Axion dark matter

(a biased overview)

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General QCD lagrangian

$$\mathcal{L}_{\rm QCD} = \sum_{\text{quarks } q} \bar{\psi}_q \left(i\not{D} - m_q e^{i\theta_q} \right) \psi_q - \frac{1}{4} G_{\mu\nu,\mathrm{a}} G^{\mu\nu}_{\mathrm{a}} - \theta \frac{\alpha_s}{8\pi} G_{\mu\nu,\mathrm{a}} \tilde{G}^{\mu\nu}_{\mathrm{a}}$$

SU(3) covariant derivative $\not{D} = \gamma^\mu \partial_\mu - i g_3 \gamma^\mu G^{\mathrm{a}}_\mu T^{\mathrm{a}}$

q quark matt, real

phase of Yukawa coupling

angle [-π, π]

CP-odd quantity $\propto \vec{E}_{\mathrm{a}} \cdot \vec{B}_{\mathrm{a}}$

θ-factor :

- Contribution from QCD vacuum topology
- EW contribution from phase of $\mathcal{M}_q$

θ_q can be removed with chiral transformation $\psi_q \to e^{-i\gamma_5 \theta_q/2} \psi_q$

$$\mathcal{L}_{\rm QCD} = \sum_{\text{quarks } q} \bar{\psi}_q \left(i\not{D} - m_q \right) \psi_q - \frac{1}{4} G^2 - \left(\theta - \arg\det \mathcal{M}_q \right) \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\boxed{\theta = \theta_{\rm vacuum} + \theta_{\rm weak}}$$

Constraints on the θ factor

- $\theta \neq 0 \Rightarrow$
  - $\eta \longrightarrow \pi^+\pi^-$
  - Neutron electric dipole moment $d_n = 4.5\ 10^{-5}\ \theta\ e\mathrm{cm}$
- Measurements :
  - $BR\left(\eta \to \pi^+\pi^-\right) < 1.5 \times 10^{-15}$
  - $|d_n| < 2.9 \times 10^{-26}\ e\mathrm{cm}$

$$\theta < 10^{-11}$$

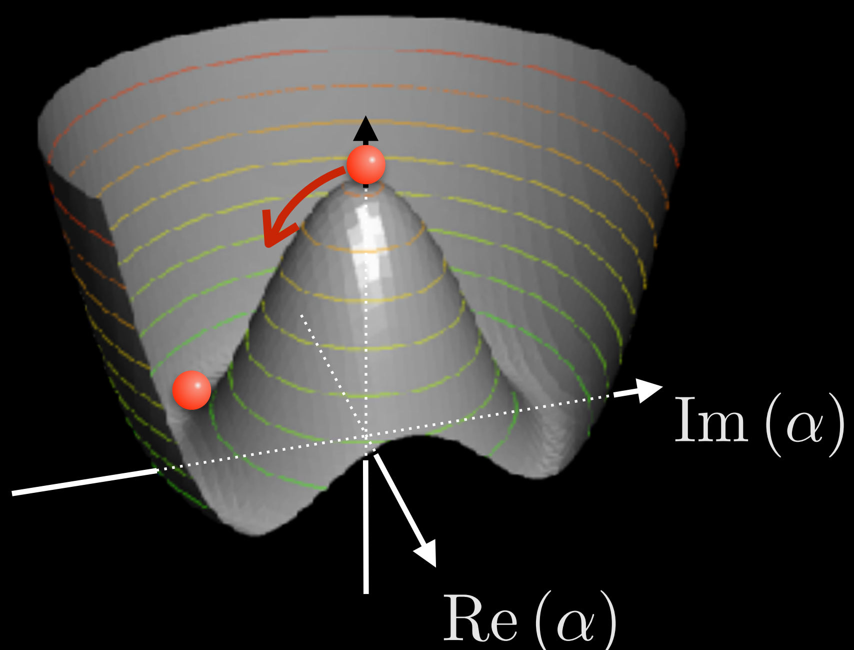
- Fixed value, not dynamic

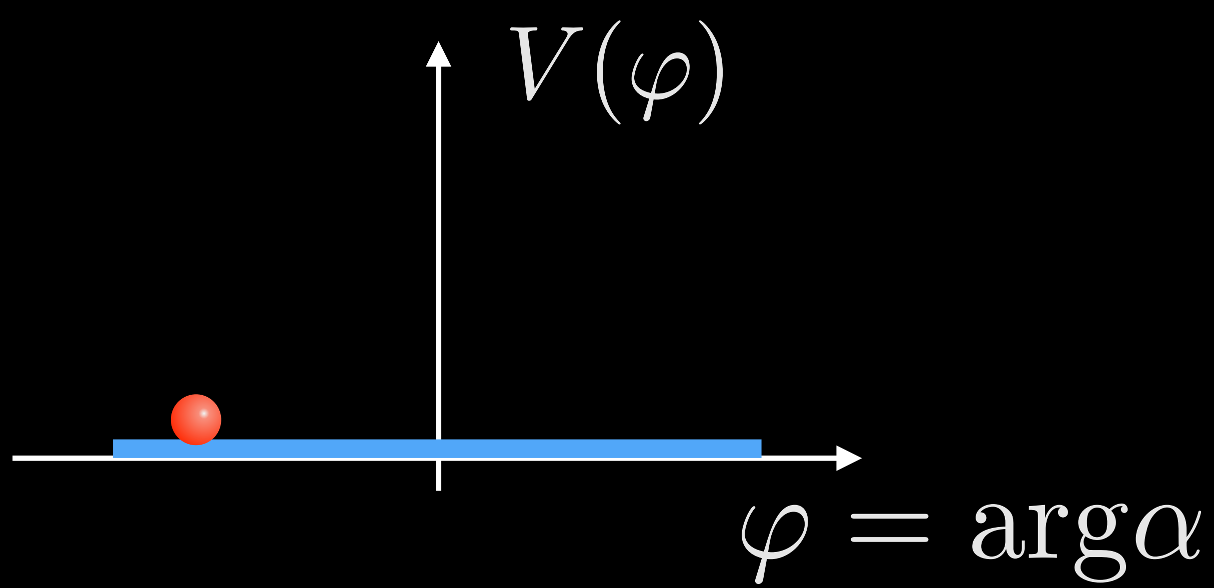
Textbook-case of a fine-tuning problem :
strong CP problem

Peccei-Quinn and the axion

- ⋆ New symmetry: U(1) Peccei-Quinn

- ⋆ $U(1)_{PQ}$ spontaneously broken at some high scale f_a





- ⋆ Goldstone boson: **the axion**

- ⋆ Axion φ is introduced massless

Coupling to gluons

- ★ $U(1)_{PQ}$ built to induce axion/gluon coupling

$$\mathcal{L}_{\rm axion} = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi - \frac{\alpha_s}{8\pi f_{\rm a}}\varphi G\tilde{G} \quad \Rightarrow \quad \mathcal{L}_\theta = \left(\theta - \frac{\varphi}{f_{\rm a}}\right)\frac{\alpha_s}{8\pi}G\tilde{G}$$

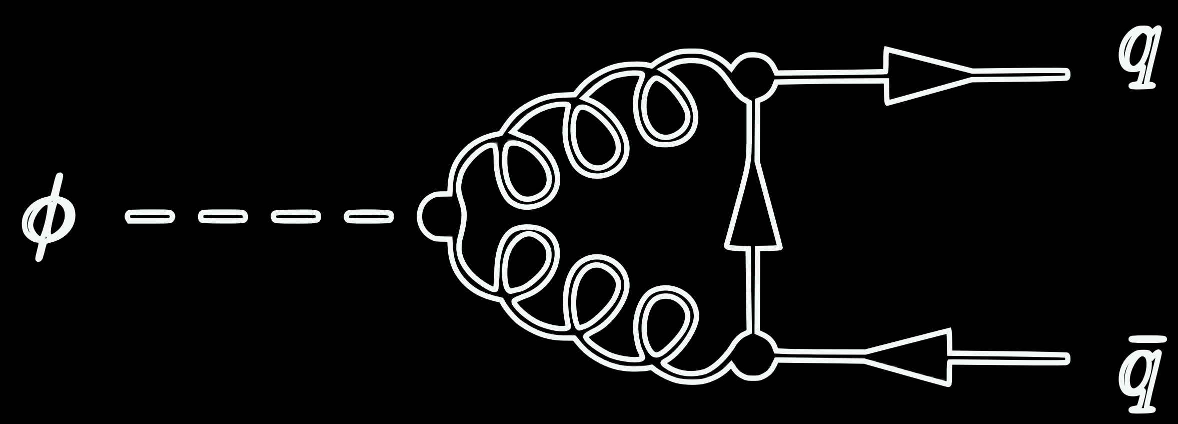
- ★ No mass : lagrangian is invariant through $\varphi \to \varphi + \delta$

- ★ re-definition of the field: $\phi = \varphi + f_{\rm a}\theta$

$$\mathcal{L}_{\rm axion} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{\alpha_s}{8\pi f_{\rm a}}\phi G\tilde{G}$$

Generating the axion mass

QCD phase transition : $\langle \bar{\psi}_{q,L} \psi_{q,R} \rangle \neq 0$



Axion-π^0 mixing

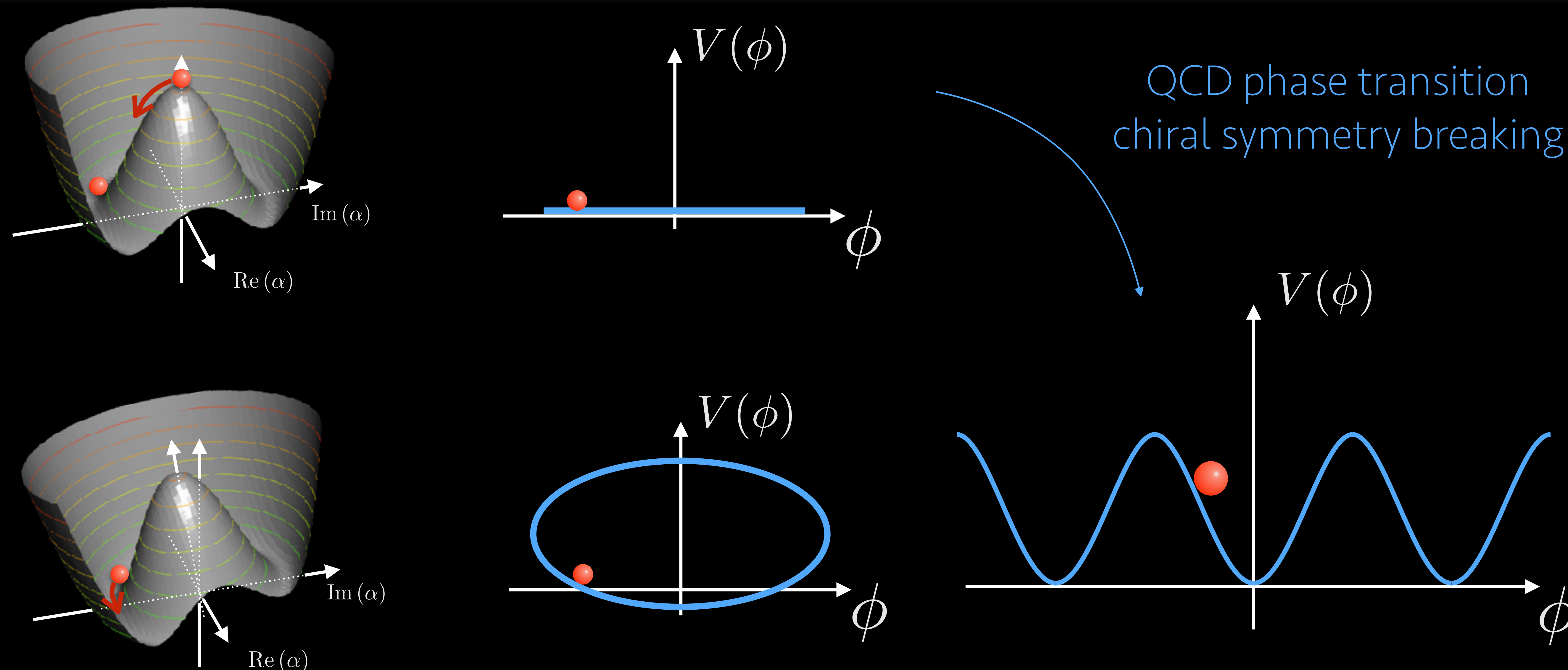
$$m \sim \frac{m_\pi f_\pi}{f_a}$$

$$\mathcal{L}_{\rm axion} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \phi \frac{1}{f_a}\frac{\alpha_s}{8\pi} G_{\mu\nu,\rm a}\tilde{G}^{\mu\nu}_{\rm a} - \frac{1}{2} m^2 \phi^2 - \frac{g_{\rm a\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

(ϕ is shifted φ)

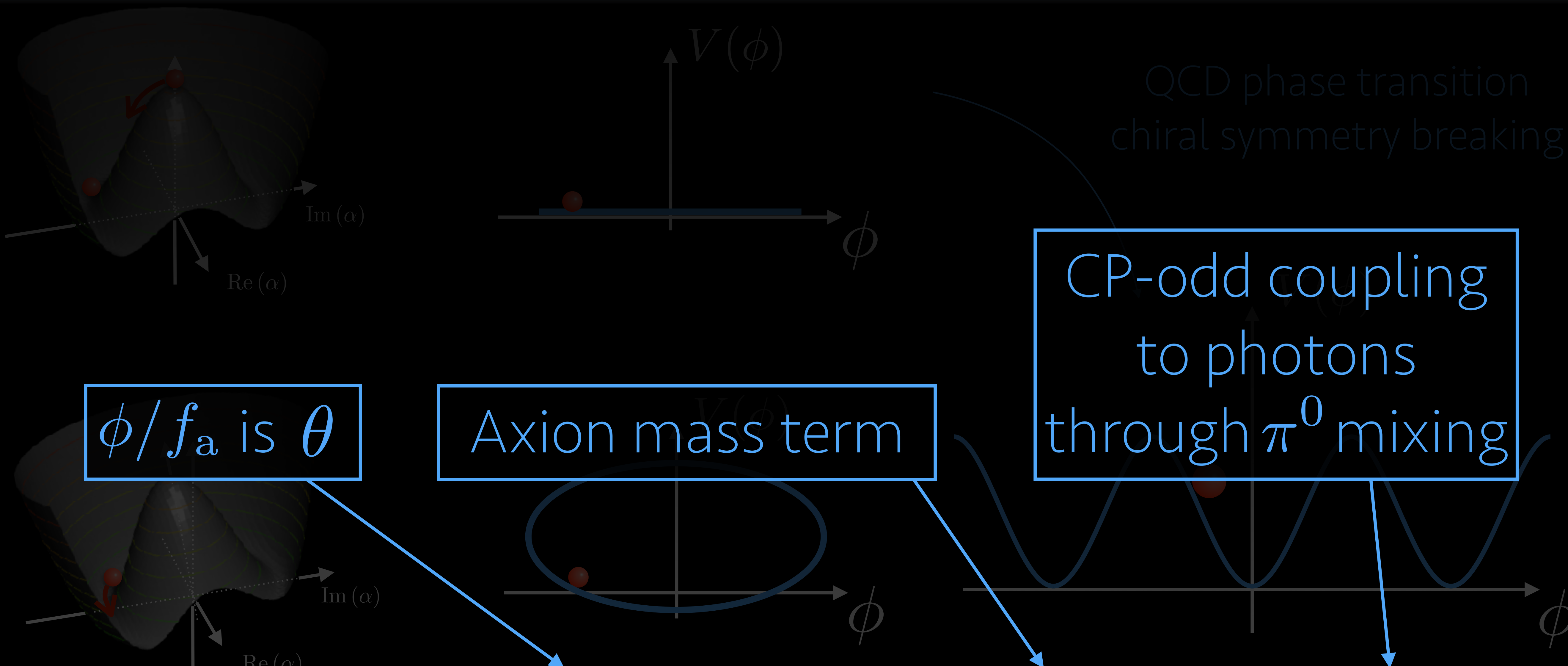
lowest order

Generating the axion mass



$$\mathcal{L}_{\text{axion}} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \phi\frac{1}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu,\text{a}}\tilde{G}^{\mu\nu}_{\text{a}} - \frac{1}{2}m^2\phi^2 - \frac{g_{\text{a}\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Generating the axion mass



