Particle dark matter candidates and the axion case

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LPSC, Grenoble

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IN2P3

Dark Matter Neutrino Portal

Asmaa Abada

(see also this morning talk)

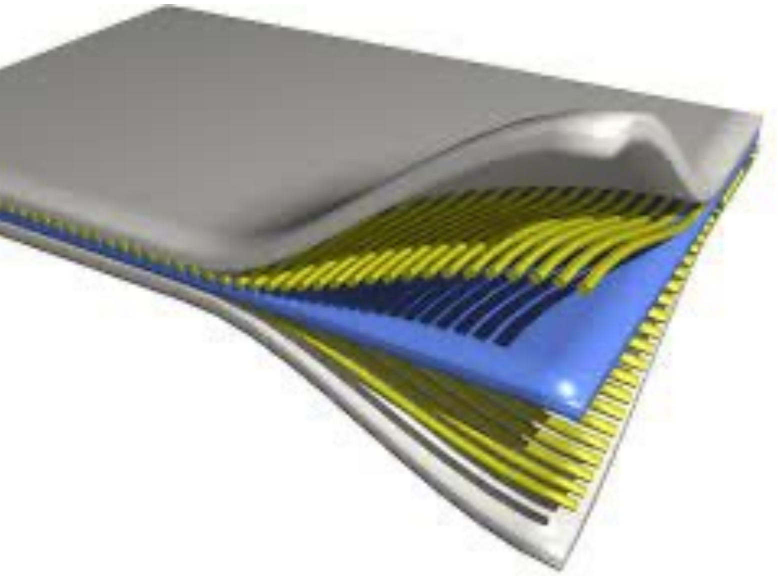
Perspectives:

Sterile neutrinos can be suitable dark matter candidates. The **freeze-in** mechanism with KeV mass dark matter candidate is **to be revisited** by taking into account **flavour effects**.

arXiv:1406.6556,
arXiv:1709.00415,
arXiv:2103.03253,
arXiv:1609.07647

Compositeness from colliders to space

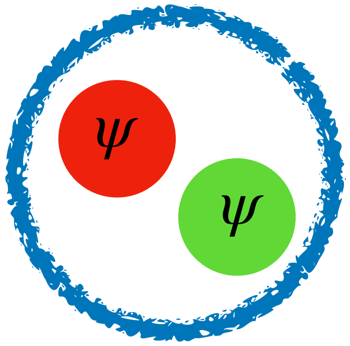
G.Cacciapaglia, A.Deandrea, B.Fuks
(see also this morning talk)



Particles have substructures: more fundamental degrees of freedom glued together by new strong interactions

This can be applied to:

- The Higgs boson and the electroweak scale
- Dark Matter
- An axion-like particle
- Inflation, …



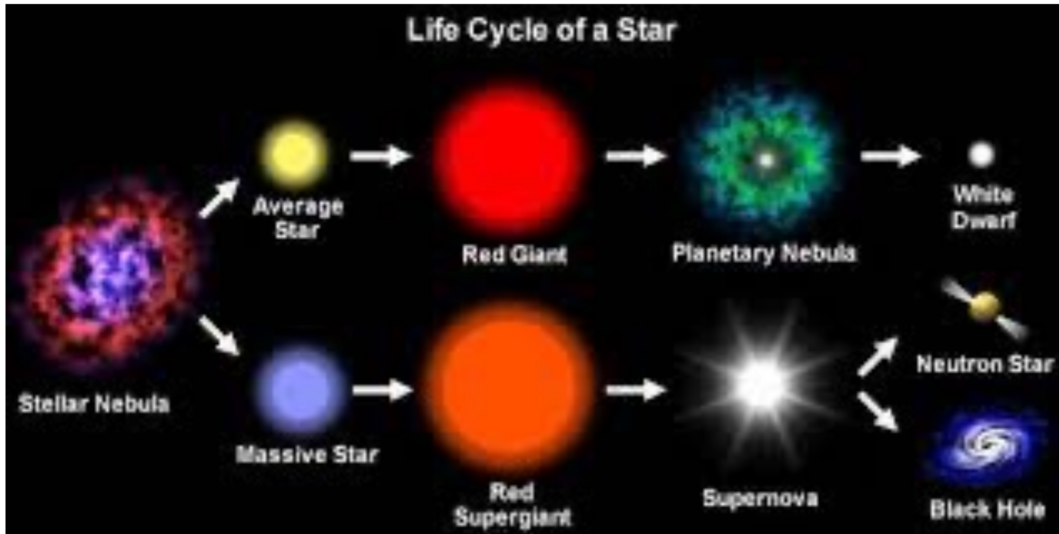
(mesonic state)

Compositeness from colliders to space

G.Cacciapaglia, A.Deandrea, B.Fuks

Perspectives :

- Early universe phase transitions generate gravitational waves (LISA, Einstein tel., …)
- Leptogenesis and Dark-matter-genesis can be studies in suitable UV completions
- Non-standard cosmological phases (symmetry non-restoration, phase transitions)
- Light states (ALPs) relevant for star evolution models (ex. XENON1T anomaly)



Axion Dark Matter

Projet IN2P3:

Axions : from particle physics to cosmology
S. Davidson, K. Martineau, J. Q, C. Smith

The strong CP puzzle in particle physics

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q \underset{\text{CPV}}{e^{i\theta_{EW}}})q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta_{QCD}\frac{\alpha_s}{8\pi}\underset{\text{CPV}}{G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}}$$

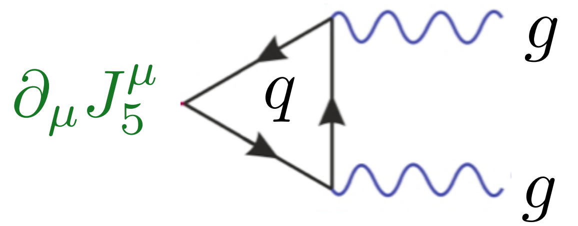
→ 4-component Dirac field

$U(1)_A$ chiral transformation: $q \to e^{i\gamma^5\theta_{EW}} q$

anomalous symmetry

(so not a symmetry!)

$J_5^\mu = \bar{q}\gamma_5\gamma_\mu q$



the measure of the path integral is not invariant under this transformation

axial anomaly shifts quark mass phase to QCD vacuum

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q)q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - (\overbrace{\theta_{QCD} - \underset{\neq 0}{\theta_{EW}}}^{\bar{\theta}})\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

Yukawa coupling to the Higgs are complex $\theta_{CKM} \neq 0$ from K and B physics

Why is this strong CP-violation term so puzzling? $\mathcal{L}_{\cancel{CP}} = \bar{\theta}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$

this induces a huge electric dipole moment for the neutron:

Theory: $|d_n| \sim |\bar{\theta}| 10^{-16} e.cm$ vs Experiment: $|d_n| \lesssim 10^{-26} e.cm$

→ $\bar{\theta} < 10^{-10}$

The strong CP problem
=Why is $\bar{\theta}$ so small?

The strong CP problem is really why the combination of QCD and EW parameters make up should be so small...

The Peccei-Quinn axion solution

axial anomaly: $\theta_{EW}^{CPV} \longleftrightarrow \theta_{QCD}^{CPV}$

Solution to the strong CP problem of QCD: add fields such that rotate $\bar{\theta}$ to the phase of a complex SM-singlet scalar who gets a VEV and dynamicaly drives $\bar{\theta} \to 0$ Peccei & Quinn

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q e^{i\theta_{EW}})q - \frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a - \theta_{QCD}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{\mu\nu}^a$$

1. Introduce a new global anomalous axial $U(1)_{PQ}$ symmetry S.B. at high scale
   ⟶ the low-energy theory has a **Goldstone boson** (the **axion** field)

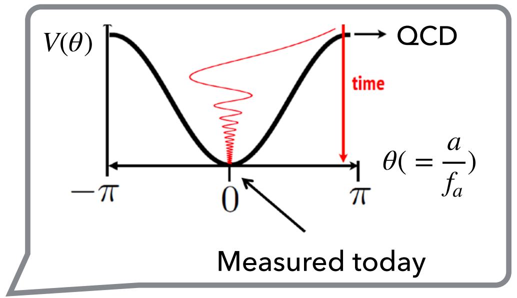
cf. global vector $U(1)_{\mathcal{B},\mathcal{L}}$

2. Design $\mathcal{L}_{axion}$ such that $Q(q_L) \neq Q(q_R) \longrightarrow$ this makes the $U(1)_{PQ}$ **anomalous** :

   $\partial_\mu J^\mu \sim G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}$

   net effect: $\mathcal{L}_{axion} = \mathcal{L}_{QCD} + \frac{a}{v}G_{\mu\nu}\tilde{G}^{\mu\nu} + \dots$

3. Non-perturbative QCD effects induce:



$$\mathcal{L}_{axion} = \mathcal{L}_{ChPT}(\partial_\mu a, \pi, \eta, \eta', \dots) + V_{eff}(\bar{\theta} + \frac{a}{v}, \pi, \eta, \dots)$$

$$\sim -\Lambda_{QCD}^4 cos(\bar{\theta} + \frac{a}{v})$$

minimum of the potential: $\bar{\theta} + \frac{<a>}{v} = 0$

new energy scale!

CP-violating term cancels!

CP symmetry is dynamically restored!

A shift of paradigm

- **Supersymmetry** : -enlarges Poincaré algebra (new energy scale)
  -needs many new particles
  -can preserve SM gauge group

- **'Peccei-Quinn' theory :** -enforces CP-symmetry
  -needs a new global 'no symmetry'
  (anomalous+spontaneously broken)
  (new energy scale)
  -entangled with SM gauge group :
  (careful!)

$$[SU(3)_c \otimes SU(2)_L \otimes U(1)_{Y}]_{local} \times [U(1)_{\mathcal{B}},_{\mathcal{L}},_{PQ}]_{global}$$

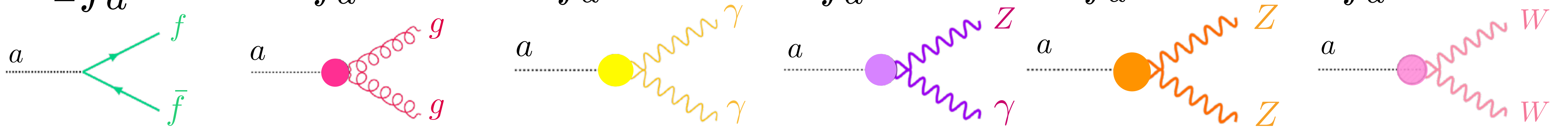
the axion: Goldstone bosons combination $\perp Z_L$

Axion couplings

Energy

At energies below f_a (SSB):

$$\mathcal{L}_{axion} \supset \frac{\partial_\mu a}{2 f_a} j_a^\mu + \# \frac{a}{f_a} G\tilde{G} + \# \frac{a}{f_a} F\tilde{F} + \# \frac{a}{f_a} Z\tilde{F} + \# \frac{a}{f_a} Z\tilde{Z} + \# \frac{a}{f_a} W\tilde{W}$$



electroweak couplings recently computed
do not follow the expected pattern
(J.Q. and C. Smith, arXiv:1903.12559)
It needs to be phenomenologically explored (baryogenesis, ...)

