Old problems and New directions on axion DM

“Frontiers of New Physics: Colliders and Beyond”

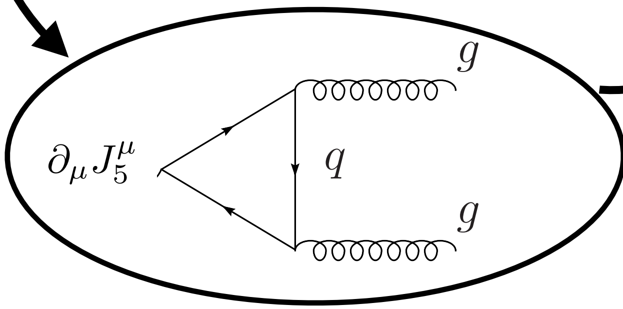
ICTP, Trieste, 26 Jun 2014

Javier Redondo (LMU/MPP Munich)

The strong CP "hint" and axions

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

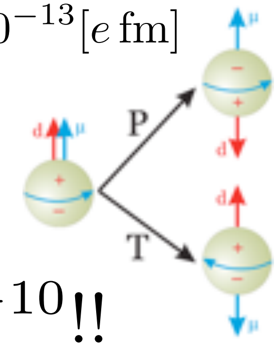
$$\mathcal{L}_{\rm SM} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta} & 0 & \dots \\ 0 & m_d e^{i\delta} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\rm QCD}$$



Neutron EDM

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

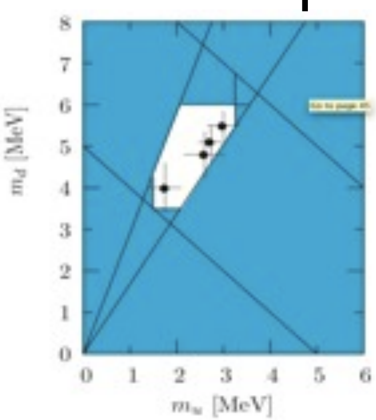
$d_n^{\rm exp} < 3 \times 10^{-13}[e\,{\rm fm}]$



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

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

massless q?



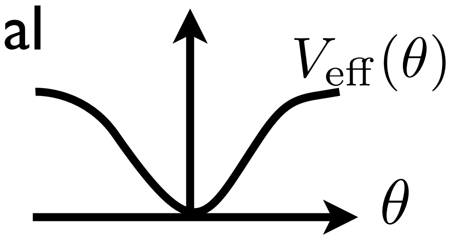
P,CP symmetries?

- (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

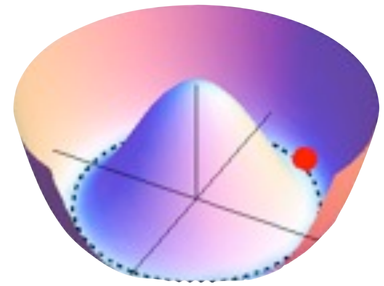
$\theta \to 0$



Axion mass and couplings (and model dependencies)

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

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

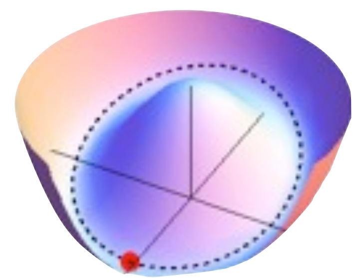


$$\Phi(x) = \rho(x) e^{i\frac{a(x)}{f_a}}$$ (KSVZ model)

- 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 $\Lambda_{\rm QCD}$, $\quad a - \eta' - \pi^0 - \eta - \ldots$ mixing

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

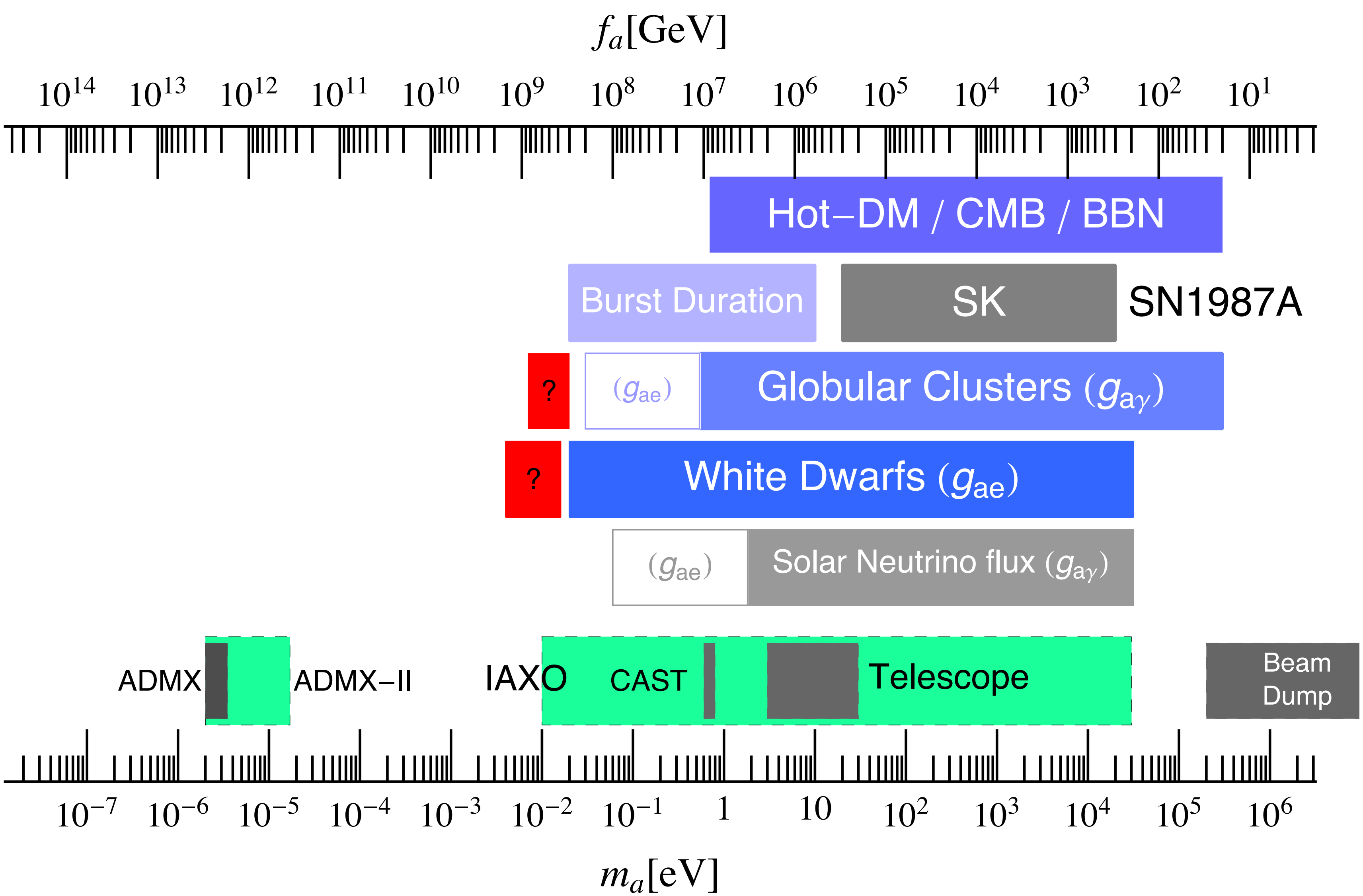


axion couplings

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

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

Parameter spaces: generic

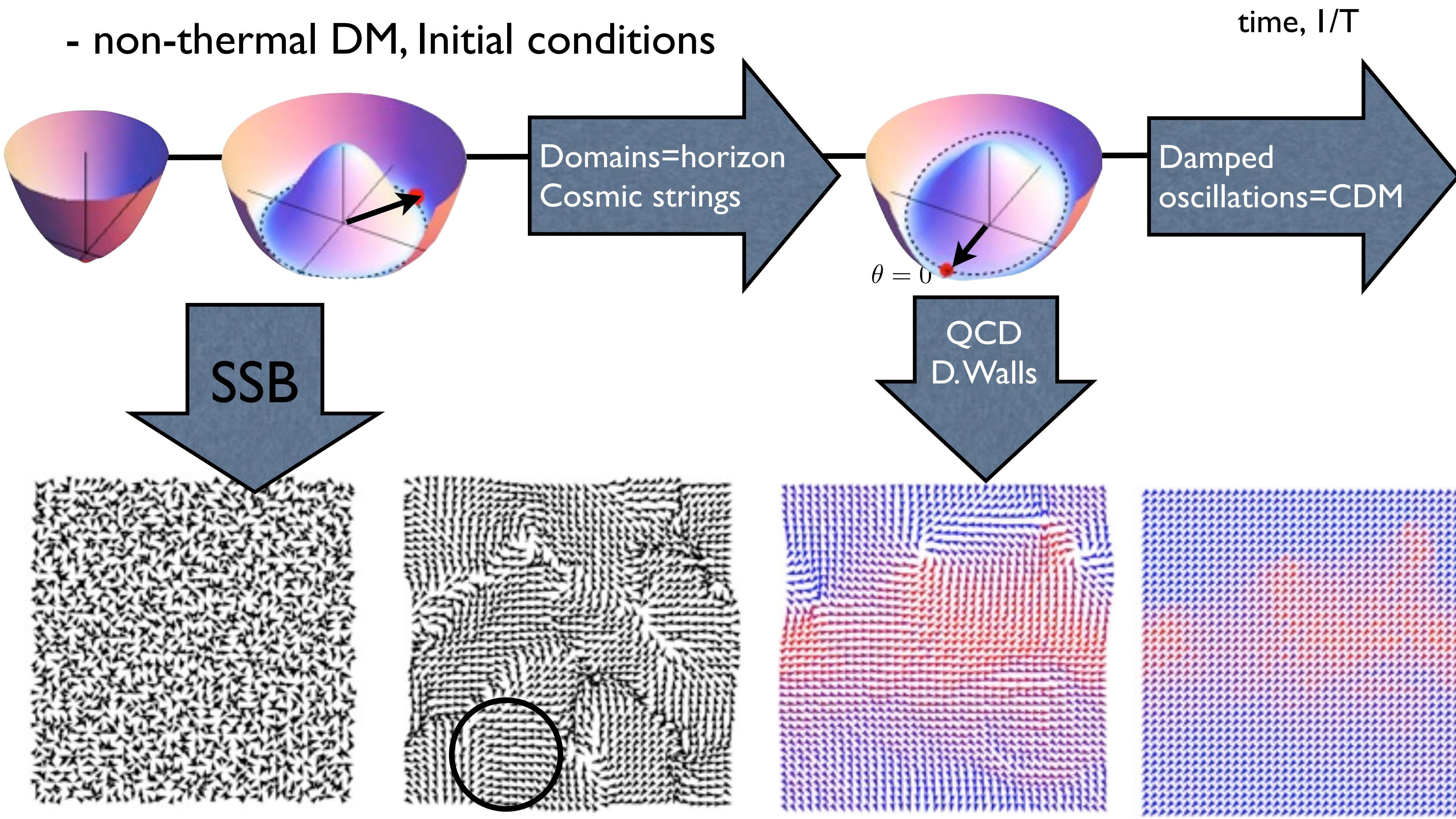


- Axions (if existing) are very light and very weakly interacting!

