A new experiment to search for axion dark matter

TH Seminar, IFAE, UAB
Bellaterra, September 2014

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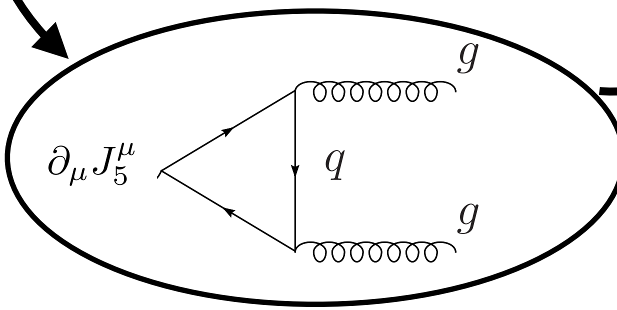
outline

- Axions and strong CP
- Axion CDM
- Isocurvature problems
- Detecting Axion CDM
- Dish antenna
- Cavities

The strong CP "hint" and axions

- $U(1)_A$ is color anomalous, CP-violating phase $\theta = \theta_{\rm QCD} + \delta$ is physical

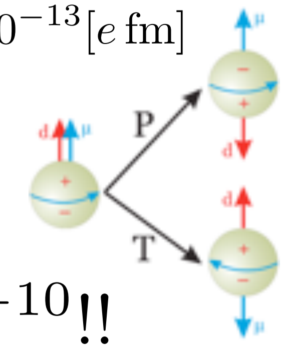
$$\mathcal{L}_{\rm SM} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta} & 0 & \dots \\ 0 & m_d e^{i\delta} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\rm QCD}$$



Neutron EDM

$$d_n \sim \theta \times \mathcal{O}(10^{-2})[e\,{\rm fm}]$$

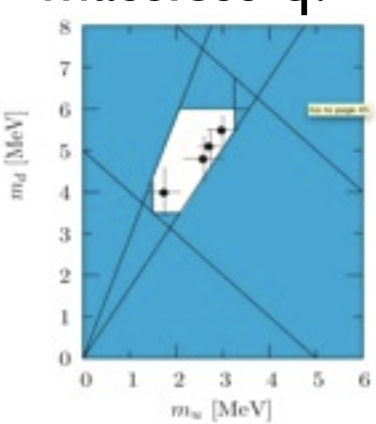
$$d_n^{\rm exp} < 3 \times 10^{-13}[e\,{\rm fm}]$$



$\theta < 10^{-10}$!!

- why is soooo small? is there any fundamental reason?

massless q?



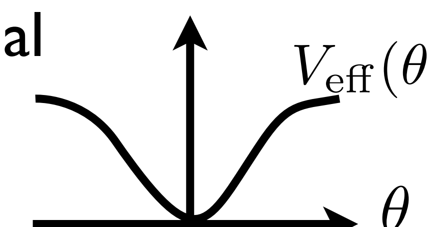
P,CP symmetries?

- (not in SM)
- set tree level
- loop problems
- still ~ok

Axion a

- New axial U(1) c.a. symmetry
- spontaneously broken (PGB!)
- θ promoted to field $\theta \to a/f_a$
- QCD potential

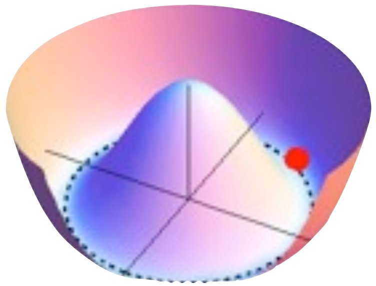
$\theta \to 0$



Axion mass and couplings (and model dependencies)

- Peccei-Quinn symmetry, color anomalous, spontaneously broken at f_a

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{Q}DQ - (y\bar{Q}_L Q_R \Phi + {\rm h.c}) - \lambda|\Phi|^4 + \mu^2|\Phi|^2$$

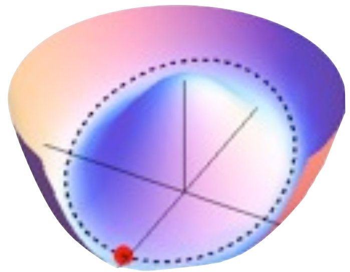


$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$ (KSVZ model)

- At energies below f_a $\quad \mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi} G\widetilde{G}\frac{a}{f_a}$

- At energies below $\Lambda_{\rm QCD}$, $\quad a - \eta' - \pi^0 - \eta - \dots$ mixing

axion mass $\quad m_a \simeq \frac{m_\pi f_\pi}{f_a} \sim 6{\rm meV}\frac{10^9{\rm GeV}}{f_a}$

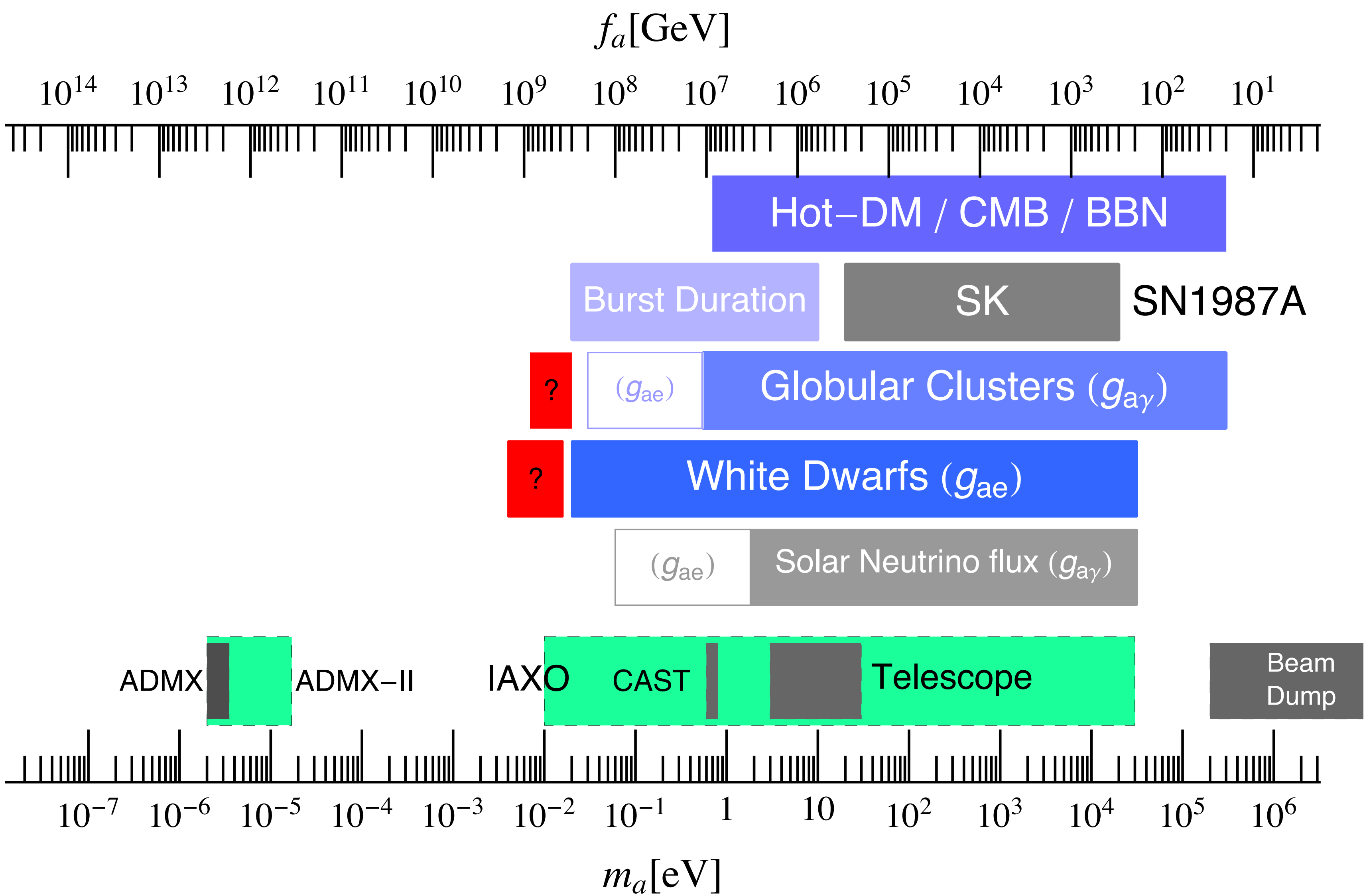


axion couplings

$$\mathcal{L}_{a,I} = \sum_N c_{N,a}\bar{N}\gamma^\mu\gamma_5 N\frac{a}{f_a} + c_{a\gamma}\frac{\alpha}{2\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\frac{a}{f_a} + \dots$$

nucleons ... **photons ...** **mesons ...**

Parameter spaces: generic

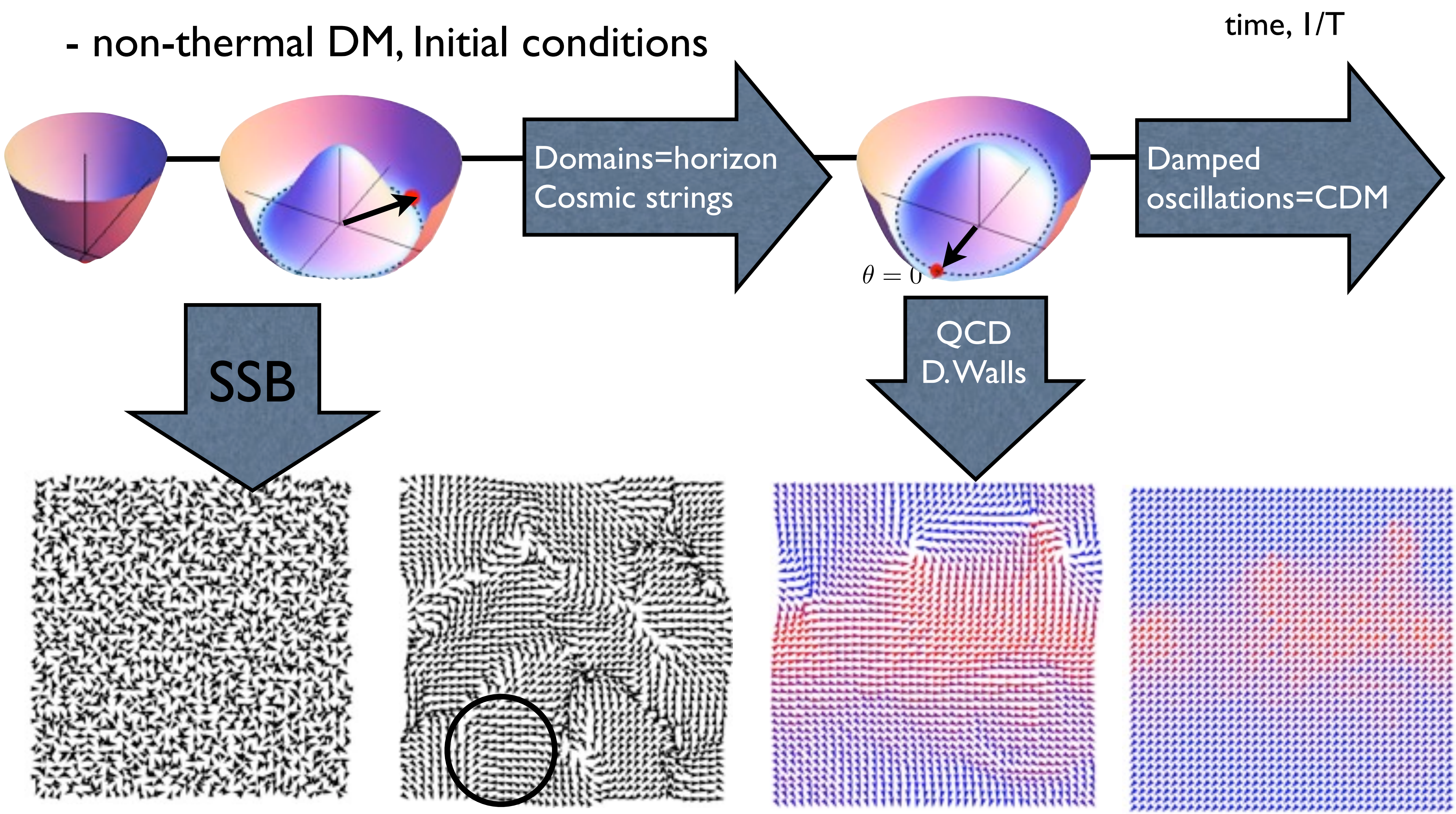


- Axions (if existing) are very light and very weakly interacting! -> WISP!