At energies below $\Lambda_{QCD} : a - \eta' - \pi^0 - \eta - \ldots$ mixing

axion mass: $m_a = m_\pi \frac{f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \sim \frac{\Lambda_{QCD}^2}{f_a}$

axion couplings to electrons, nucleons, mesons, photons, ...

(EDMs)

mostly explored:

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\boxed{\frac{E}{N}} - \boxed{1.92}\right)$$

model dep.

model indep. below confinement

Symmetry breaking in cosmology

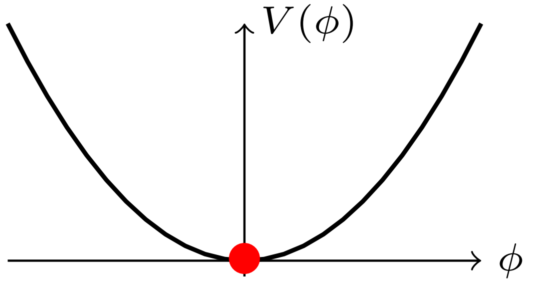
Temperature

$\delta\phi \sim T$

$$V_{\rm PQ}(\phi) = \frac{\lambda}{4}(|\phi|^2 - f_a^2)^2$$

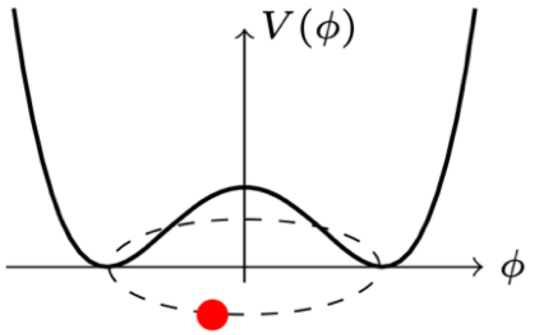
$T > f_a$

T determines the PQ vev:
$< \phi >= 0$

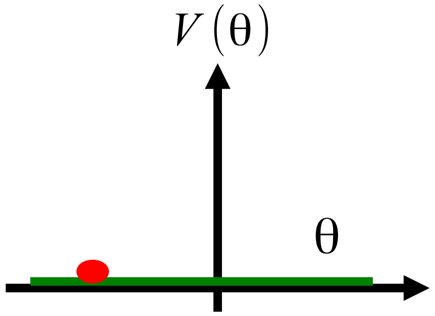


$T \sim f_a$

PQ symmetry is spontaneously broken:
$< \phi >= f_a e^{i\frac{a(x)}{f_a}}$



The axion is born:
Relic of symmetry breaking



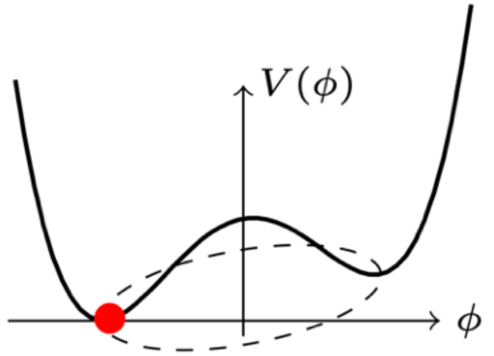
$\theta = \frac{a}{f_a} \in [-\pi, \pi]$

$T \sim \Lambda_{QCD}$

PQ symmetry is explicitly broken

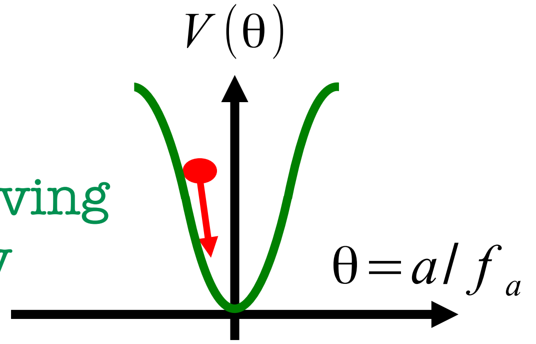
$$m_a^2(T) \begin{cases} \propto T^{-n} & T \gtrsim 100 \text{ MeV} \\ = m_a(T=0) & T \lesssim 100 \text{ MeV} \end{cases}$$

Instanton effects
[lattice QCD]



$$+V_{QCD}^{\text{Non-Pert.}} = f_a^2 m_a^2(T)(1 - cos(N_{DW}\theta))$$

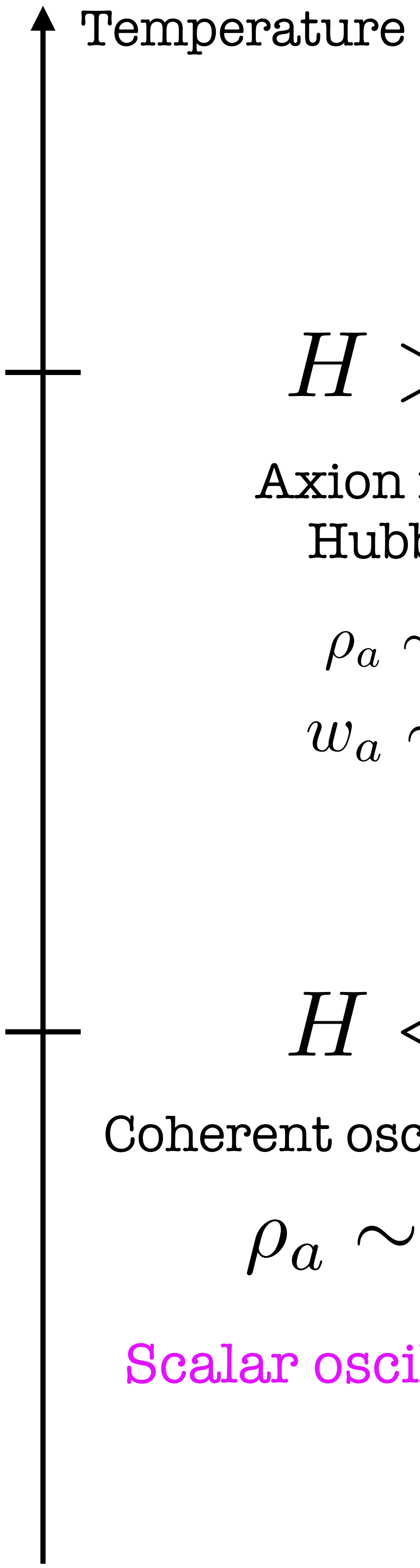
CP-concerving theory



model dependent:
KSVZ: $N_{\rm DW} = 1$
DFSZ: $N_{\rm DW} = 6$

Crucial role played by inflation...

Dark matter from vacuum realignment



Equation of motion:
(Klein-Gordon)

$$\ddot{\phi} + 3\boxed{H}\dot{\phi} + \boxed{m_a(T)}^2\phi = 0$$

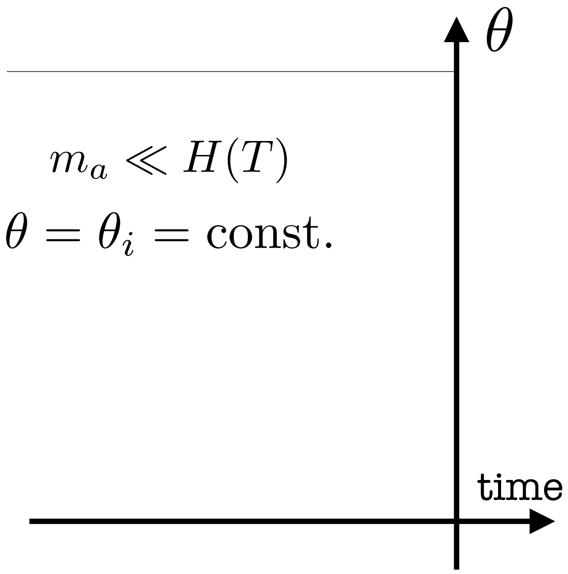
$$V(\phi) = \frac{m_a^2}{2}\phi^2$$

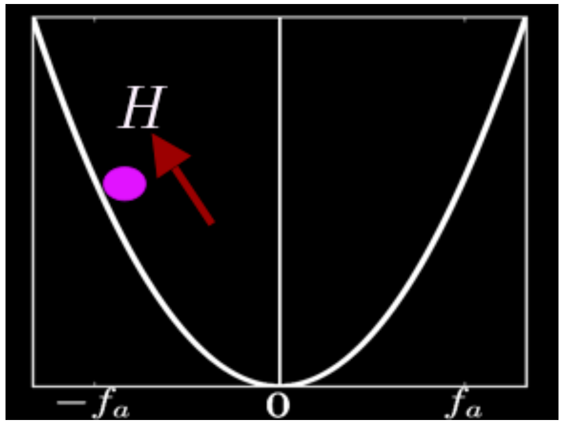
$$H \gg m_a$$

Axion is ‘frozen’ by Hubble friction

$$\rho_a \sim \text{const}$$

$$w_a \sim -1$$



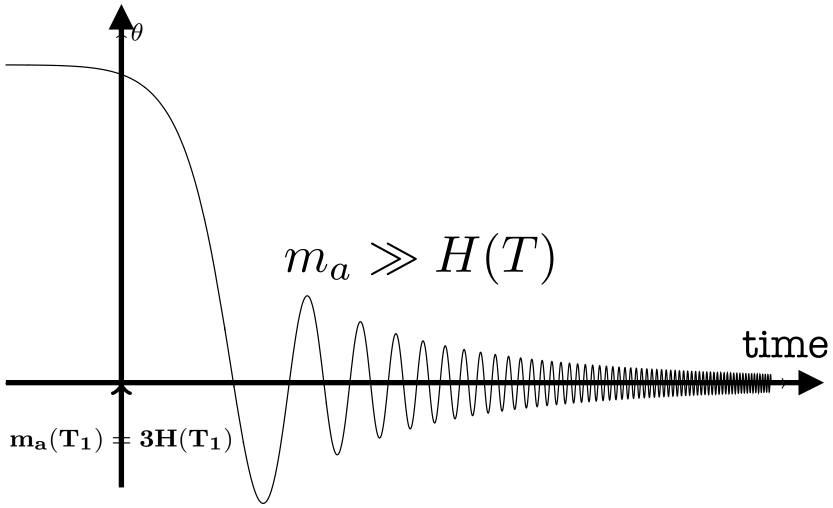


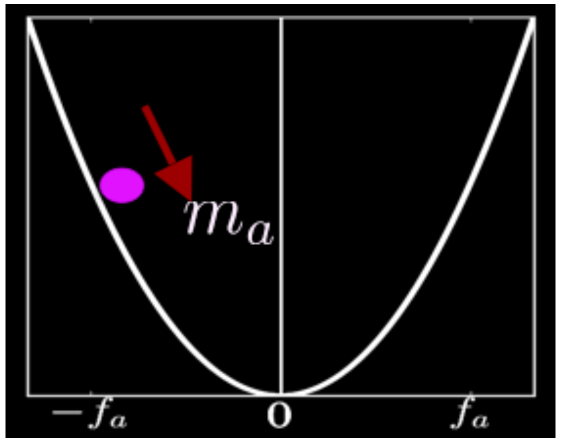
$$H \ll m_a$$

Coherent oscillations of axion field

$$\rho_a \sim \rho_a(\boxed{a_{\text{osc}}})a^{-3}$$

Scalar oscillations behave as matter





- Zero momentum condensate (Classical field oscillations)
- Cold Dark Matter!
- Axions are born as non relativistic, classical field oscillations

$$\boxed{\Omega_a h^2 \approx 0.195\left(\frac{f_a}{10^{12}\,\text{GeV}}\right)^{1.184}\boxed{\theta^2_{\text{ini}}}}$$