Axion cold dark matter: vacuum alignment

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

- non-thermal DM, Initial conditions



Axion cold dark matter: vacuum alignment

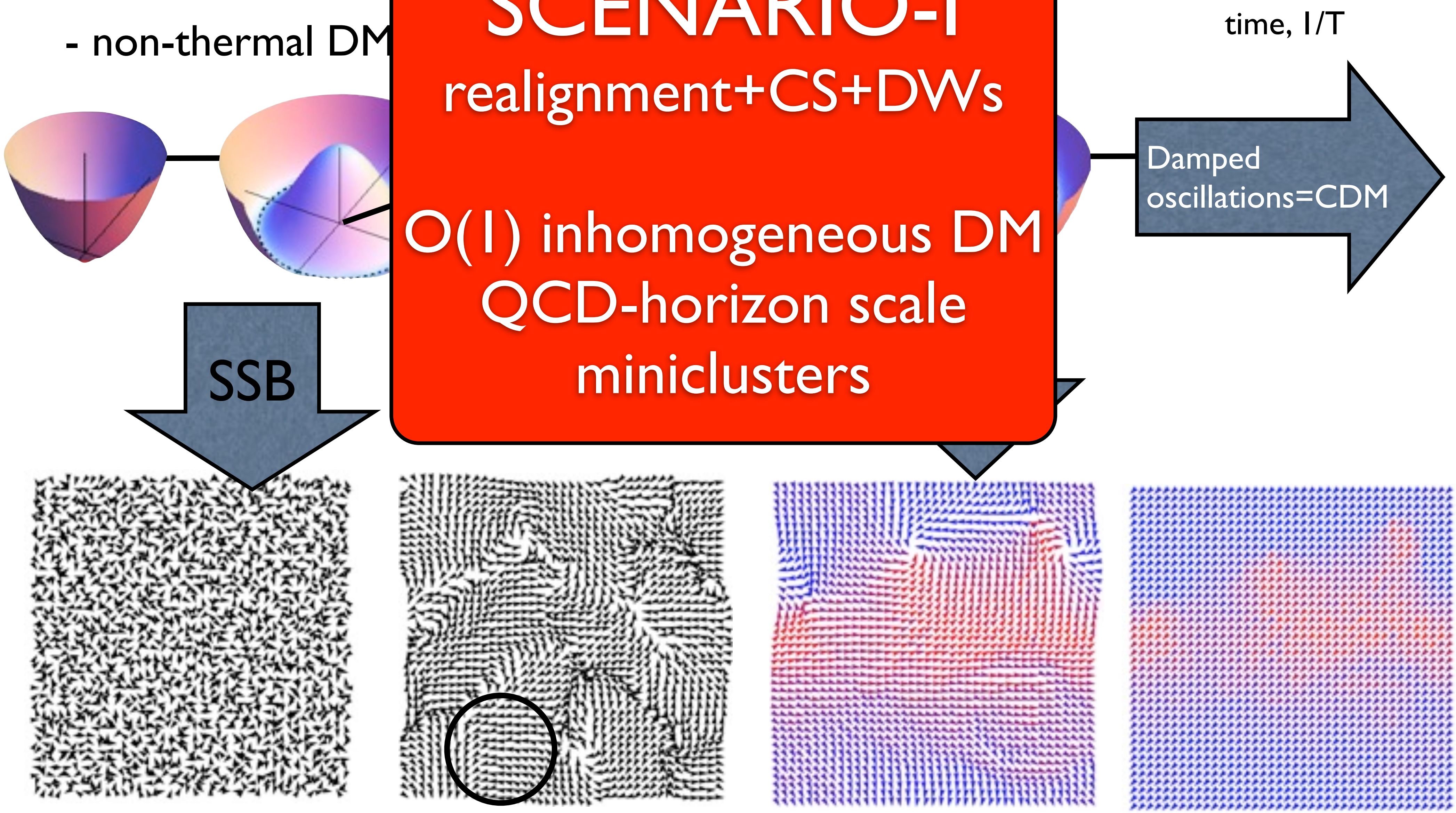
- Axions: small ma

- non-thermal DM

SCENARIO-I

realignment+CS+DWs

O(1) inhomogeneous DM
QCD-horizon scale
miniclusters



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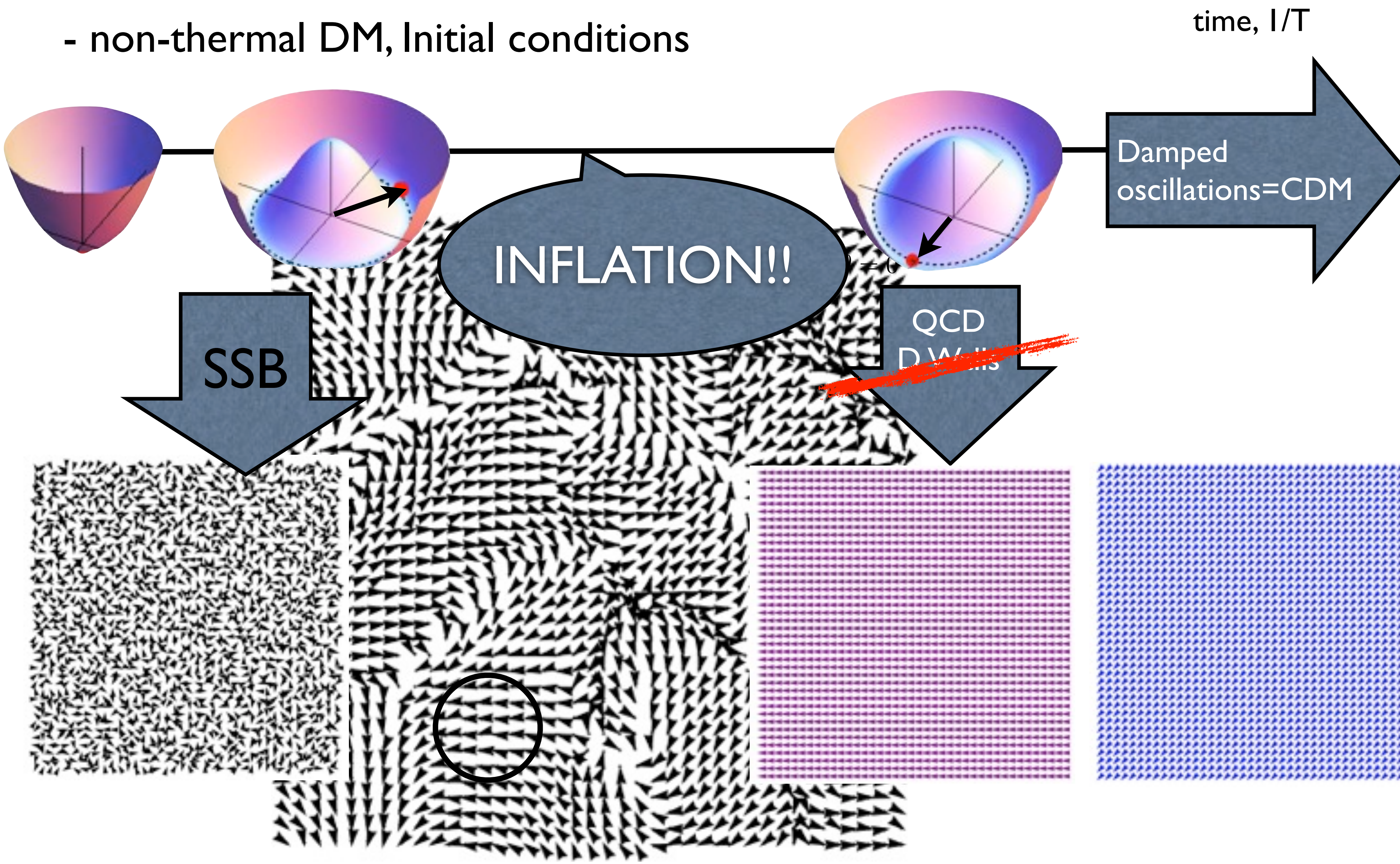
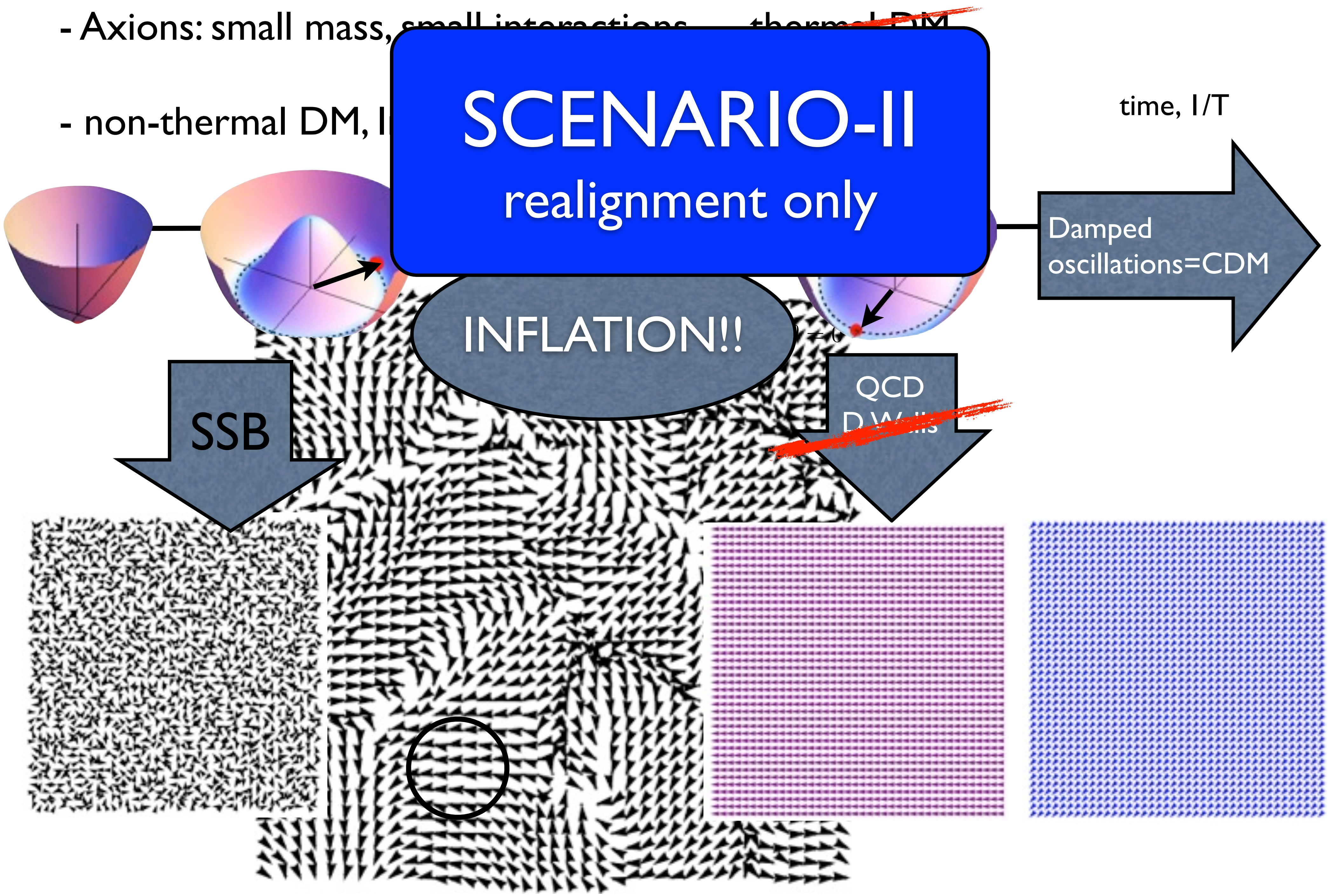