Axion cold dark matter: vacuum alignment

- Axions: small mass, small interactions, ~~thermal DM~~

- non-thermal DM, Initial conditions



Axion cold dark matter: vacuum alignment

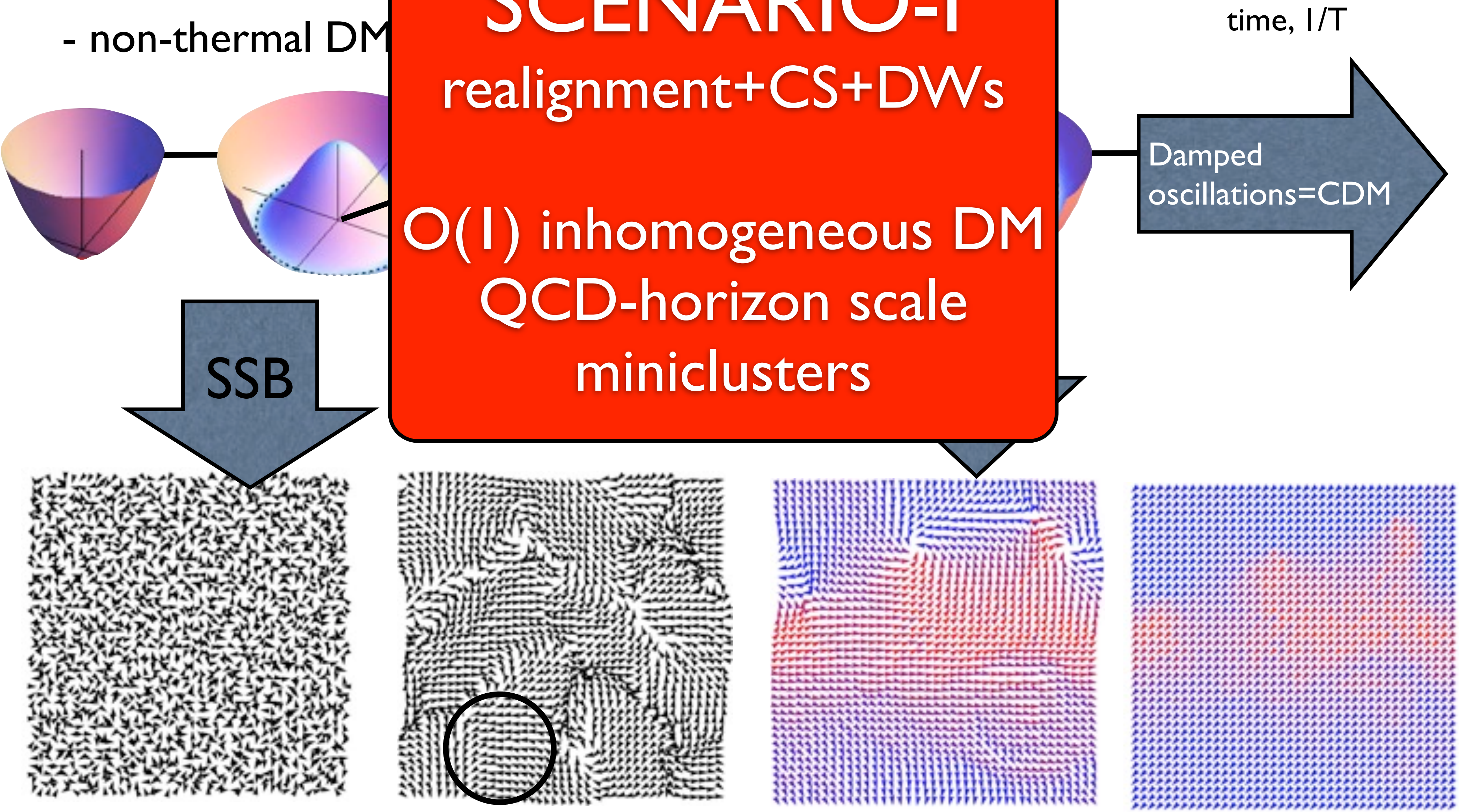
- Axions: small ma

- non-thermal DM

SCENARIO-I

realignment+CS+DWs

O(1) inhomogeneous DM
QCD-horizon scale
miniclusters



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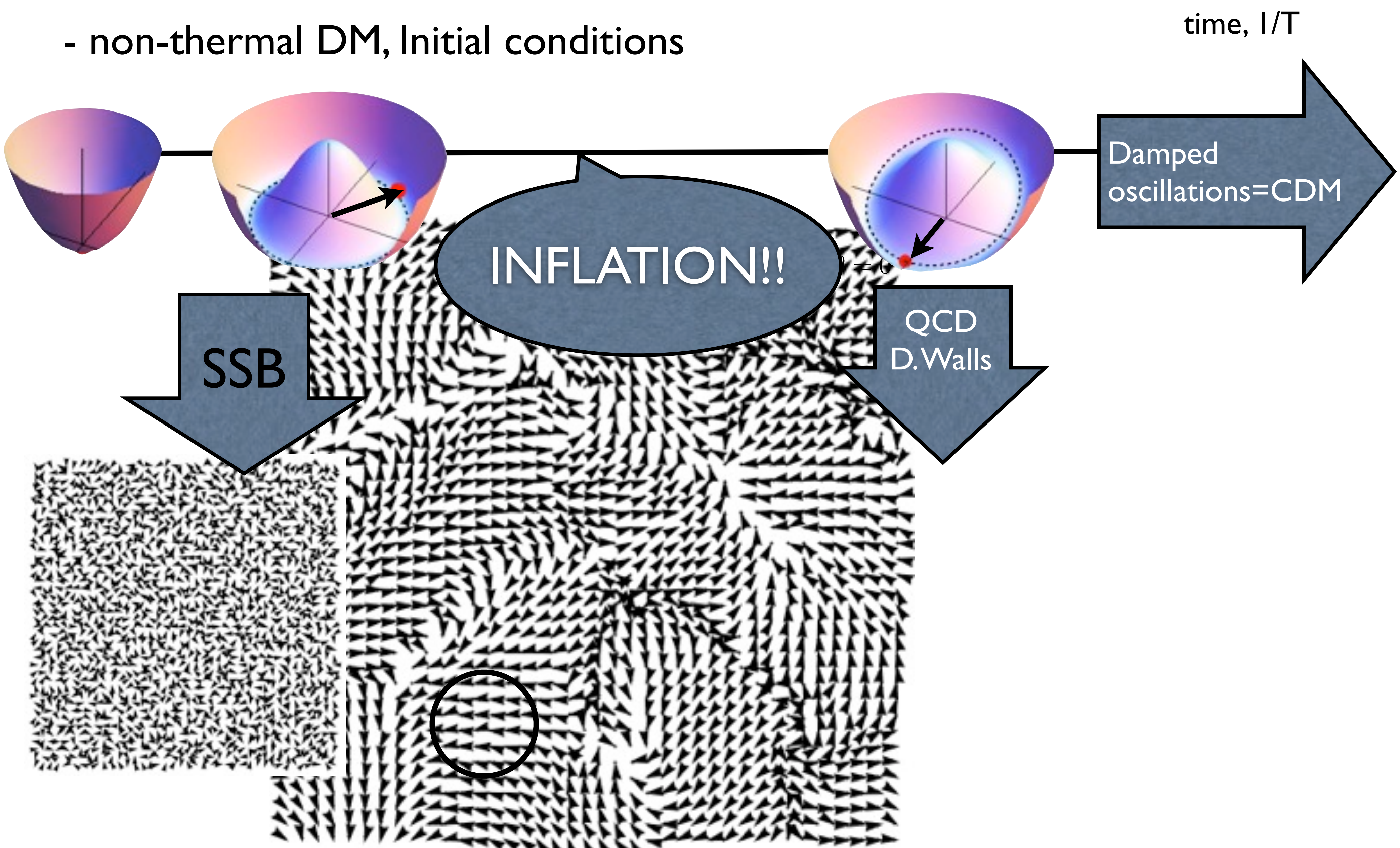

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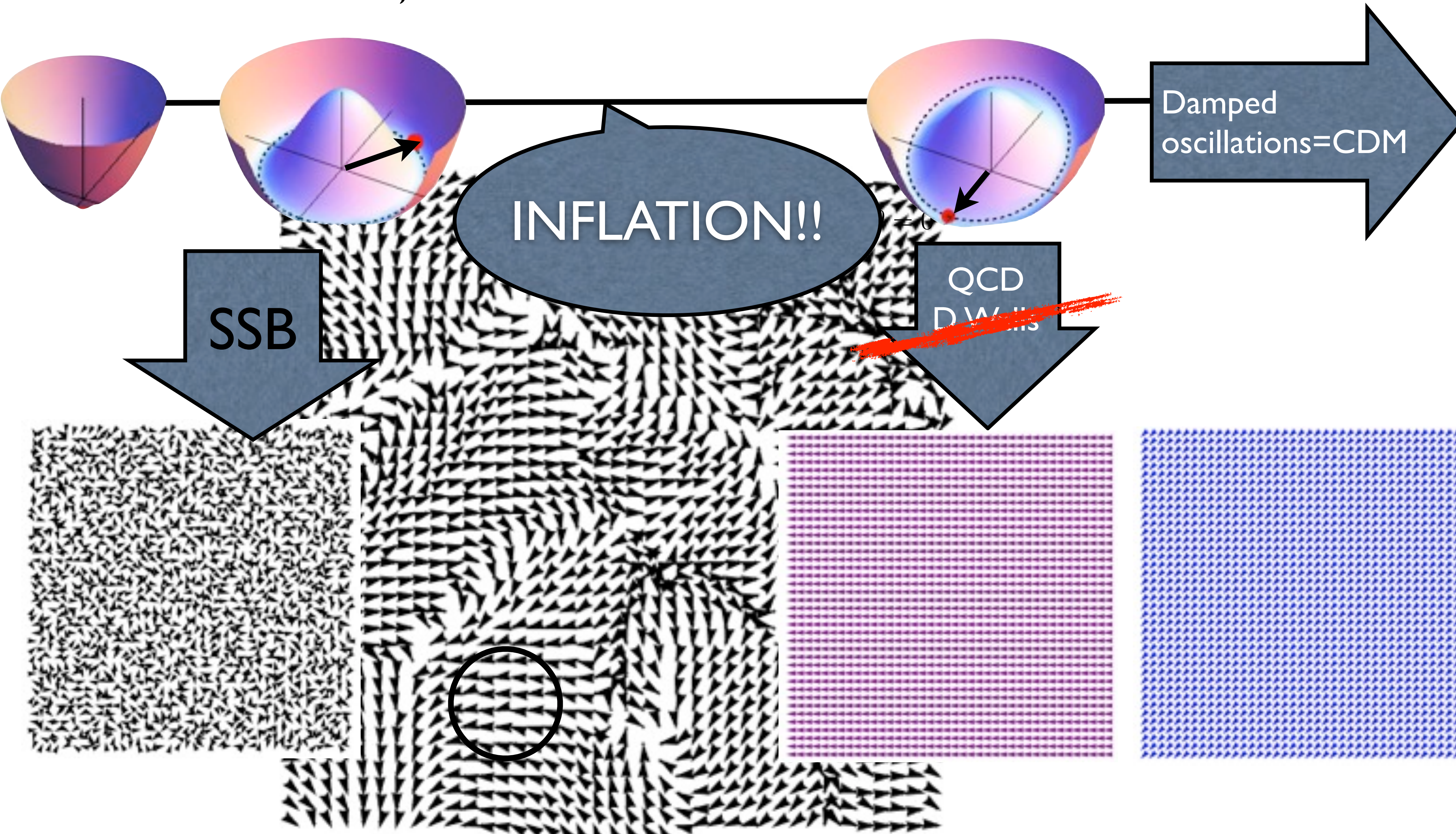