← 2 scenarios

Other axion production in non-standard cosmological histories to explore

Initial conditions and inflation

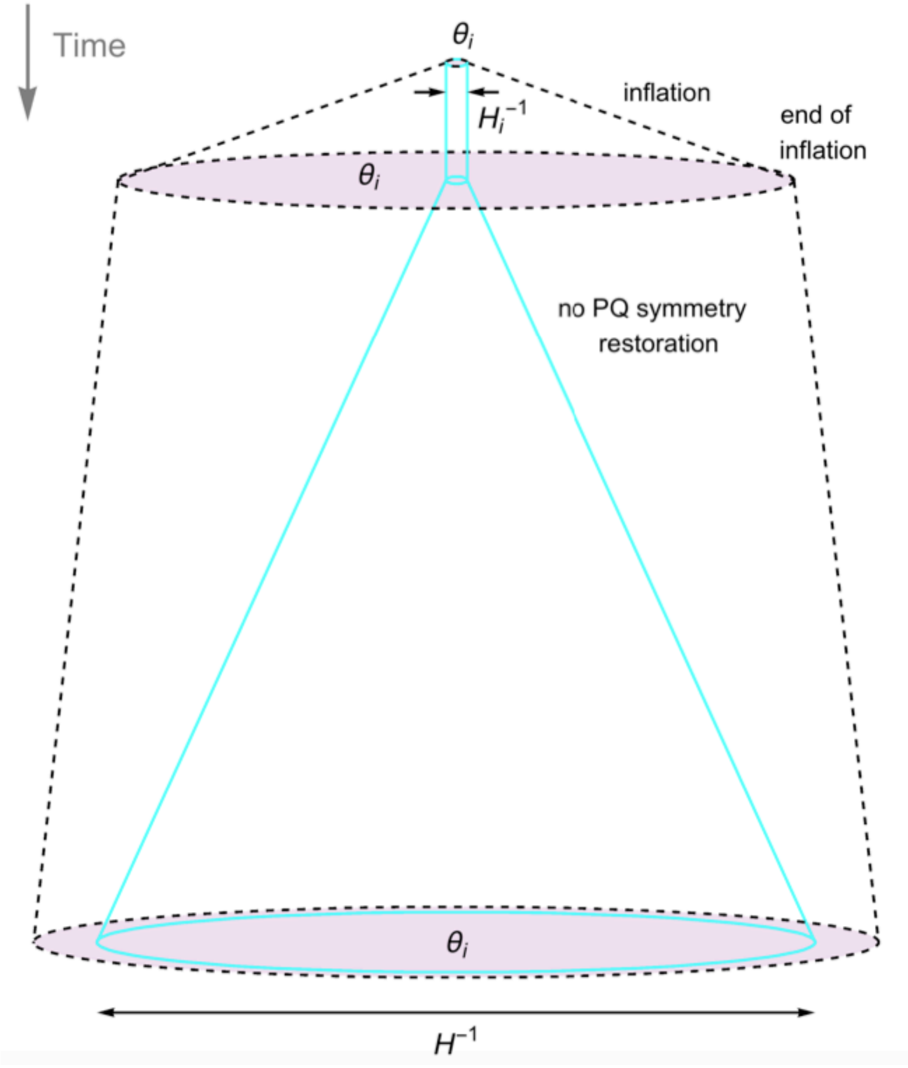
Crucial question: did SSB occur before or after inflation?

$$\Omega_a h^2 \approx 0.195 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.184} \theta_{\mathrm{ini}}^2$$

← 2 scenarios

SSB before inflation

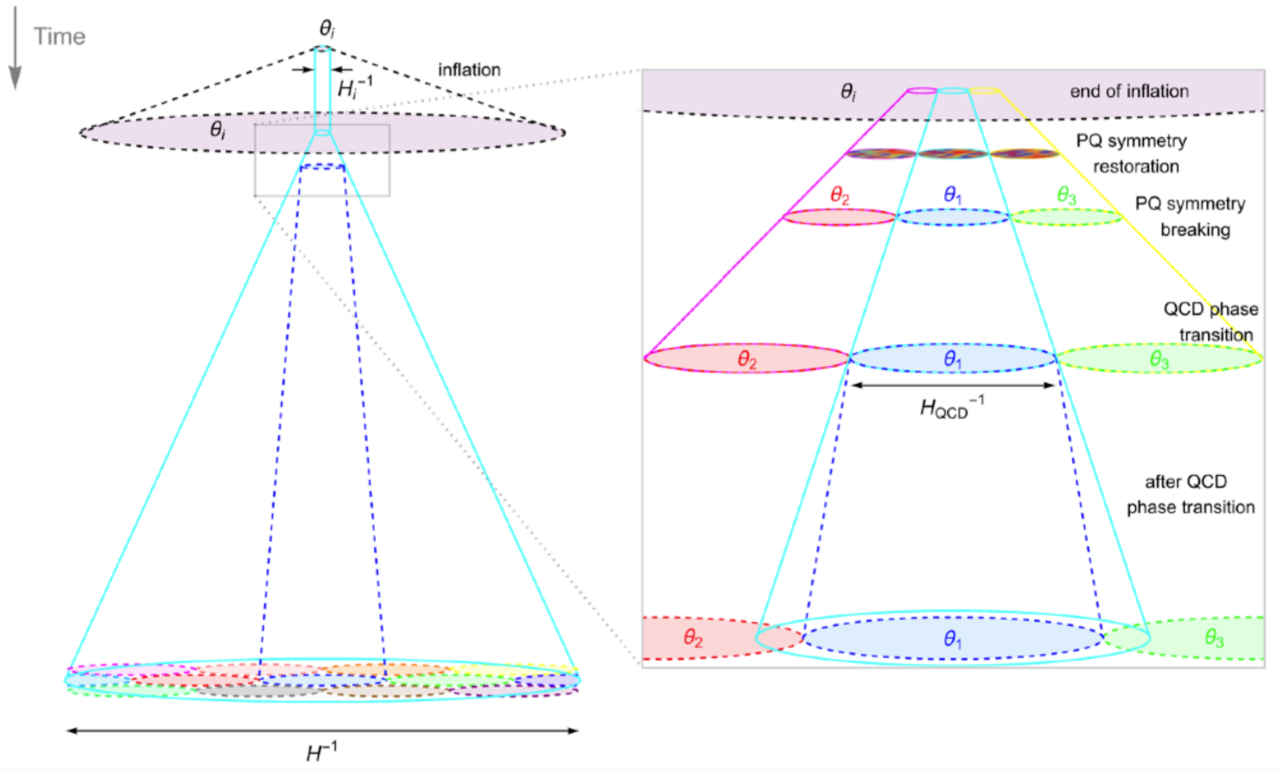
$f_a \gtrsim 10^{13}\mathrm{GeV}$



- isocurvature fluctuation from large quantum fluctuations (strong CMB bounds)

SSB after inflation

May occur for low f_a



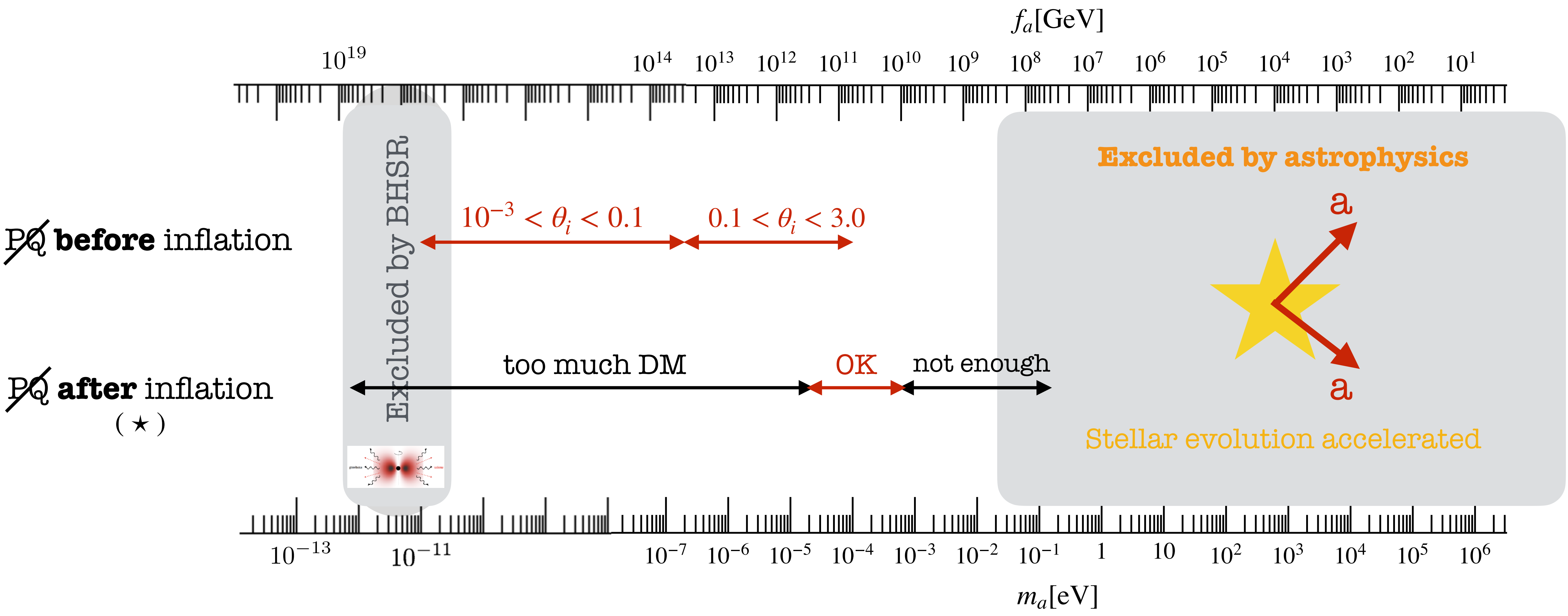
- Many different $-\pi \le \theta_{ini} \le \pi$ in the visible universe, average field value fixed: $\langle \theta_{\mathrm{ini}}^2 \rangle = \frac{1}{2\pi}\int_{-\pi}^{\pi} \theta^2 d\theta = \frac{\pi^2}{3}$