Axion cold dark matter: vacuum alignment



Rough relic abundance of axion Dark matter

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

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

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

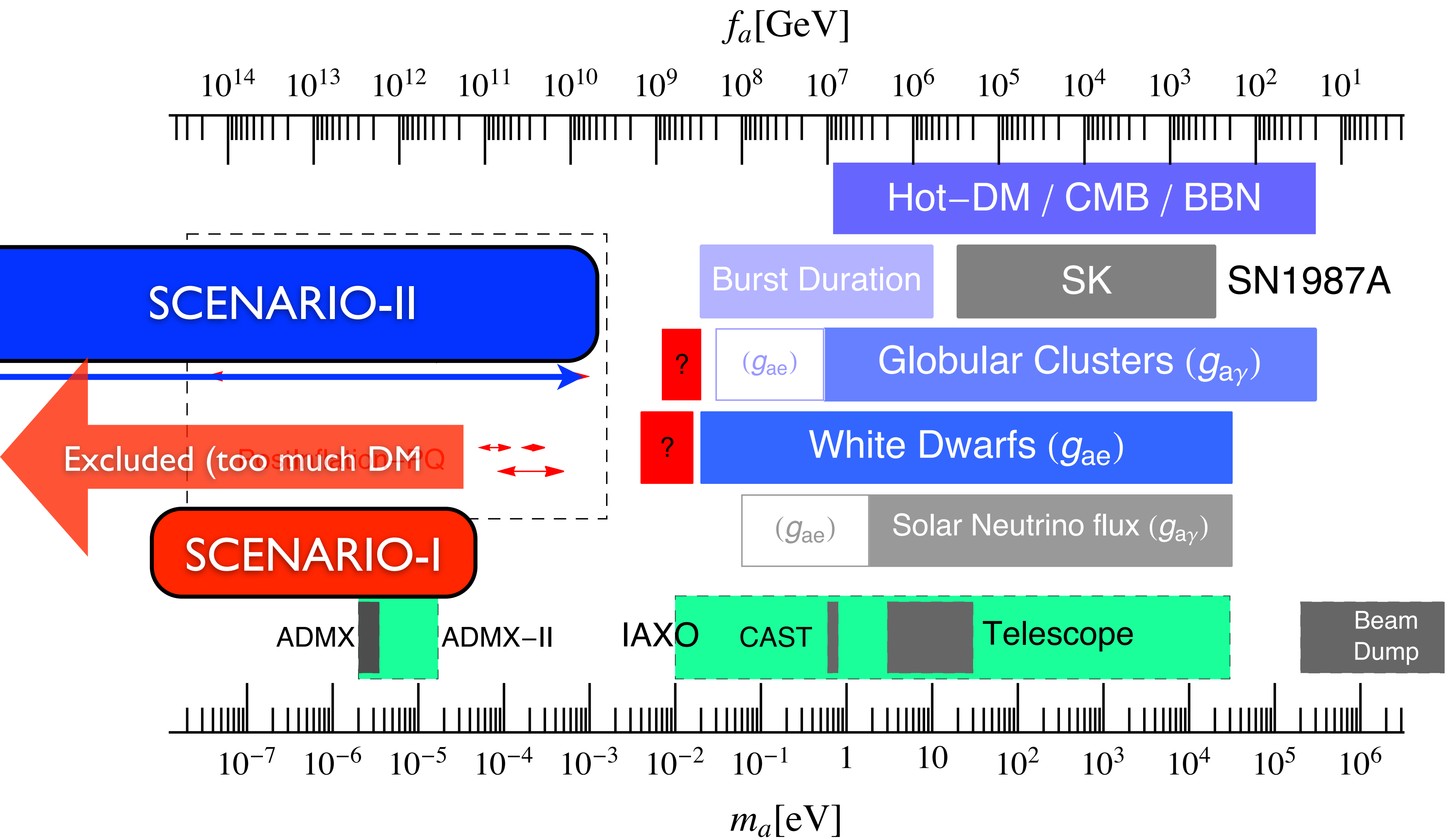
- **today...**

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

- **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

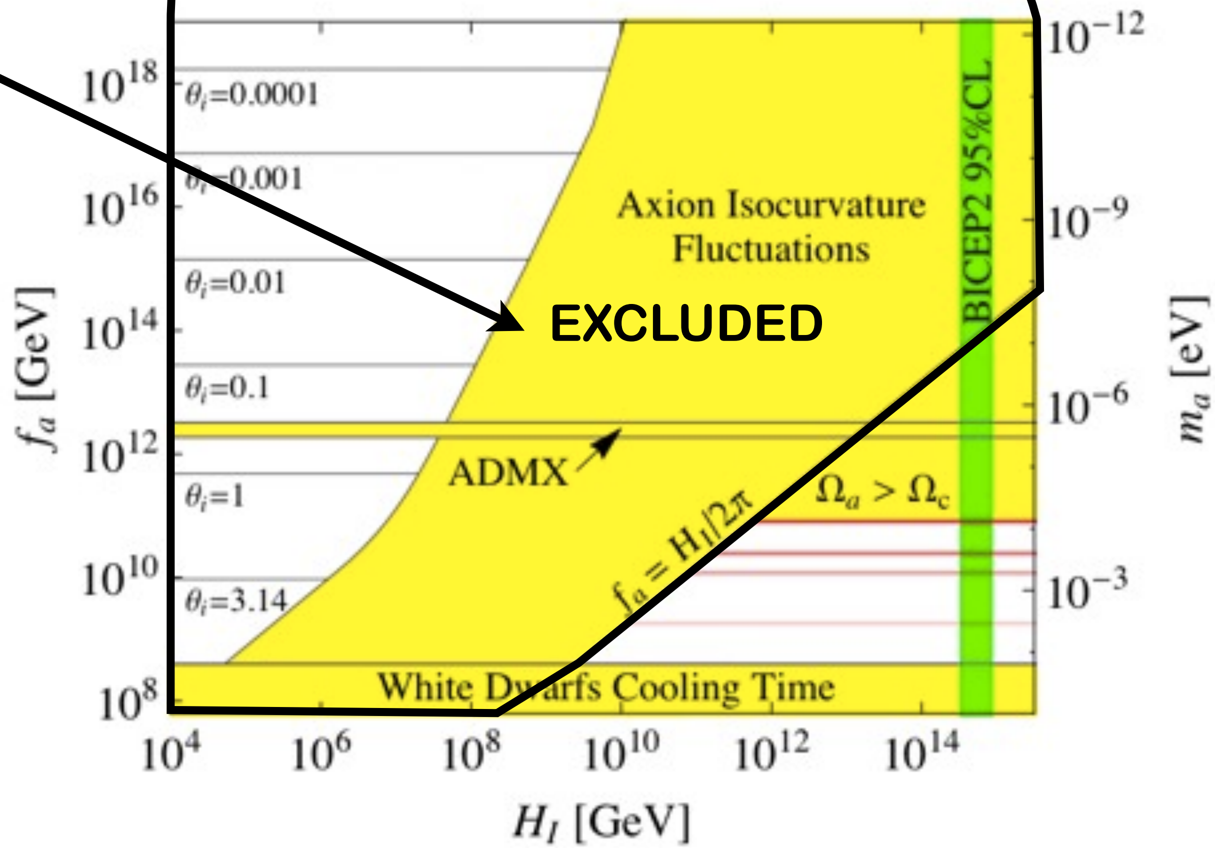
- Axion fluctuates during inflation (entropy perturbations)