Axion cold dark matter: vacuum alignment

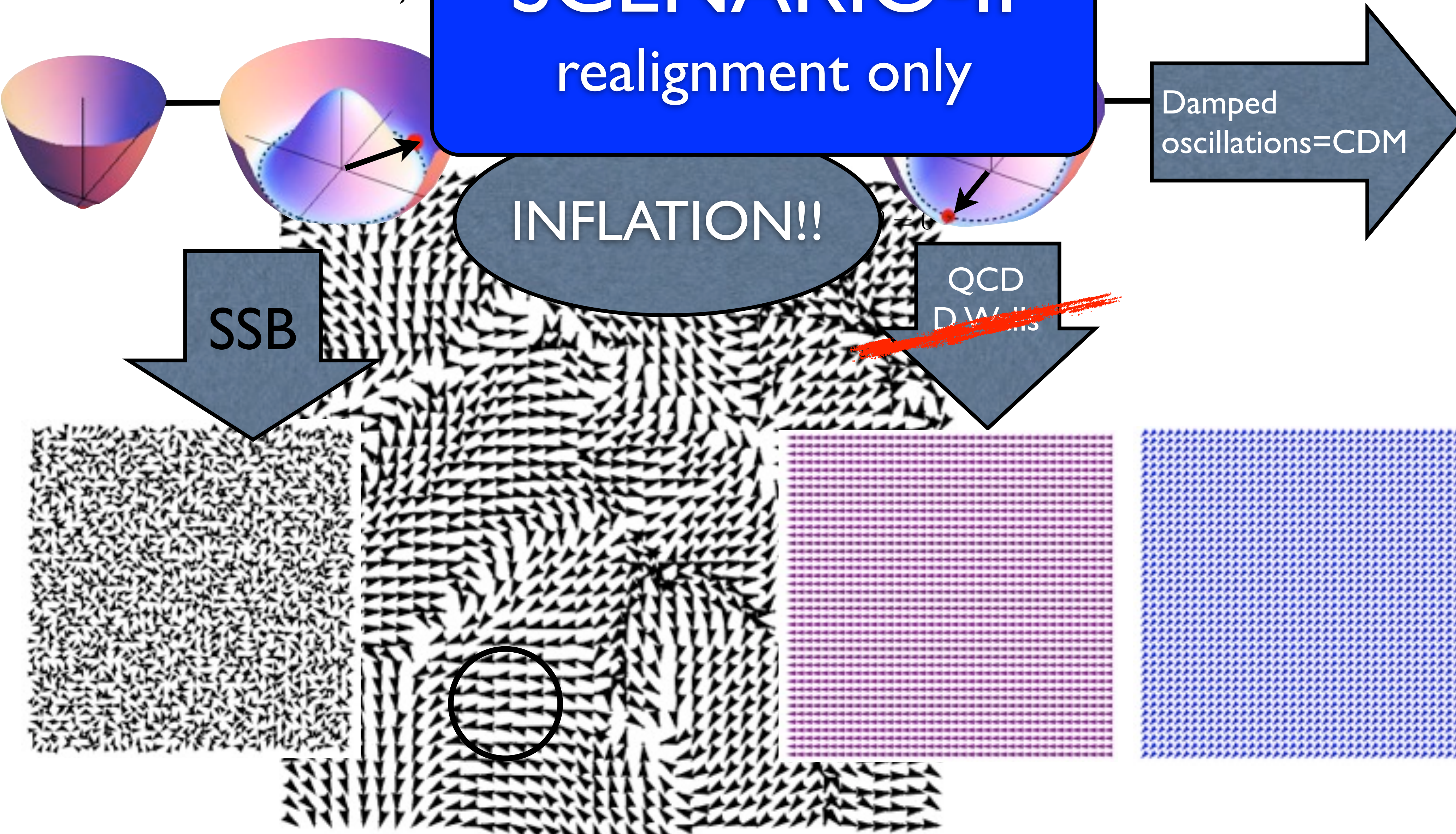
- Axions: small mass, small interactions ~~thermal DM~~

- non-thermal DM, I

SCENARIO-II

realignment only

time, 1/T



Rough relic abundance of axion Dark matter

- Energy density redshifts as matter, from the onset of oscillations

$$\rho_a(t) \sim \theta_I^2 \Lambda_{\rm QCD}^4 \left(\frac{R_1}{R(t)} \right)^3$$

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

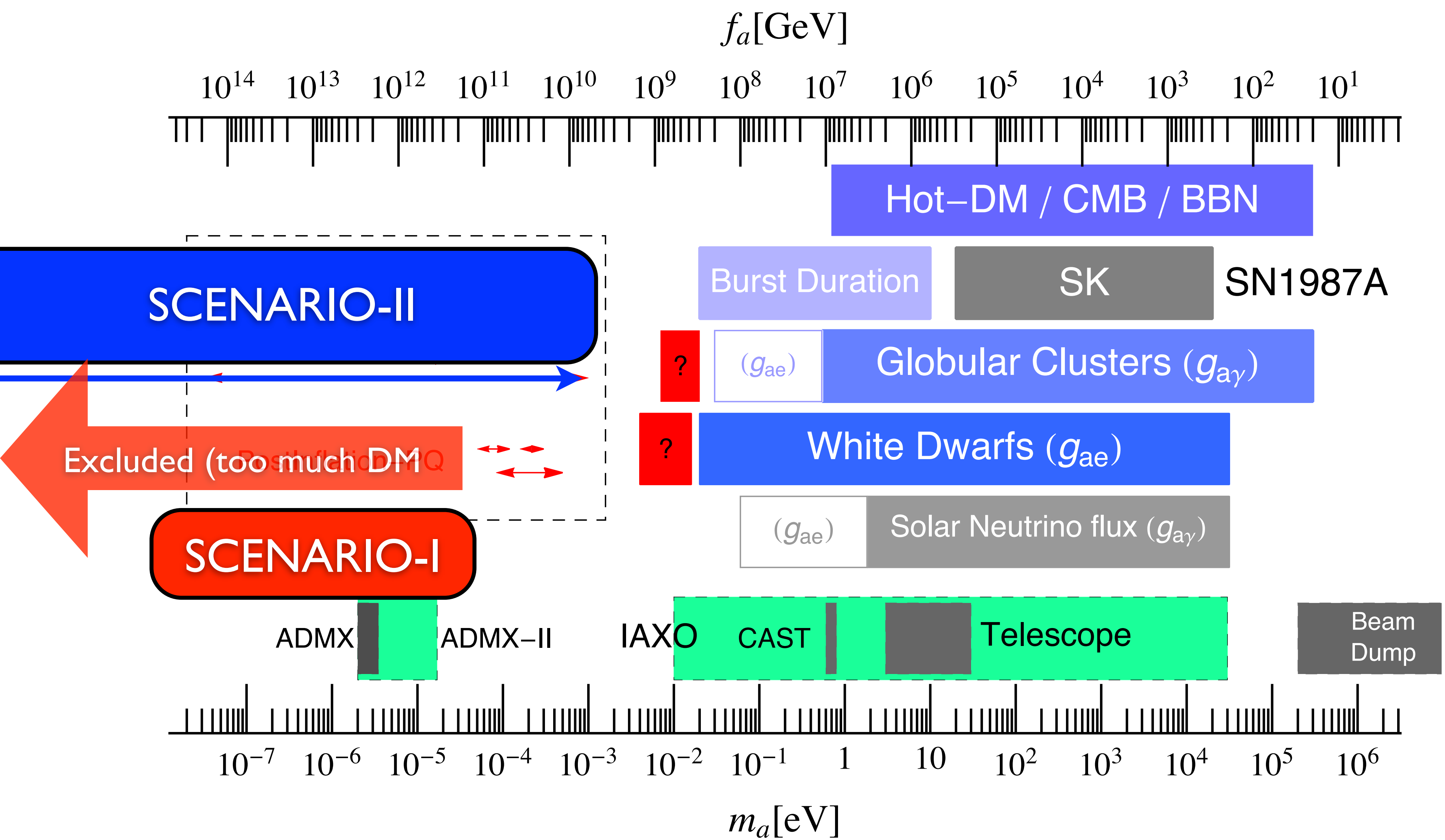
- today...

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

- doing it properly... (thermal axion mass)

$$\rho_a(t_0) \propto \theta_I^2 m_a^{-7/6}$$

Axion DM abundance fitting the observations



The isocurvature problem after BICEP2

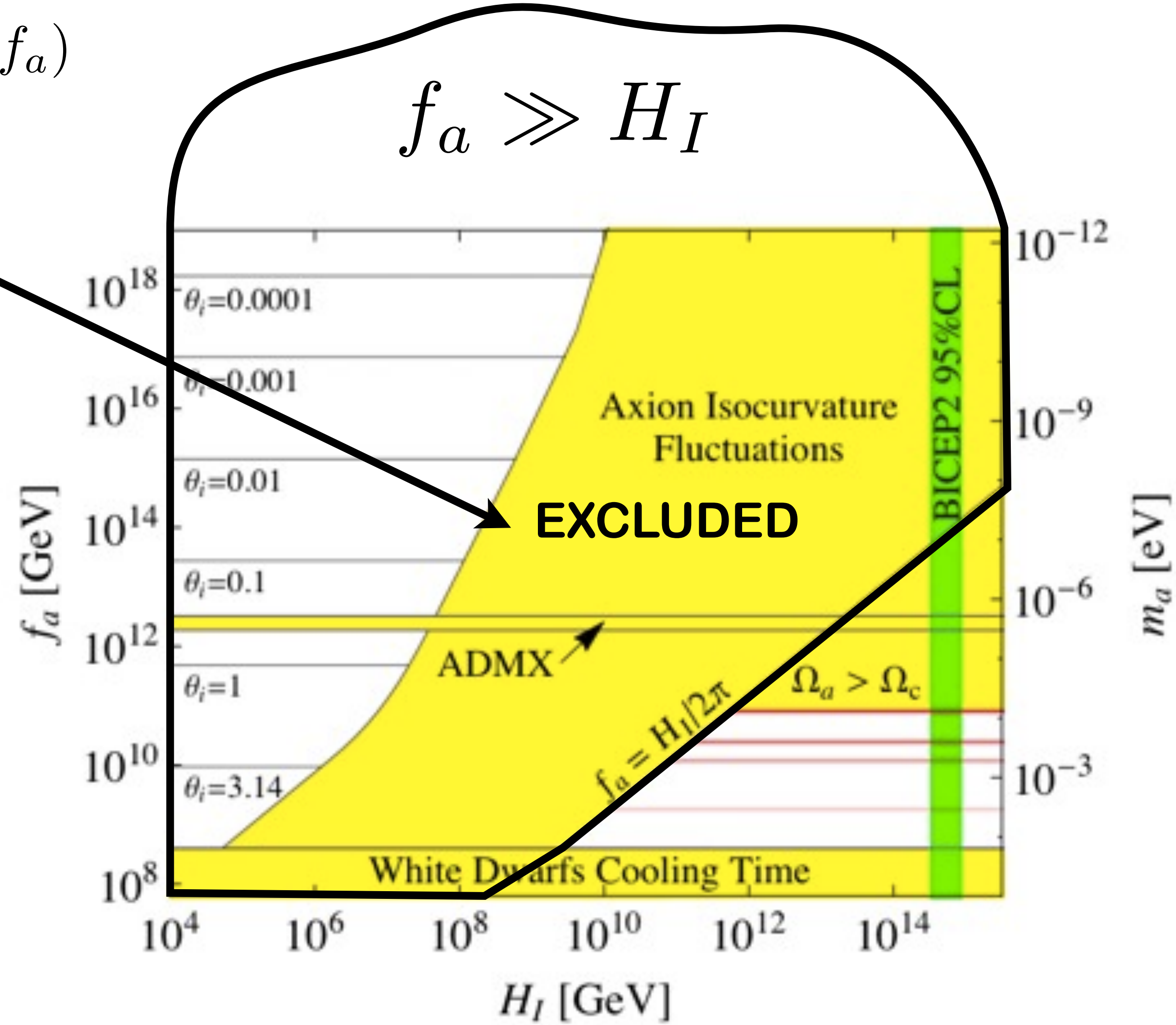
SCENARIO-II

- Axion fluctuates during inflation (entropy perturbations)