$\longrightarrow$ Ω_a independent of initial conditions

DM relic density, narrow mass window: $\Omega_c h^2 = 0.12 \rightarrow$ $50 \lesssim \frac{m_a}{\mu\mathrm{eV}} \lesssim 200$

Landscape

Axions should be very light and feebly interacting



~~PQ~~ **before** inflation

$10^{-3} < \theta_i < 0.1$

$0.1 < \theta_i < 3.0$

~~PQ~~ **after** inflation
(⋆)

too much DM

OK

not enough

(⋆) for $N_{DW} > 1$, predictions spoiled by topological defects

Axion DM constraints from **laboratory** experiments, from **stars** and **cosmos** observations

Detecting axion dark matter

- Local DM density: $\rho_{\rm CDM} \simeq 0.3 \dfrac{\rm GeV}{\rm cm^3} = m_a n_a$ occupation number is huge

QFT has two classical limits:

limit of point particles (WIMPs, ...)

$\hbar \to 0 \qquad \omega, \vec{k} \to \infty$

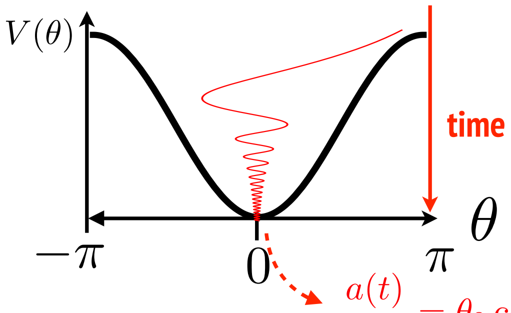
$E = \hbar\omega$ and $\vec{p} = \hbar\vec{k}$ fixed

limit of classical fields (axions)

$\hbar \to 0 \qquad N \to \infty$

$E = N\hbar\omega$ and $\vec{p} = N\hbar\vec{k}$ fixed

axion behaves as a classical coherent (NR) field:

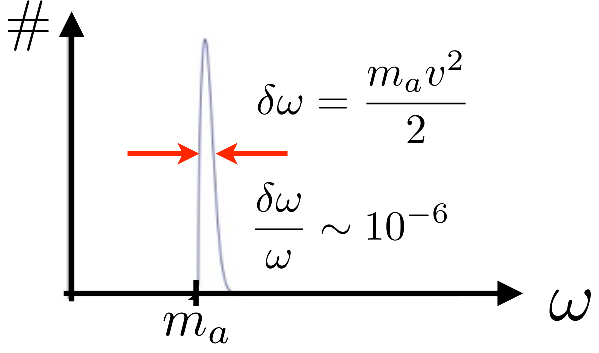


$$\frac{a(t)}{f_a} = \theta_0 \cos(m_a t)$$

$$\longrightarrow \quad \rho_{\rm CDM} = \frac{1}{2}\dot{a}^2 + \frac{1}{2}m_a^2 a^2 \simeq \frac{1}{2} m_a^2 f_a^2 \theta_0^2 \xrightarrow[\text{axion}]{\text{QCD}} \theta_0 \sim O(10^{-19})$$

- DM halo bounds to our galaxy: $v_a^{\oplus} = v_g \sim 10^{-3} c$

velocity of DM in the galaxy $\Rightarrow$ the axion spectrum is not monochromatic



$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

$$\omega \simeq m_a(1 + \underbrace{v^2/2}_{\sim 10^{-6}} + \ldots)$$

coherence time : $\delta t \sim \dfrac{1}{\delta\omega} \sim 0.13 {\rm ms} \left(\dfrac{10^{-5}{\rm eV}}{m_a}\right)$

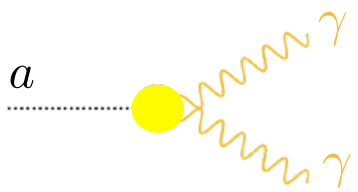
coherence length : $\delta L \sim 20 {\rm m} \left(\dfrac{10^{-5}{\rm eV}}{m_a}\right)$

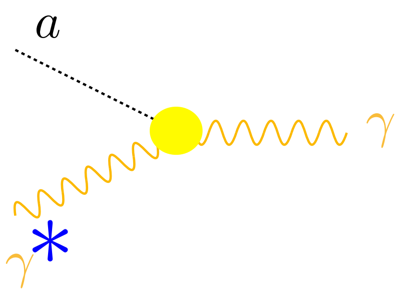
Fundamental detection strategy: macroscopic coherence leads to coherent enhancement

Axion conversion to photon

$$\mathcal{L}_{axion} \supset \# \frac{a}{f_a} F\tilde{F} \longleftrightarrow \# \frac{a}{f_a} \vec{E}.\vec{B}$$

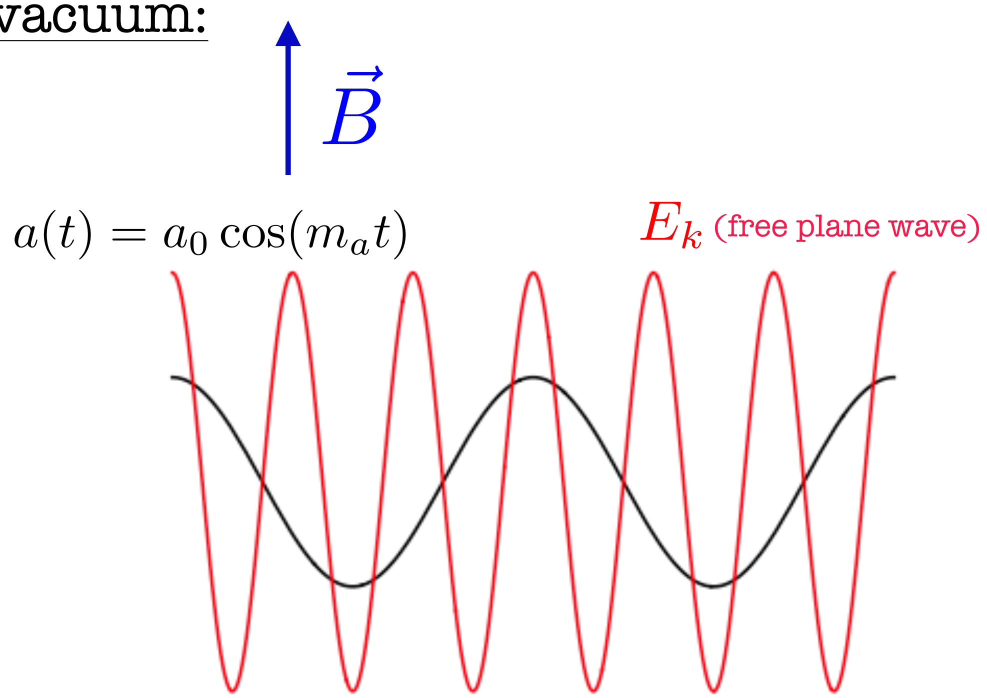
in an external B-field
the axion sources an E-field





Matrix element given by the **overlap** of the **axion** and **virtual photon** wave functions

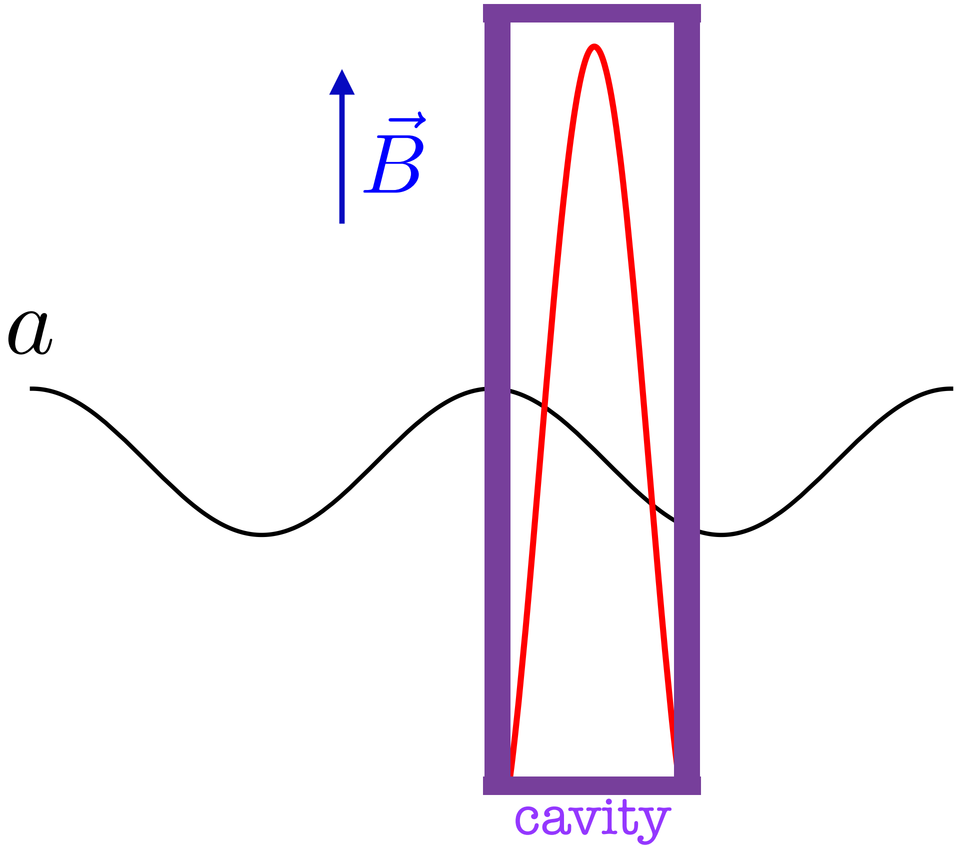
In vacuum:



Oscillatory integral vanishes (moment conservation)
⟶ **no** axion-photon conversion