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

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

Constraint $f_a(H_I)$

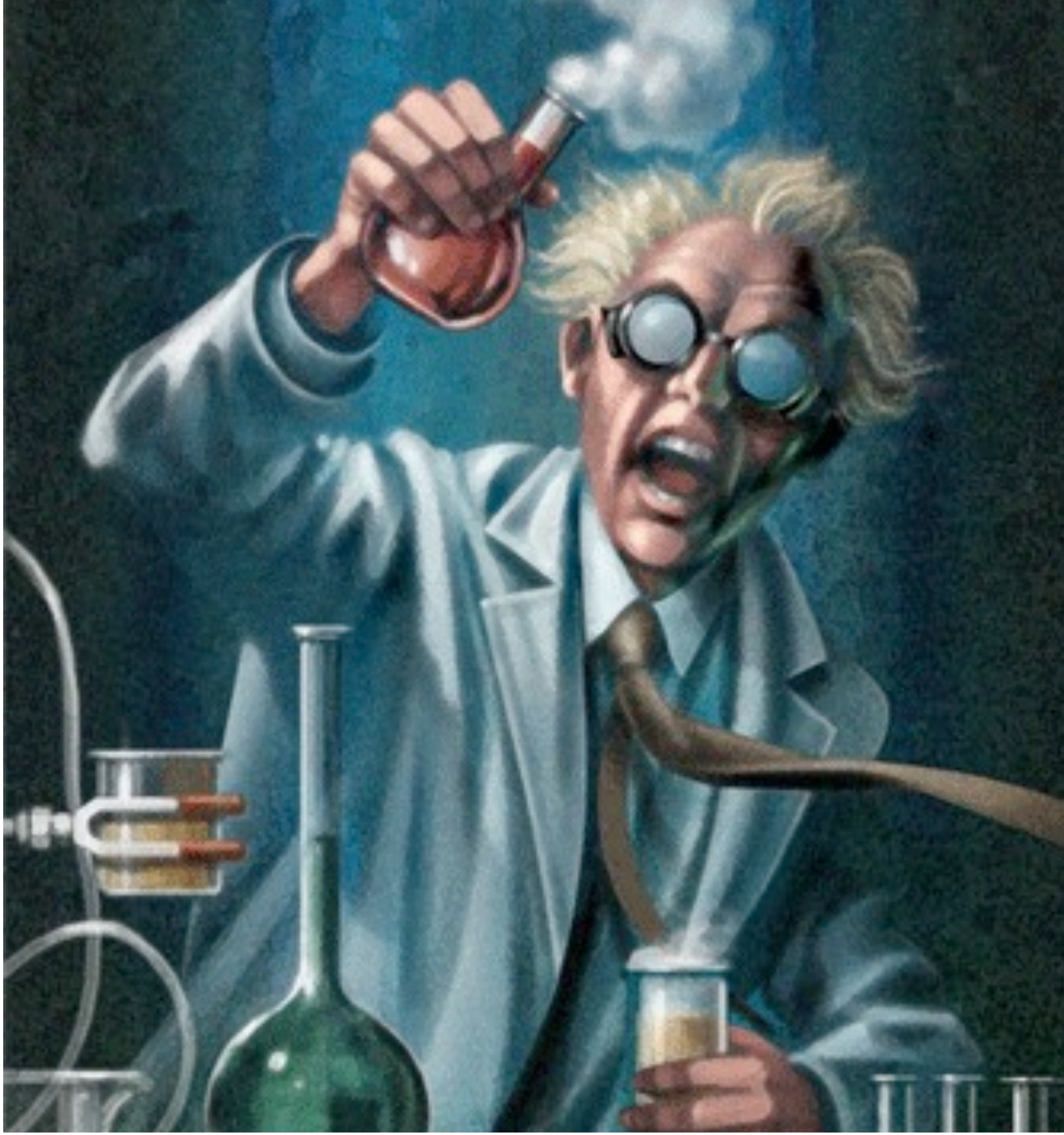
$f_a \gg H_I$



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

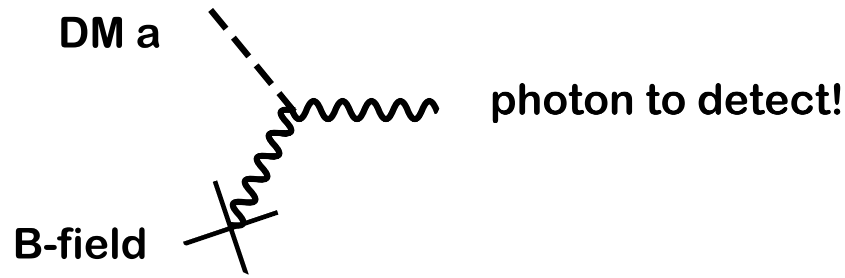
of course, there are plenty of ways out ...

Laboratory

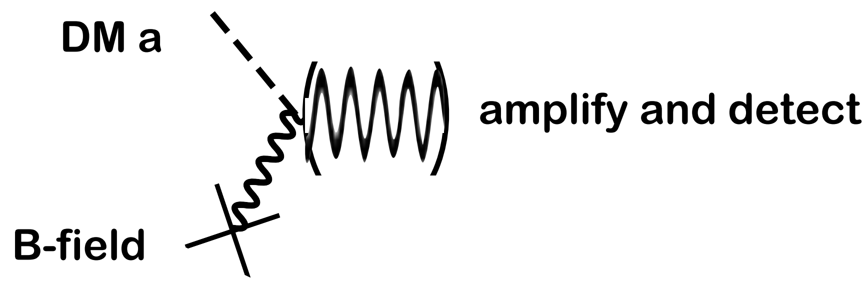


Experiments to detect axion DM

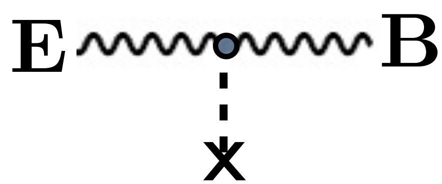
- Dish antenna



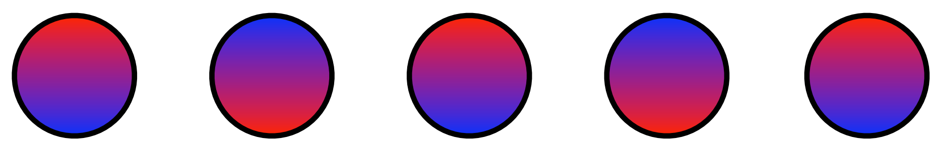
- Cavity experiments



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

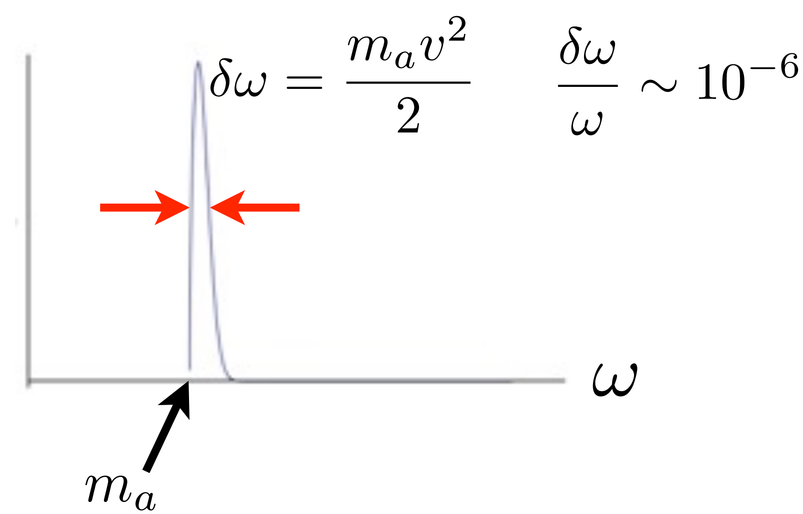
phase space density $$\frac{n_a}{\frac{4\pi p^3}{3}} \sim 10^{29}\left(\frac{\mu{\rm eV}}{m_a}\right)^4$$

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

Roughly ... $$a(t) = a_0\cos(m_a t)$$

Fourier-transform $a(x)$

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

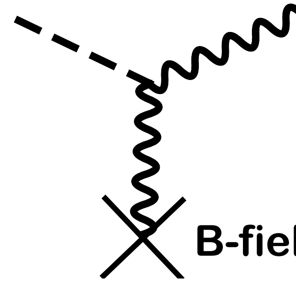


Axion - photon mixing in a magnetic field

Raffelt, PRD'88

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

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



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,SUMICO and IAXO ...
- 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 $v = \frac{k}{\omega} \quad ; \quad \omega \simeq m_a(1 + v^2/2 + ...)$