$\phi/f_{\rm a}$ is θ

Axion mass term

CP-odd coupling to photons through π^0 mixing

$$\mathcal{L}_{\rm axion} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \phi\frac{1}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu,{\rm a}}\tilde{G}^{\mu\nu}_{\rm a} - \frac{1}{2}m^2\phi^2 - \frac{g_{{\rm a}\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

θ naturally driven to 0

Example : KSVZ

Early model : Kim, Shifman, Vainshtein, Zakharov ('79-'80)

Transformations $\phi \to \phi + 2\pi f_a$: phase of a scalar field

New fields introduced :

- scalar field Φ $\mathrm{SU(2)} \times \mathrm{U(1)}$ singlet (no weak interaction)

- new fermion Ψ, $\mathrm{SU(3)}$ triplet (new quark without mass term)

$$\mathcal{L} = \left(\frac{i}{2}\bar{\Psi}\gamma_\mu\partial^\mu\Psi + h.c\right) + \partial_\mu\Phi^\dagger\partial^\mu\Phi - V\left(|\Phi|\right) - h\left(\bar{\Psi}_L\Psi_R\Phi + h.c.\right)$$

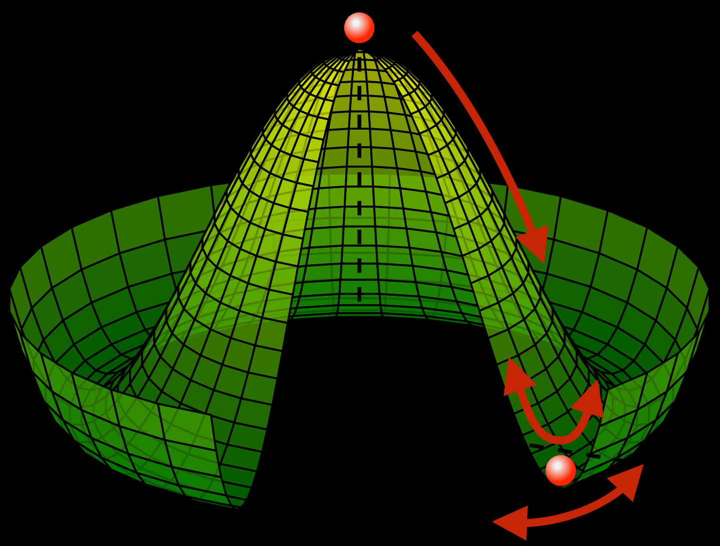
$$\Psi_L \equiv \frac{1}{2}\left(1-\gamma_5\right)\Psi \qquad \Psi_R \equiv \frac{1}{2}\left(1+\gamma_5\right)\Psi$$

Invariant through chiral phase transformation

$$\Phi \to e^{i\alpha}\Phi \qquad \Psi_L \to e^{i\alpha/2}\Psi_L \qquad \Psi_R \to e^{-i\alpha/2}\Psi_R$$

Example : KSVZ

Mexican hat potential



Vacuum expectation value: $\langle \Phi \rangle = \frac{f_{\mathrm{a}}}{\sqrt{2}} e^{i\varphi}$

$$\Phi \frac{1}{\sqrt{2}} \left(f_{\mathrm{a}} + \rho \right) e^{i\phi/f_{\mathrm{a}}}$$

Mass term $\mathcal{O}(f_{\mathrm{a}})$ for $\mathbf{\Psi}$

Let $M = \frac{h f_{\mathrm{a}}}{\sqrt{2}}$, disregarding all terms with ρ :

$$\mathcal{L} = \left(\frac{i}{2} \bar{\Psi} \gamma_\mu \partial^\mu \Psi + h.c. \right) + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - M \left(\bar{\Psi}_L \Psi_R e^{i\phi/f_{\mathrm{a}}} + h.c. \right)$$

Example : KSVZ

$$\mathcal{L} = \left(\frac{i}{2}\bar{\Psi}\gamma_\mu\partial^\mu\Psi + h.c.\right) + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - M\left(\bar{\Psi}_L\Psi_R e^{i\phi/f_\mathrm{a}} + h.c.\right)$$

Chiral phase transformation:

- $\mathscr{L}$ invariant
- $\boldsymbol{\Psi}$ changes as shown before
- $\boldsymbol{\phi \to \phi + \alpha f_\mathrm{a}}$: shift symmetry, axion is massless

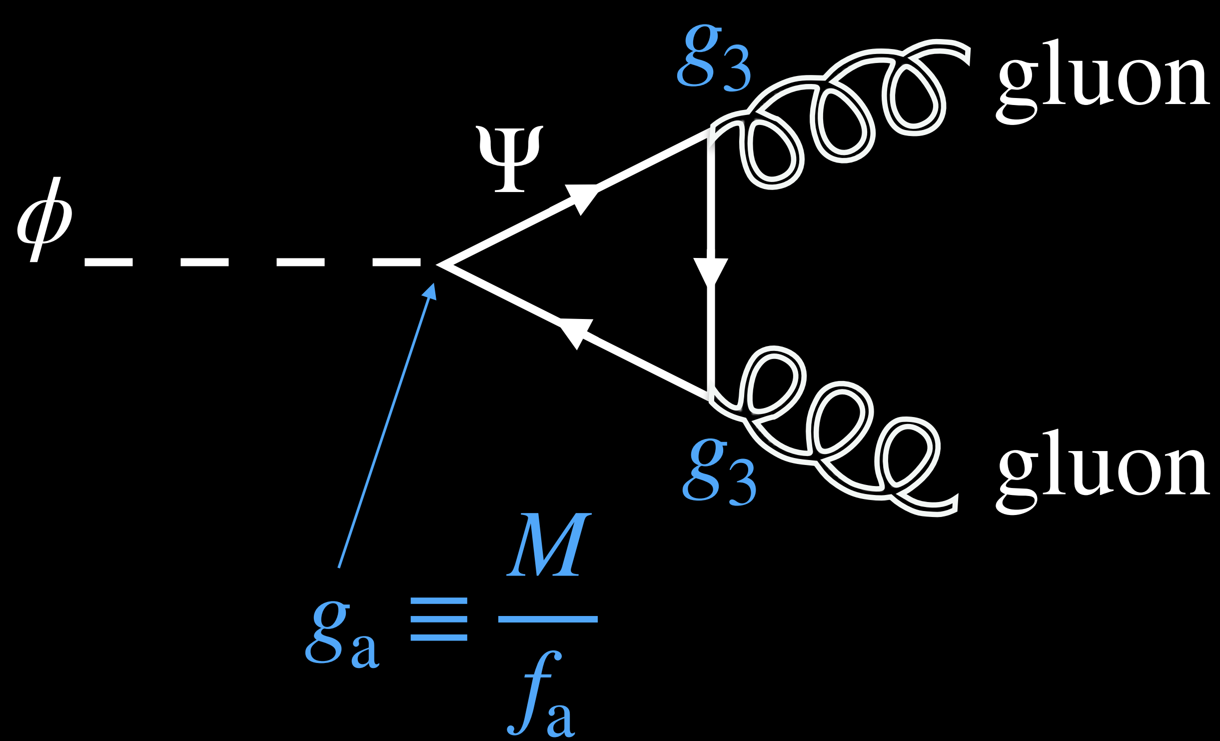
Remark : $M\bar{\Psi}_L\Psi_R e^{i\phi/f_\mathrm{a}} = M\bar{\Psi}e^{i\gamma_5\phi/f_\mathrm{a}}\Psi$

$$= M\bar{\Psi}\Psi + \underbrace{i\frac{M}{f_\mathrm{a}}\phi\bar{\Psi}\gamma_5\Psi}_{} + \dots$$

gives the axion / heavy quark coupling

Example : KSVZ

Interaction d'ordre le plus bas :



Dans la limite $k \ll M$

$$\mathcal{L}_{\phi\mathrm{glu}} = -\frac{g_a}{M}\frac{g_3^2}{32\pi^2}\,\phi\,G\tilde{G}$$

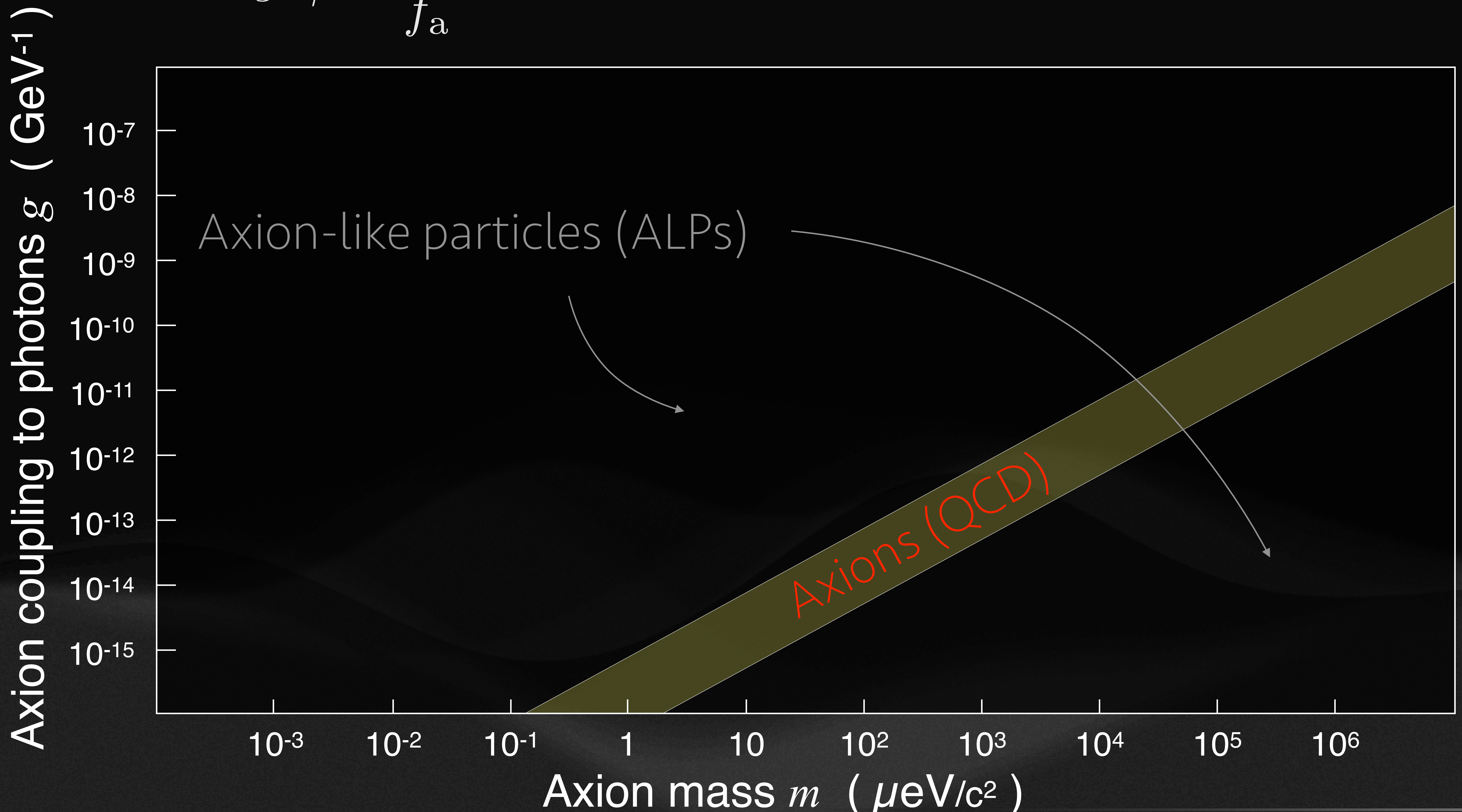
ici, proportionnel au nombre de champs lourds

In a nutshell...

- ⋆ Axions is a Standard Model problem
- ⋆ Strong interaction should display a θ term
- ⋆ $\theta \neq 0 \;\Rightarrow$ CP violation : not observed
- ⋆ SM do not have d.o.f. to relax $\theta \to 0$
- ⋆ Peccei-Quinn mechanism drives naturally θ to 0
- ⋆ New massive field : the axion
- ⋆ Axions are weakly coupled to photons

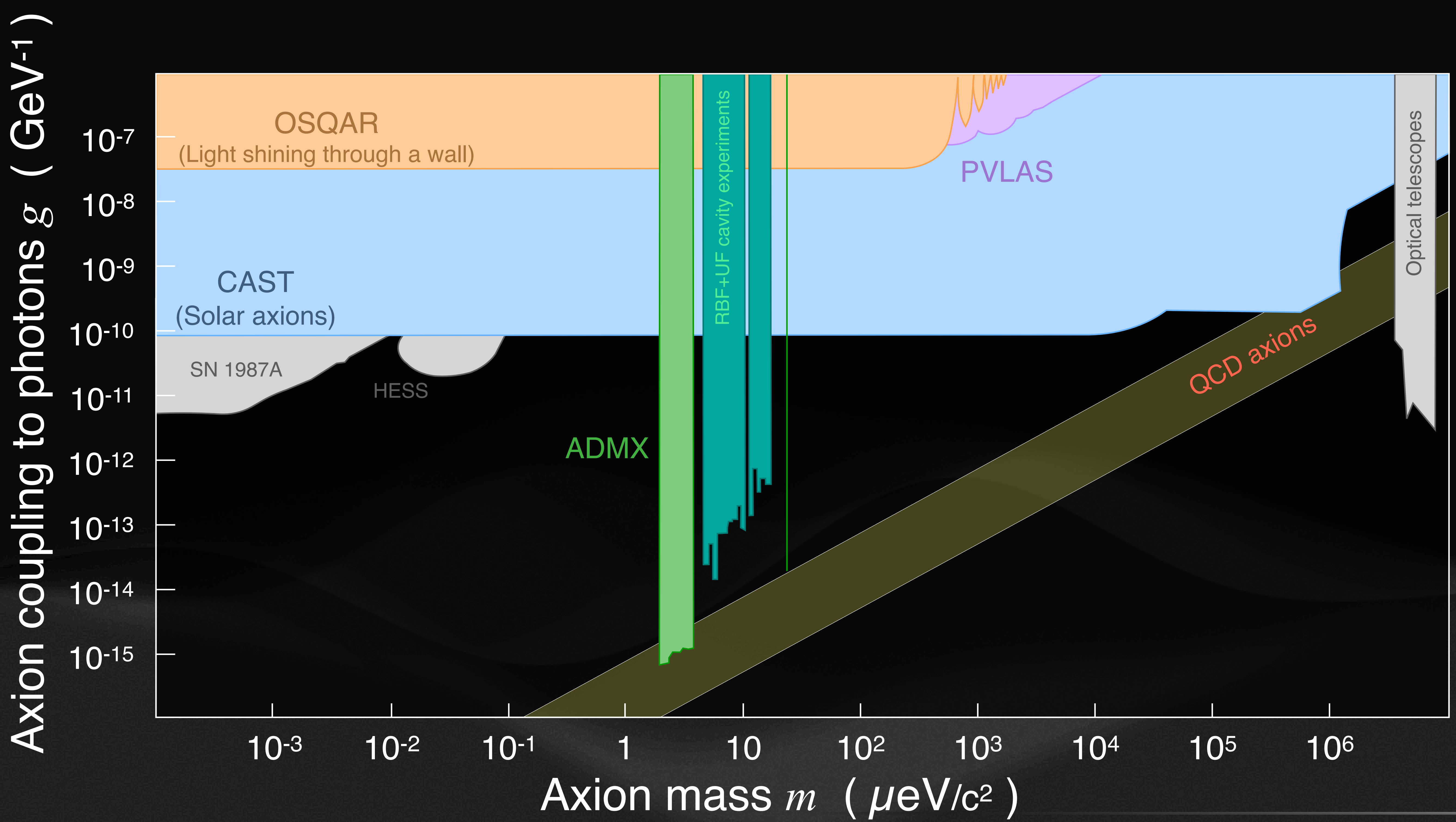
Axion-photon parameter space

$$g_{a\gamma} \sim \frac{\alpha_s}{f_a}$$ x $\mathcal{O}(1)$ model-dependent factors