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

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

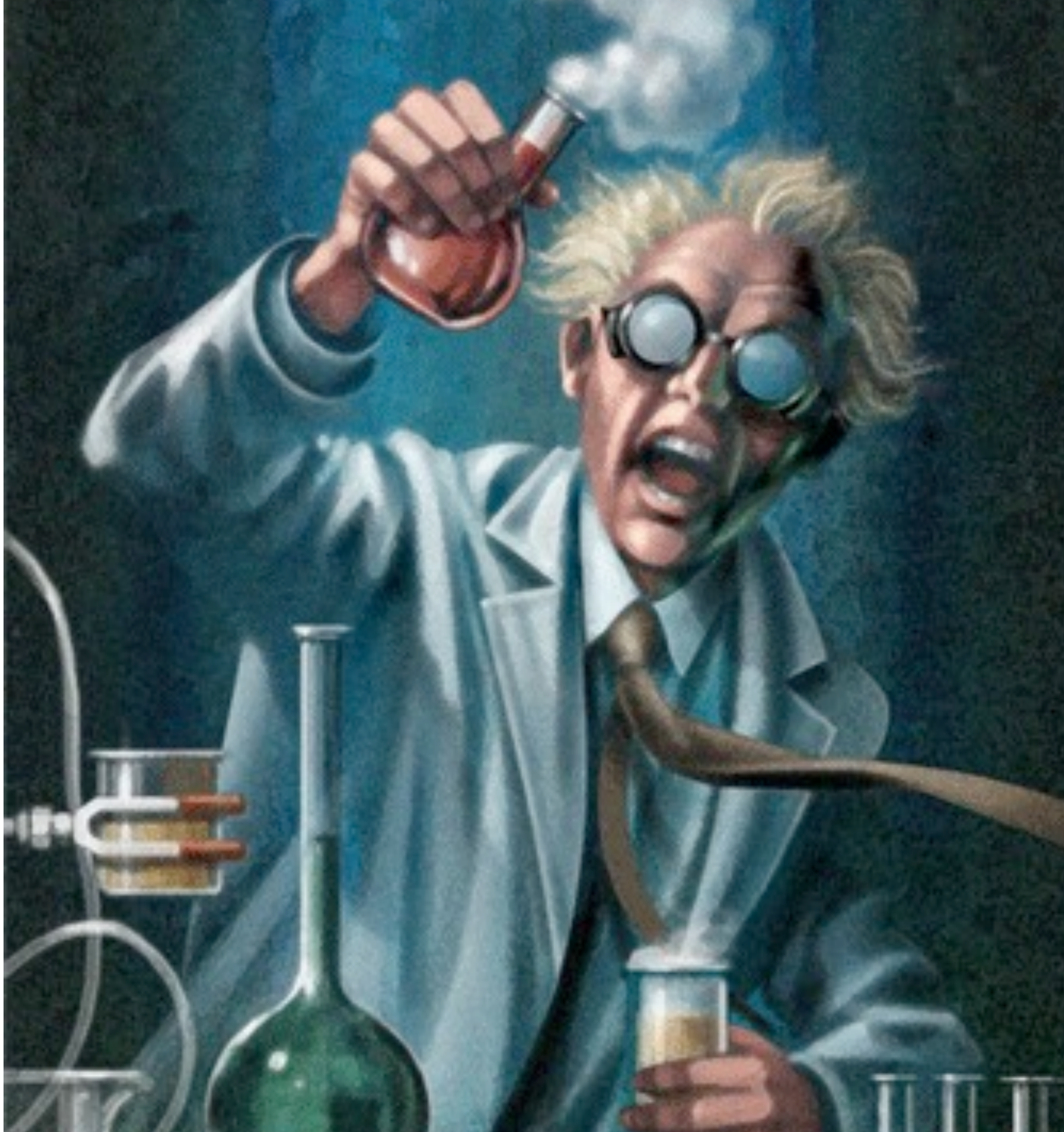
Constraint $f_a(H_I)$



BICEP2 would exclude SC-II in the simplest models...

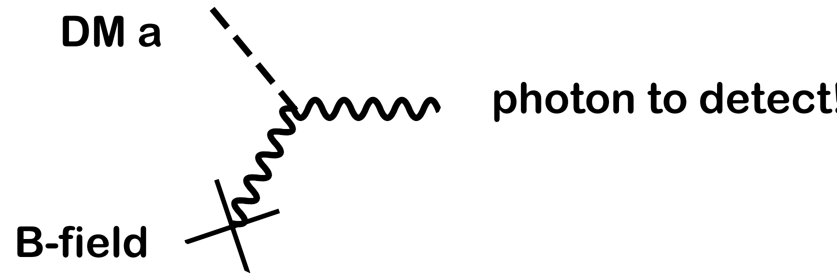
of course, there are plenty of ways out ...

Laboratory

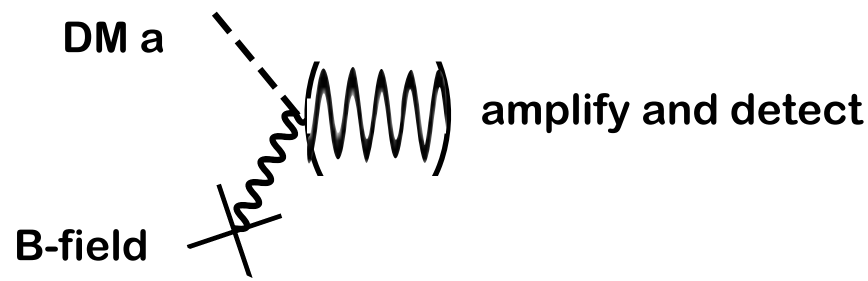


Experiments to detect axion DM

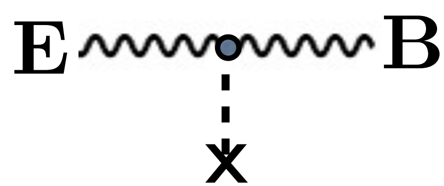
- Dish antenna



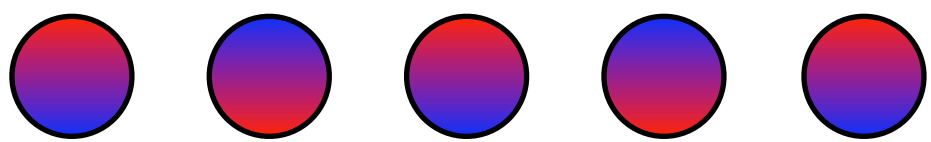
- Cavity experiments



- Light propagation



- Oscillating EDM



DM around us

$$\rho_{\rm CDM} \simeq 0.3 \frac{\rm GeV}{\rm cm^3} = m_a n_a \simeq \frac{1}{2} m_a^2 f_a^2 \theta^2 \longrightarrow \theta \sim O(10^{-19})$$

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

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

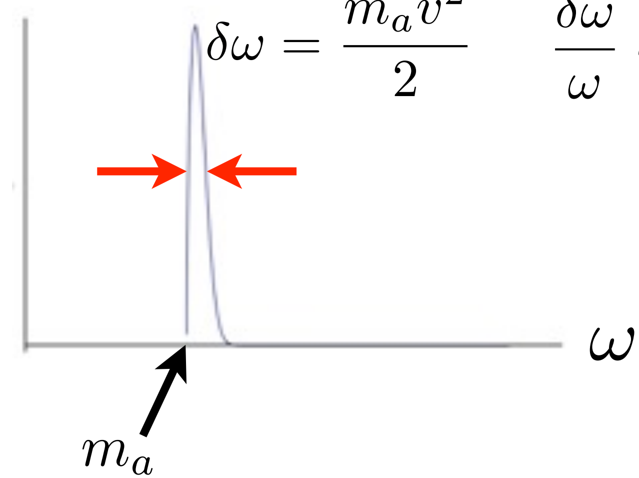
occupation number is HUGE! ⟶ **still can treat it like a classical (NR) field**

Roughly … $$a(t) = a_0 \cos(m_a t)$$

Fourier-transform $a(x)$

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

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

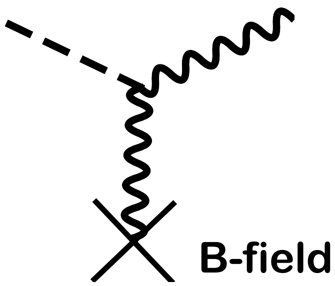


E-fields from axion CDM in a B-field

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

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

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



- Electric fields of order $|\mathbf{E}| \sim \mathcal{O}(10^{-12}V/m)|\mathbf{B}_{\rm ext}|\,c_\gamma\,\cos(m_a t)$

- oscillating at a frequency given by the axion mass

Do not depend on mass or coupling strength!

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

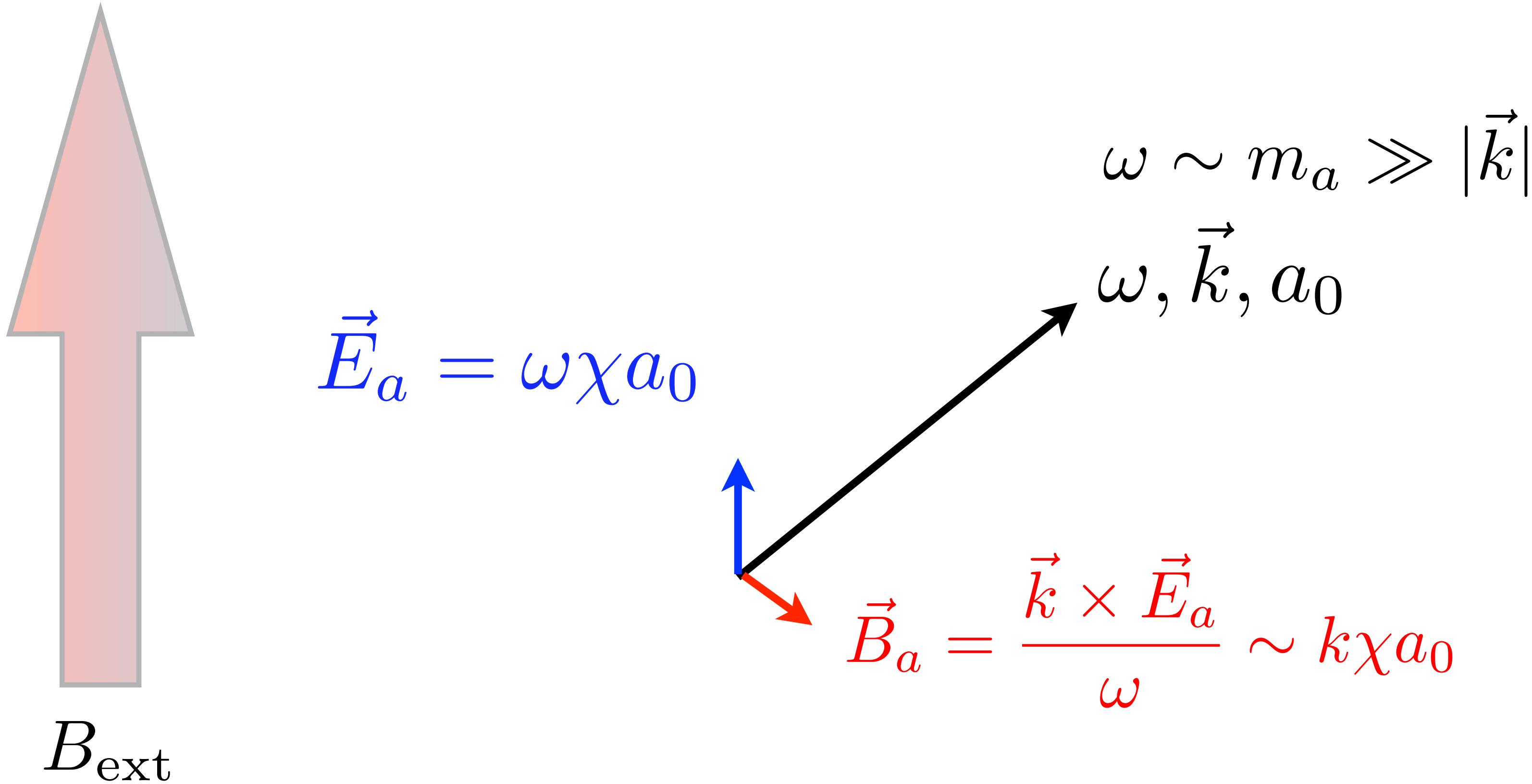
$$\left.\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix}\right|_{\rm DM} \propto \begin{pmatrix} -\chi_a \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

It has a small E field!