One needs to modify the free wave function

Inside a cavity: E_k becomes the cavity modes

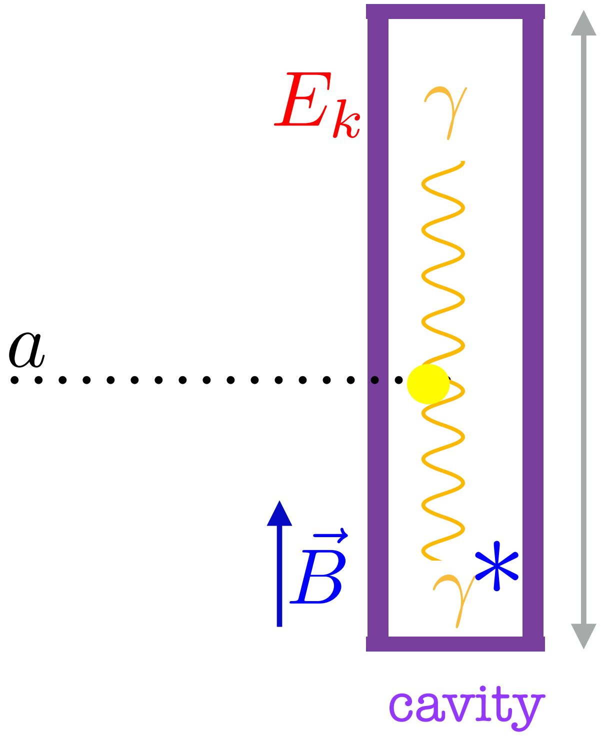


⟶ axion-photon conversion is allowed

Axion haloscope

Amplify resonantly the EM field in a resonant cavity

(forced oscillator)



$\lambda/2 = 0.62$ cm $(100\,\mu\mathrm{eV}/m_a)$

Power extracted from a cavity: $P_{signal} \propto g_{a\gamma}^2 B^2 QV$ to amplify

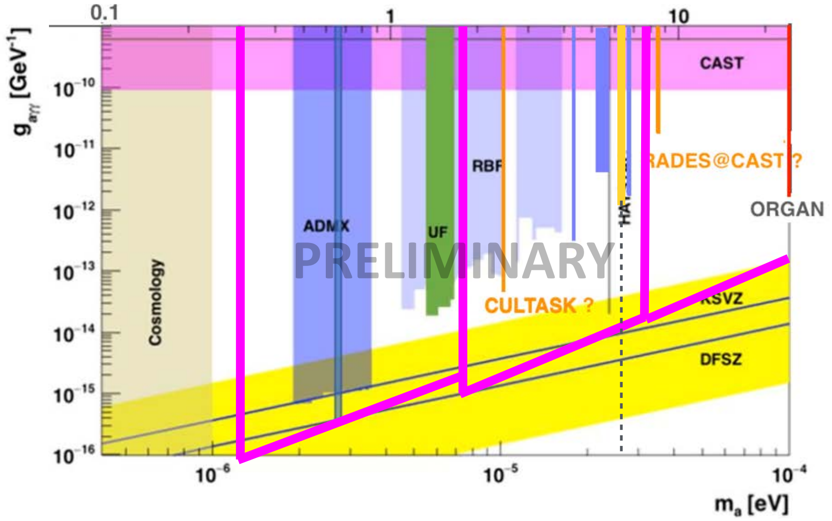
$P_{noise} \propto T_{sys}\delta\omega$

GrAHal : a European haloscope project

Grenoble Axion Haloscopes

1. Hybride Magnet 43 T (34 mm), 40 T (50 mm), 27 T (170mm), 9 T (800 mm) **LNCMI**
2. $T_{sys} \sim 20\mathrm{mK}$ **Institut Néel**
3. quantum amplifiers SQUID &JPA **Institut Néel**

$$g_{a\gamma\gamma}^{\text{1st point}} = 25 \times g_{a\gamma\gamma}^{\text{KSVZ}}$$
$$m_a = 23\mu\mathrm{eV}$$



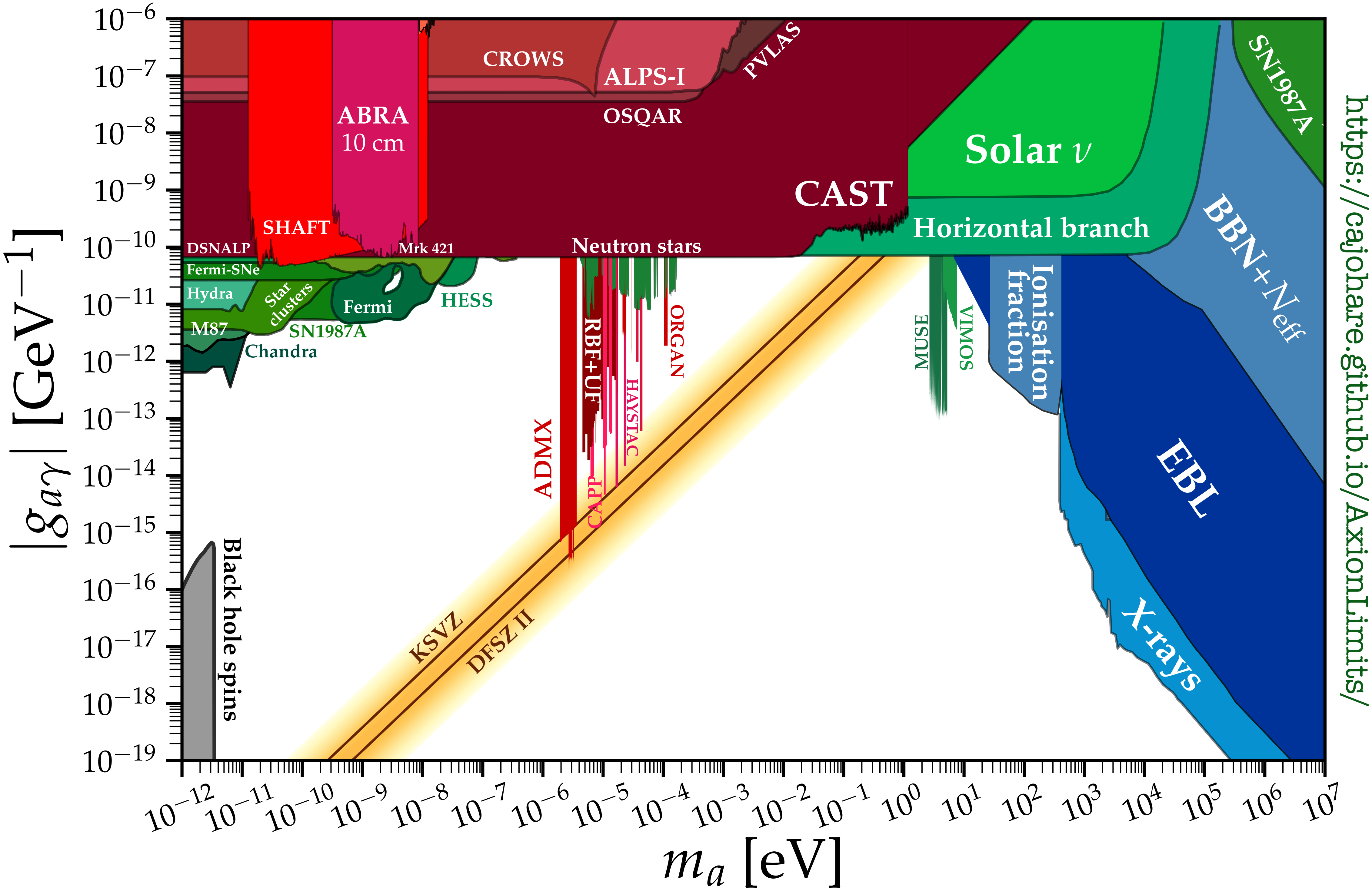
- New interesting idea : **'plasmon haloscope'** : [condensed matter]

  -resonance when the **axion** and **plasma** frequencies match

  -thin wire metamaterials (~cm spacing ⇒ ~ GHz plasma frequency)

  -tuneable with wire spacing ⇒ haloscopes not anymore V limited?

Axion limits



From theoretical topological defects to cosmological astrophysical objects

Physics left invariant by a $U(1)_{\mathrm{PQ}}$ rotation only if it rotates the QCD angle of $G\tilde{G}$

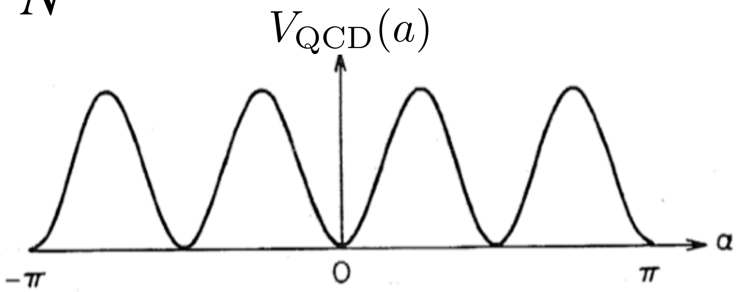
$$\phi \to e^{i\alpha}\phi \qquad \theta_{QCD} \to \theta_{QCD} + \boxed{N}\alpha$$

model dependent

Strong interaction effects break $U(1)_{\mathrm{PQ}}$ but are 2π periodic $\Rightarrow \alpha = \mathbb{Z}\dfrac{2\pi}{N}$ still a good symmetry

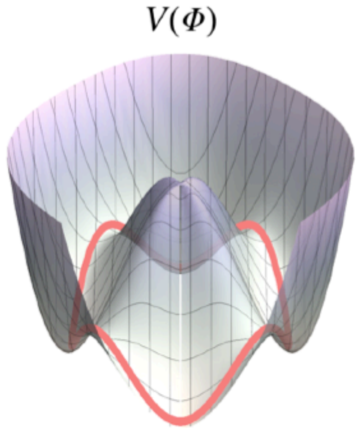
$$\boxed{U(1)_{PQ} \xrightarrow{\text{QCD instantons}} \mathbb{Z}_N}$$

Ex: $N = 4$ axion model
(4 degenerate minima)

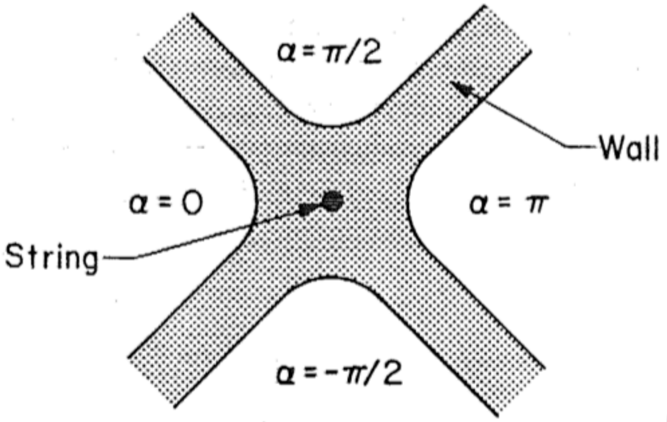


In QFT:

$T << T_{\mathrm{QCD}}$

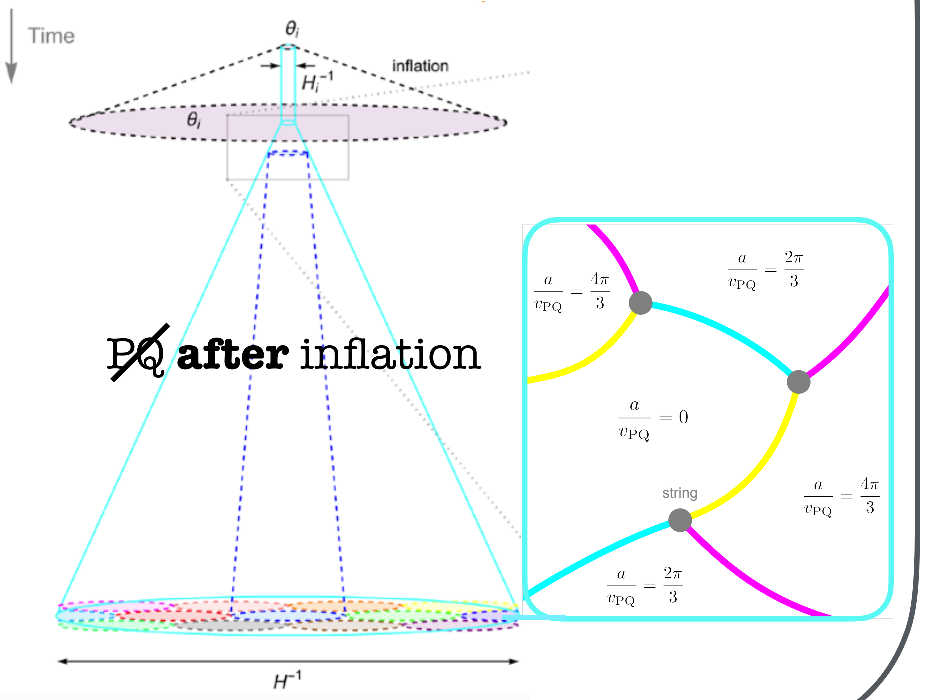


In position space:



$N = 4$ domain walls meet in a string

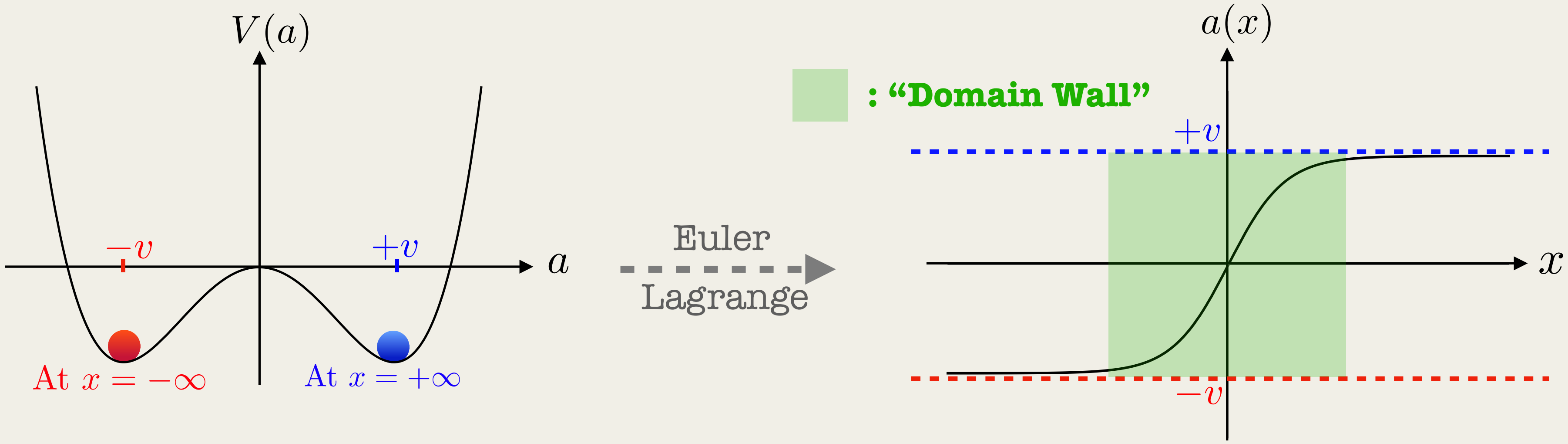
In the early universe:



$\cancel{\text{PQ}}$ **after** inflation

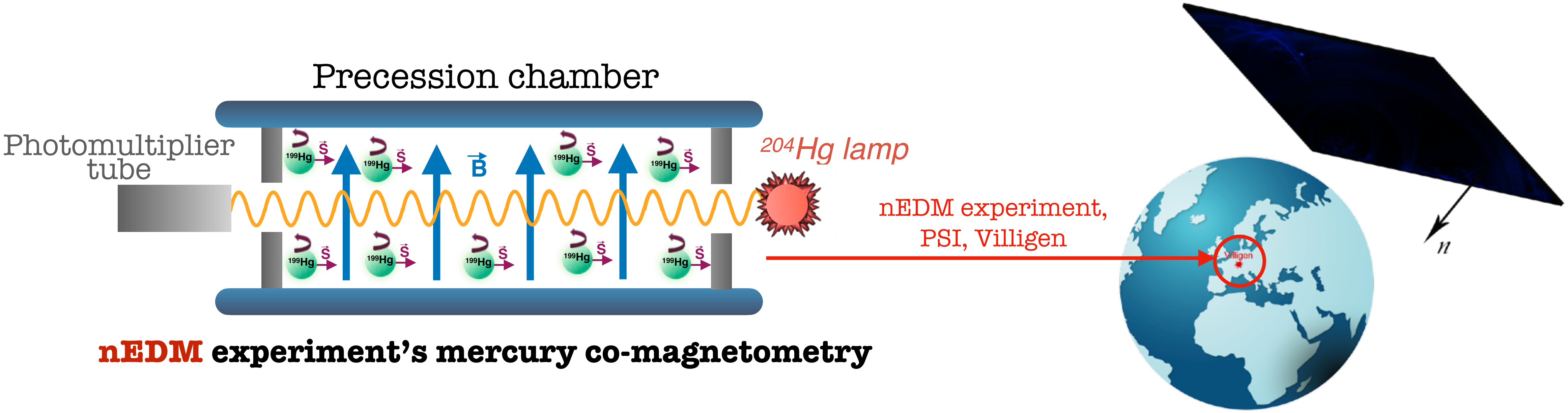
Detecting axion transient with nEDM

Example : $V(a) = -\mu^2 a^2 + \lambda a^4$



$$\mathcal{L}_{\text{int}} = \bar{\psi}\gamma^\mu\gamma^5\psi \times \frac{\partial_\mu a}{f_a} \xrightarrow[\text{limit}]{\text{Non relativistic}} H_{\text{int}} = \sum_{i=e,n,p} 2\vec{s}_i\cdot\left(f_i^{-1}\vec{\nabla} a\right)$$

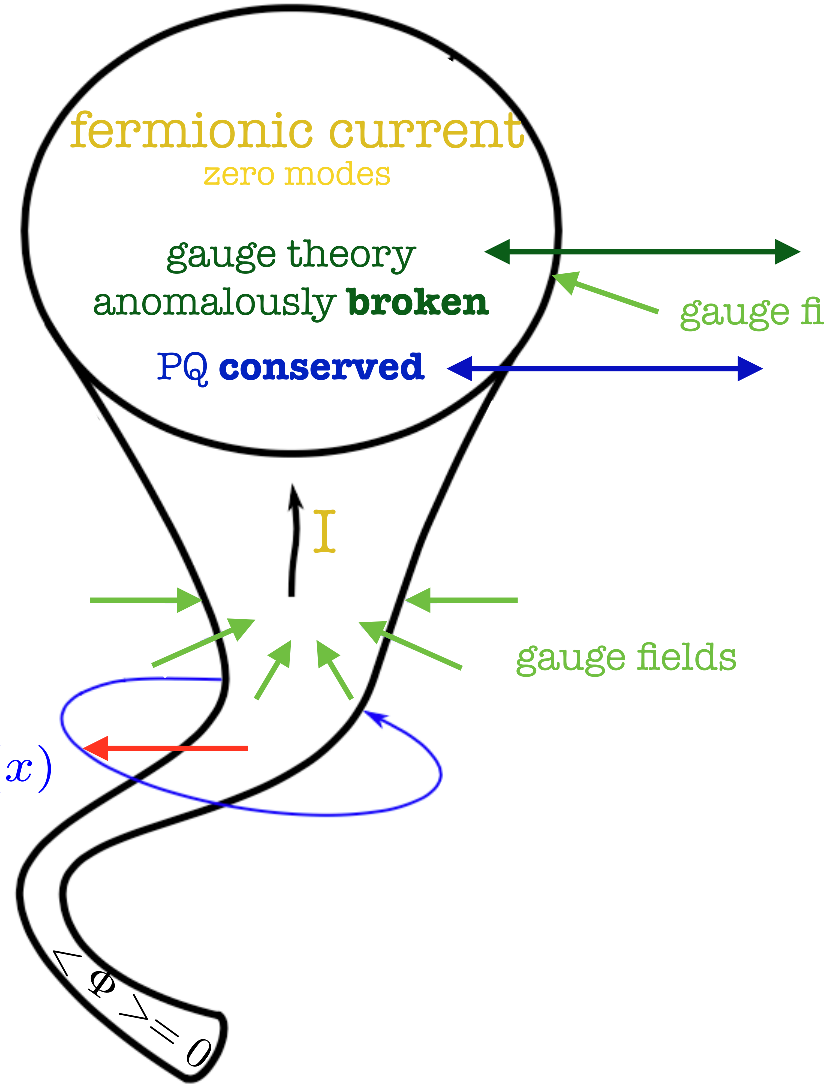
Pseudo-magnetic field



nEDM experiment's mercury co-magnetometry

in collaboration with G. Pignol et K. Martineau (LPSC)

