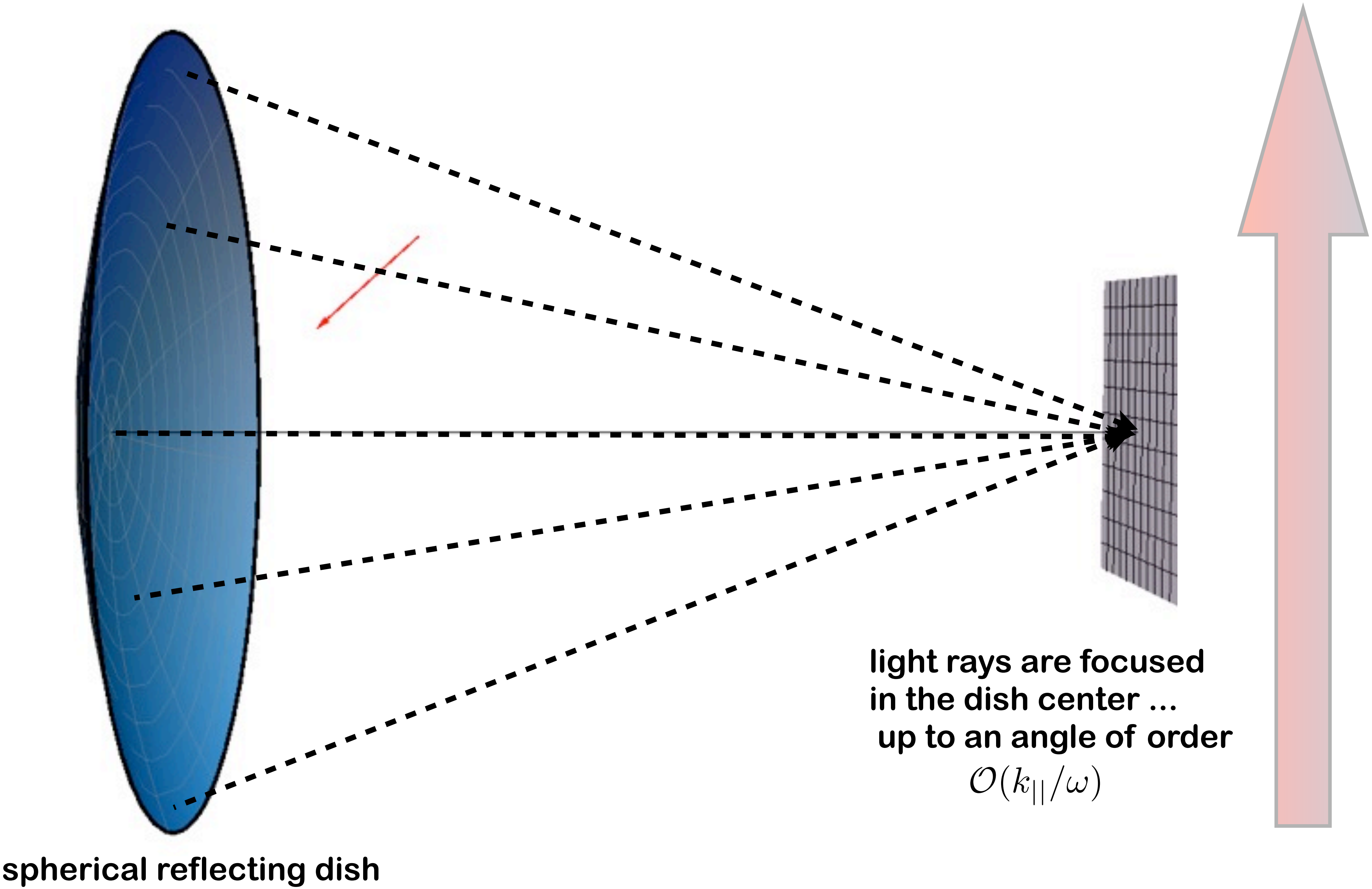
whose frequency is

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


3D situation
- emitted wave perpendicular to the surface
- up to O(k/w) corrections ~ 0.001
- polarized ~ along the magnetic field
$\omega, \vec{k}, a_0$
$k_{||1}$
$k_\perp$
$k_{||2}$
$\vec{E}_\gamma \simeq -\vec{E}_a$
$k^\mu_\gamma = (\omega, k_{||1}, k_{||2}, \sqrt{\omega^2 - k^2_{||}} \sim \omega)$
$k^\mu_\gamma \sim (\omega, 0, 0, \omega)$