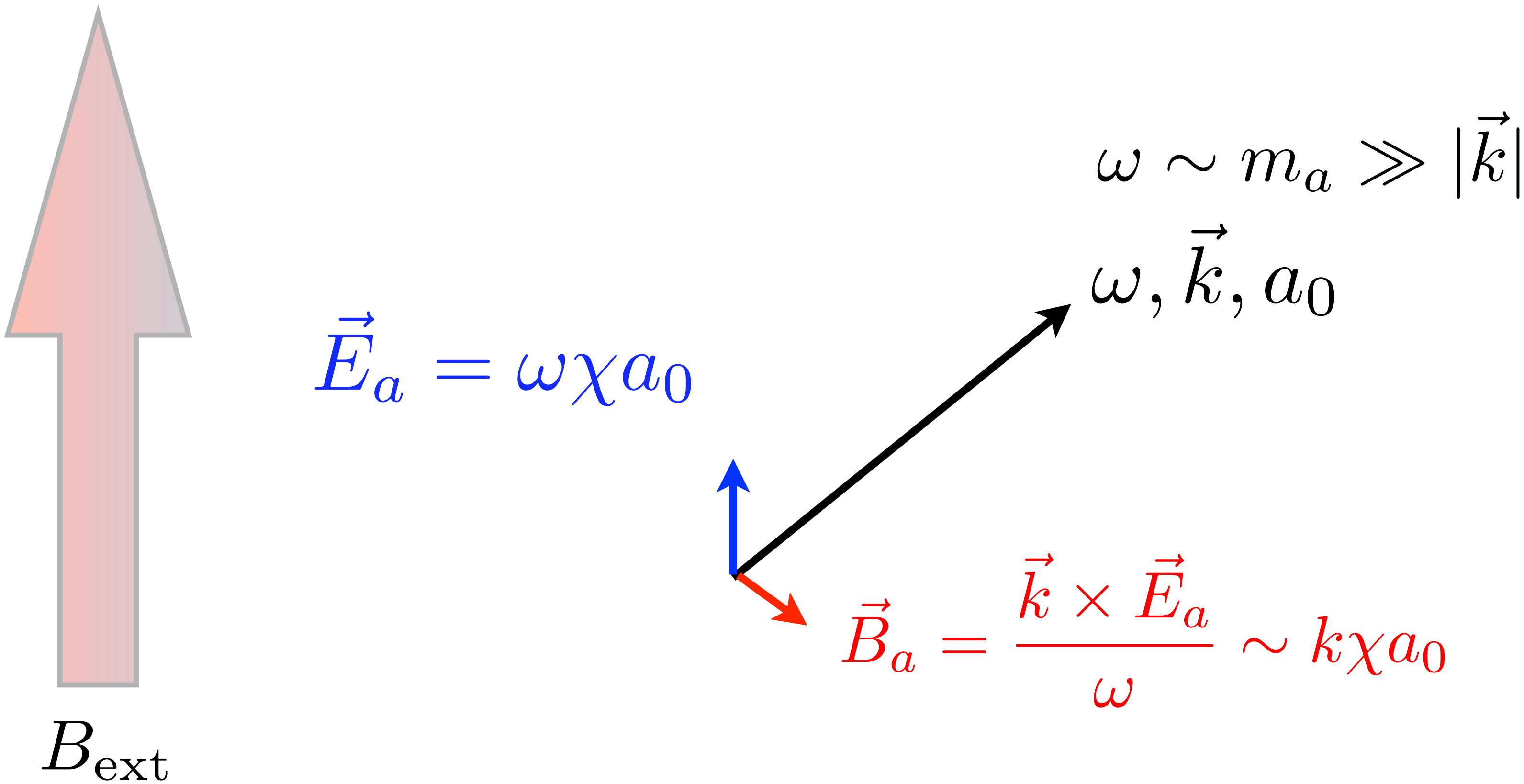
$$\left.\begin{pmatrix} \mathbf{A}_{||} \\ a \end{pmatrix}\right|_{\mathrm{DM}} \propto \begin{pmatrix} -\chi_a \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).$$

It has a small E field!

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

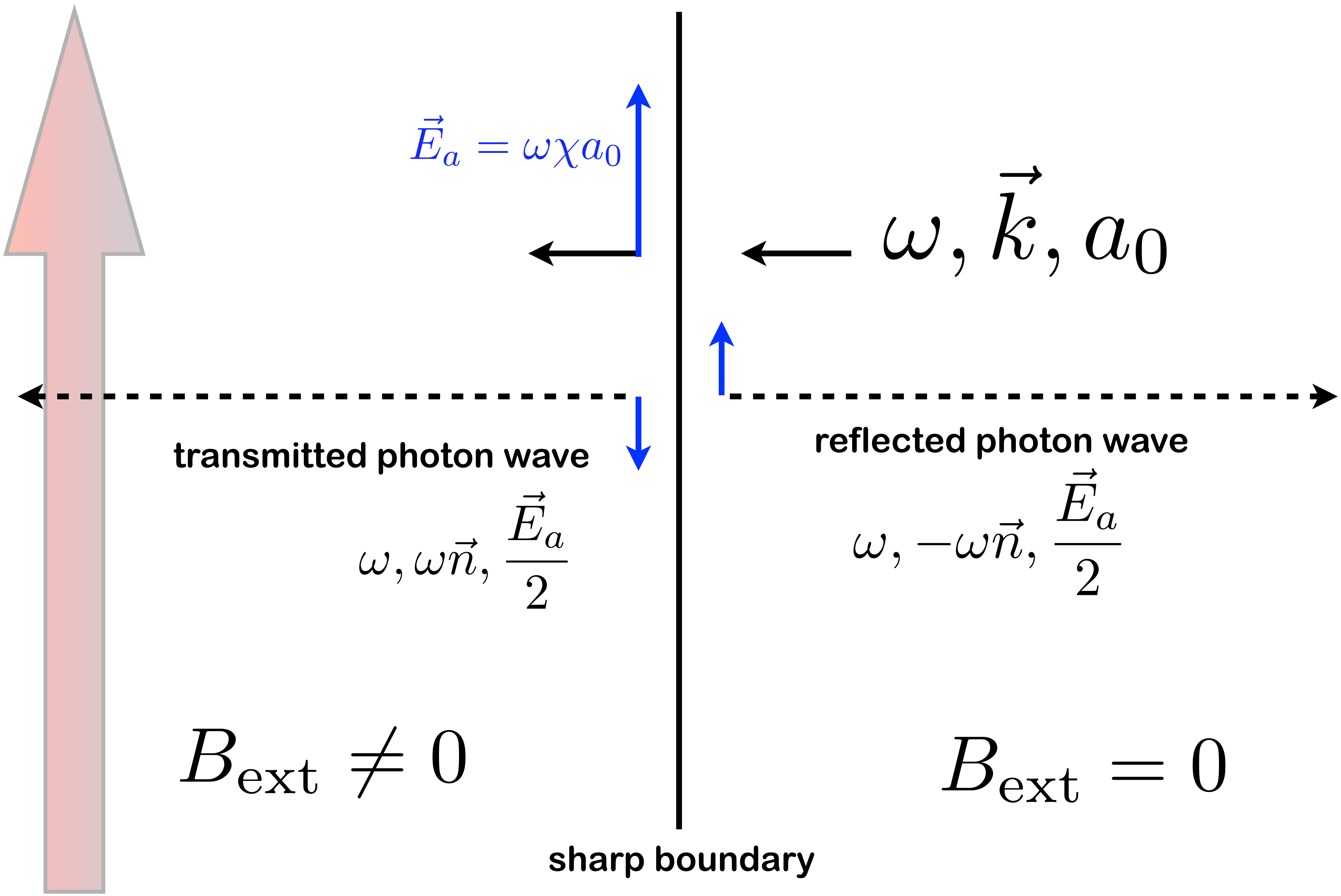
$$\mathbf{E_a} \sim \partial_t \mathbf{A}_{||} \sim m_a a_0 \chi \sim \sqrt{\rho_{\mathrm{CDM}}}\chi$$

DM axions in a magnetic field



Photons from Transition radiation!