Axion cosmic strings



fermionic current
zero modes

gauge theory
anomalously **broken**

PQ **conserved**

gauge symmetry **conserved**

gauge fields current lead to anomaly cancelations

chiral PQ symmetry anomalously **broken**

gauge fields

PQ complex scalar field: $\Phi(x) = f(r)e^{i\theta(x)}$

$< \Phi >= f_a$

Axion mixes with SM U(1) symmetries

Interesting model building features to explore

Implications for DM, baryon asymmetry, ...,
still to be explored

Axion miniclusters

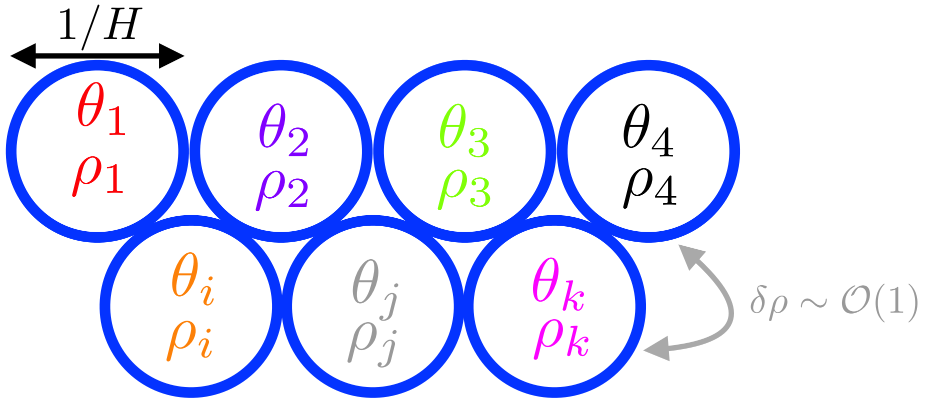
Temperature

...Inflation occurred already

$T \sim f_a$ SSB of PQ

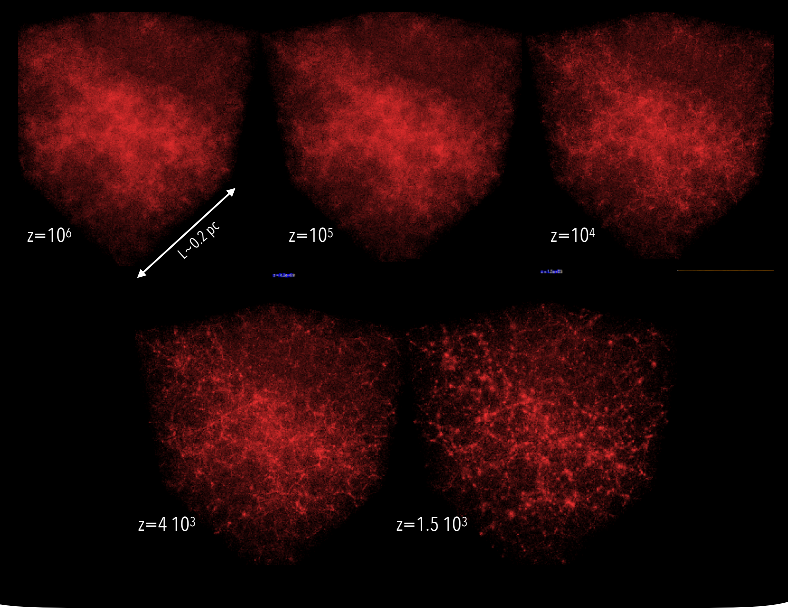
$T \sim \Lambda_{QCD}$ $m_a \neq 0$

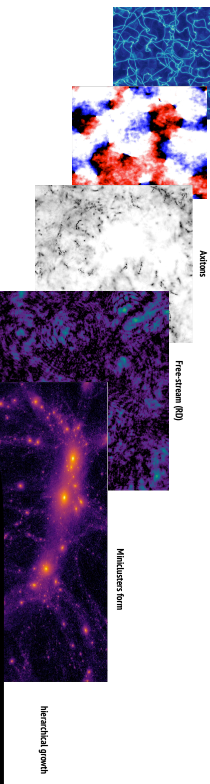
$T_{\rm osc}$ $H(T_{\rm osc}) \sim m_a$:



Axion DM inhomogeneous a ~ pc scales

first structures form at $z > z_{eq}$





- density perturbations grow under gravity as usual
- collapsing into gravitationally bound objects known as **miniclusters**
- total axion mass contained within the horizon at $t_{\rm osc}$ sets the characteristic minicluster mass at $z_{\rm eq}$:

Hogan & Reese (1988)

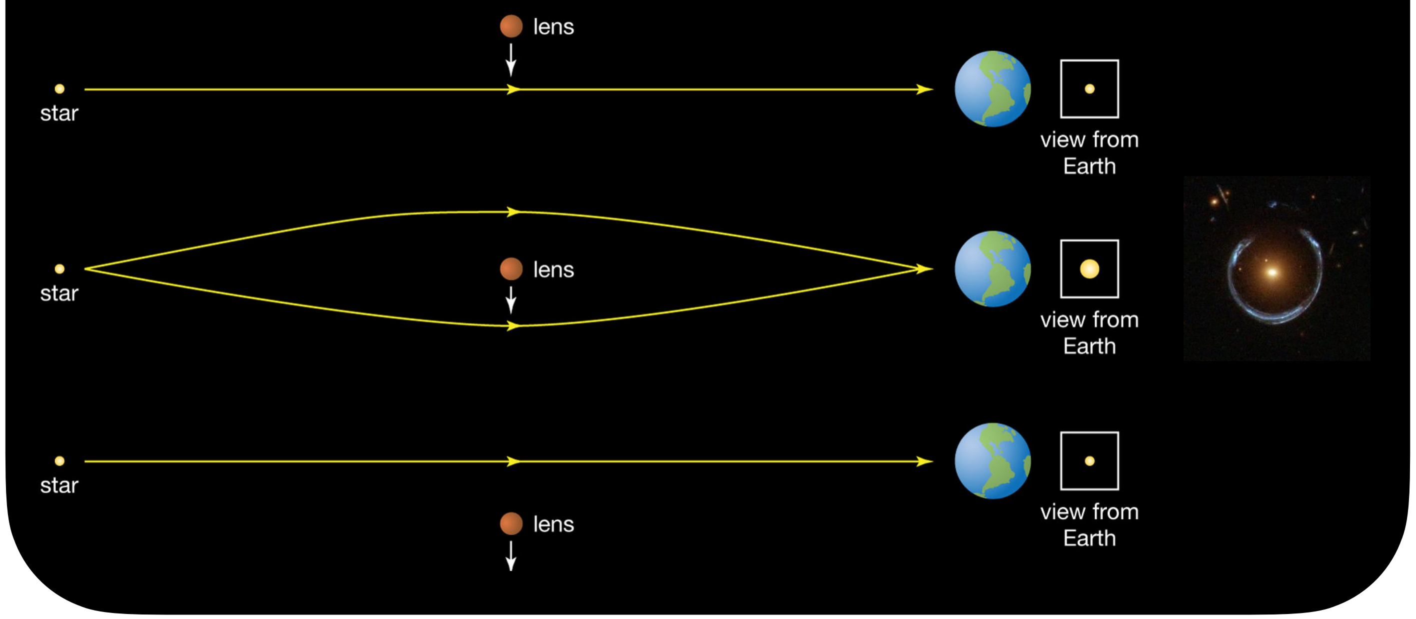
$$M_0 = \overset{\text{today}}{\bar{\rho}_a} \frac{4}{3}\pi \left(\frac{\pi}{a(T_0)H(T_0)} \right)^3 \left\{ \begin{array}{l} M_0 \sim 10^{-12} M_\odot \\ \text{size } \sim 10^7 \text{ km} \\ \sim 10^{25} \text{ in the Galaxy} \\ \text{through the Earth every } \sim 10^5 \text{ years} \end{array} \right.$$

Smaller than smallest WIMP structures ($\sim 10^{-6} M_\odot$)

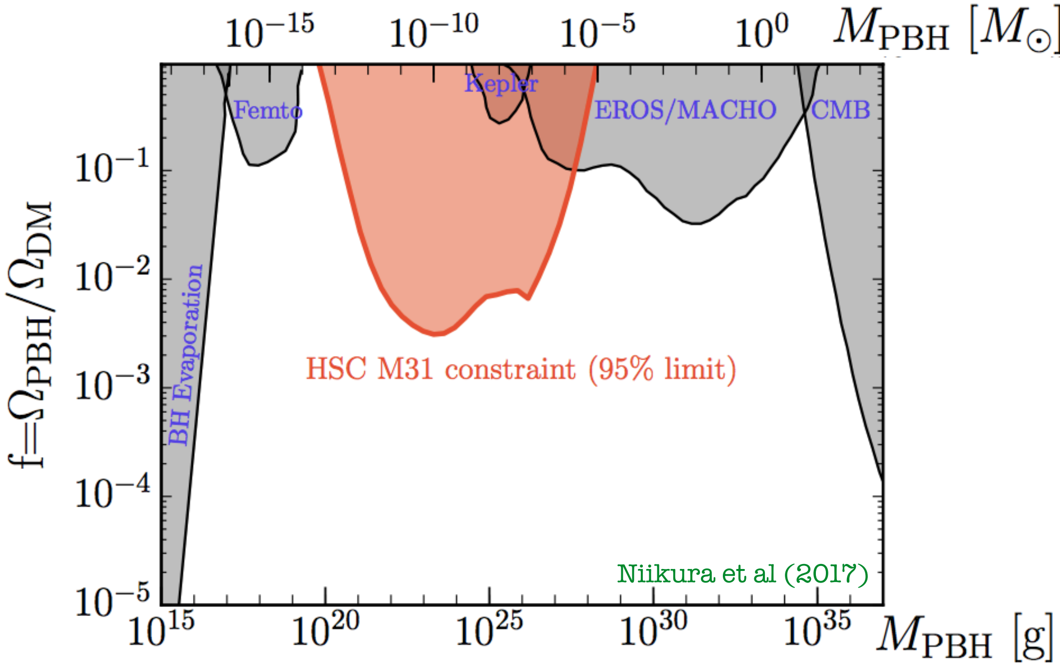
Implications of alternative cosmological scenarios on axion MC, needed