Simplest experiment

Horns at al JCAP04(2013)016



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**

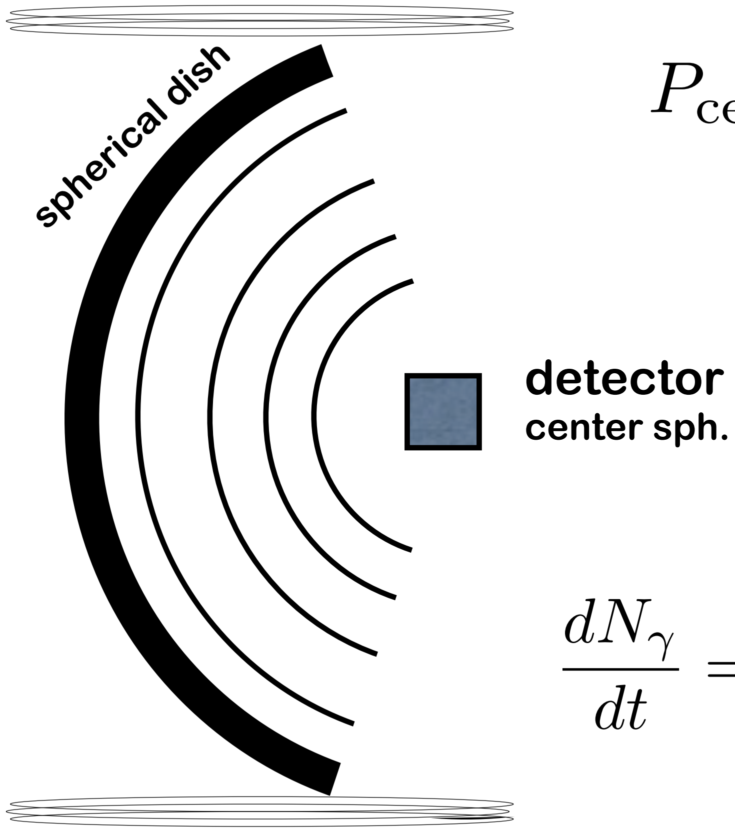
$$\rho_{\mathrm{CDM}} = \frac{1}{2}m_a^2 a_0^2 = 0.3\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

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

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

Signal size

Horns et al , JCAP04(2013)016



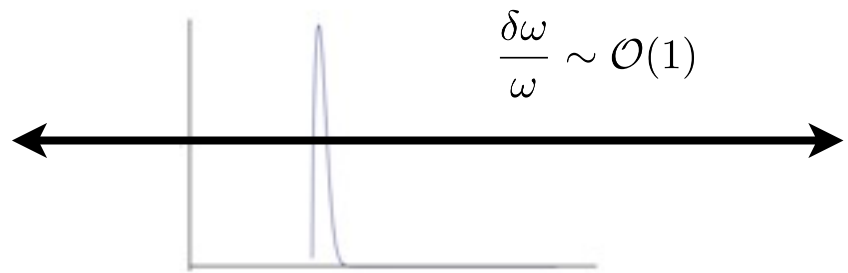
$$P_{\rm center} \approx \langle |\mathbf{E}_a|^2 \rangle A_{\rm dish} \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$

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

$$\frac{dN_\gamma}{dt} = \frac{P}{m_a} \sim 2 \left(\frac{10^{-4}{\rm eV}}{m_a} \right) \left(\frac{\rm B}{\rm 5T} \frac{c_\gamma}{2} \right)^2 \frac{\rm A}{\rm 1m^2} \frac{\gamma' {\rm s}}{\rm hour}$$

broadband! :-)

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



Signal to noise

$$\frac{S}{N} = \frac{P_{\rm signal}}{P_{noise}} \rightarrow \frac{P_{\rm signal}}{T_S}\sqrt{\frac{\rm time}{\rm Bandwidth}} \qquad (P_{\rm noise} \equiv T_S \Delta\nu)$$