Jaeckel and JR arXiv:1308.1103



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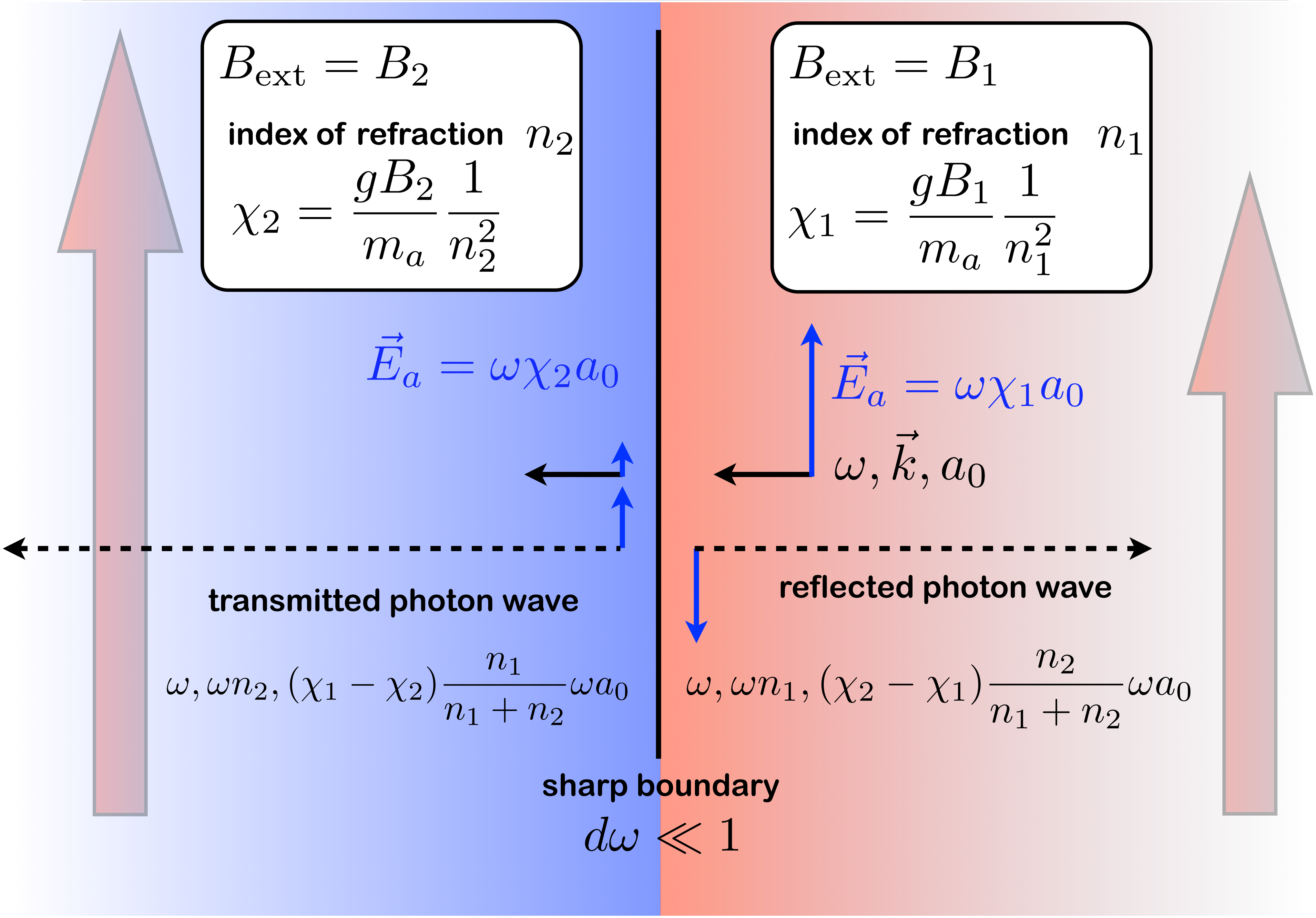
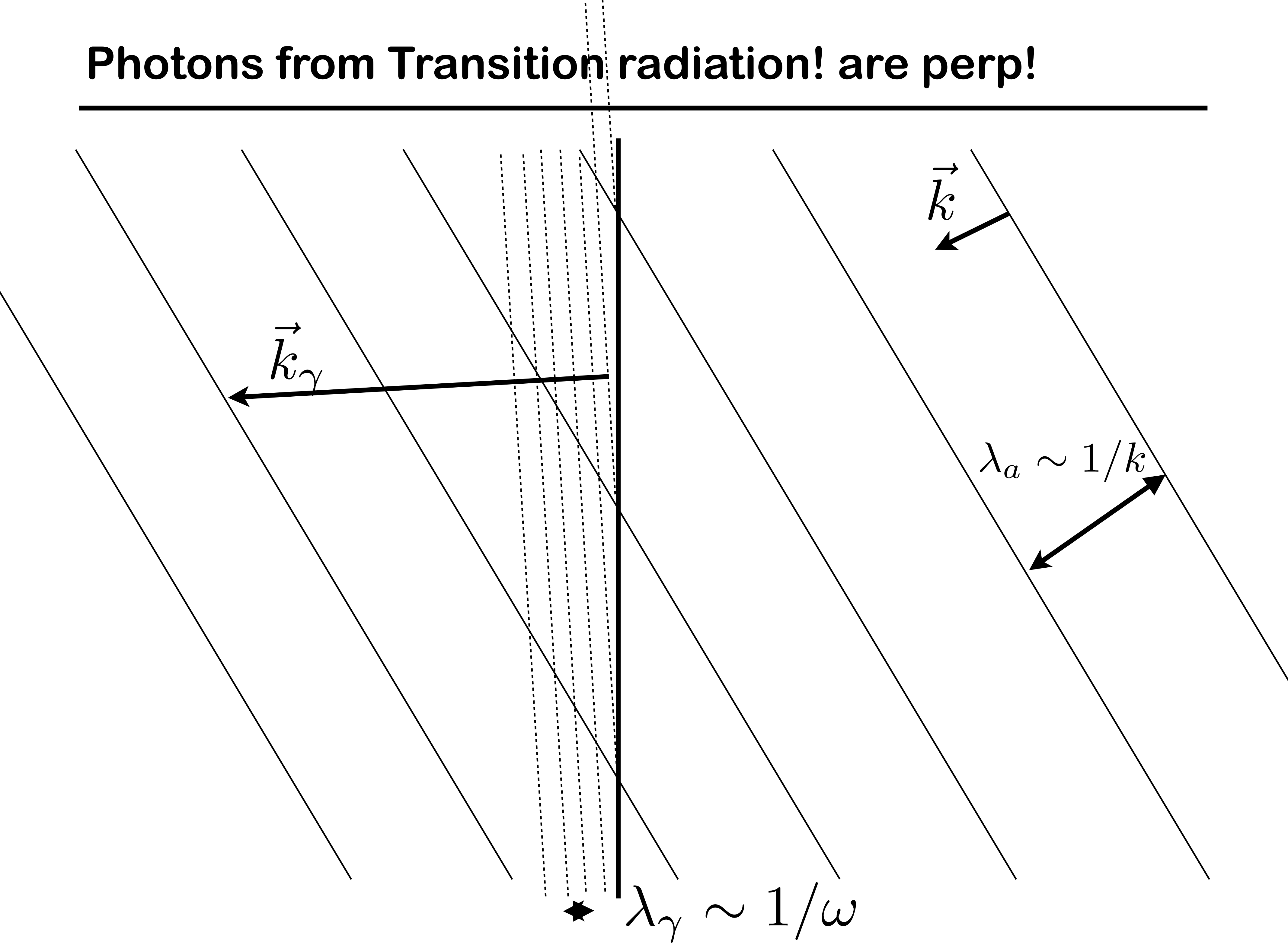


Photons from Transition radiation! are perp!