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

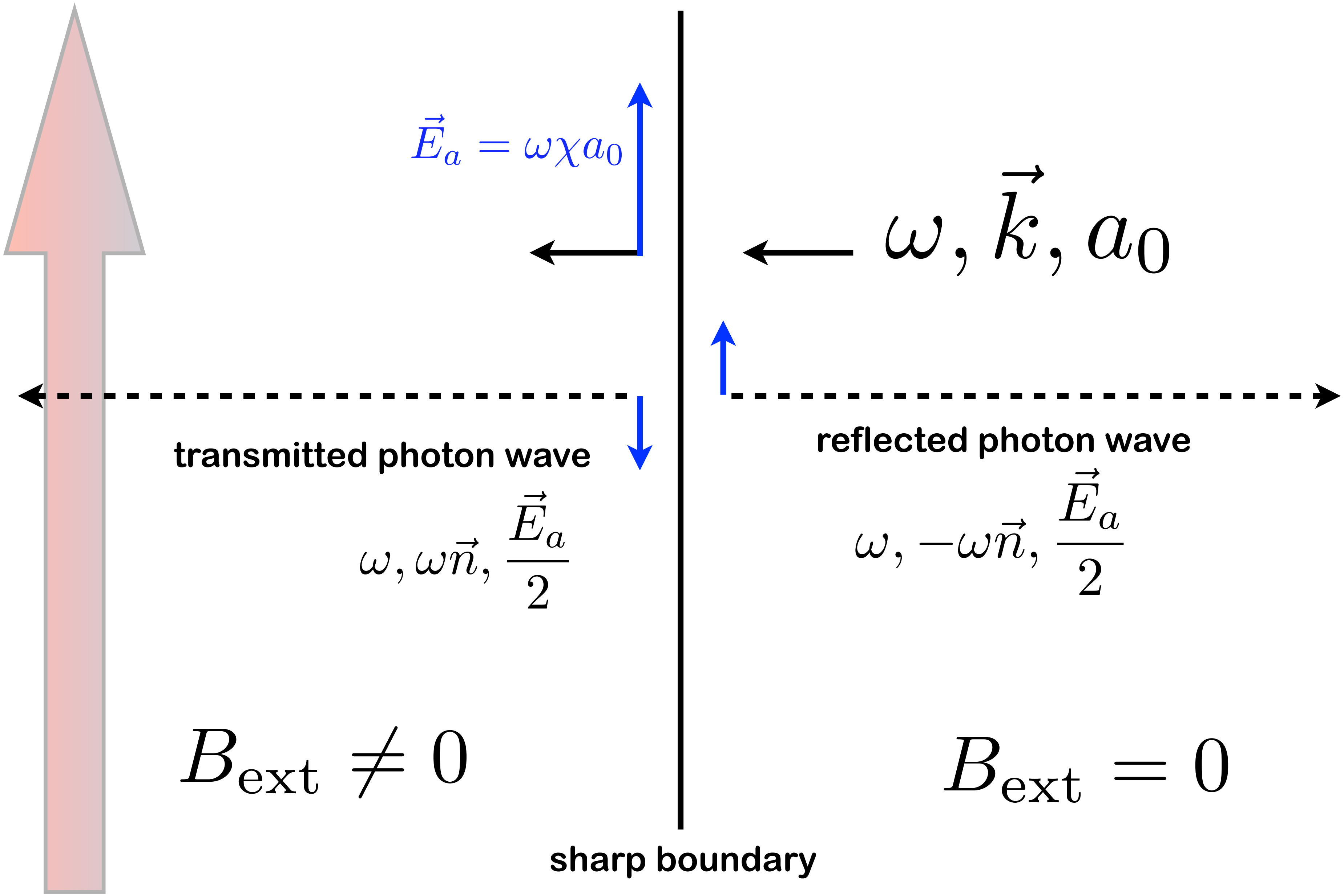
$$\mathbf{E_a} \sim \partial_t \mathbf{A}_{||} \sim m_a a_0 \chi \sim \sqrt{\rho_{\rm CDM}}\chi$$

DM axions in a magnetic field



Photons from Transition radiation!

Jaeckel and JR arXiv:1308.1103



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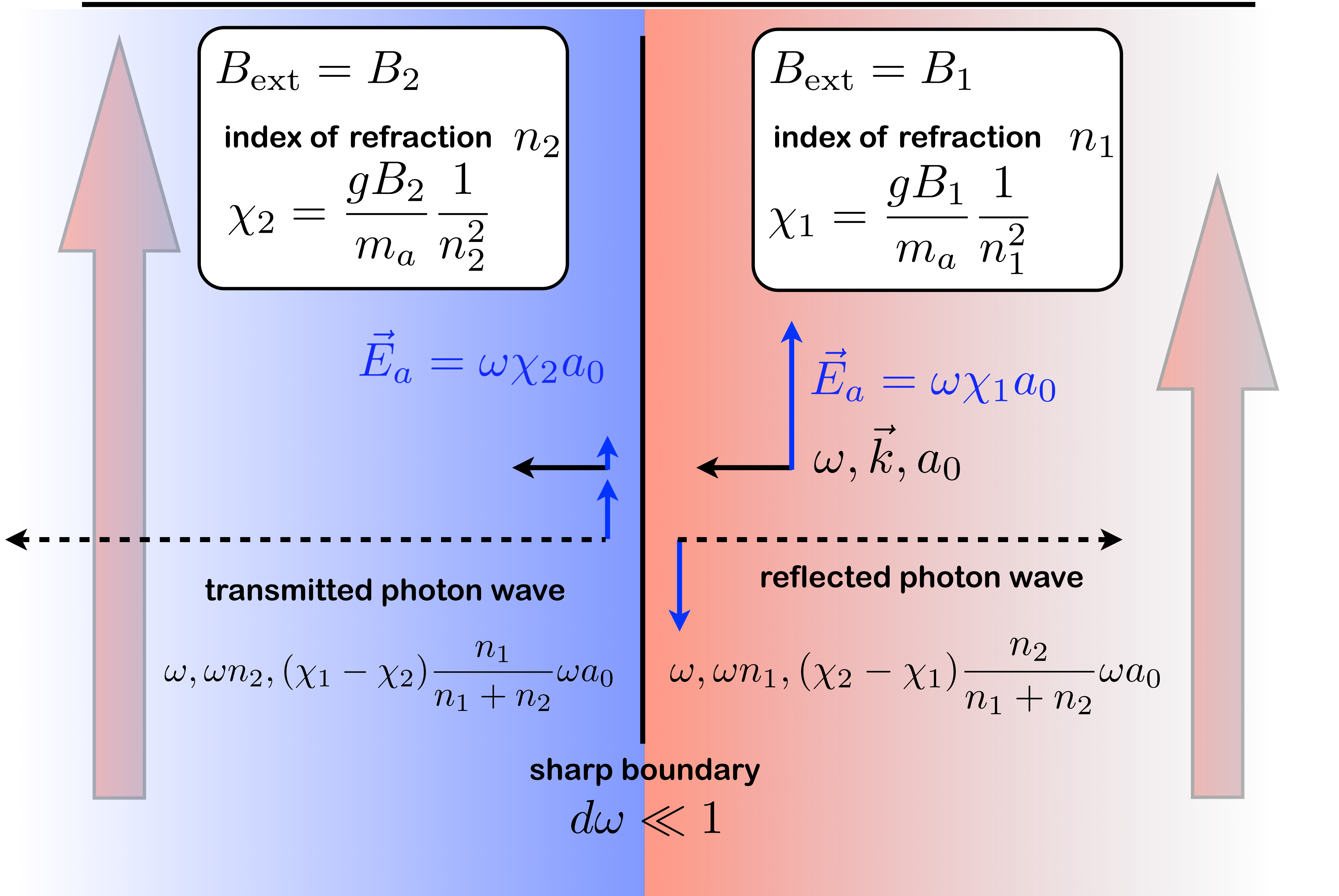
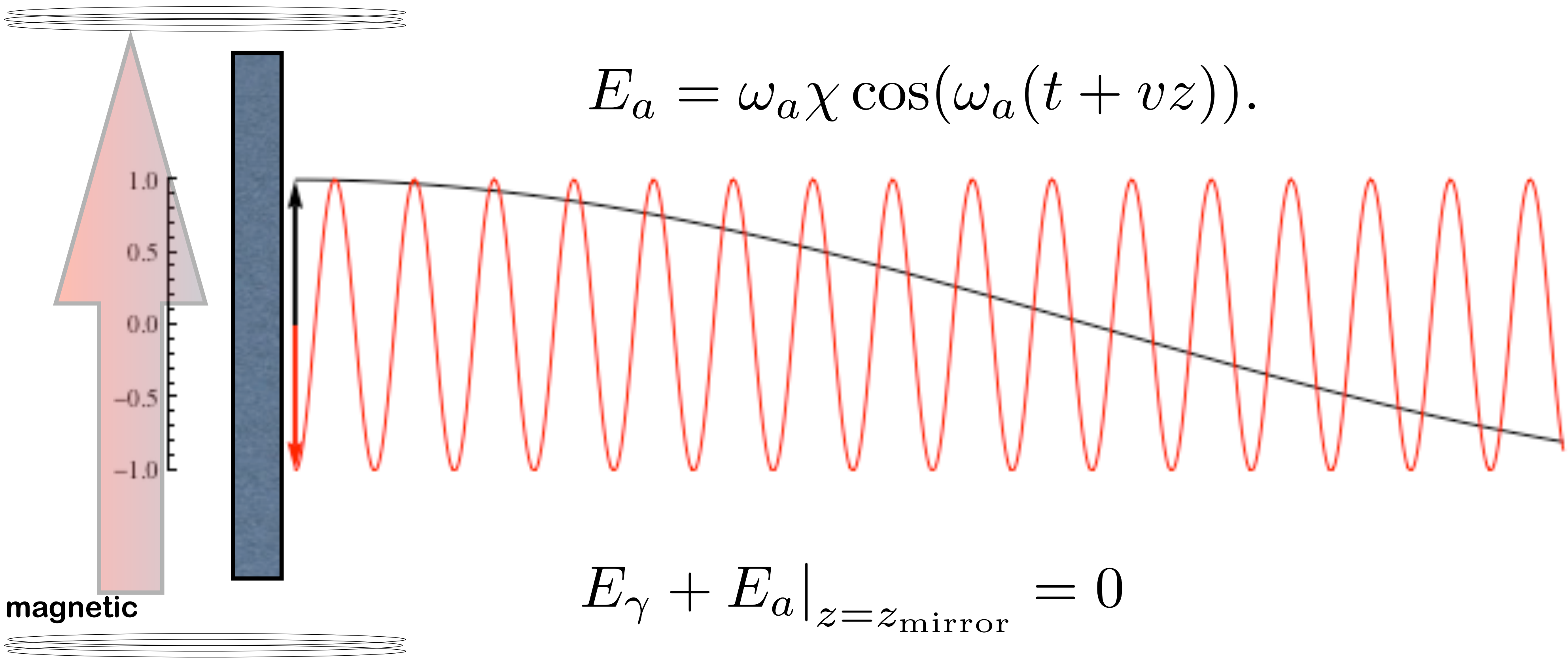