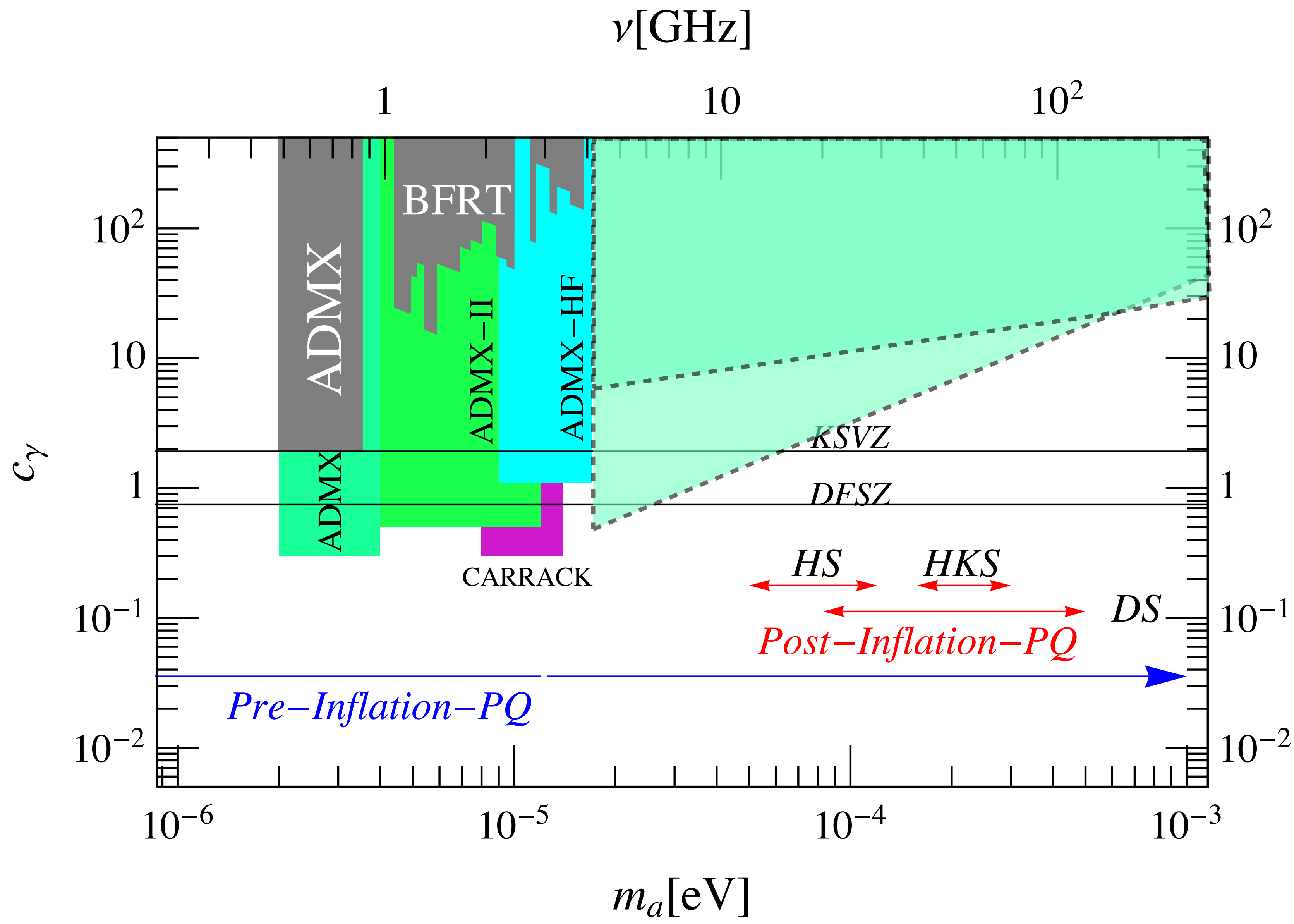
$$(T_{S\rm q.lim.} = \omega)$$

measurement dominated by background

$$\frac{S}{N} = 8\times 10^{-2}\frac{5{\rm K}}{T_S}\frac{\rm Area}{10\ {\rm m}^2}\left(\frac{B}{5\ {\rm T}}\frac{c_\gamma}{2}\right)^2\sqrt{\frac{\rm time}{1\ {\rm year}}\frac{10^{-6}}{\Delta\omega/\omega}\frac{10\ \mu{\rm eV}}{m_a}}$$

but we can do better ... up to the quantum limits (one can even do better...)

$$\frac{S}{N} = 14\frac{T_{S\rm q.lim}}{T_S}\frac{\rm Area}{10\ {\rm m}^2}\left(\frac{B}{10\ {\rm T}}\frac{c_\gamma}{2}\right)^2\sqrt{\frac{\rm time}{1\ {\rm year}}\frac{10^{-6}}{\Delta\omega/\omega}}\left(\frac{10\ \mu{\rm eV}}{m_a}\right)^{3/2}$$



ν[GHz]
1
10
10^2
BFRT
ADMX
ADMX−II
ADMX−HF
KSVZ
DFSZ
ADMX
CARRACK
HS
HKS
DS
Post−Inflation−PQ
Pre−Inflation−PQ
c_γ
10^2
10
1
10^−1
10^−2
10^−6
10^−5
10^−4
10^−3
m_a[eV]

Cavity searches (haloscopes)

- Different understanding of the conventional

HALOSCOPES

Cavity searches (haloscopes)

Sikivie PRL '83

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

transmission coefficient t

$$E_{\rm out} \simeq t\, E_\gamma \left(1 - r e^{i\omega L}\right) \sum_{b=0}^{\infty} (r^2 e^{i2\omega L})^b \rightarrow t\, E_\gamma \frac{1 - r e^{i\omega L}}{1 - r^2 e^{i2\omega L}}$$

round trip losses & phase

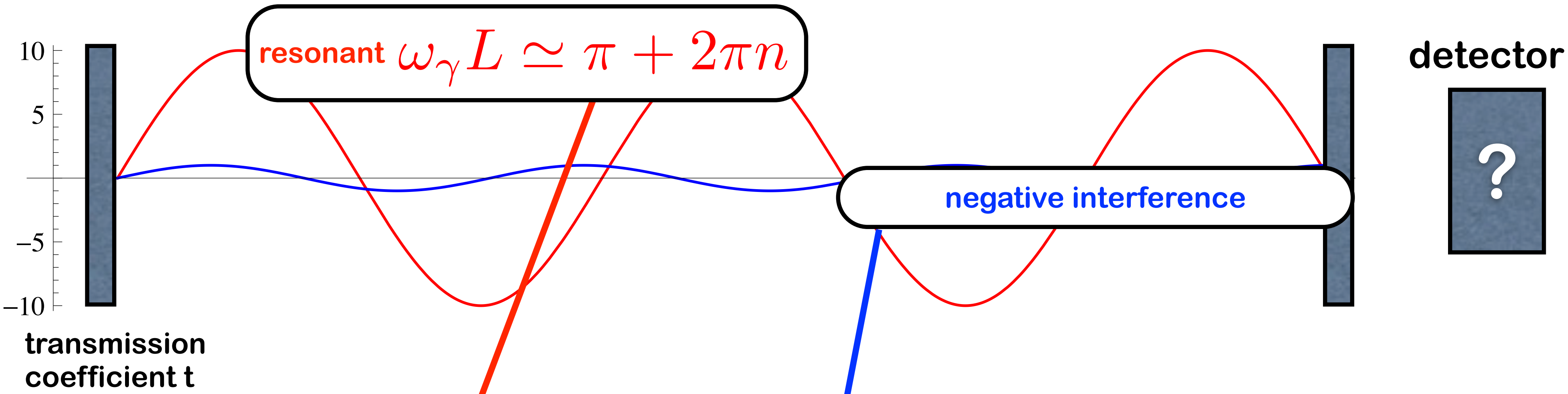
(optical resonator fed from both sides)