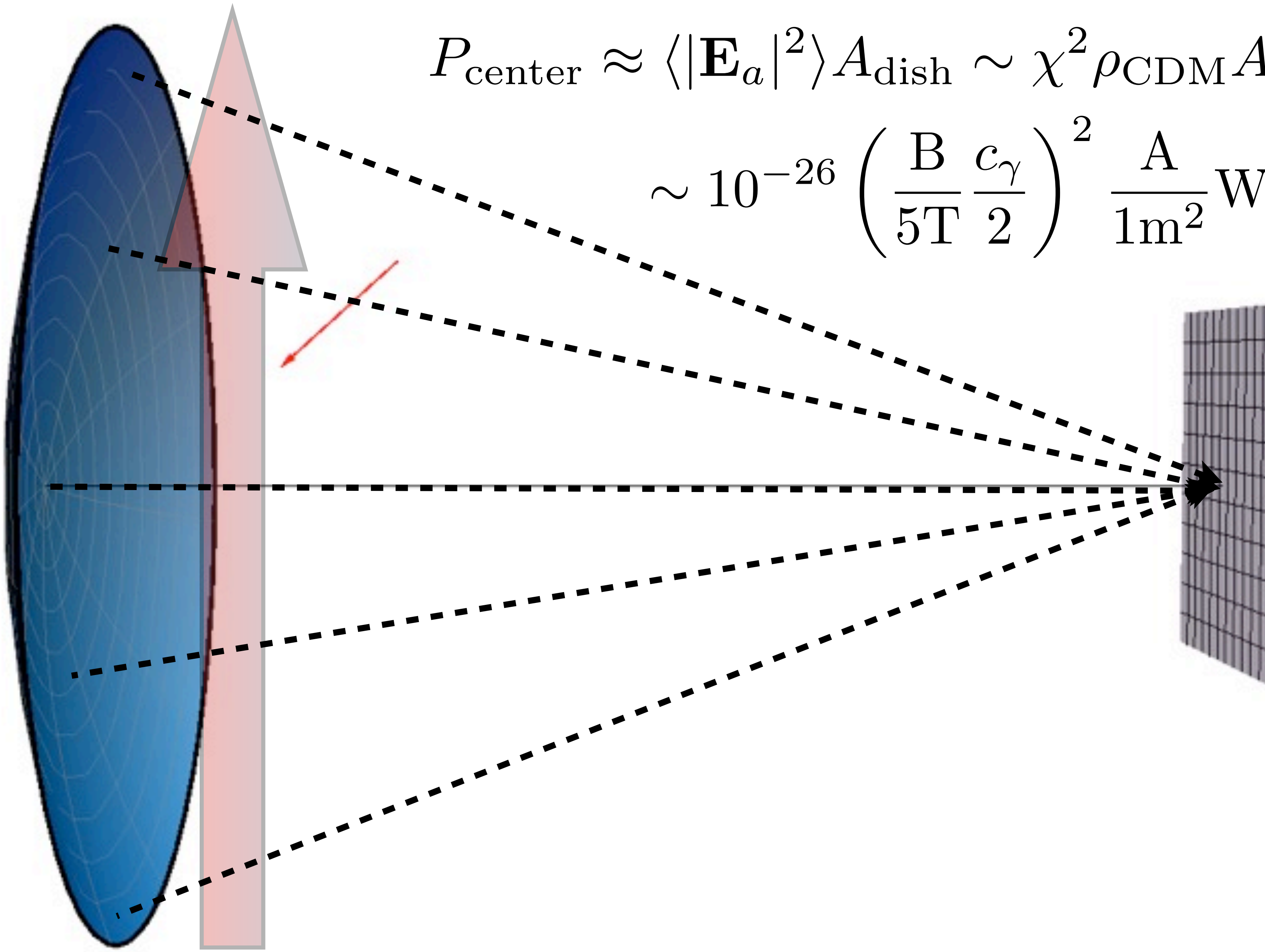


Simplest experiment: Dish antenna

Horns at al JCAP04(2013)016

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

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



spherical reflecting dish

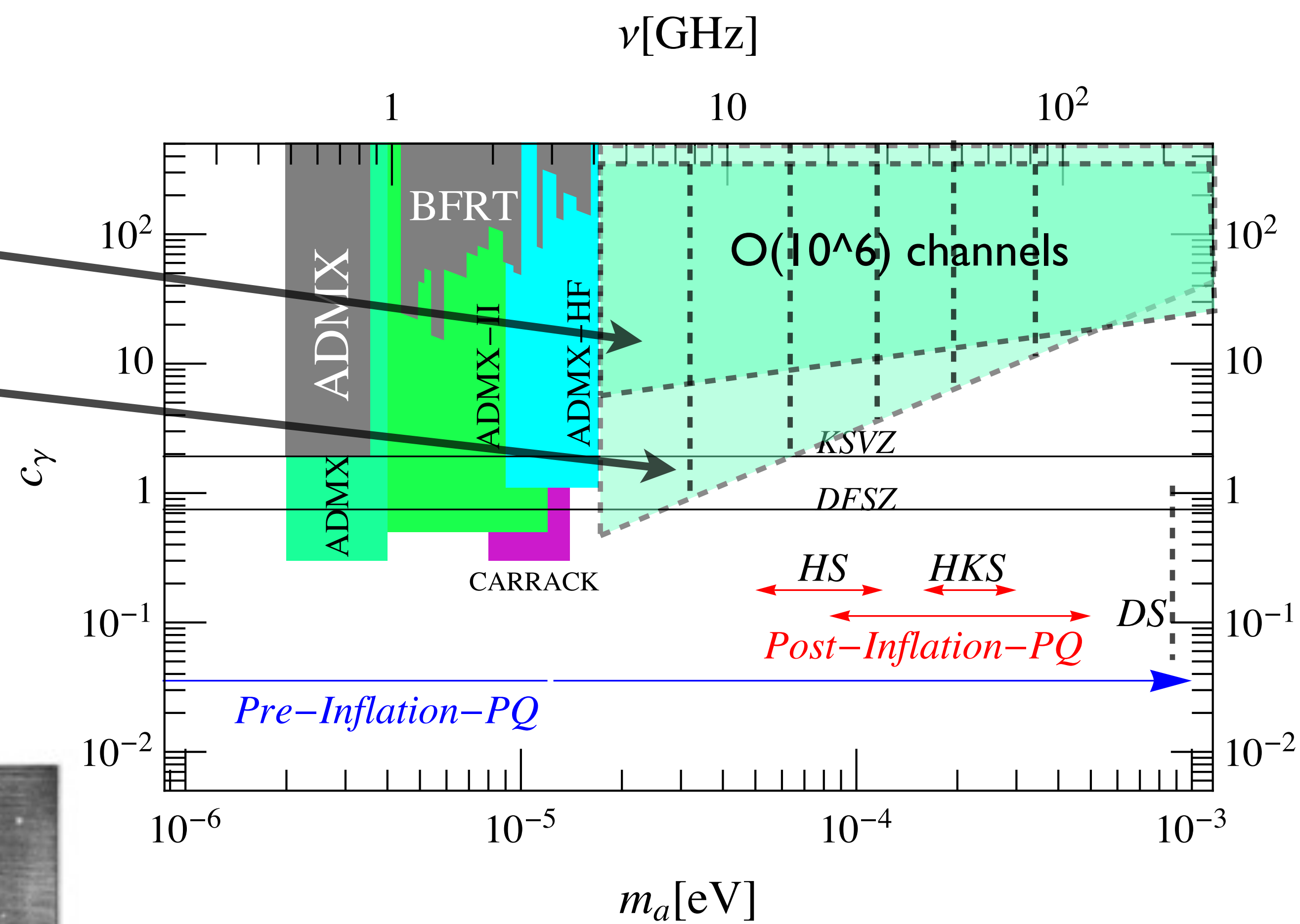
Simplest experiment: Dish antenna

Horns at al JCAP04(2013)016

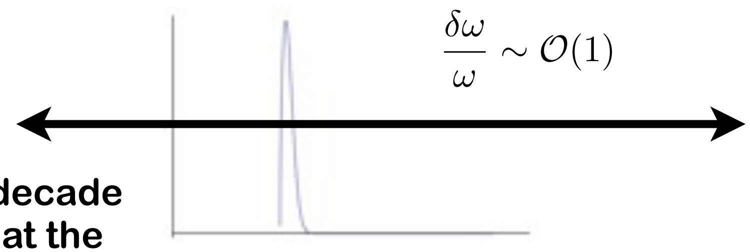
A=10m2,T=5K,B=5T,t=1year,

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

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



broadband! :-)

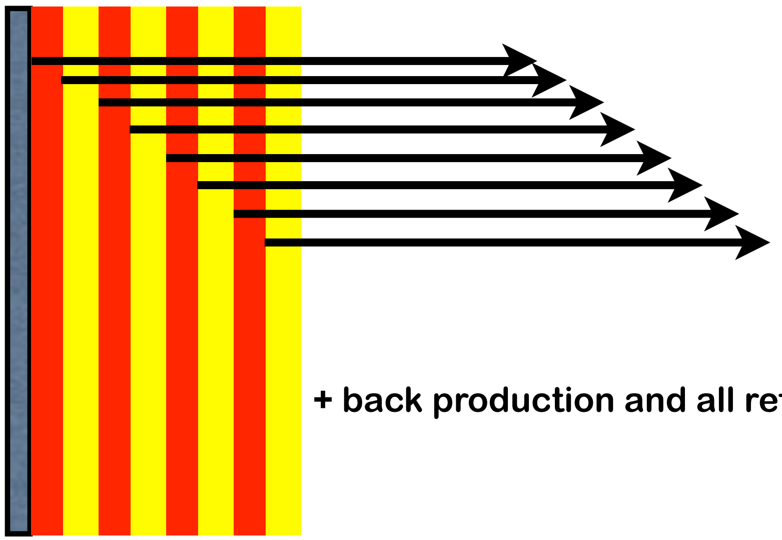


$$\frac{\delta\omega}{\omega} \sim \mathcal{O}(1)$$

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

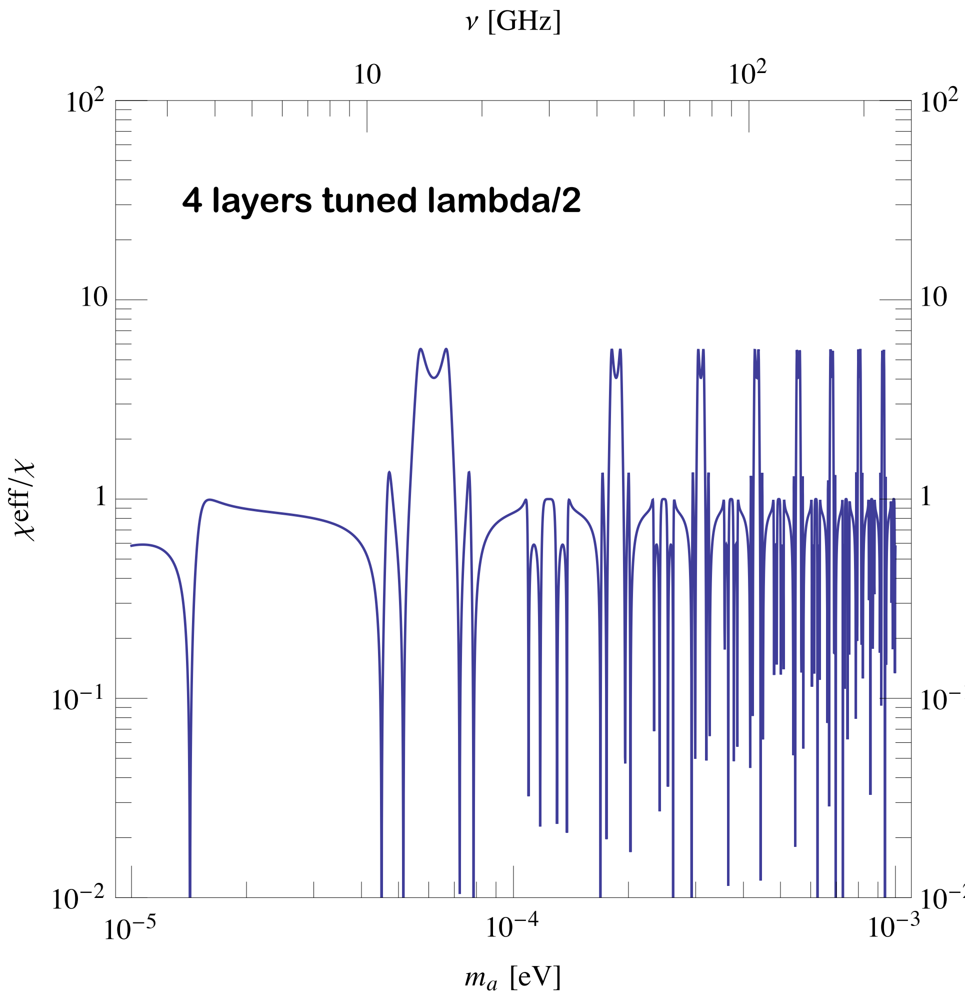
Possible improvement

Enhance the emissivity by multilayers of dielectric



+ back production and all reflexions ...

$$\chi \to \chi_{\text{eff}} \sim \chi \times N$$



Increases sensitivity
but losses bandwidth

Cavity searches (haloscopes)

- Different understanding of the conventional

HALOSCOPES

Cavity searches (haloscopes)

Sikivie PRL '83

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

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

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)