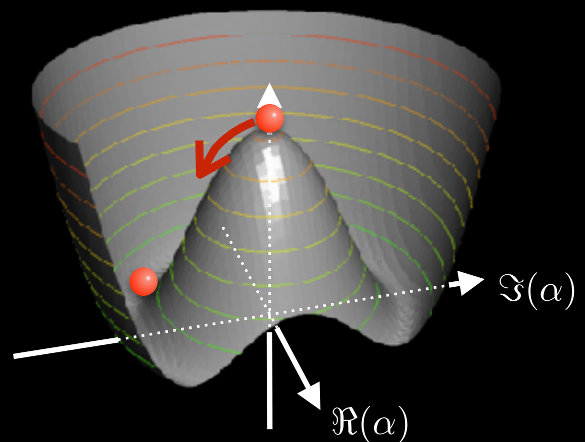
Examples of constraints

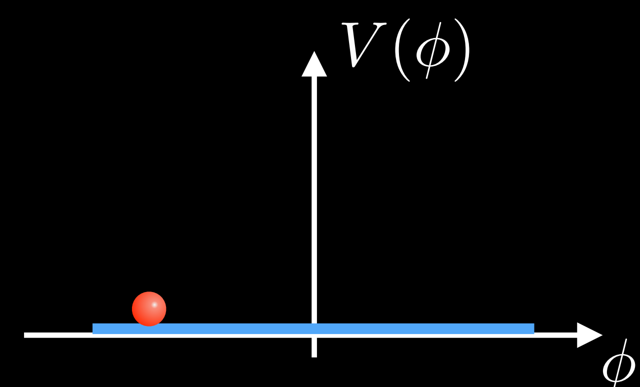
Astrophysics / dedicated observations / laboratory experiments



Axions in the early universe

★ Breaking of the Peccei-Quinn symmetry

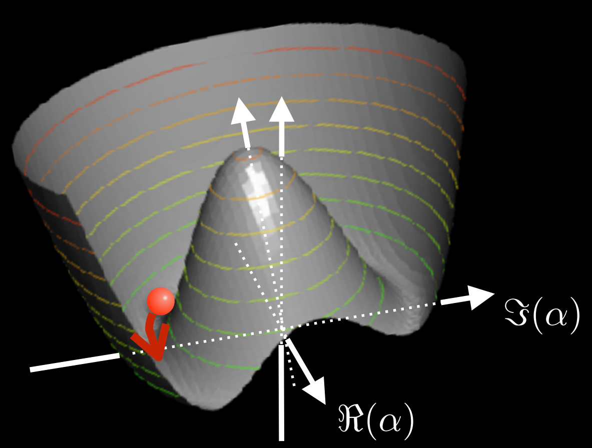


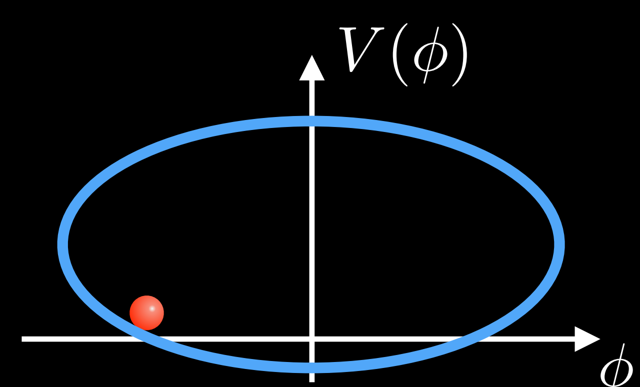


$$T_{PQ} \stackrel{?}{=} 10^{14}\ \mathrm{GeV}$$

Random choice of initial angle

★ QCD phase transition





$$T_{QCD} \sim 400\ \mathrm{MeV}$$

Random misalignment

★ Axions oscillate in their potential = dark matter

Axion as dark matter

- ⋆ Energy density $\rho = \frac{1}{2}\dot{\phi}^2 + \frac{m^2}{2}\phi^2$
- ⋆ Pressure $p = \frac{1}{2}\dot{\phi}^2 - \frac{m^2}{2}\phi^2$
- ⋆ From equipartition $\frac{1}{2}\langle\dot{\phi}^2\rangle = \frac{m^2}{2}\langle\phi^2\rangle$
- ⋆ Non relativistic matter equation of state $p = 0$

Evolution in FRLW

Metric: $\mathrm{d}\ell^2 = c^2\mathrm{d}t^2 - R^2(t)\mathrm{d}\vec{u}^{\,2}$

Evolution of θ, w/ $\phi = f_\mathrm{a}\theta$:

drives the dynamics

$$\ddot{\theta} + 3H\dot{\theta} - \frac{1}{R^2}\nabla^2\theta + \frac{1}{f_a}\partial_\theta V_\mathrm{QCD}(T,\theta) = 0$$

QCD vacuum susceptibility: $m^2 f_\mathrm{a}^2 = \dfrac{\partial^2 V_\mathrm{QCD}}{\partial\phi^2} \equiv \chi$

$$V_\mathrm{QCD}(T,\theta) \simeq \chi(T)(1-\cos\theta)$$

gives the mass at lowest order in θ :

$$V_\mathrm{QCD}(T,\theta \ll 1) = \chi(T)\frac{\theta^2}{2}$$

$$\Rightarrow \quad \frac{1}{f_\mathrm{a}^2}\partial_\theta V_\mathrm{QCD}(T,\theta) = \frac{\chi(T)}{f_\mathrm{a}^2}\sin\theta = m^2(T)\sin\theta$$

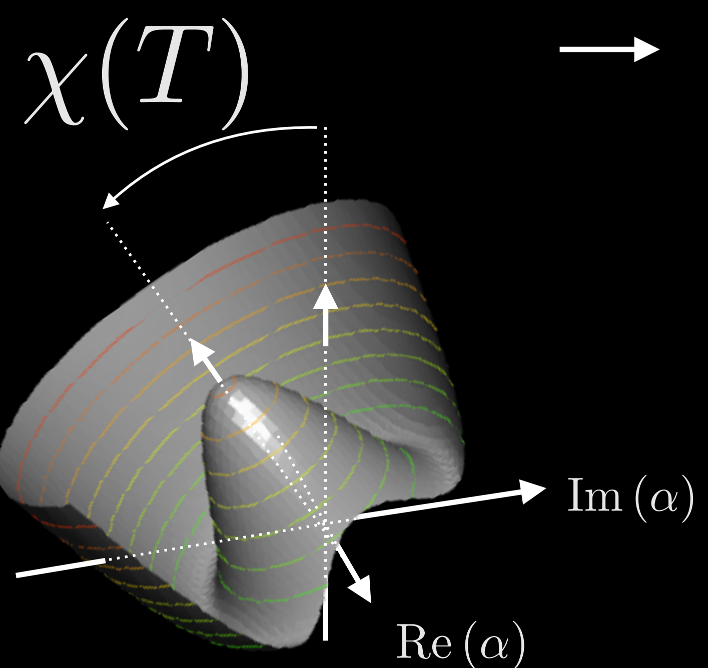
Homogeneous evolution

For the $k = 0$ mode :

$$\ddot{\theta} + 3H\dot{\theta} + m^2(T)\sin\theta = 0$$

depend on T (or t) $\longrightarrow$ numerical resolution

$\longrightarrow H(t)$ from cosmology



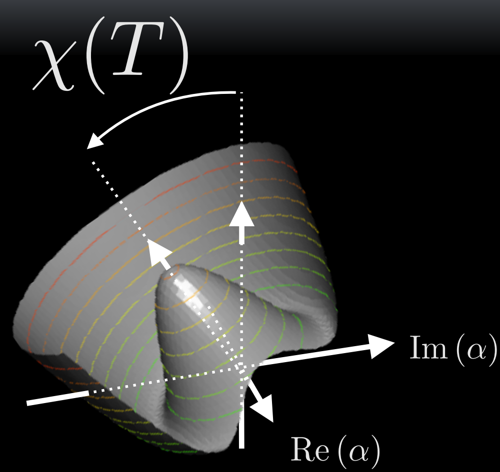
$\longrightarrow \chi(T) \equiv m^2(T) f_\mathrm{a}^2$

Many methods, approx., etc.

O. Wantz, E. Shellard, 2011

S. Borsanyi et al., 2016

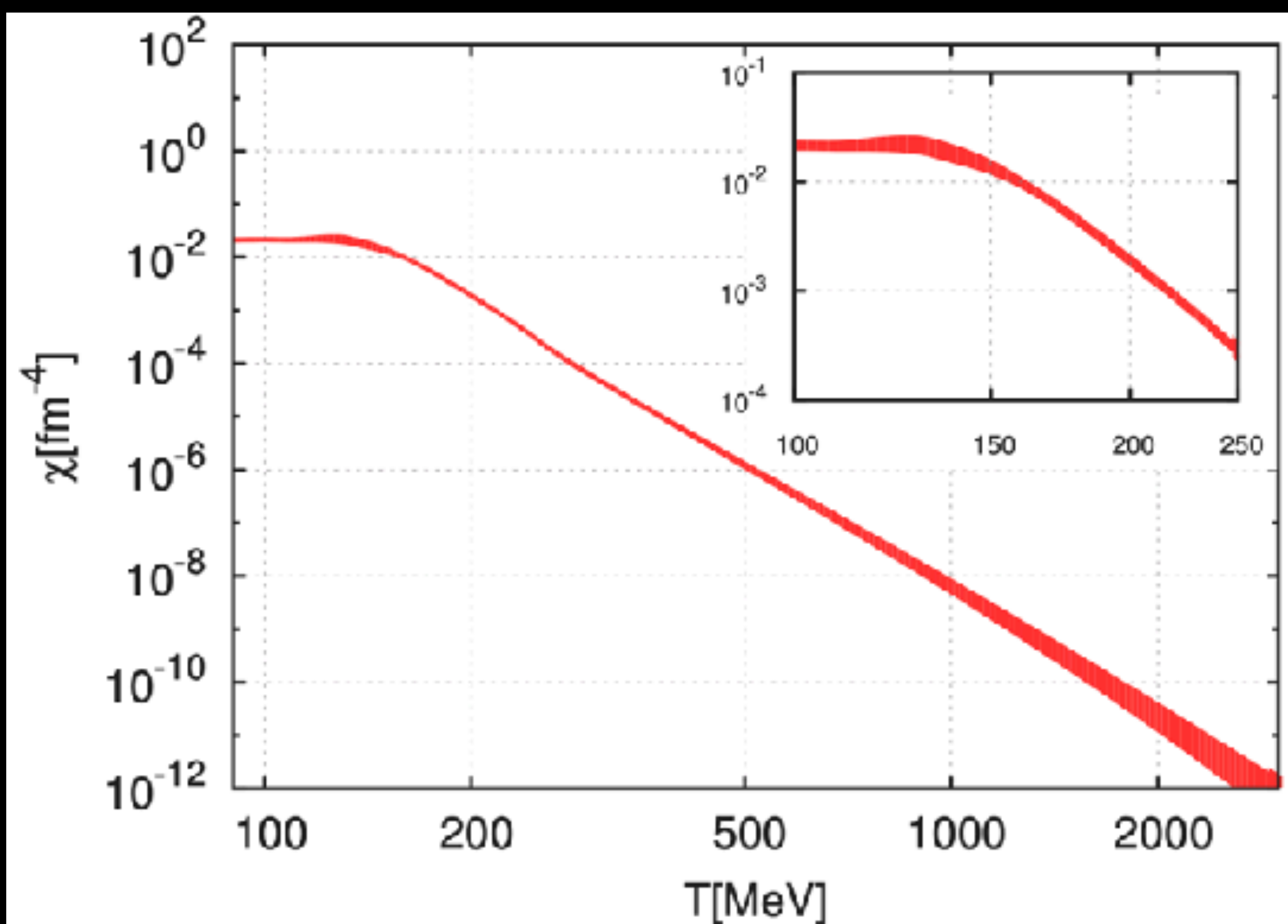
QCD vacuum susceptibility



$$\chi(T) \equiv m^2(T) f_{\rm a}^2$$

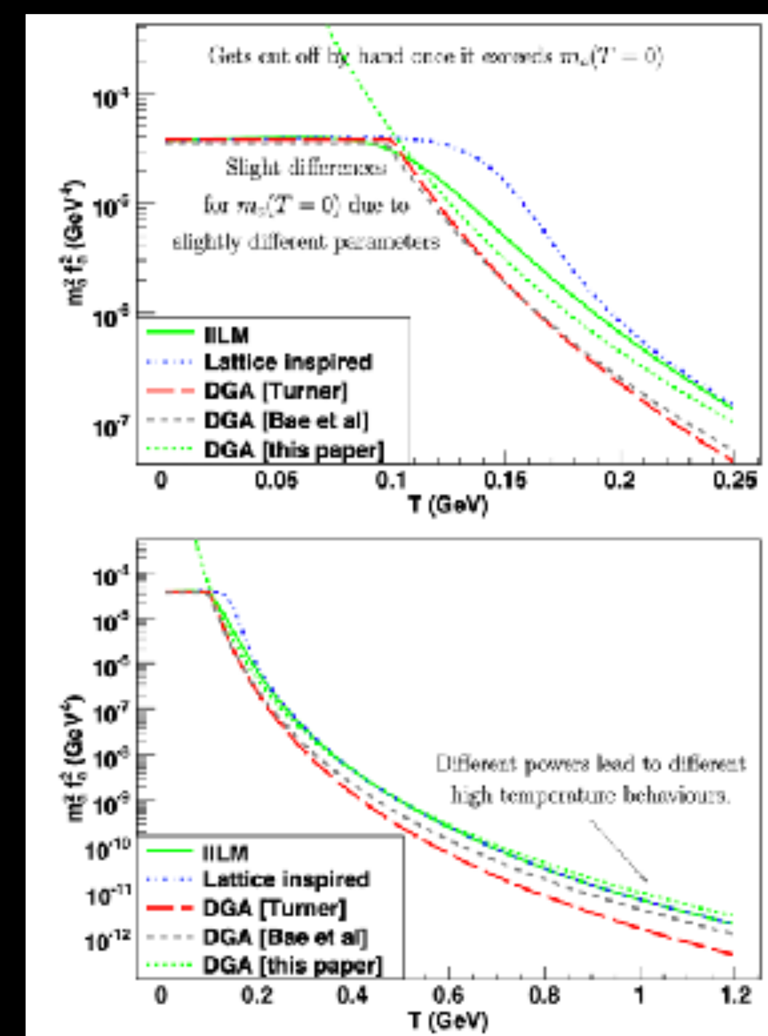
Many methods, approximations, etc.