Radiation from a magnetised mirror

Horns at al JCAP04(2013)016

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



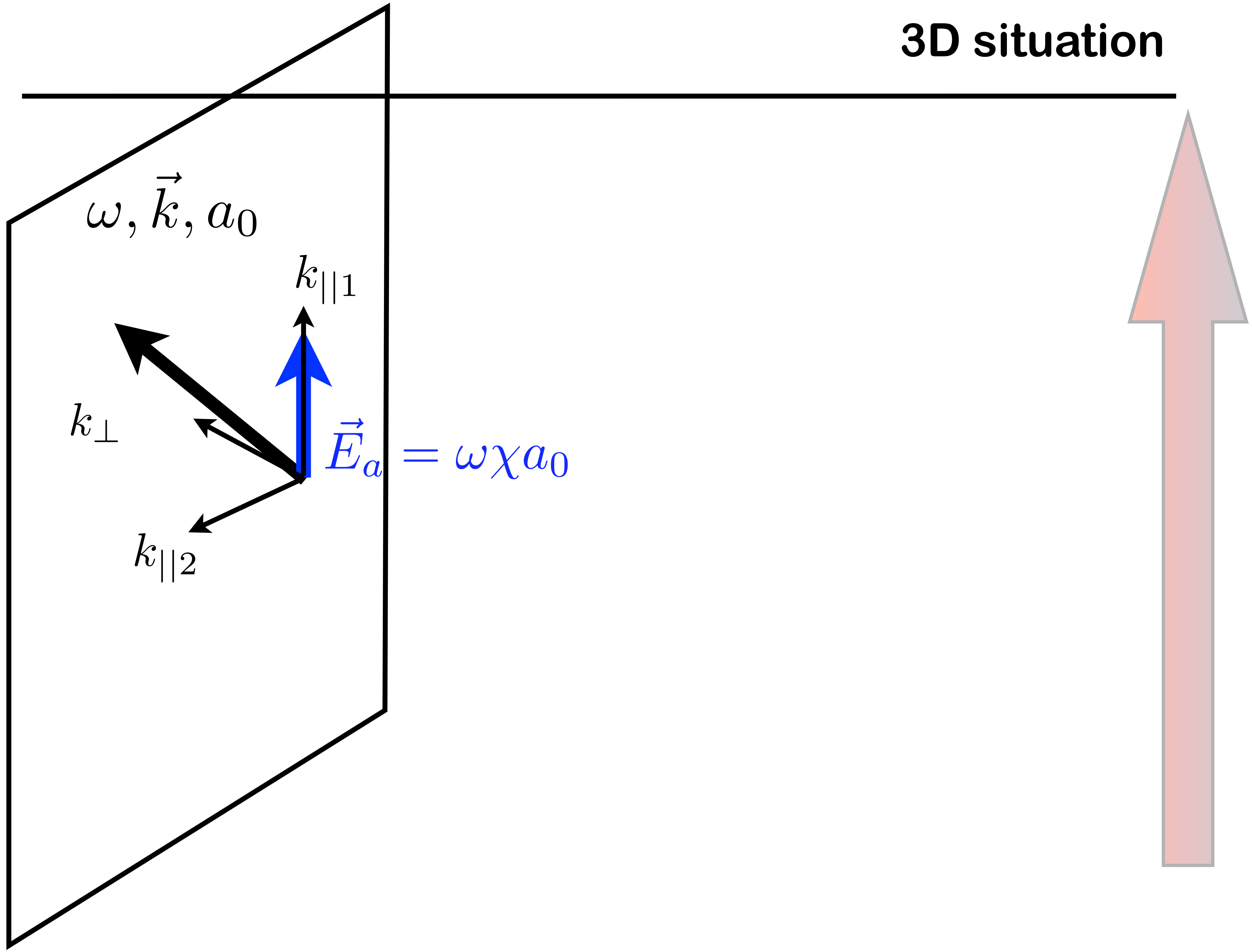
$$E_\gamma + E_a|_{z=z_{\mathrm{mirror}}} = 0$$

Radiated photon wave

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

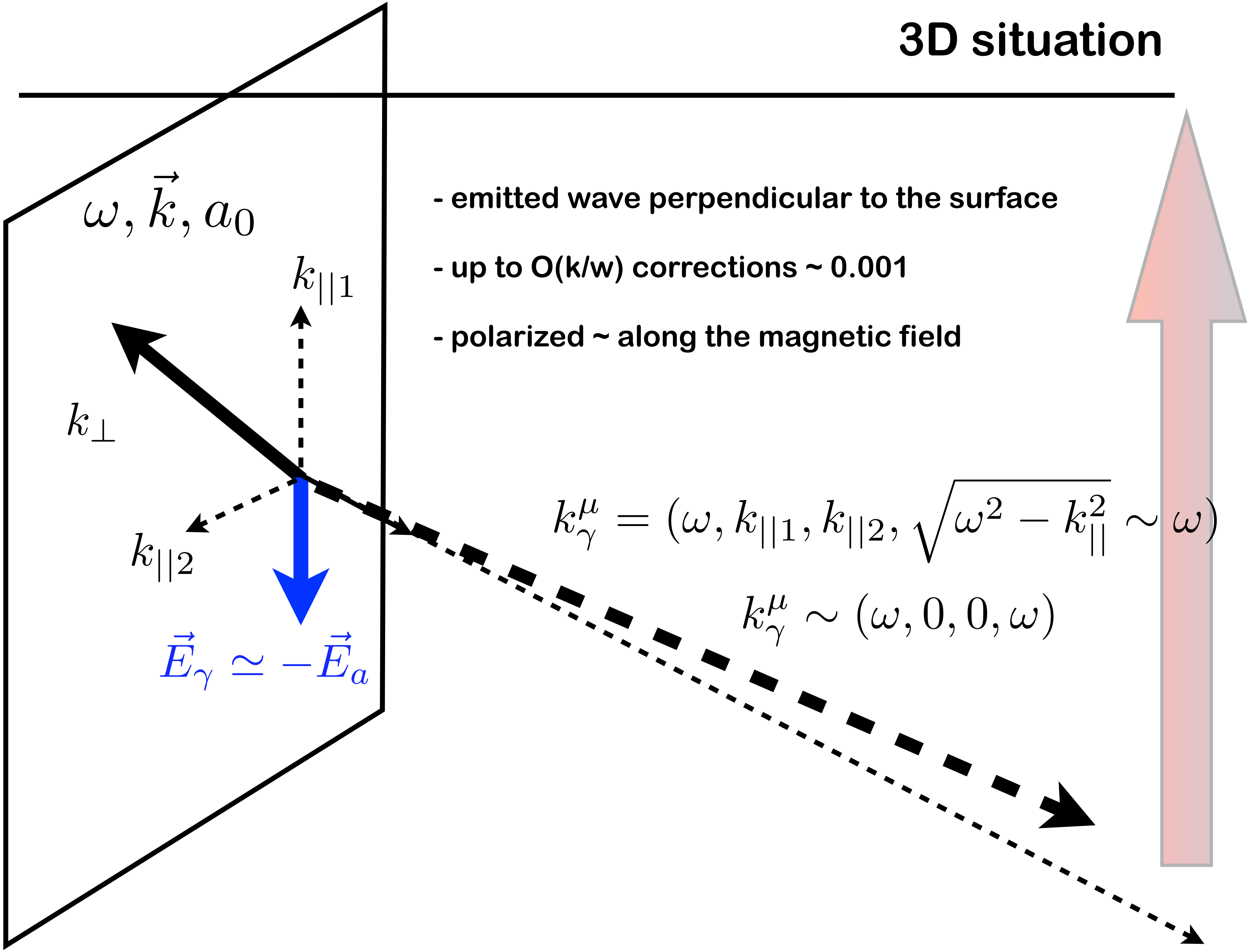
whose frequency is

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



3D situation
$\omega, \vec{k}, a_0$
$k_{||1}$
$k_\perp$
$\vec{E}_a = \omega\chi a_0$
$k_{||2}$

3D situation



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

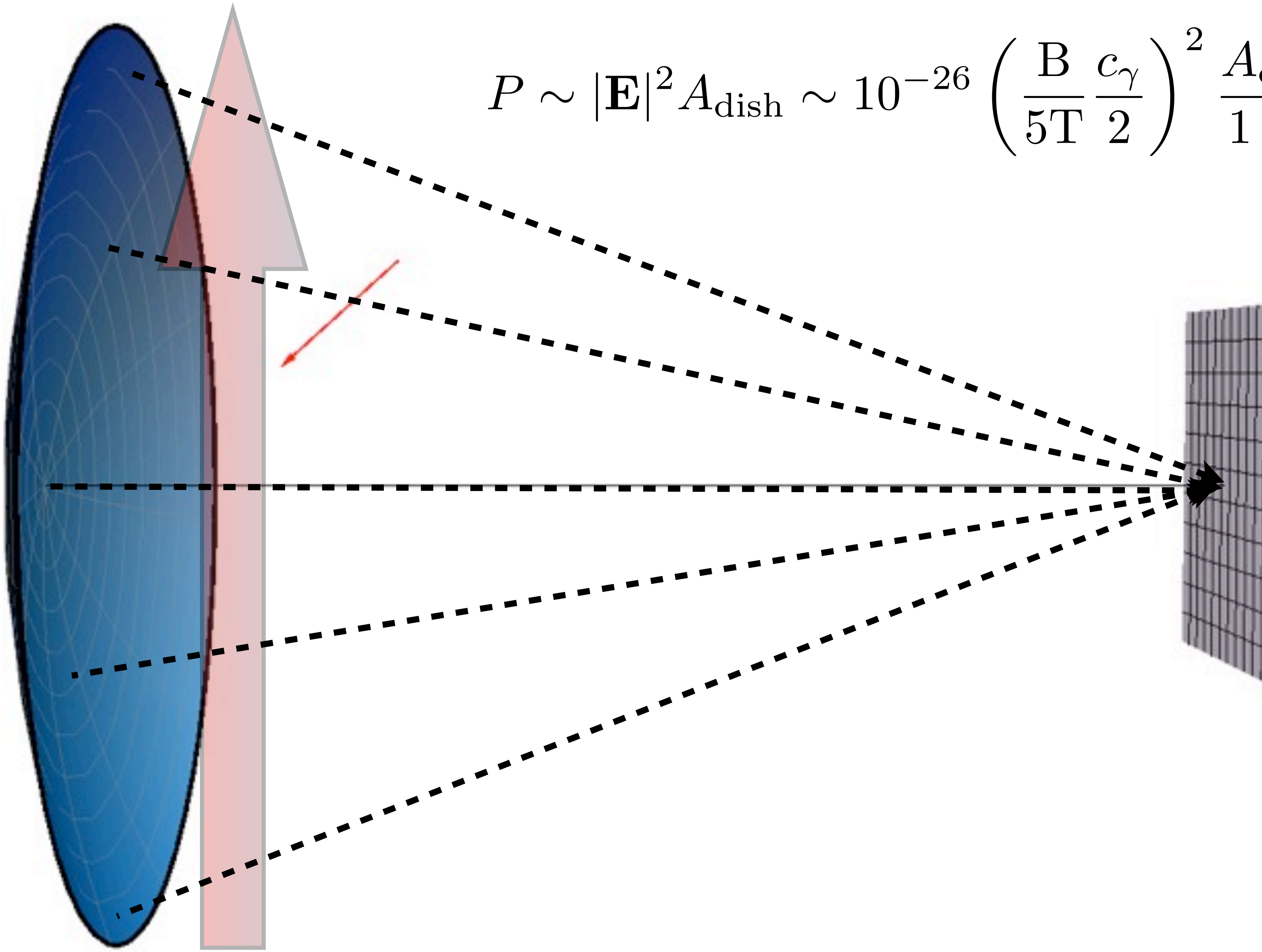
$$k_\gamma^\mu = (\omega, k_{||1}, k_{||2}, \sqrt{\omega^2 - k_{||}^2} \sim \omega)$$

$$k_\gamma^\mu \sim (\omega, 0, 0, \omega)$$

Simplest experiment: Dish antenna

Horns at al JCAP04(2013)016

$$P \sim |\mathbf{E}|^2 A_{\rm dish} \sim 10^{-26}\left(\frac{\rm B}{\rm 5T}\frac{c_\gamma}{2}\right)^2 \frac{A_{\rm dish}}{1\,{\rm m}^2}\,{\rm Watt}$$