Detecting axion miniclusters with gravitational microlensing

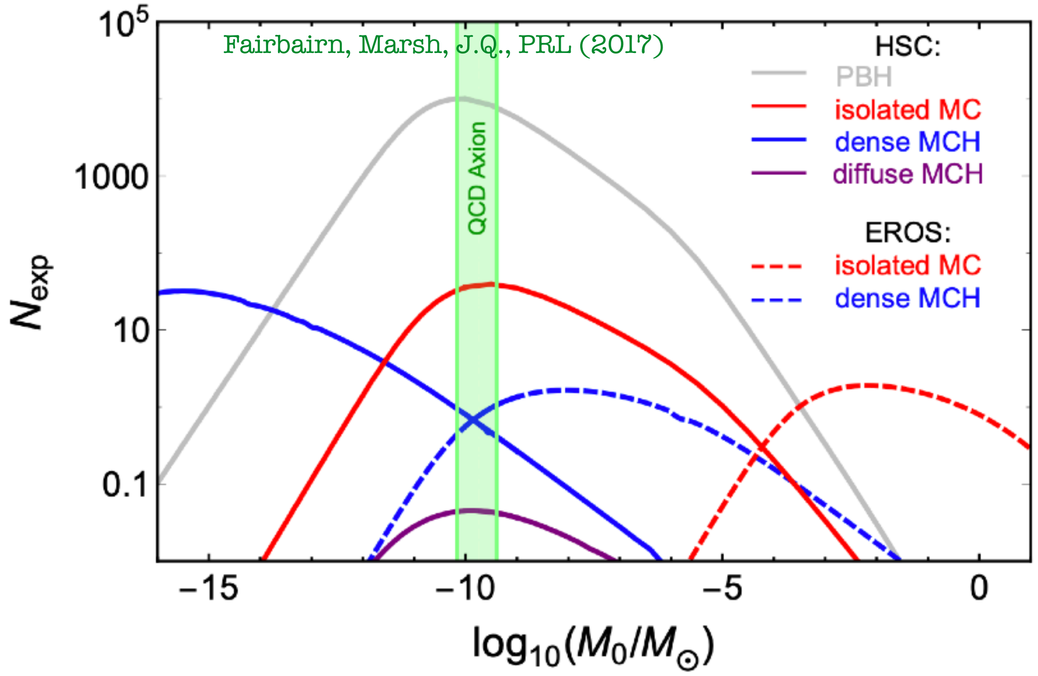
Microlensing: fugitive amplification of a background star which occurs when a compact object passes close to the line of sight to that star.

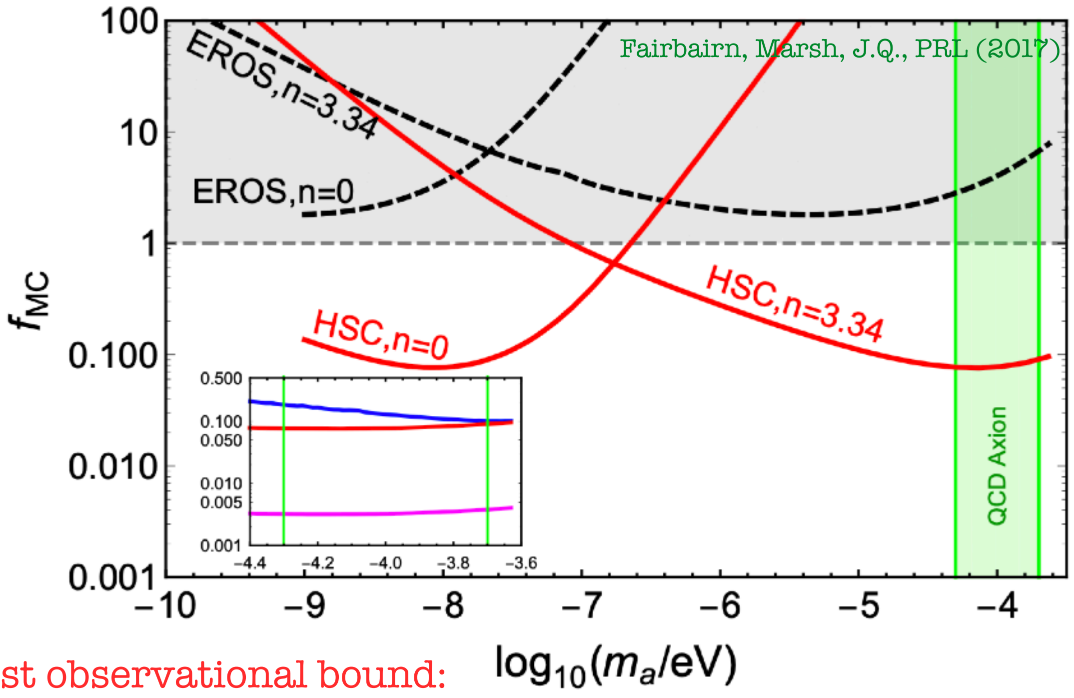


For PBH (point masses), the amount of DM in compact objects is strongly constrained:



Expected microlensing events:



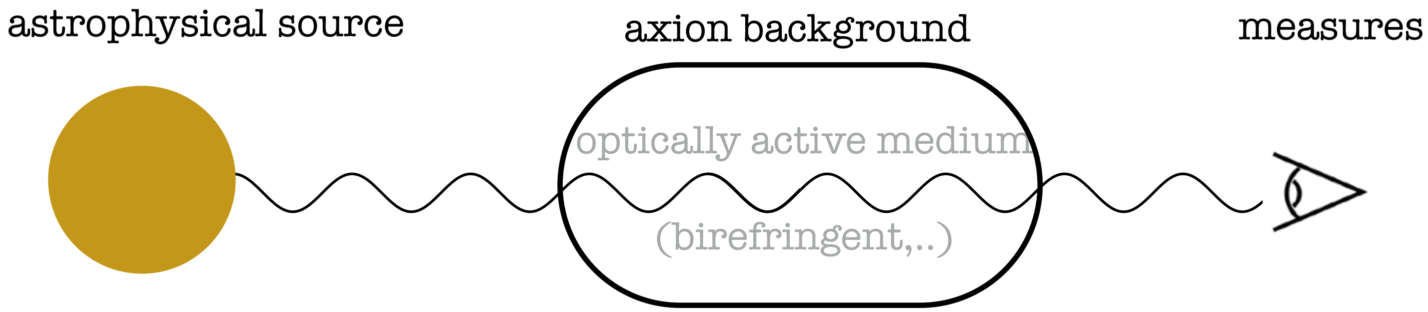


Place the first observational bound:

$$\boxed{f_{\rm MC} < 0.083(m_a/100\,\mu{\rm eV})^{0.12}}$$

Huge and renewed global effort in axion direct detection. If $f_{\rm MC}$ is high, rare MC encounters → axion DM detection is limited.

How do photons propagate through axion background?



axion electrodynamics:

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a\,,$$
$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma\gamma}\dot{a}\mathbf{B} + g_{a\gamma\gamma}\nabla a \times \mathbf{E}\,,$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\dot{\mathbf{B}} + \nabla \times \mathbf{E} = 0\,.$$

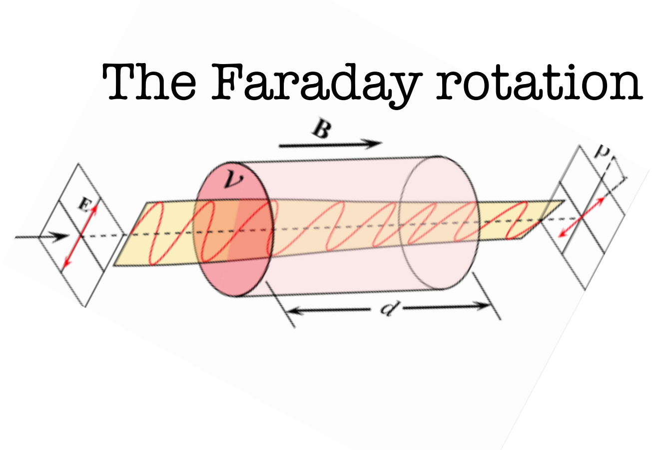
dispersion relation:

$$\omega_\pm \sim k \pm \frac{g_{a\gamma\gamma}}{2}\left(\partial_t a + \frac{\boldsymbol{k}}{k}.\boldsymbol{\nabla} a\right) \mp g_{a\gamma\gamma}\omega_p^2\frac{\partial_t a}{4k^2} + \mathcal{O}(g_{a\gamma\gamma}^2)$$

Apply carefully Hamilton's optic

$$v^\pm_{phase} = \frac{\omega^\pm}{k}$$

The Faraday rotation



axion induces photon **polarisation rotation**:
Harrari-Sikivie (1992)

$$\theta = \frac{1}{2}\int_{t_i}^{t_f}(\omega_+ - \omega_-)dt$$
$$\theta = \frac{1}{2}\int_{t_i}^{t_f} g_{a\gamma\gamma}\left(\partial_t a + \frac{\boldsymbol{k}}{k}.\boldsymbol{\nabla} a\right)dt$$

VLT observations of neutron star

$$v^\pm_{group} = \frac{d\omega^\pm}{dk}$$

Group velocity splitting between L/R polarisations:

$$v_g^+ - v_g^- = \pm\frac{g_{a\gamma\gamma}}{4k_0}\frac{\omega_p^2}{k_0^2}\left[a' - \dot{a}\right]$$

time delay

$$\Delta t_p = \mp\frac{g_{a\gamma\gamma}}{4k_0}\frac{\omega_p^2}{k_0^2}\int_0^{t_f} dt'\left[a' - \dot{a}\right]$$

Constraints from :

-Gamma-ray burst

-radio waves from pulsars & fast radio bursts

No refraction at $\mathcal{O}(g_{a\gamma\gamma})$ in absence of plasma

Blas et al. 'No chiral bending of light by axion clumps' (2019) cf. Weinberg (1962)

$$\Delta k^i = \pm\frac{g_{a\gamma\gamma}}{2}\partial_i[a(t_f,\boldsymbol{x}_f) - a(t_i,\boldsymbol{x}_i)]$$
$$\Delta\omega = \mp\frac{g_{a\gamma\gamma}}{2}\partial_0[a(t_f,\boldsymbol{x}_f) - a(t_i,\boldsymbol{x}_i)]$$

Suggests a new way to use atomic clocks to constraints axion DM:

$$\frac{\Delta\omega}{\omega} \sim 10^{-16}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)\left(\frac{1\,\mathrm{GHz}}{\omega}\right)\sqrt{\frac{\rho_{\mathrm{DM}}}{0.3\,\mathrm{GeV/cm^3}}}$$

-optical effects should be examined further in specific axion backgrounds

-investigate precision terrestrial optical experiments to probe axion backgrounds

Conclusions

- Axions are multidisciplinary: a chance/challenge
- Axion physics is a mature field but new fundamental properties are expected
- Deeper connexions between the strong CP problem, the DM matter and the particle flavour sector should be explored (neutrinos, baryogenesis, etc.)
- This is the perfect time to be studying axion DM detection.

  New experiments, new experimental ideas & technics along with alternative DM scenarios
- Axion topological defects are theo/astro objects that one needs to deal with
- Axion Miniclusters are a fairly generic, but largely overlooked, aspect of axion DM phenomenology.

  What fraction of the axion dark matter ends up in miniclusters?
- Optical effects should be examined further in specific axion backgrounds
- Investigate precision terrestrial experiments to probe axion backgrounds