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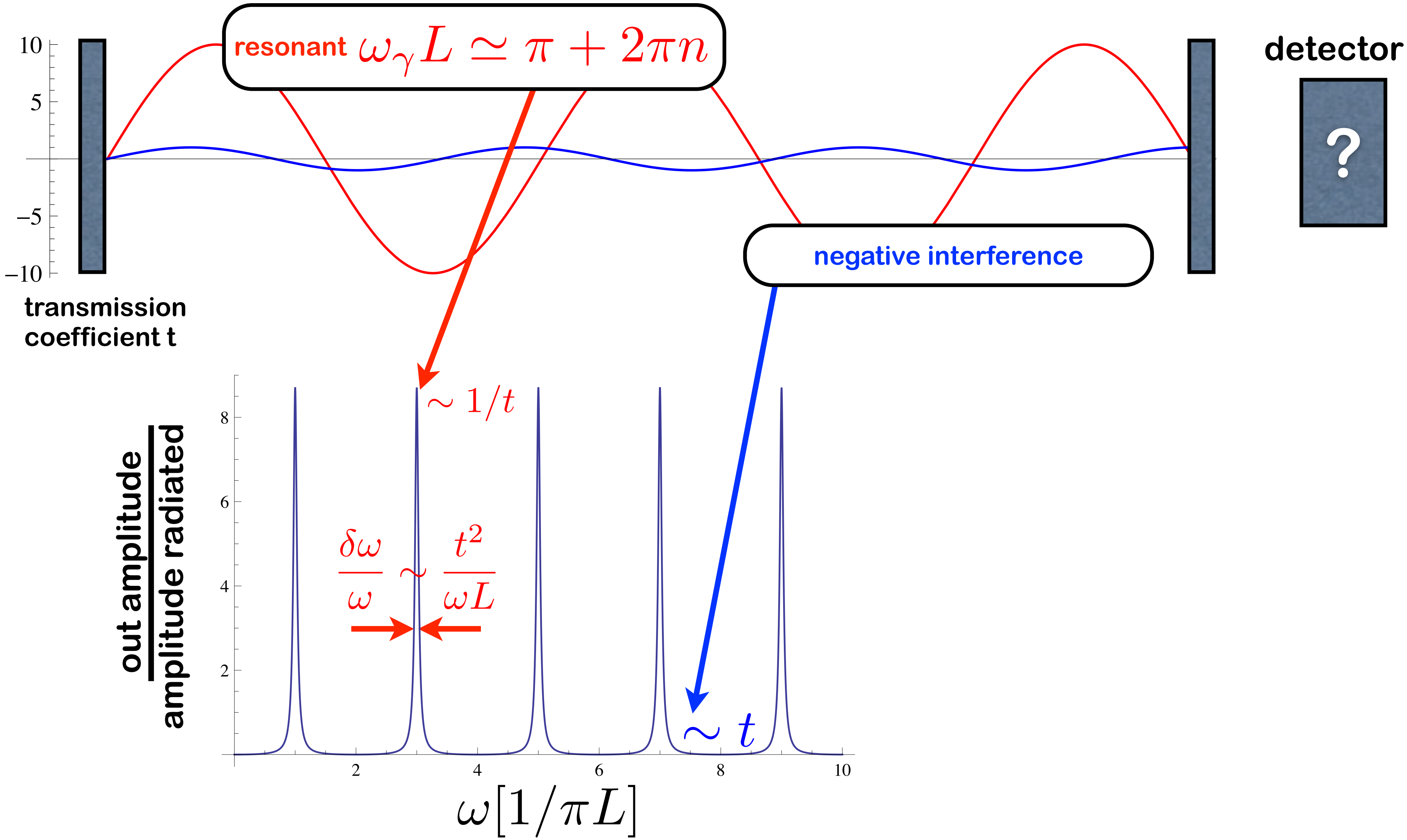

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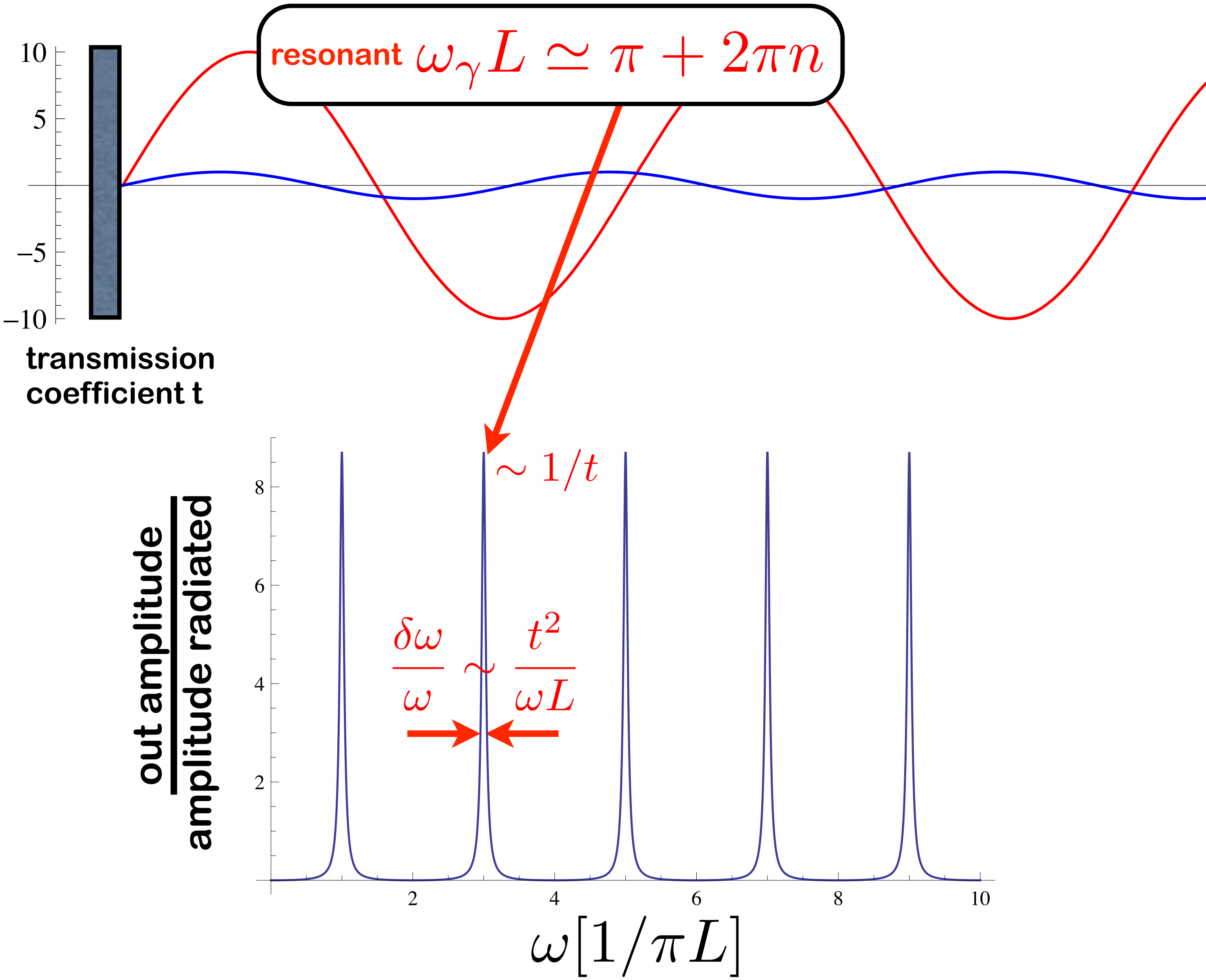
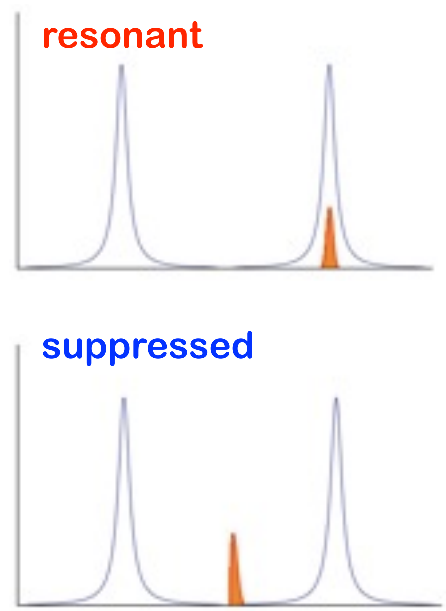




Cavity searches (haloscopes)

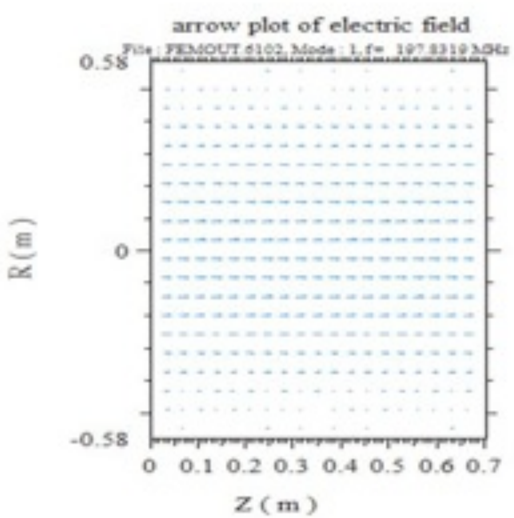
- **Power Loss (cavity tuned!!); putting an pickup we can ideally extract the same**

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

$$P_{\rm out} \sim 10^{-21}\frac{\rm W}{\rm m^2}\left(\frac{\rm B}{10\,T}\frac{c_\gamma}{2}\right)^2$$

- **Usual 3-D formula is**

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



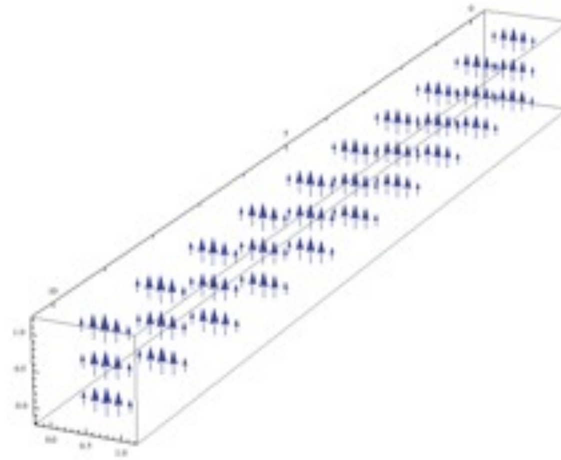
Q **quality factor**

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

κ **coupling**

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
  - broadband/miniclusters!
  - good for ALPs, hidden photons!
  - boost with dielectric layers!

- New understanding of the old experiments

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
    - CASPER

- Europe getting involved
    - CASPER, Budker@Mainz
    - DESY, CERN, Unizar

- International AXion Observatory

 main goal:
  solar axions
  but also DM