Lattice QCD :



S. Borsanyi et al., 2016

Fits :



O. Wantz, E. Shellard, 2011

Mass: T-dependance

Parametrization of simulations:

$$\star\ T > \Lambda_{\mathrm{QCD}}: \quad m^2(T) = \frac{\alpha\,\Lambda_{\mathrm{QCD}}^4}{f_{\mathrm{a}}^2 \left(\frac{T}{\Lambda_{\mathrm{QCD}}}\right)^n} \qquad \begin{cases} \alpha = 1.68 \times 10^{-7} \\ n = 6.68 \end{cases}$$

$$\star\ T < \Lambda_{\mathrm{QCD}}: \quad \begin{cases} \chi(T=0) = (75.5\ \mathrm{MeV})^4 \\ m(T=0) = 57\ \mu\mathrm{eV} \left(\frac{10^{11}\ \mathrm{GeV}}{f_{\mathrm{a}}}\right) \end{cases}$$

T=0 value similar from lattice QCD and NNLO

NB : same order of magnitude as KSVZ :

$$m^2 f_{\mathrm{a}}^2 = m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2} \longrightarrow m \sim 75\ \mu\mathrm{eV}$$

Solution for $k = 0$ mode

$$\ddot{\theta} + 3H\dot{\theta} + m^2(T)\sin\theta = 0$$

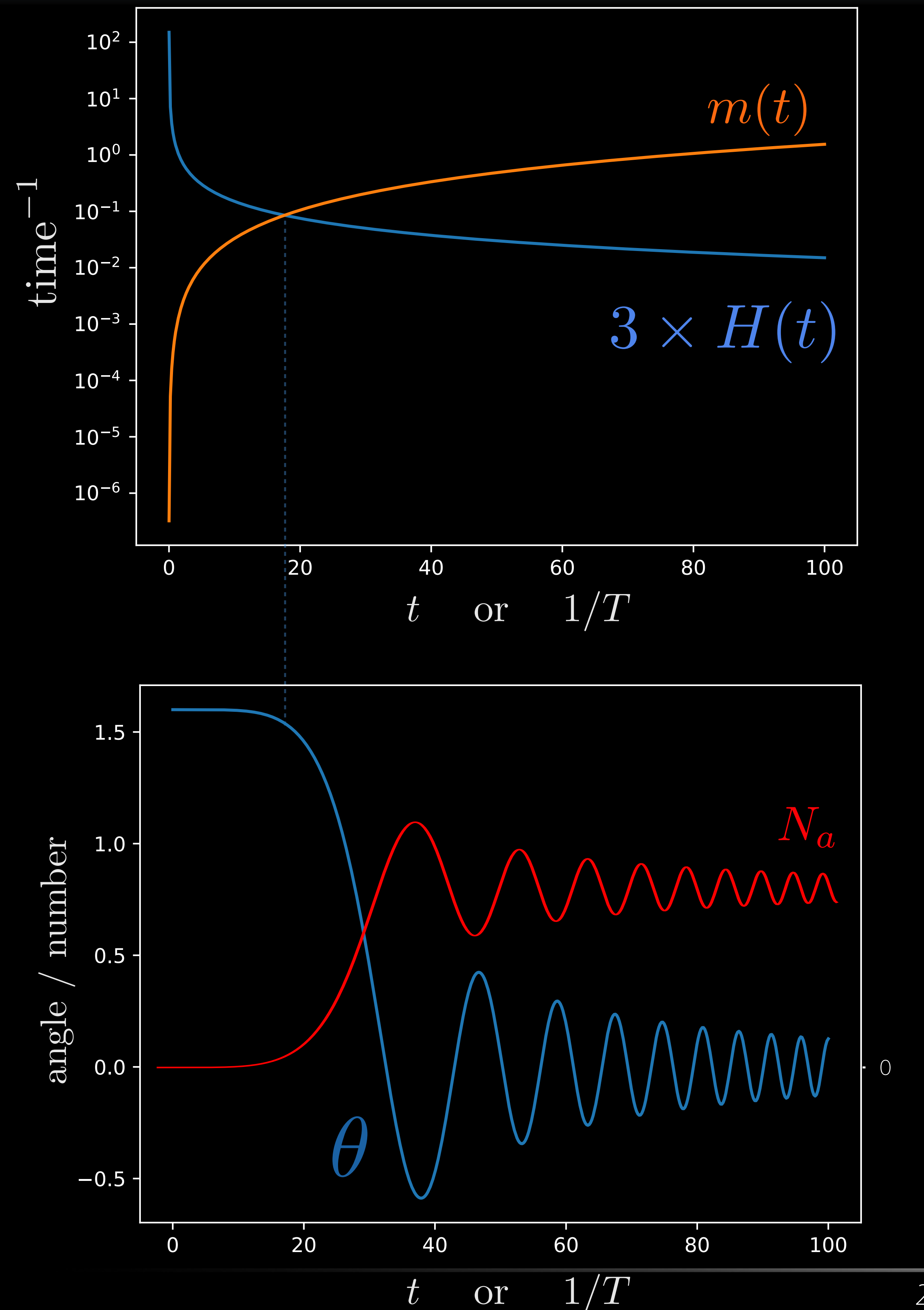
$$H = \frac{1}{2t}$$

Two regimes:

$$\frac{3\dot{\theta}}{2t} \gg m^2 \sin\theta$$: axion frozen

$$\frac{3\dot{\theta}}{2t} \ll m^2 \sin\theta$$:

- axion oscillates, small dissipation
- axion number conserved



Initial oscillation temperature

★ Radiation era: $H^2 = \dfrac{8\pi^3}{90 m_{\rm Pl}^2}\, T^4\, g_\star(T)$

$$m_{\rm pl} = \sqrt{\frac{1}{\mathcal{G}}} = 1.22 \times 10^{19}\ \mathrm{GeV}$$

★ Transition temperature: $m \sim 3H$

$$m^2(T) = \frac{\alpha\, \Lambda_{\rm QCD}^4}{f_{\rm a}^2 \left(\frac{T}{\Lambda_{\rm QCD}}\right)^n}$$

$$\Downarrow$$

$$T_i = \left(3.3 \times 10^{-31}\ \mathrm{GeV}^{-2}\right)^{\frac{-1}{n+4}} g(T_i)^{\frac{-1}{n+4}} f_{\rm a}^{\frac{-2}{n+4}} \Lambda_{\rm QCD}$$

Axion number conservation

$\langle\,.\,\rangle$: average over a period

$$\ddot{\theta} + 3H\dot{\theta} + m^2(T)\sin\theta = 0 \quad \Rightarrow \quad \langle\dot{\rho}\rangle = \langle\rho\rangle\left(\frac{\dot{m}}{m} - 3\frac{\dot{R}}{R}\right)$$

$$\langle\rho\rangle = f_{\rm a}^2\, m^2\, \theta^2$$

$$\boxed{\frac{\langle\rho\rangle R^3}{m} = cte}$$

For $k = 0$, $E = m$ et $\dfrac{\langle\rho\rangle}{m} = N$ number of axions

- ★ Energy is not conserved
- ★ Number of axions is conserved

Relic density

$$N = \frac{\rho R^3}{m} \qquad \frac{\rho_{\rm a}^0 R_0^3}{m} = \frac{\rho_i R_i^3}{m_i}$$

initial conditions
when oscillations starts

$$\rho_{\rm a} = \frac{\sqrt{\alpha}\, f_{\rm a}\, m\, \theta_i^2}{T_0^3} \frac{g_{\star{\rm s}}(T_i)}{g_{\star{\rm s}}(T_0)} \Lambda_{\rm QCD}^{2-n} T_i^{3-n}$$

$$T_i = \left(3.3 \times 10^{-31} {\rm GeV}^{-2}\right)^{\frac{-1}{n+4}} g(T_i)^{\frac{-1}{n+4}}\ f_a^{\frac{-2}{n+4}}\ \Lambda_{\rm QCD}$$

$$\rho_{\rm a} = \left(3.3 \times 10^{-31}\ {\rm GeV}^{-2}\right)^{\frac{n-3}{n+4}} \frac{\sqrt{\alpha}\, f_{\rm a}\, m\, \theta_i^2}{T_0^3\, g_{\star{\rm s}}(T_0)} g_{\star{\rm s}}(T_i)^{\frac{n+3}{n+4}} f_{\rm a}^{\frac{n+2}{n+4}} \Lambda_{\rm QCD}^{3-n}$$

$$\langle \rho_{\rm a} \rangle = \theta_i^2\ \left(5.79 \times 10^{-48}\ {\rm GeV}^4\right) \left(\frac{10\ \mu{\rm eV}}{m}\right)^{1.19}$$

Mass-initial $\boldsymbol{\theta}$ relation

Critical density: $\rho_c = \dfrac{3m_{\rm Pl}^2}{8\pi} H^2$

Cosmological parameters

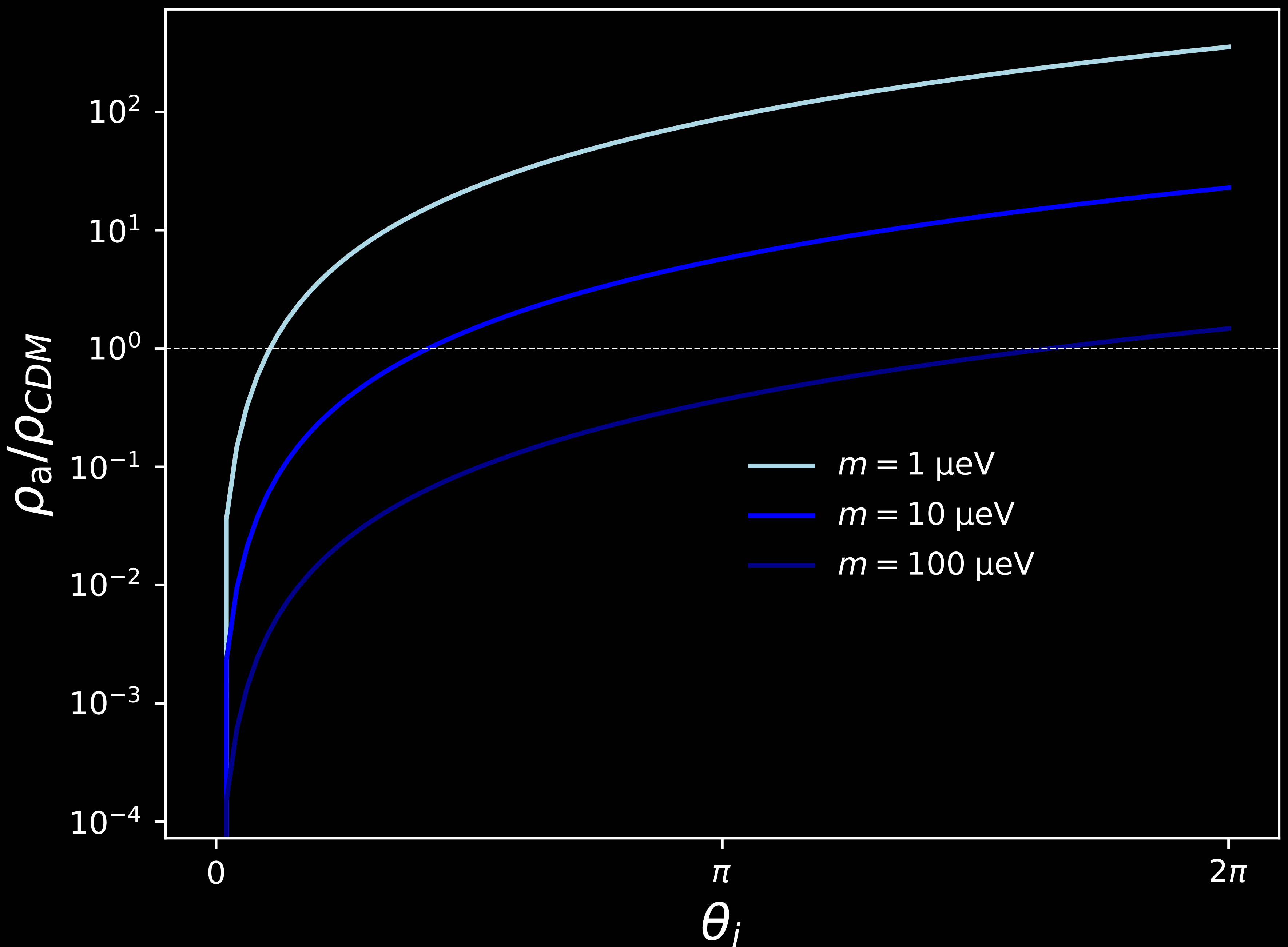
Dark matter density: $\rho_{\rm CDM} \simeq 0.84 \times 0.3 \times \dfrac{3m_{\rm Pl}^2 H_0^2}{8\pi} = 10^{-47}\ {\rm GeV}^4$

$$\rho_{\rm CDM} = 1.3\ {\rm GeV/m^3} = 1.3 \times 10^{-6}\ {\rm GeV/cm^{-3}}$$

Imposing $\rho_{\rm a} = \rho_{CDM}$ gives:

$$\theta_i = 1.314 \left(\frac{m}{10\ \mu{\rm eV}} \right)^{0.595}$$

Limit on the axion mass

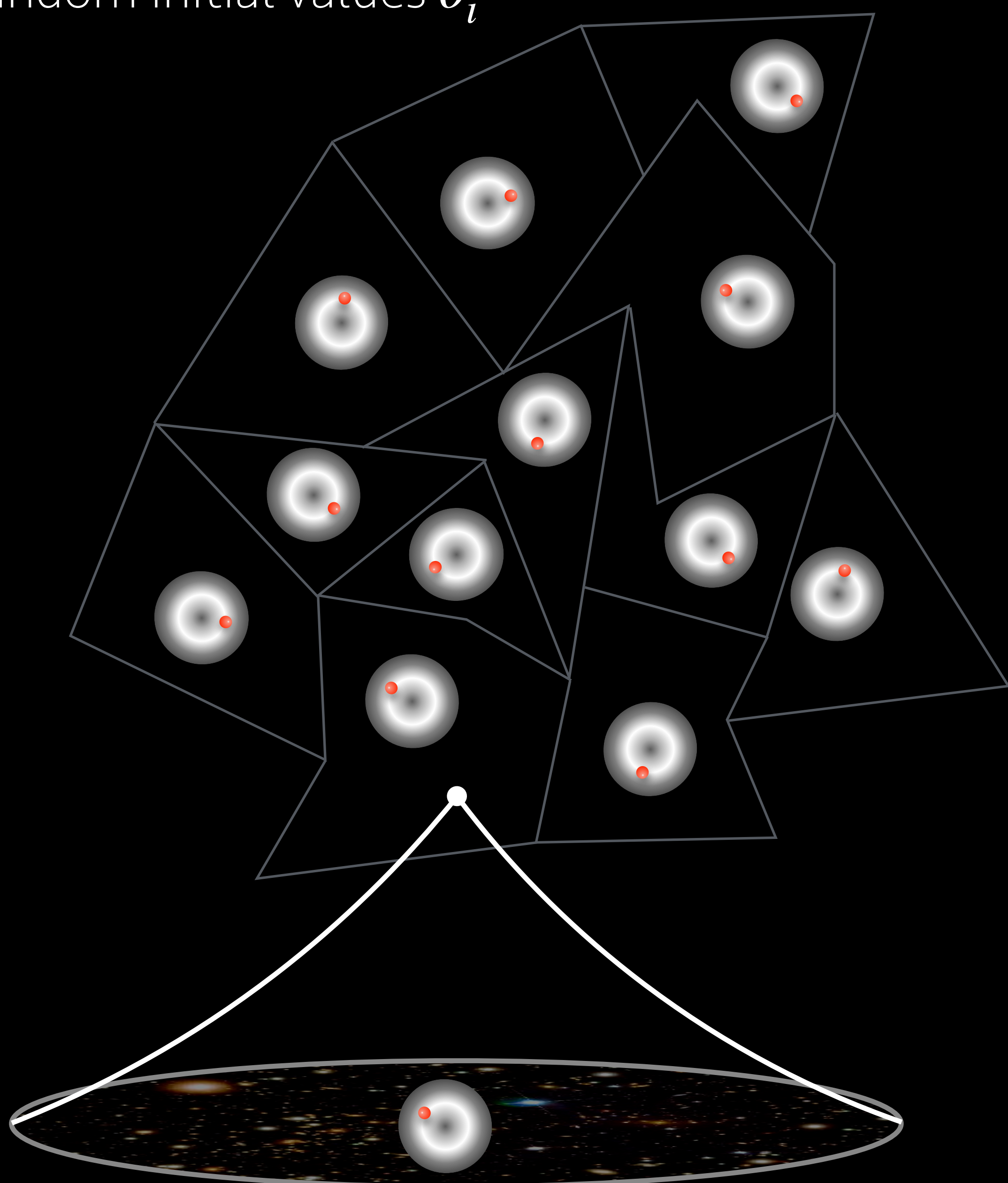


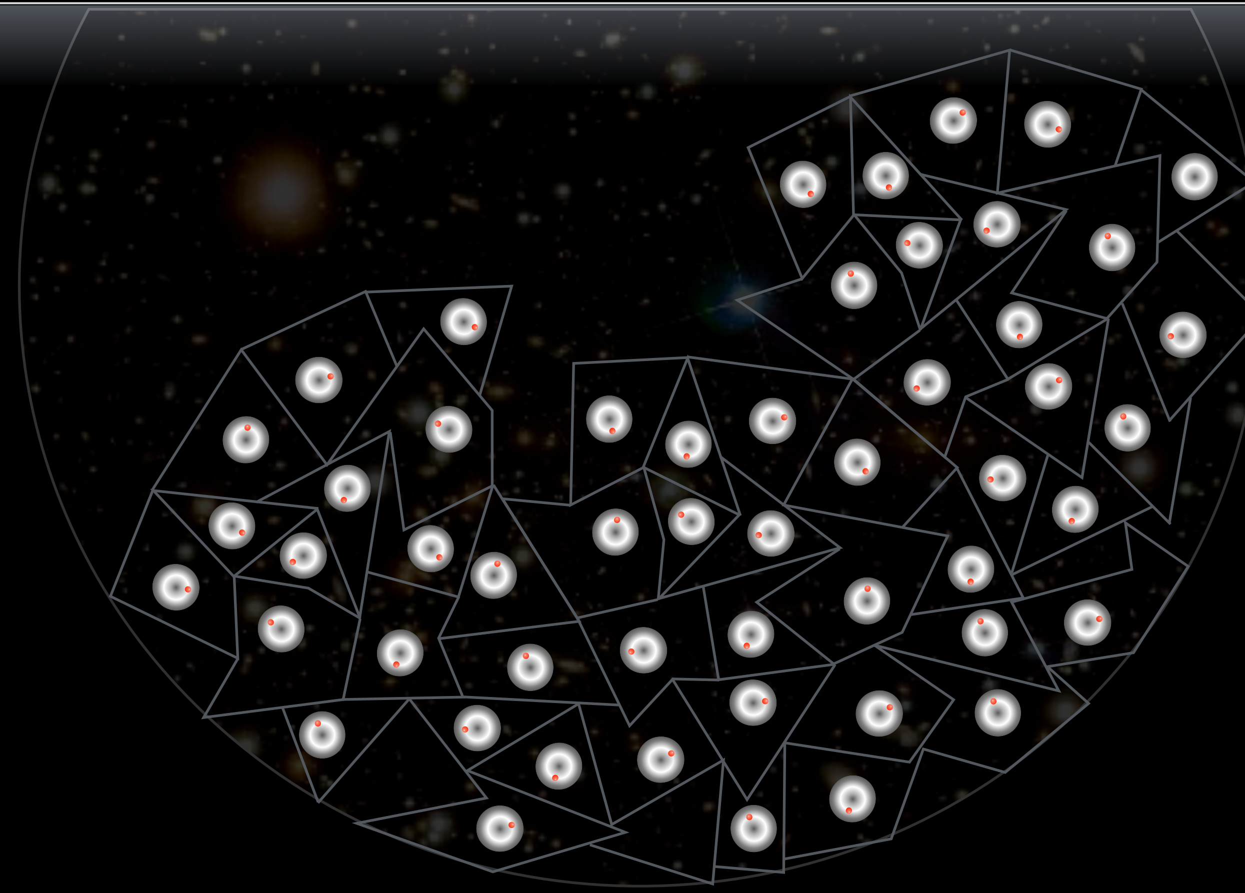
$\theta_i \sim 1$ gives an upper limit on the mass: $m \lesssim 6\ \mu\text{eV}$

NB : $\theta_i = \pi \Rightarrow m = 43\ \mu\text{eV}$

How many initial conditions?

Random initial values θ_i





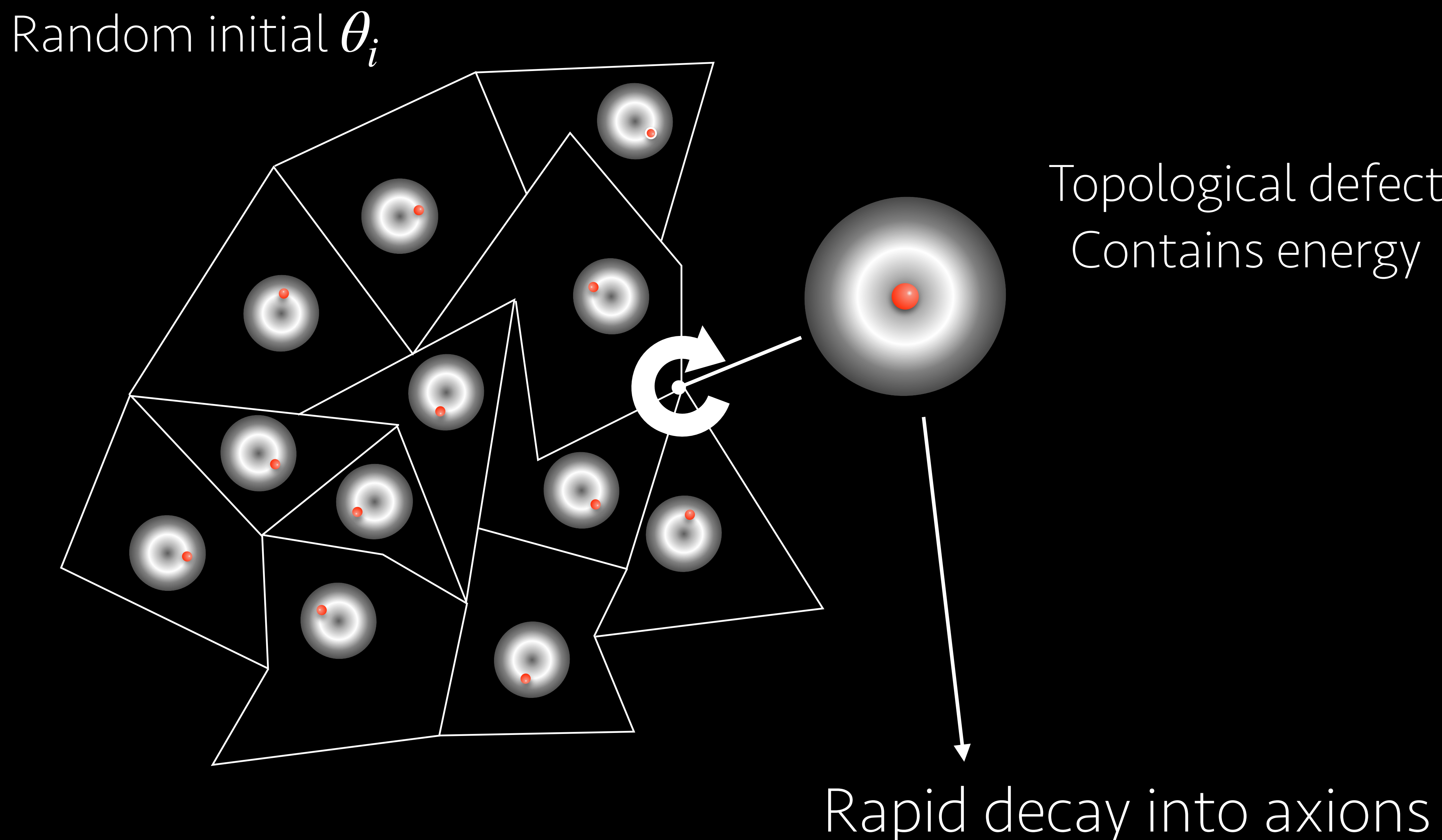
High-energy inflation

- θ_i picked up *after* inflation
- Our Hubble radius contains many θ_i
- thermalisation = new production

Low-energy inflation

- θ_i picked up *before* inflation
- Our Hubble radius contains one single θ_i

Topological defects



next : only principles, many hidden details

High-energy inflation

Two contributions to cold axion relics population:

- ★ Misalignment, ρ_d :

  density from averaging over all θ_i : $\sqrt{\langle\theta_i^2\rangle} = \frac{\pi}{\sqrt{3}}$

$$\langle\rho_0\rangle = (1.9 \times 10^{-47}\ \mathrm{GeV}^4)\left(\frac{10\ \mu\mathrm{eV}}{m}\right)^{1.19}$$

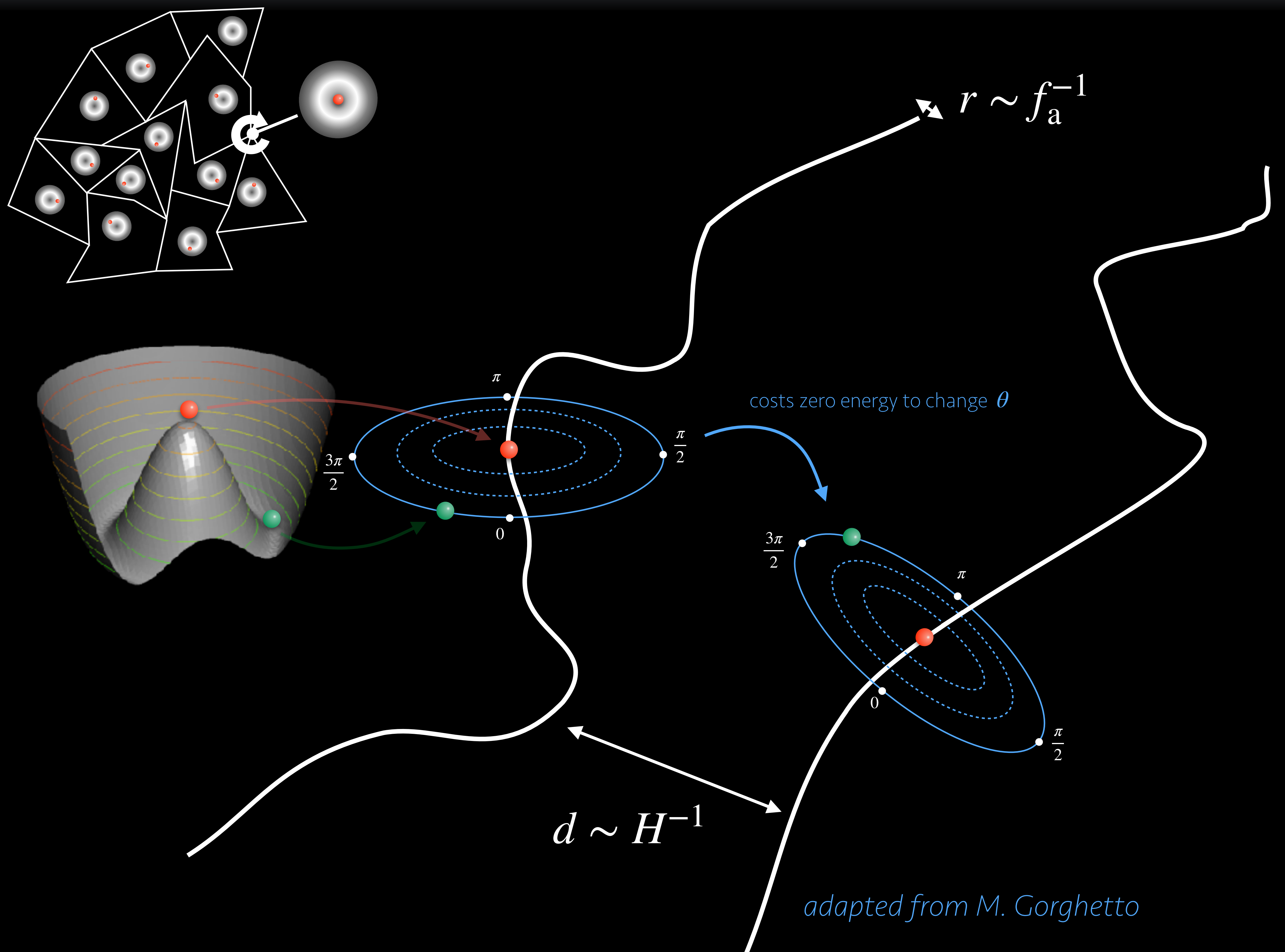
Order 1 anharmonic corrections

- ★ Decay of topological defects, ρ_td :

  from numerical simulations $\rho_\mathrm{td} \propto m^{-b}$

$\rho_{CDM} = \rho_\mathrm{d} + \rho_\mathrm{td} \quad \Rightarrow \quad$ higher values of m