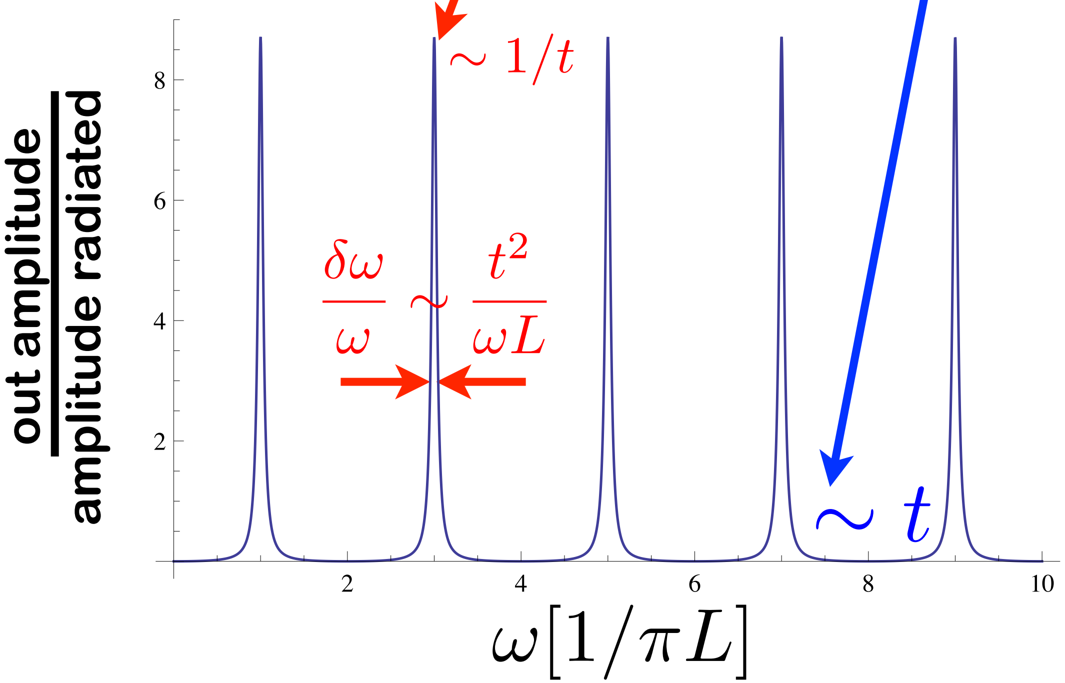
$$\frac{\sim 0 \quad \text{for} \quad \omega L = 2\pi n}{\sim 0 \quad \text{for} \quad \omega L = \pi + 2\pi n}$$

Cavity searches (haloscopes)