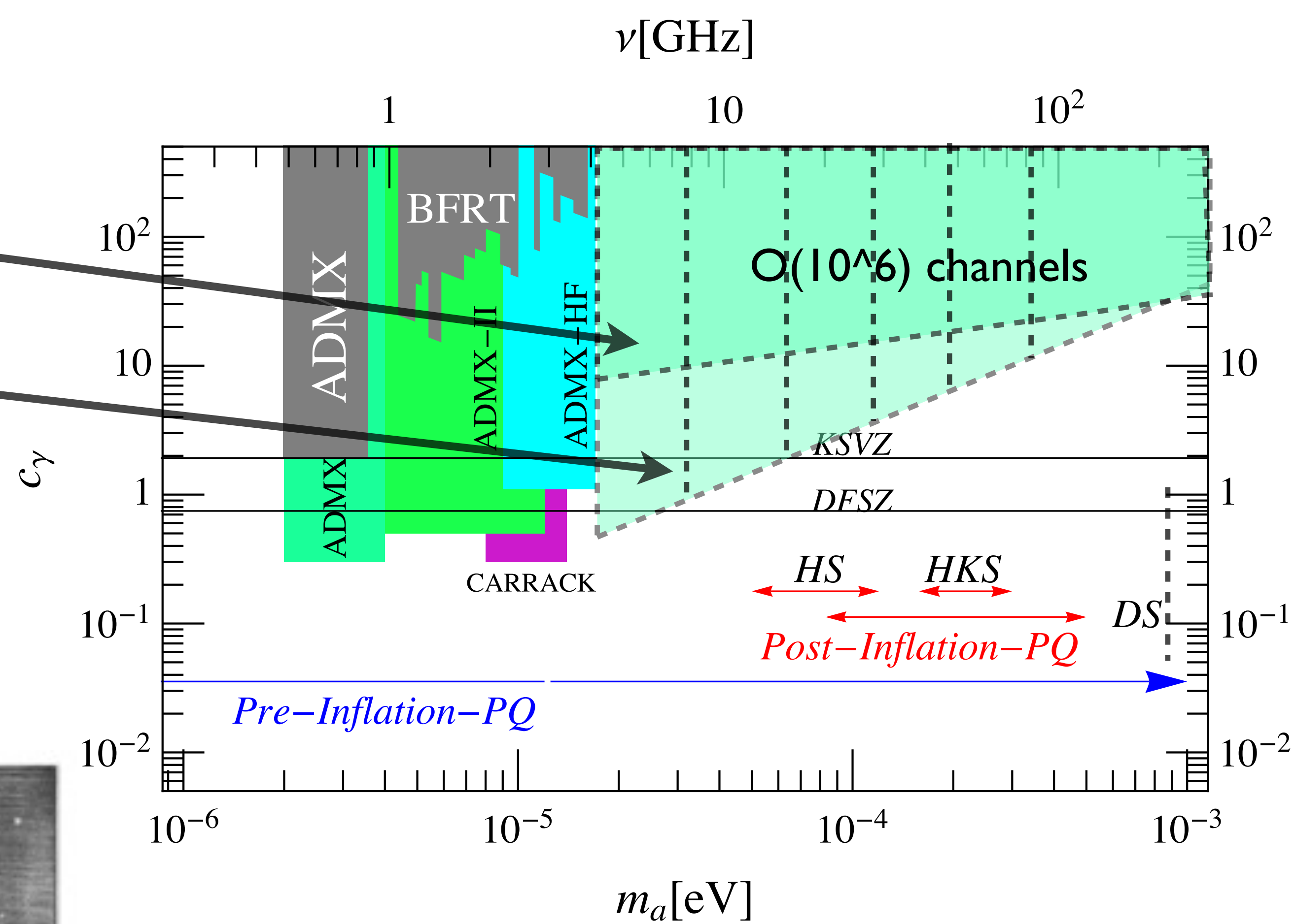
spherical reflecting dish

Simplest experiment: Dish antenna

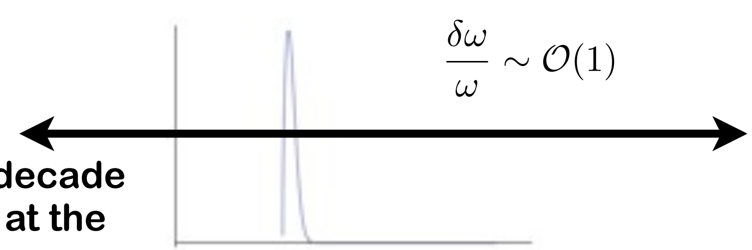
A=10m2,T=5K, B=5T, t=1year,

A=10m2, T=QL, B=10T, t=1year,

$$\rho_{\mathrm{CDM}} \sim \frac{0.3\mathrm{GeV}}{\mathrm{cm}^3}$$



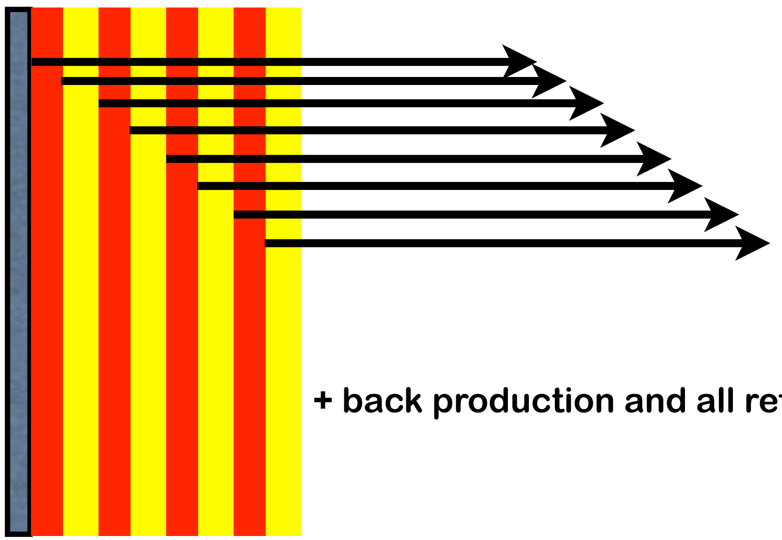
broadband! :-)



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

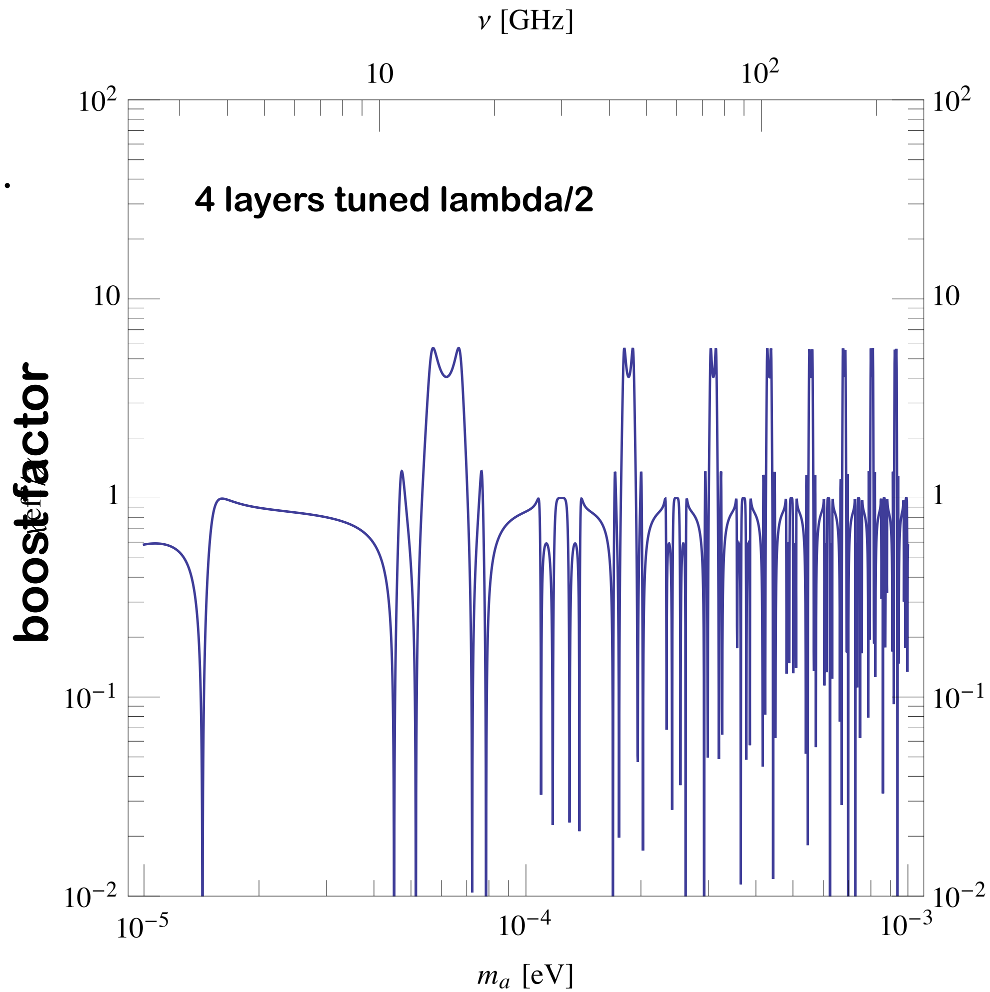
Possible improvement

Enhance the emissivity by multilayers of dielectric



+ back production and all reflexions ...

$$|\mathbf{E}_a| \to |\mathbf{E}_a| \times N$$



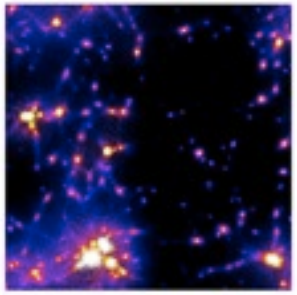
Increases sensitivity
but losses bandwidth

Dish antenna and miniclusters

- Typical Dish antenna experiments fall a bit short, if the DM density is just $\rho_{\rm CDM} = 0.3{\rm GeV/cm}^3$

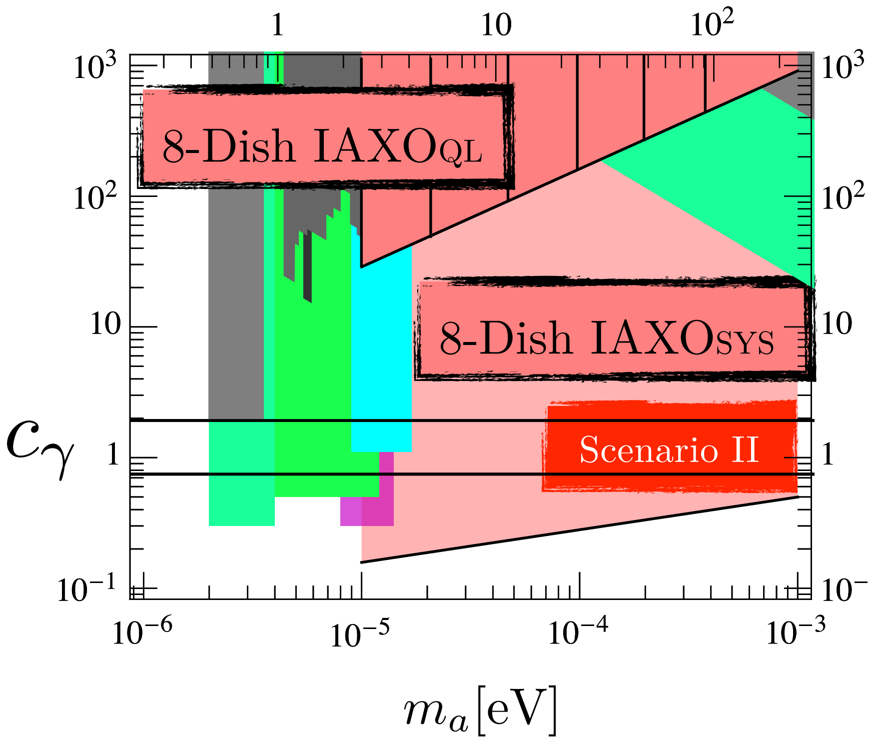
- 0.1-1 meV range is most interesting in Scenario-II

- S-II predicts miniclusters of axion CDM



$$M_{\rm mc} \sim 10^{-12} M_\odot$$
$$\Omega_{mc}/\Omega_{a\rm CDM} \sim O(1)$$

Zurek et al 07, See also Kolb & Tkachev 94



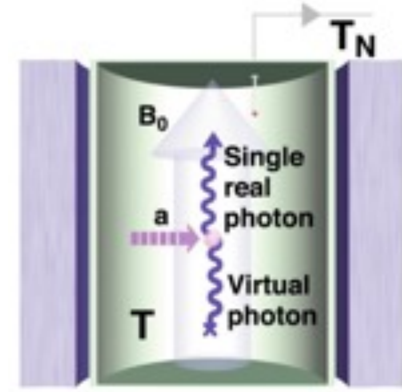
- Encounter with the Earth (every 10^4 years)

$$\rho_{\rm CDM} \times 10^6, Q_a \sim 10^9, t \sim 3{\rm days}$$

- Even with a modest realistic experiment one can get a huge signal ! (if lucky...)