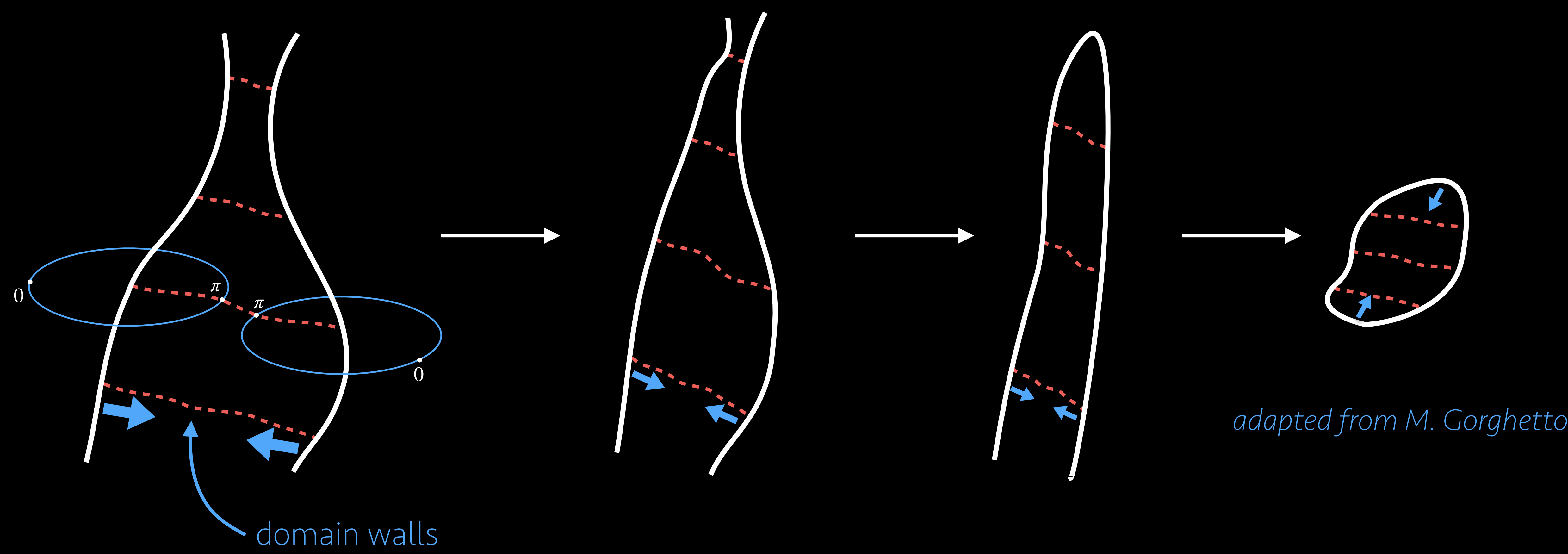
Axionic strings



adapted from M. Gorghetto

Decays and domain walls

Once $m \neq 0$, formation of domain walls



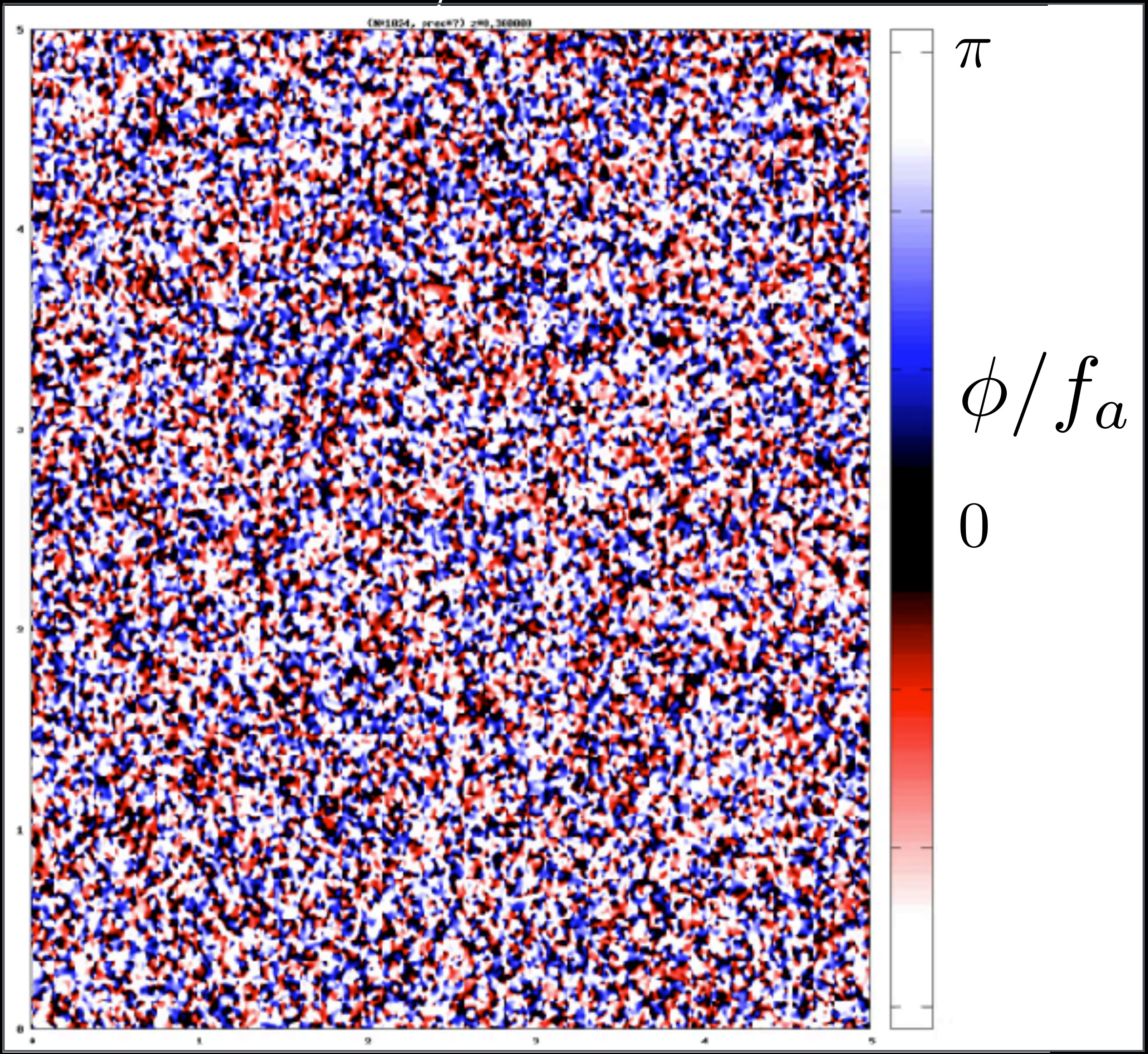
String evolution + decays of domain walls :

New production of CDM axions

Evolution of the axion field

~ 10 comoving

solar systems



Courtesy of J. Redondo

T_0 ~ 4 GeV

fraction of a second

Relevant distances at $z = 0$

$$1 + z = \frac{400\ \mathrm{MeV}}{k \times 2.73\ \mathrm{K}} = \frac{400\ \mathrm{MeV}}{2.35 \times 10^{-10}\ \mathrm{MeV}} = 1.7 \times 10^{12}$$

$$\underbrace{z \times 1.1\ \mathrm{km} = 0.06\ \mathrm{pc} \simeq 12\,500\ \mathrm{AU} \simeq 0.2\ \mathrm{ly}}$$

Taille *aujourd'hui* de l'horizon causal à la transition QCD

Size today of the causal horizon at QCD transition

L'axion ne peut pas être cohérent
sur une distance plus grande aujourd'hui

Axion field cannot be coherent on larger distances today

Examples of simulations

The dark-matter axion mass

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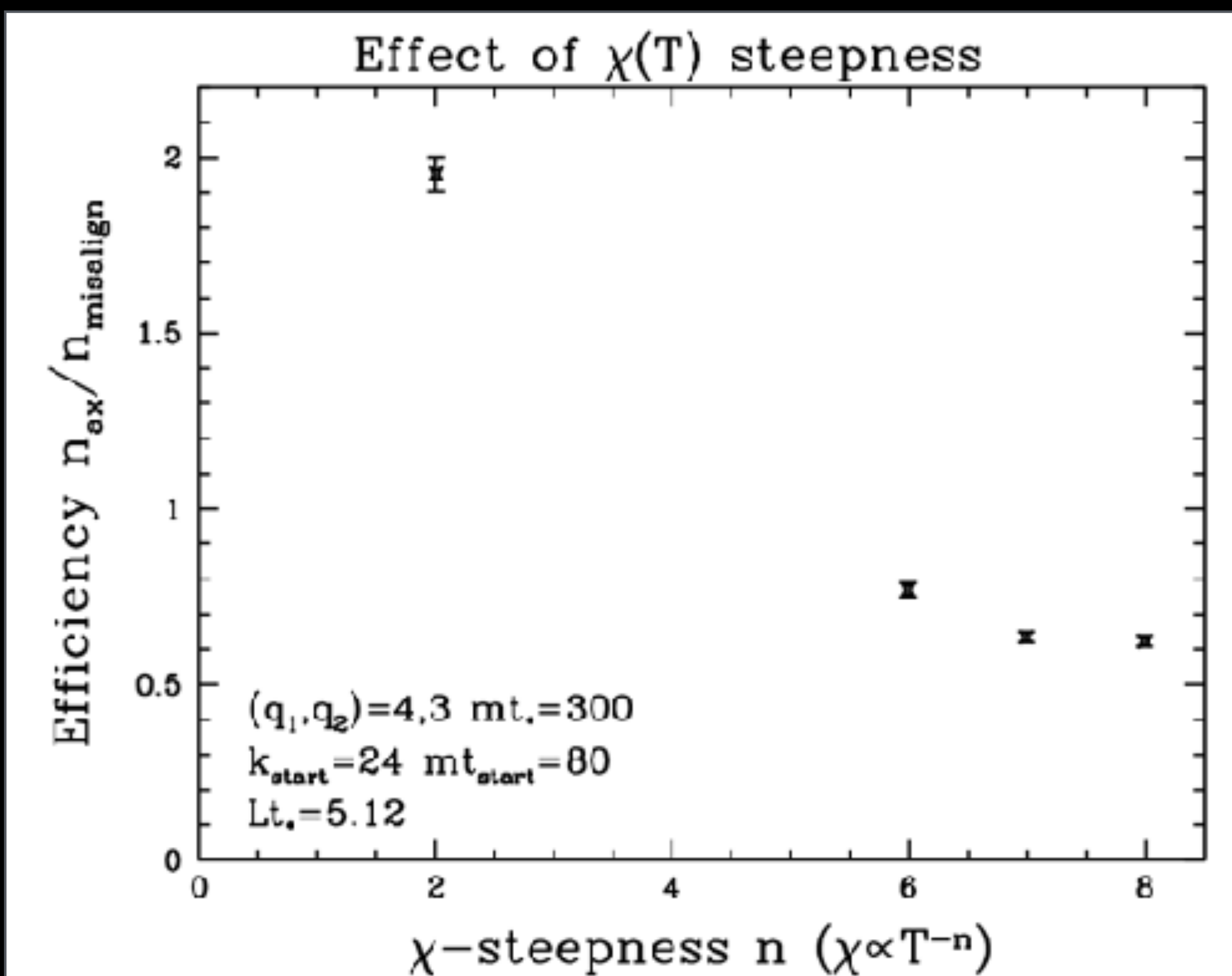

misalignment

$\simeq$

topological defects

$$m = 26.2 \pm 3.4\ \mu\text{eV}$$

$$\nu = 6.29 \pm 0.82\ \text{GHz}$$

Examples of simulations

ICRR-Report-696-2014-2

Axion dark matter from topological defects

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[2]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, The University of Tokyo, 5-1-5 Kashiwa-no-ha, Kashiwa City, Chiba 277-8582, Japan*
[3]*Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan*
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(Dated: August 12, 2015)

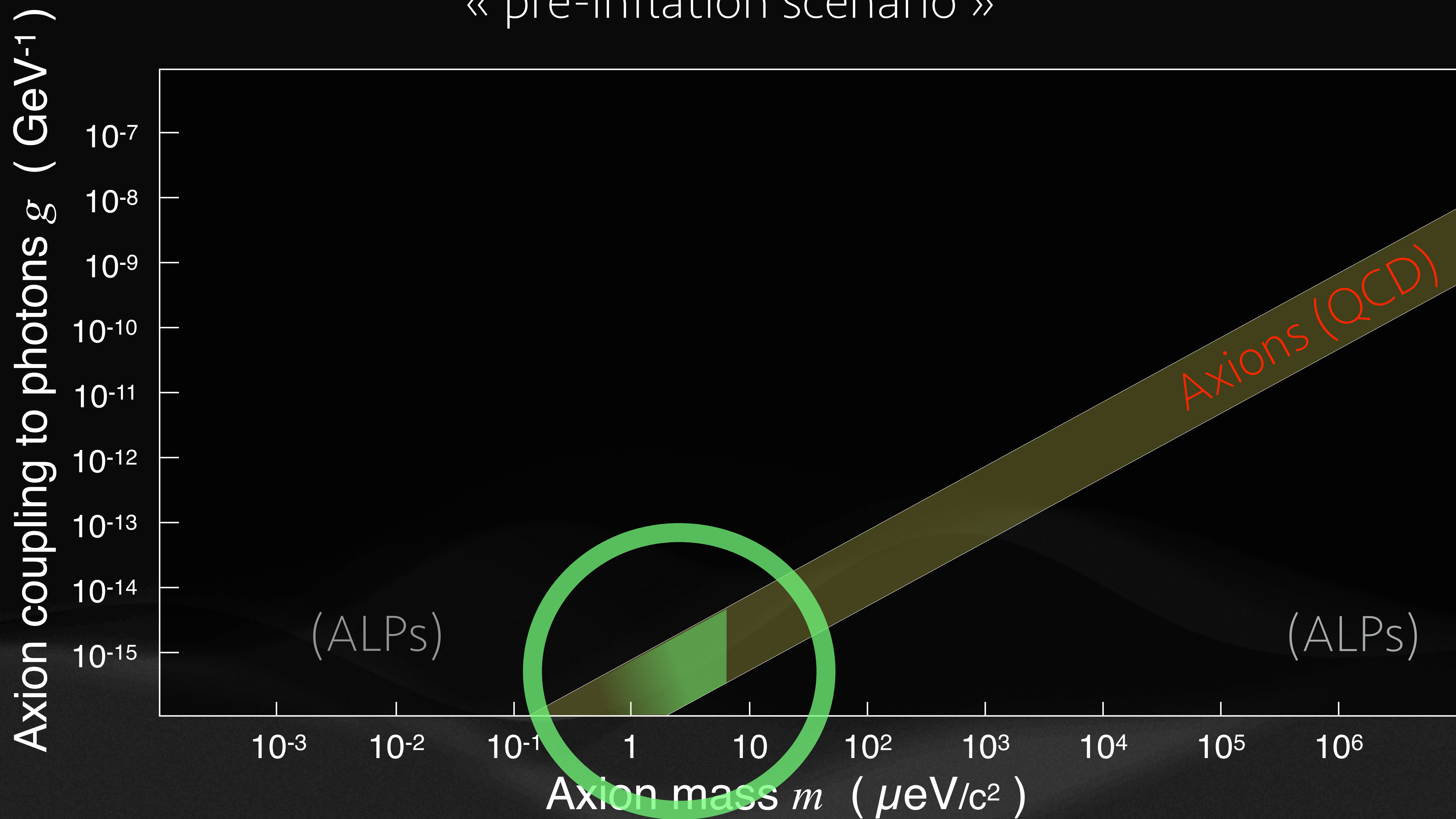
$$\begin{aligned}\Omega_{a,\mathrm{tot}}h^2 &= \Omega_{a,\mathrm{mis}}h^2 + \Omega_{a,\mathrm{string}}h^2 + \Omega_{a,\mathrm{dec}}h^2 \\ &= (1.6 \pm 0.4) \times 10^{-2} \times \left(\frac{F_a}{10^{10}\mathrm{GeV}}\right)^{(6+n)/(4+n)} \left(\frac{\Lambda_{\mathrm{QCD}}}{400\mathrm{MeV}}\right), \qquad (4.4)\end{aligned}$$

$$m = 115 \pm 25\ \mu\mathrm{eV}$$

$$\nu = 27.6 \pm 5.8\ \mathrm{GHz}$$

Axion dark matter

« pre-inflation scenario »