Sikivie PRL ‘83

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

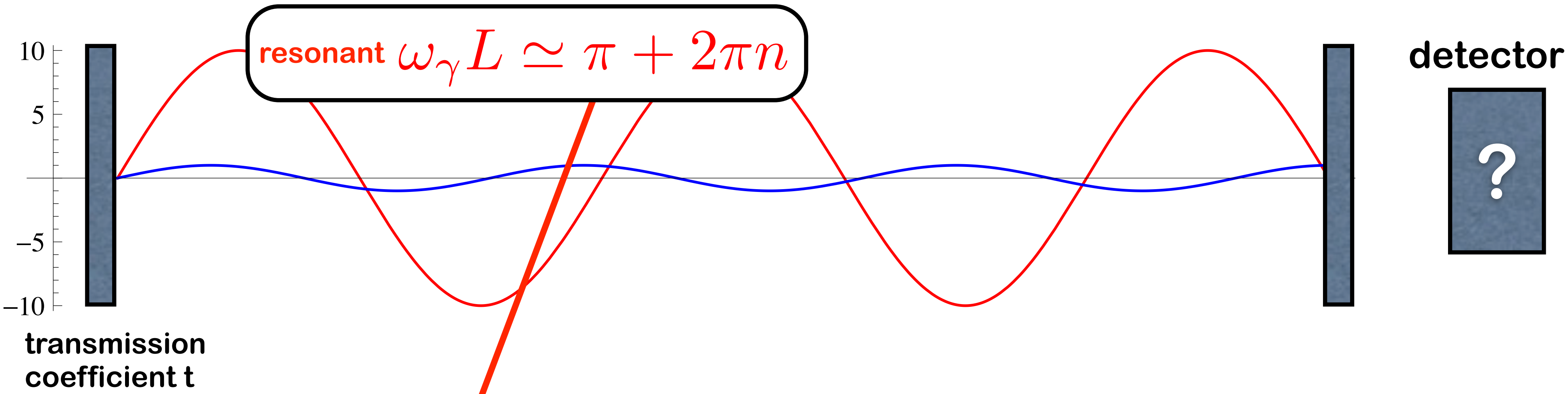


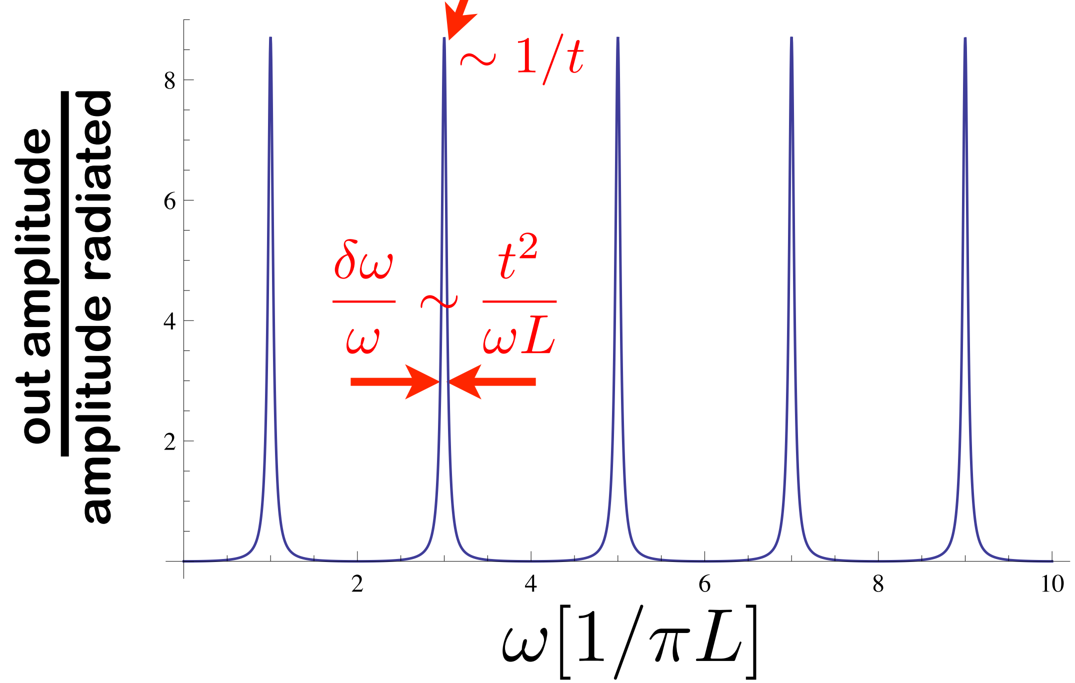


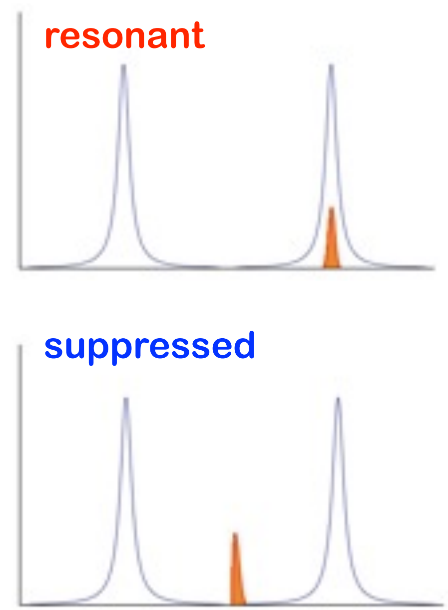
Cavity searches (haloscopes)

Sikivie PRL ‘83

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







Cavity searches (haloscopes)

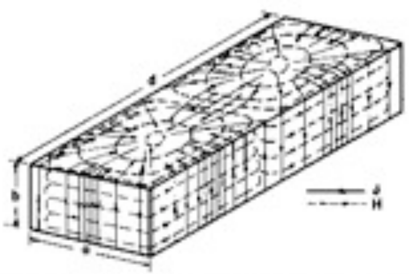
- Power Loss (cavity tuned!!); putting an pickup we can ideally extract the same

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

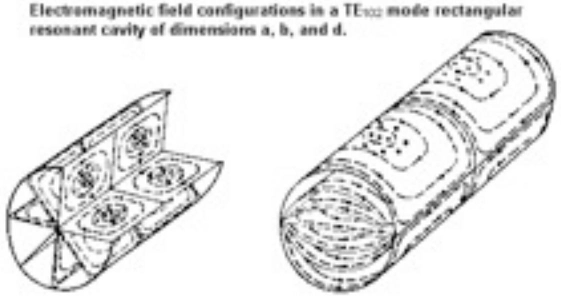
$$P_{\text{out}} \sim 10^{-20}\frac{\text{W}}{\text{m}^2}\left(\frac{\text{B}}{10\,T}\frac{c_\gamma}{2}\right)^2 \frac{\text{Area}}{1\ \text{m}^2}$$

- Usual 3-D formula is

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



Electromagnetic field configurations in a TE_{102} mode rectangular resonant cavity of dimensions a, b, and d.