Detecting EM fields from Axion Dark Matter

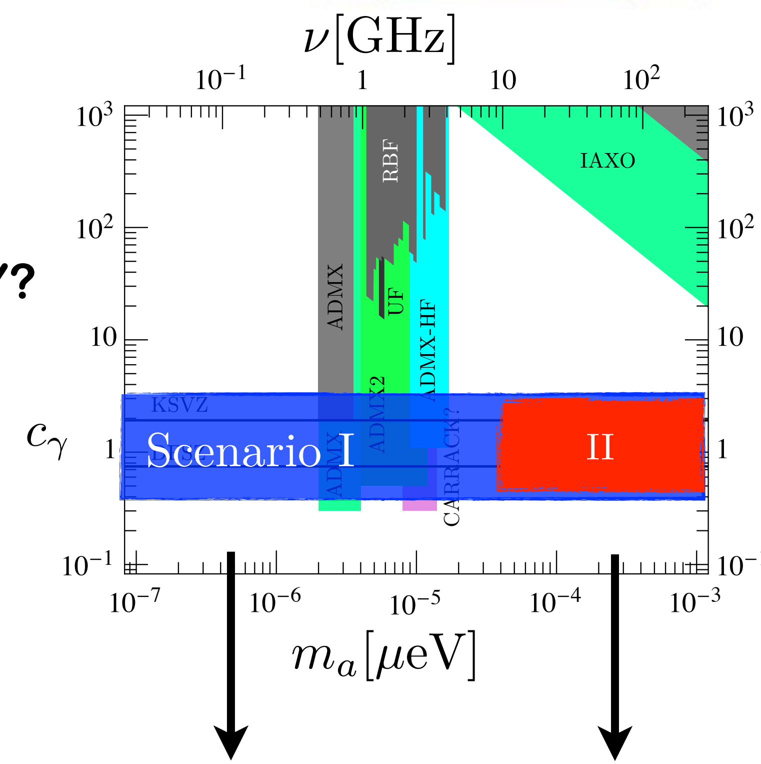
- **Haloscope (Sikivie 83)**
  "Amplify resonantly the EM fields created by axionDM in a B-field in a cavity"



$$P \sim Q|\mathbf{E}_a|^2 (V m_a) \mathcal{G} \kappa \qquad \text{(on resonance)}$$

- **Past experiments Florida U., RBF, ADMX, CARRACK**
- **Future endeavors: ADMX, ADMX-HF, YMCE, CAPP**

- **Parameters unexplored at low and high masses: WHY?**



Cylindrical cavity (h/r=b) **like ADMX but scaled**

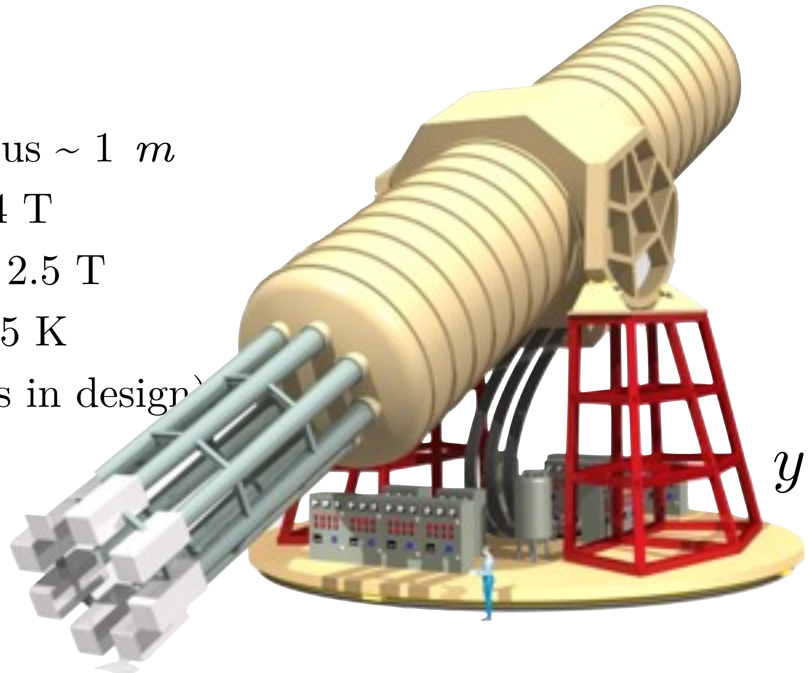
- Signal $\quad (V \propto m_a^{-3}) \quad P_{\rm out} \propto V m_a \sim \dfrac{1}{m_a^2}$
- Noise $\quad P_{\rm noise} = T_{\rm sys} \Delta\nu_a \propto m_a^2$
- Signal/noise in $\Delta\nu_a$ of time, t, $\quad \dfrac{S}{N} = \dfrac{P_{\rm out}}{P_{\rm noise}} \sqrt{\Delta\nu_a t}$
- Scanning rate $\quad \dfrac{1}{m_a}\dfrac{d\Delta m_a}{dt} \propto \dfrac{c_\gamma^4}{m_a^9}$

Very easy, but needs large magnet volume!

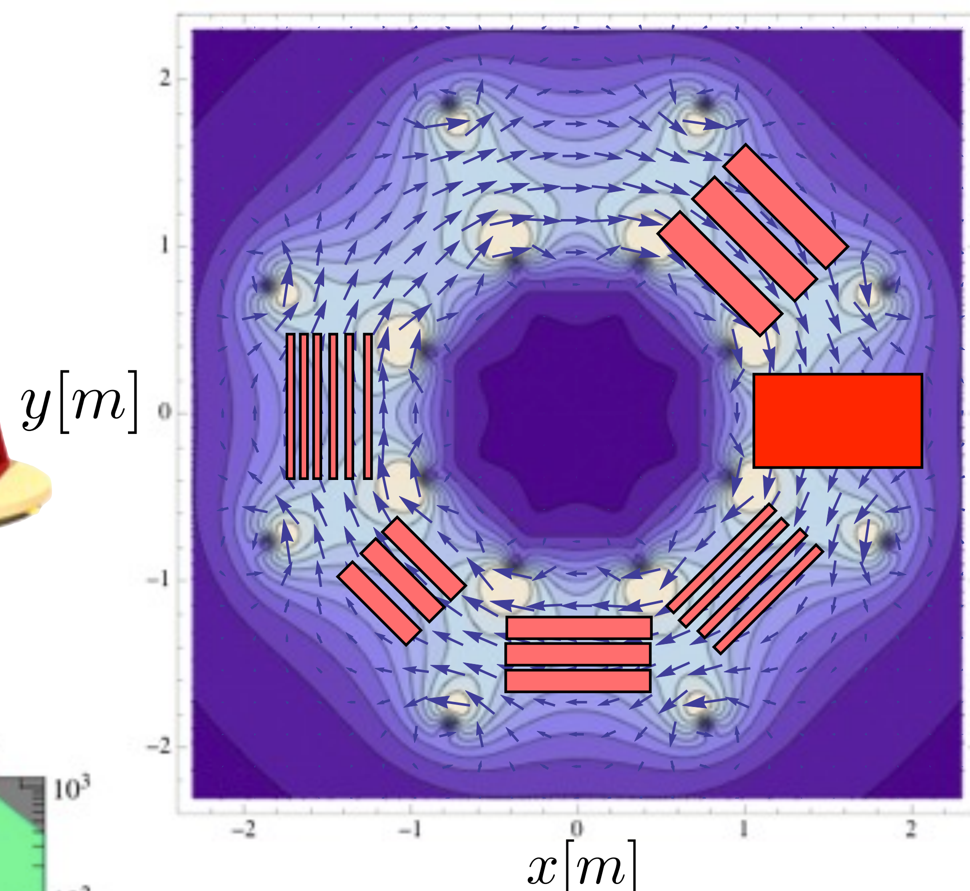
Very complicated, needs new ideas...

DM searches with future IAXO (International Axion Observatory)

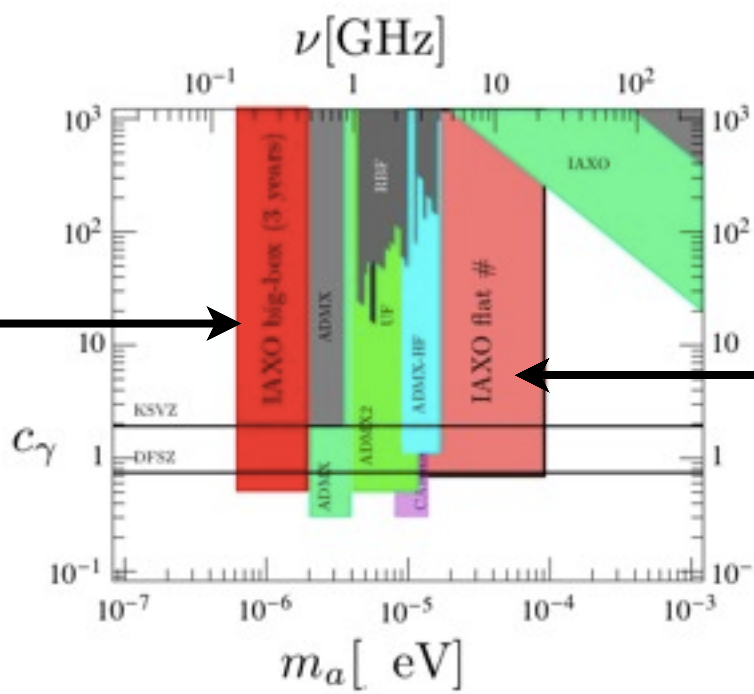
- Length = 20 m
- Magnetised radius ~ 1 m
- Peak value ~ 5.4 T
- Average in bore 2.5 T
- Available T ~ 4.5 K
  (but warm bores in design)



field map of transverse cut



- Sensitivity



Big cavity (realistic) →

← Many flat (exploit the huge volume) (very speculative, R&D needed!)

Conclusions

- Axion DM - well motivated and testable
  - but underrepresented (gets better)
  - key targets not covered
  - plenty of new ideas uncovered here

- Cavity experiments on the run
  - micro-eV range by ADMX, ADMX-HF
  - lower masses, IAXO?
  - higher masses, new ideas!

- Dish antenna
  - a little short for axions
  - broadband/miniclusters!
  - boost with dielectric layers!
  - good for ALPs, hidden photons!