Diagramatic sketch of the TE_{012} (left) and TE_{112} (right) cylindrical resonant cavity modes.

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

Analysis

$$(\partial_t^2 - \Delta) A_\nu = g_{a\gamma} \widetilde{F}_{\mu\nu} \partial_\mu a$$

$$\partial_t^2 \mathbf{A} - \Delta \mathbf{A} = g_{a\gamma} \mathbf{B} \partial_t a$$

Mode equation

$$-\Delta \mathbf{A}_l \equiv \omega_0^2 \mathbf{A}_l$$

$$\int d^3\mathbf{x} |\mathbf{A}_l|^2 = 1$$

$$\mathbf{A} = \sum_l C_l(t) \mathbf{A}_l(\mathbf{x})$$

$$\partial_t^2 C_l + \omega_0^2 C_l = g_{a\gamma} a_0 \cos(m_a t) \int d^3\mathbf{x} \mathbf{A}_l^* \cdot \mathbf{B}$$

$$C_l(t) \to \frac{g_{a\gamma} a_0 \cos(m_a t)}{\omega_0^2 - m_a^2}$$

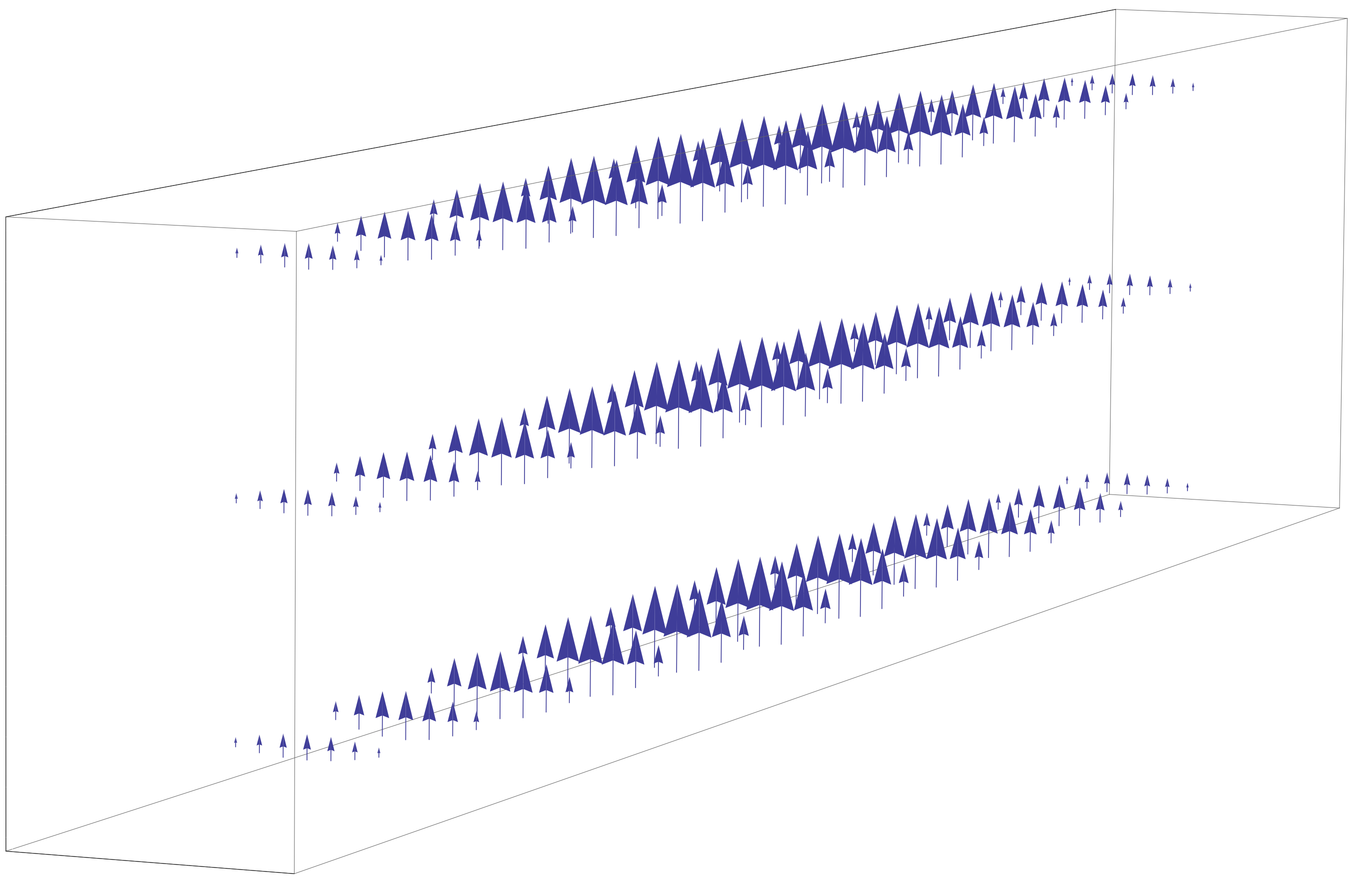
Analysis

$$\partial_t^2 C_l + \omega_0^2 C_l = g_{a\gamma} a_0 \cos(m_a t) \int d^3\mathbf{x} \mathbf{A}_l^* \cdot \mathbf{B}$$

$$C_l(t) \to \frac{g_{a\gamma} a_0 \cos(m_a t)}{\omega_0^2 - m_a^2 + i\omega_0^2/Q}$$

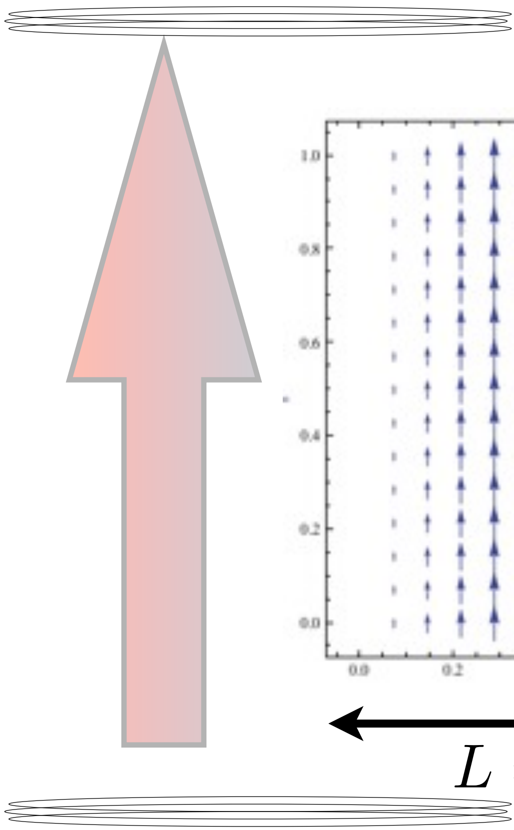
Cavity searches (haloscopes)

- Paralellepedic cavity TE101

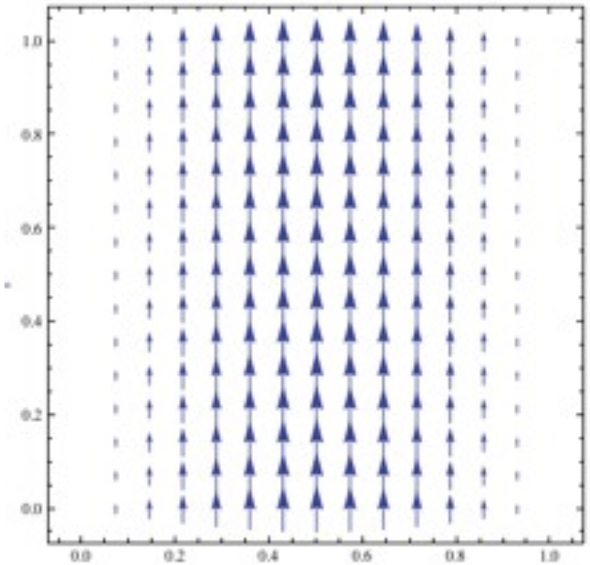


Cavity searches (haloscopes)

- Pillbox cavity

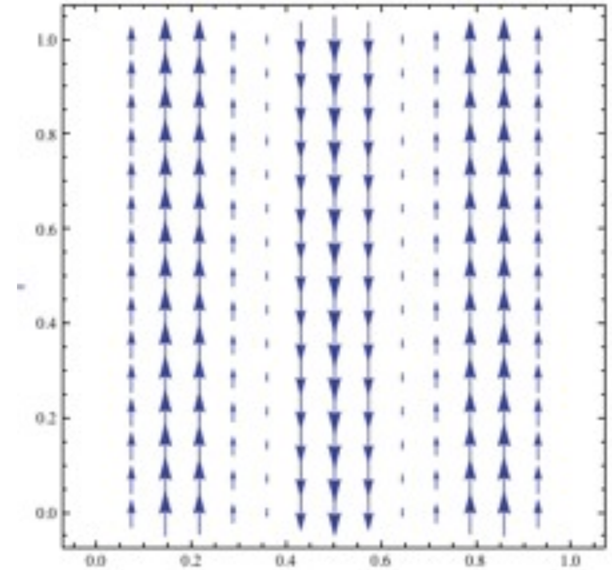


TE10



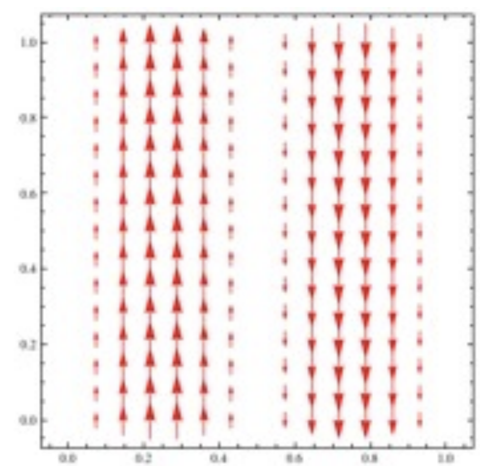
$$L = \pi/m_a$$

TE30



$$L = 3\pi/m_a$$

TE20



$$\mathcal{G} = 0$$

Cavity searches (haloscopes)

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

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

- 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!

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

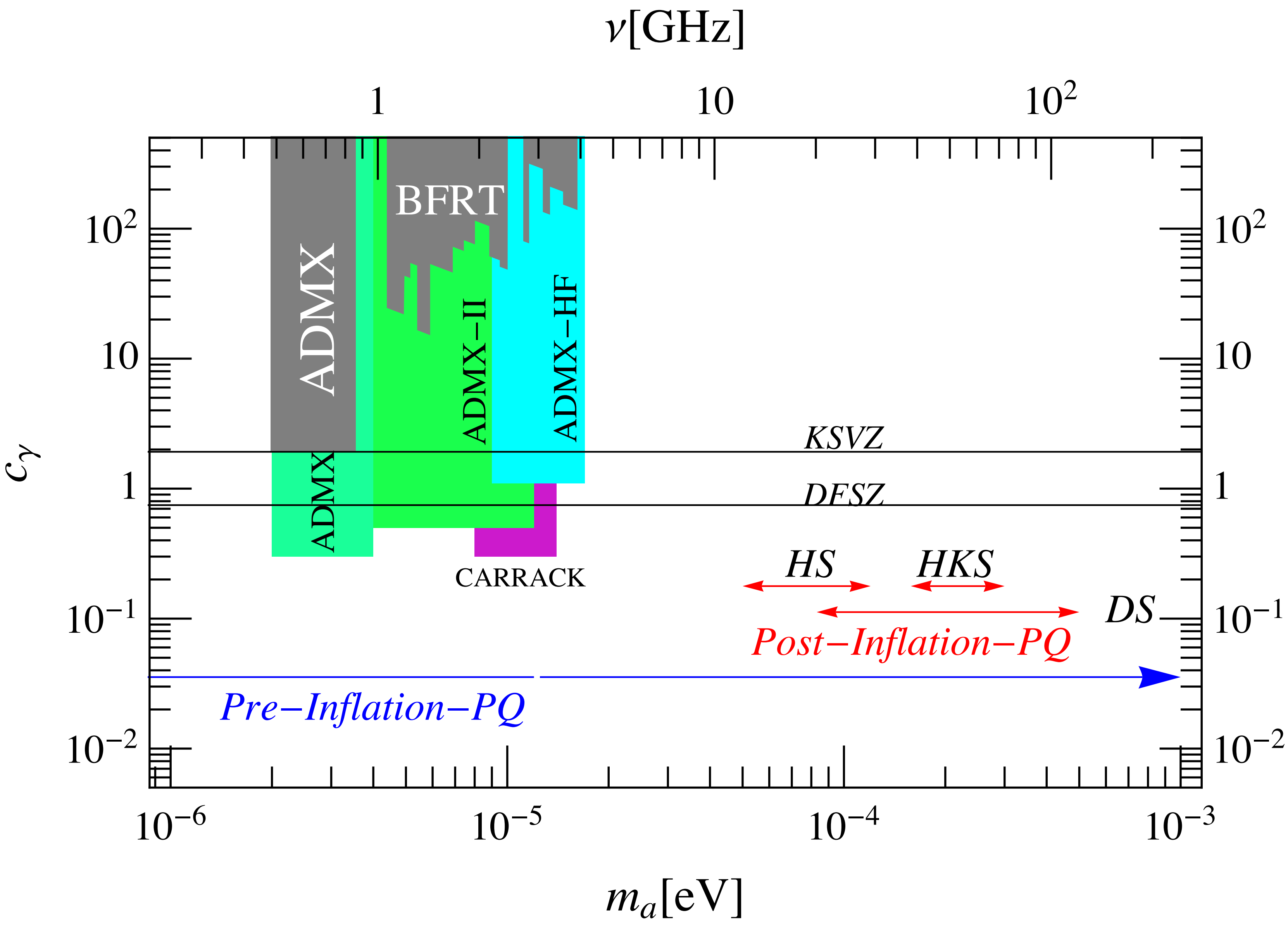
8T field, H =1 m, D =0.42m

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

- ADMX-HF

Higher the mass; (smaller cavity...), larger bandwidth, QL higher

typically smaller signal; larger background -> less sensitive



ν[GHz]
1
10
10^2
BFRT
ADMX
ADMX−II
ADMX−HF
KSVZ
DFSZ
ADMX
CARRACK
HS
HKS
DS
Post−Inflation−PQ
Pre−Inflation−PQ
c_γ
10^2
10
1
10^−1
10^−2
10^−6
10^−5
10^−4
10^−3
m_a[eV]

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