Axion dark matter

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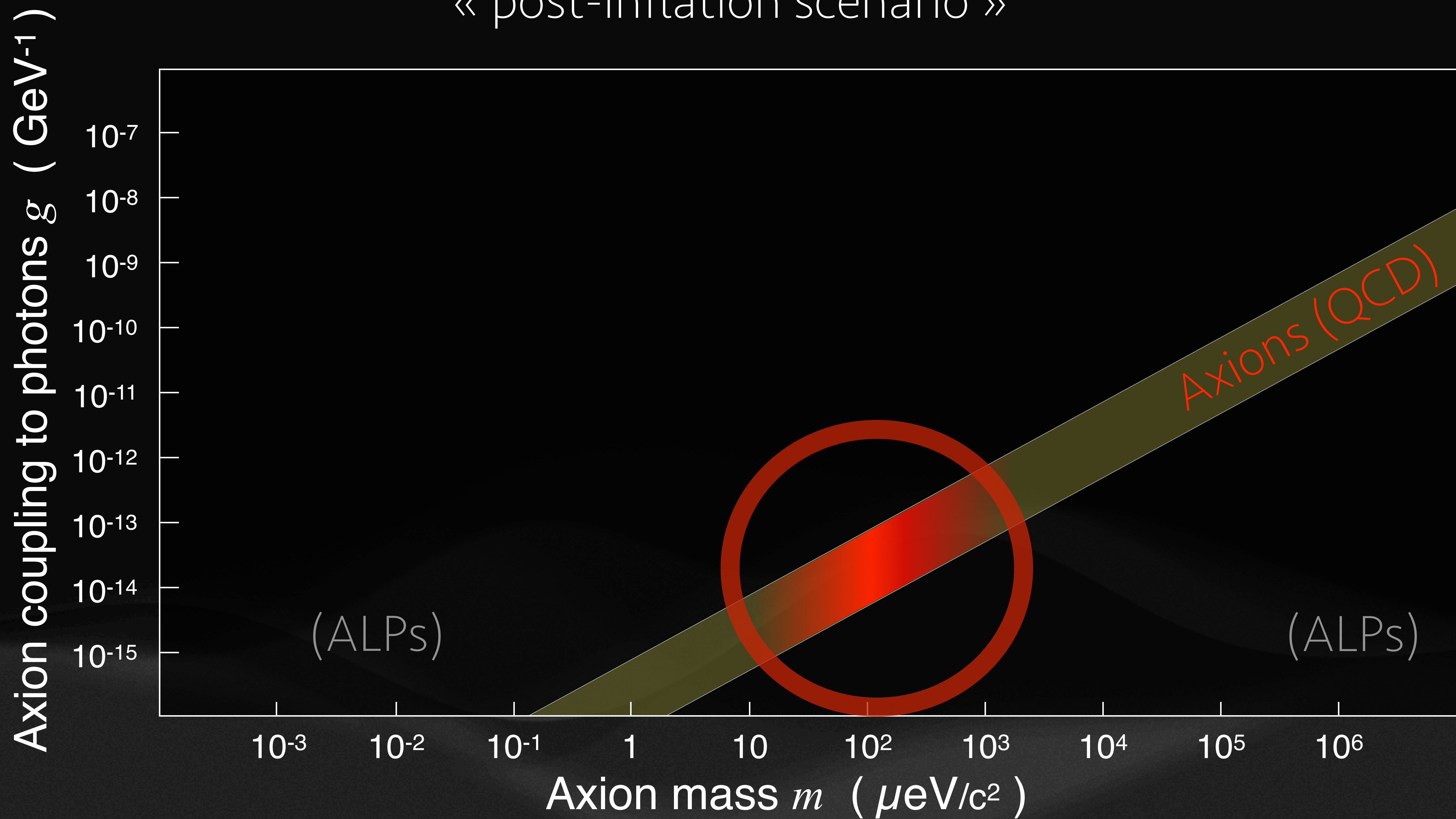
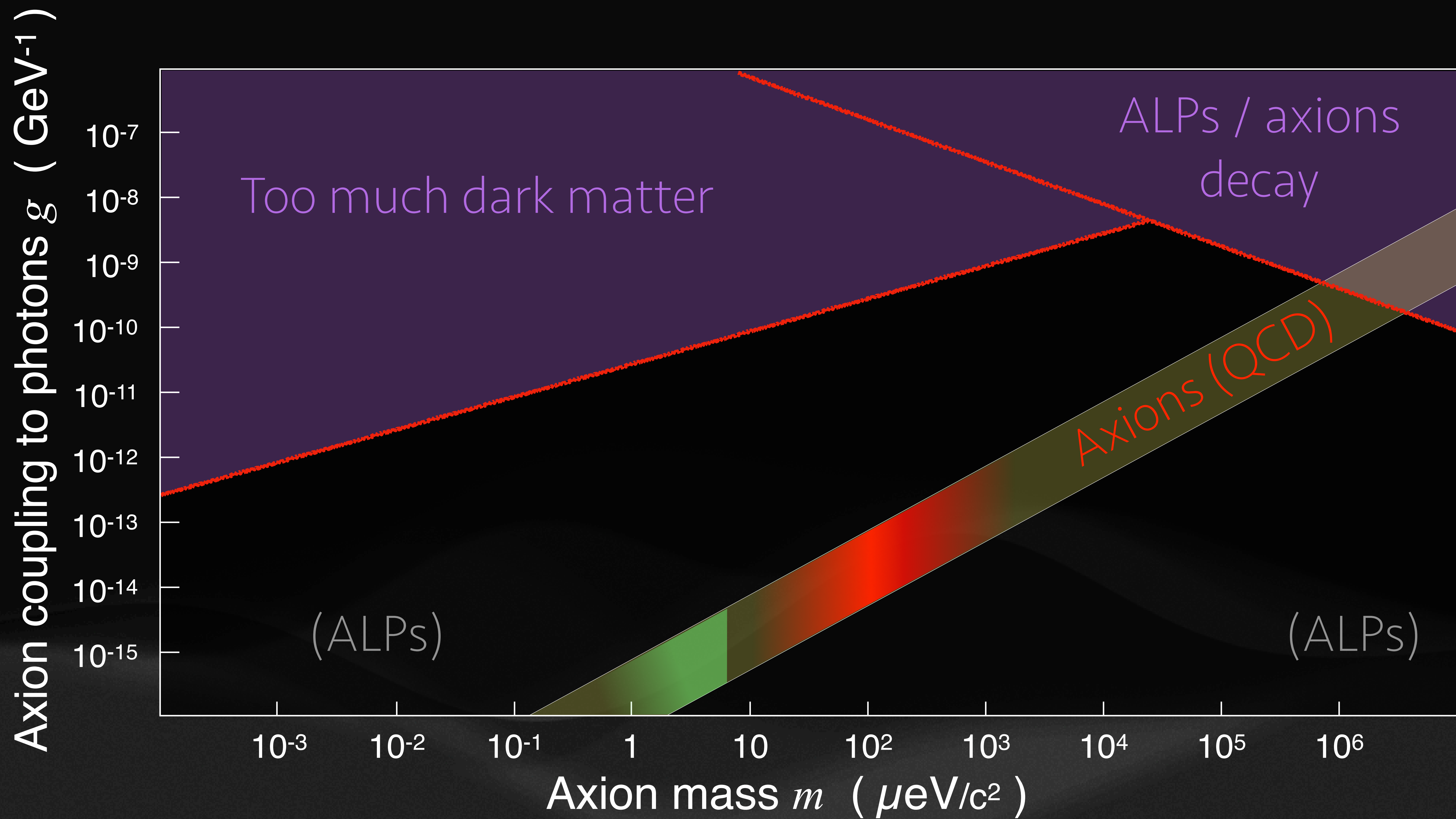
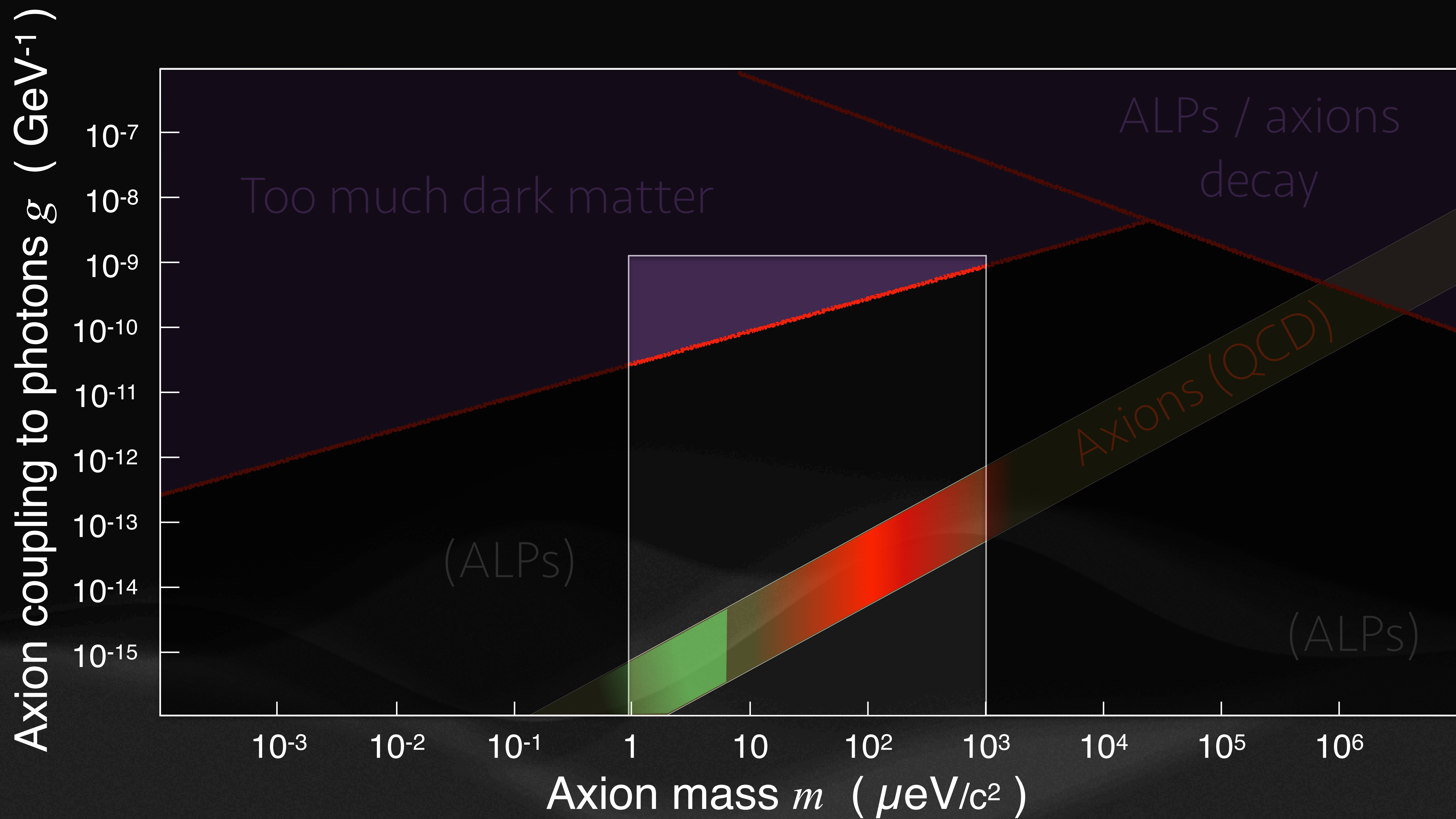


ALP dark matter



Dark matter focus region



A Galactic halo of axions

$$N_{\text{particles}} \sim \frac{10^{12}\mathrm{M}_\odot}{m} \simeq 10^{83} \times \left(\frac{10\ \mu\mathrm{eV}/c^2}{m}\right)$$

$$N_{\text{cells}} \sim \frac{\frac{4\pi}{3}p_{\max}^3 \times \frac{4\pi}{3}R^3}{2\pi\hbar^3} \simeq 2 \times 10^{59} \times \left(\frac{m}{10\ \mu\mathrm{eV}/\mathrm{c}^2}\right)^3$$

$$p_{\max} = m v_{\text{escape}} = m \times 550\ \mathrm{km/s}$$

$$R \simeq 50\mathrm{kpc}$$

$$\frac{N_{\text{particles}}}{N_{\text{cells}}} \simeq 5 \times 10^{23} \times \left(\frac{10\ \mu\mathrm{eV}/c^2}{m}\right)^4$$

$\longrightarrow$ Classical field

Mass-frequency relation

- ⋆ Axion field oscillates on scale > solar system
- ⋆ Velocity of the lab is $< 300\ \mathrm{km/s} = 10^{-3}\ c$

$$v = \frac{k\,c^2}{\omega} \qquad \omega = \frac{mc^2}{\hbar}\left(1 + \frac{v^2}{2c^2} + \dots\right)$$

- ⋆ Oscillation frequency set by axion mass

$$k = 0 \Rightarrow \omega = \frac{mc^2}{\hbar} \qquad \nu = \frac{mc^2}{2\pi\hbar} \qquad \boxed{\nu = 2.4\ \mathrm{GHz} \times \frac{m}{10\ \mu\mathrm{eV}}}$$

- ⋆ Known signal dispersion $\frac{\delta\nu}{\nu} = \frac{v^2}{c^2} < 10^{-6}$

Local phenomenology

Relevant part of the lagrangian:

Use strong magnetic field...

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g_{a\gamma}\,\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right) - g_{a\gamma}\,\phi\vec{E}\cdot\vec{B}$$

...search for new signal

Modified Maxwell's equations:

$$\vec{\nabla}\cdot\vec{B} = 0 \qquad \vec{\nabla}\cdot\vec{E} = \rho - g_{a\gamma}\vec{\nabla}\phi\cdot\vec{B}$$

$$\partial_t\vec{B} + \vec{\nabla}\wedge\vec{E} = \vec{0} \qquad \vec{\nabla}\wedge\vec{B} = \vec{\jmath} + g_{a\gamma}\dot{\phi}\vec{B} + g_{a\gamma}\vec{\nabla}\phi\wedge\vec{E}$$

Equations of motion in a constant $\vec{B}$ and homogeneous ϕ:

$$\Box\vec{e} = g_{a\gamma}\,\ddot{\phi}\left(\vec{B} + \vec{b}\right)$$

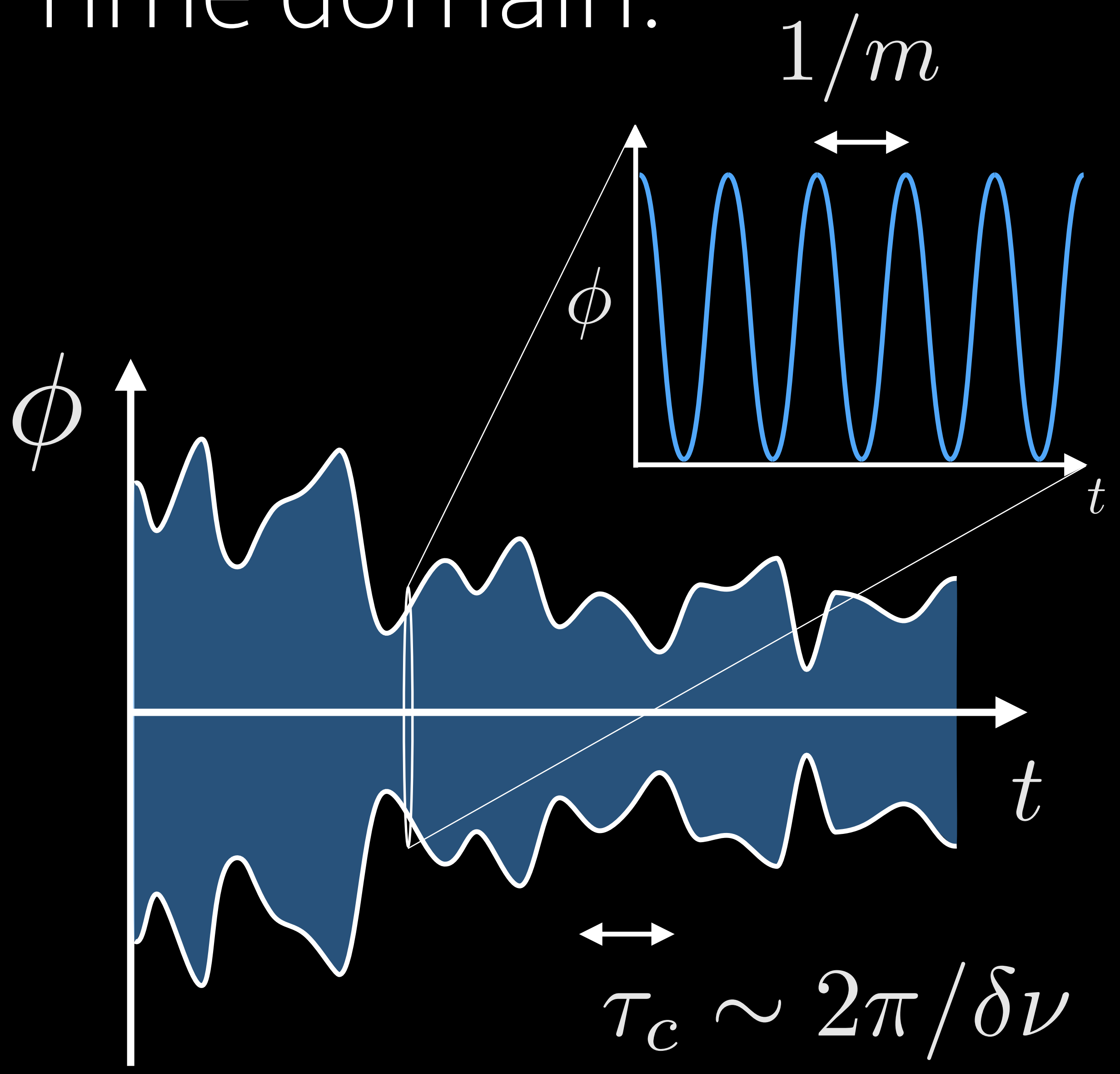
New source term

$$\Box\vec{b} = -g_{a\gamma}\,\dot{\phi}\,\vec{\nabla}\wedge\vec{b}$$

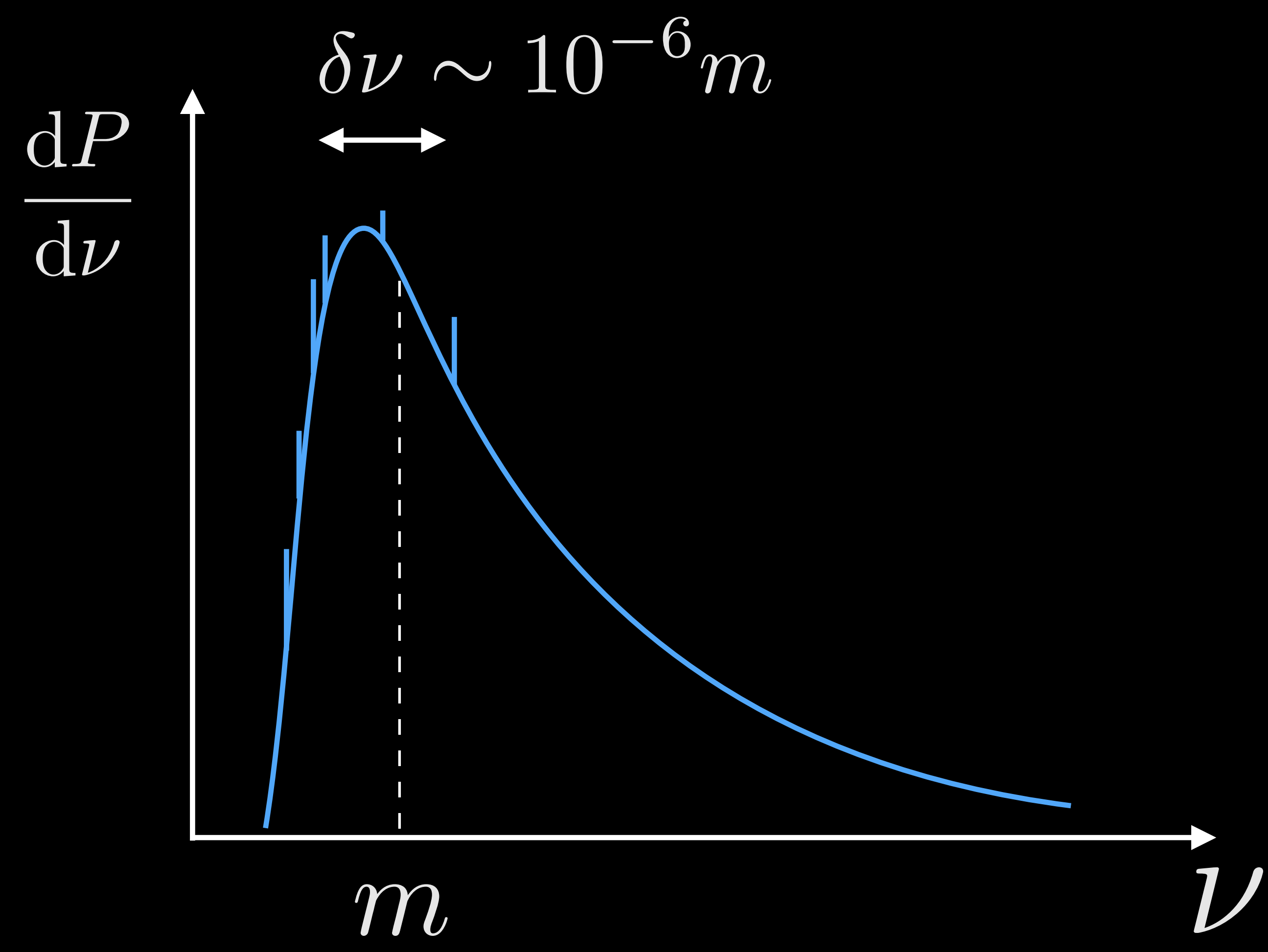
Spectral content of the signal

Coherence length: $\lambda_c \sim \dfrac{2\pi}{m\,\delta v} = 12\ \mathrm{m}\ @\ 100\ \mu\mathrm{eV} \quad \left(\ \sqrt{\langle v^2 \rangle} \sim 10^{-3}c\ \right)$

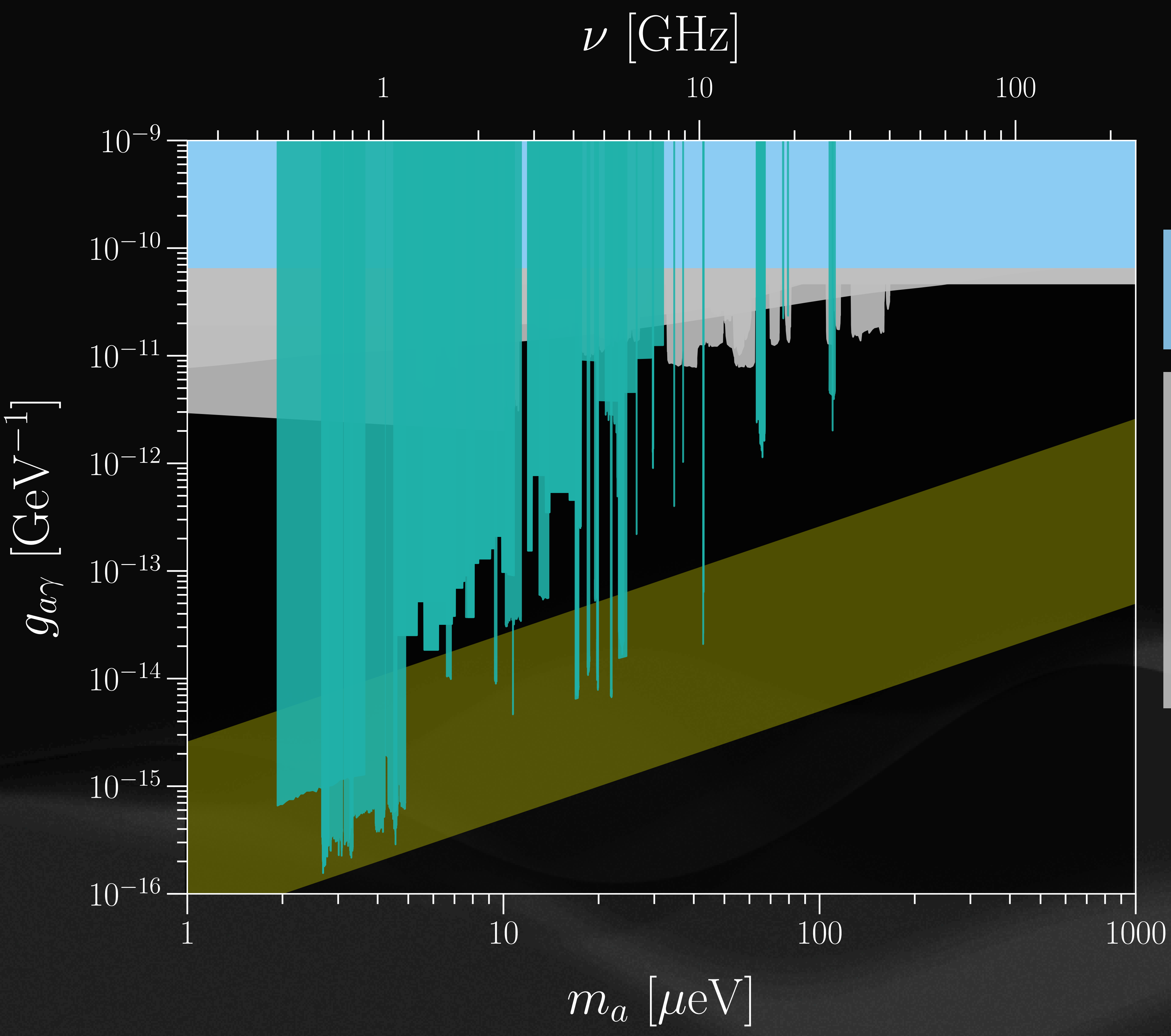
Time domain:



Frequency domain:



Dark matter focus region



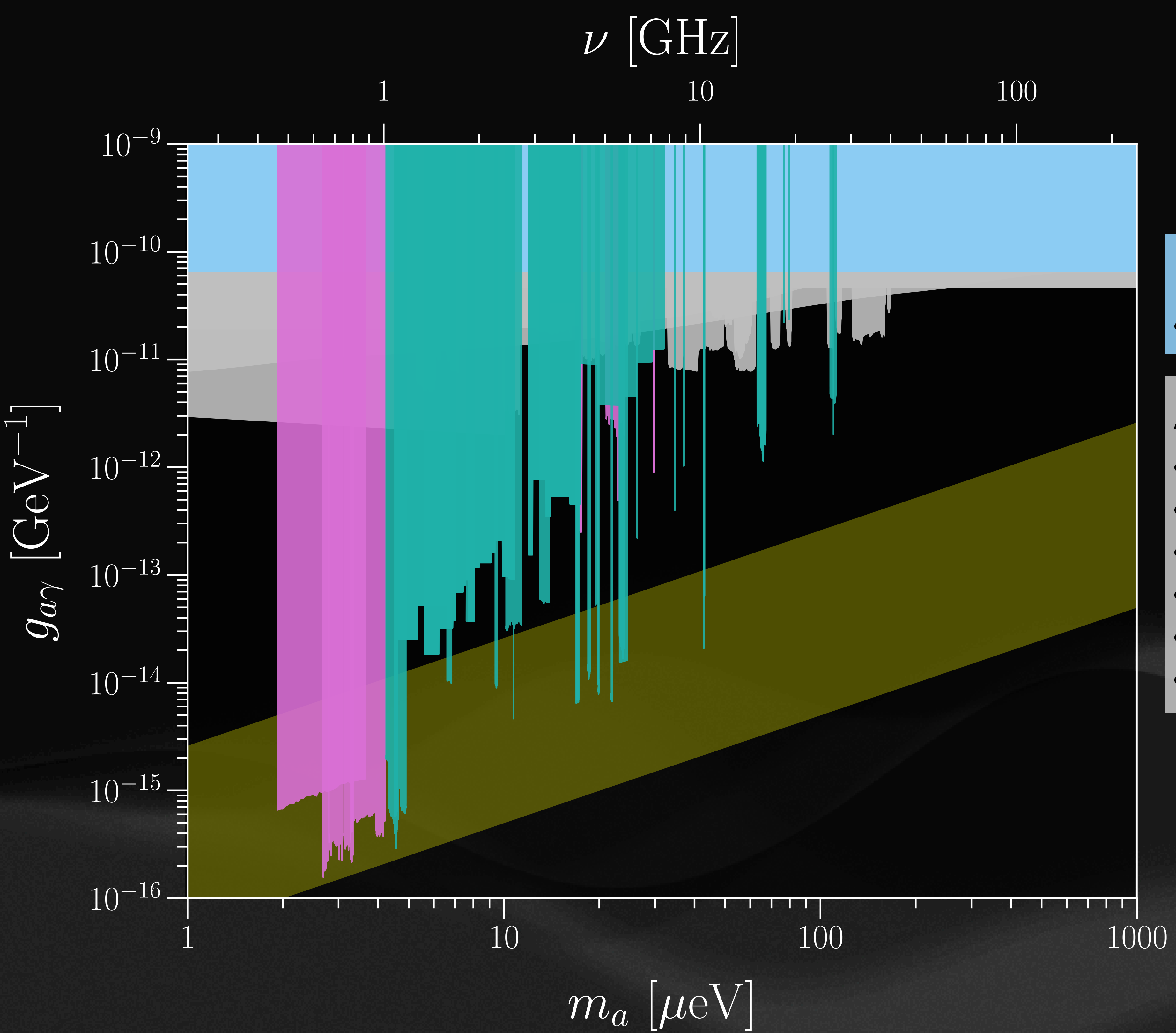
Helioscope:
- CAST

Astrophysics:
- SN1987
- HESS
- Globular clusters
- NuSTAR
- Neutron Stars
- Pulsars

Cavities:
- ADMX
- CAPP
- GrAHal
- HAYSTAC
- MADMAX
- ORGAN
- QUAX
- RADES
- RBF
- TASEH
- UF

Very nice compilation of all data:
C. O'Hare
https://cajohare.github.io/AxionLimits

Dark matter focus region



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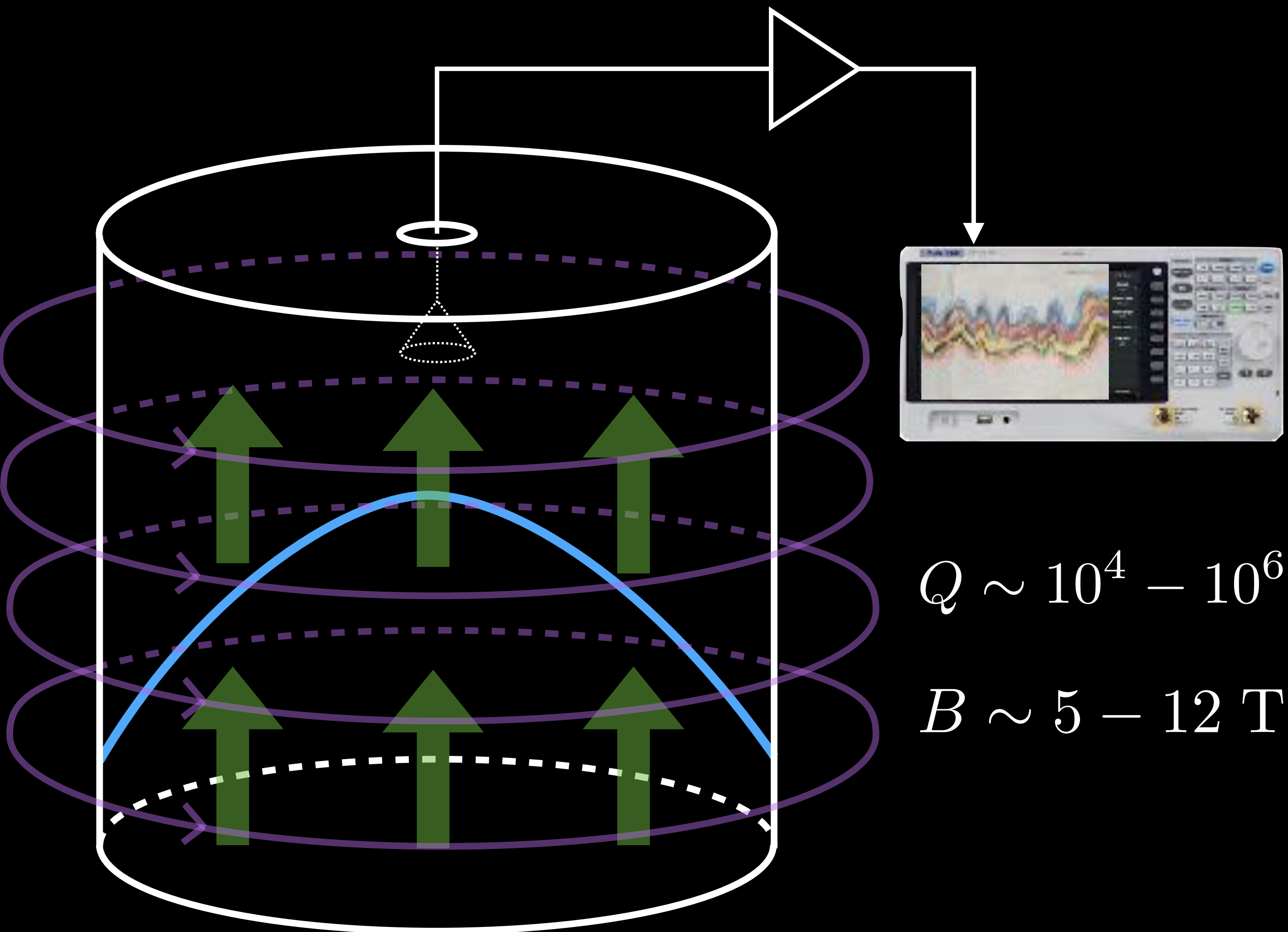
Resonant searches with cavities



$Q \sim 10^4 - 10^6$

$B \sim 5 - 12\ \mathrm{T}$

Strong magnetic field $\vec{B}$

High-Q cavity: enhance $\vec{E}$ signal

Signal strength:

$$P_{\mathrm{signal}} \propto g_{\mathrm{a}\gamma}^2 \, \frac{\rho_{\mathrm{a}}}{m} \, B^2 \, V \, Q$$

Sensitivity:

$$\sigma_{\mathrm{noise}} \sim k_{\mathrm{B}} T_{\mathrm{sys}} \sqrt{\frac{\Delta\nu}{\Delta t}}$$

High Q but narrow:

- Require variable geometry
- Tedious scan in mass

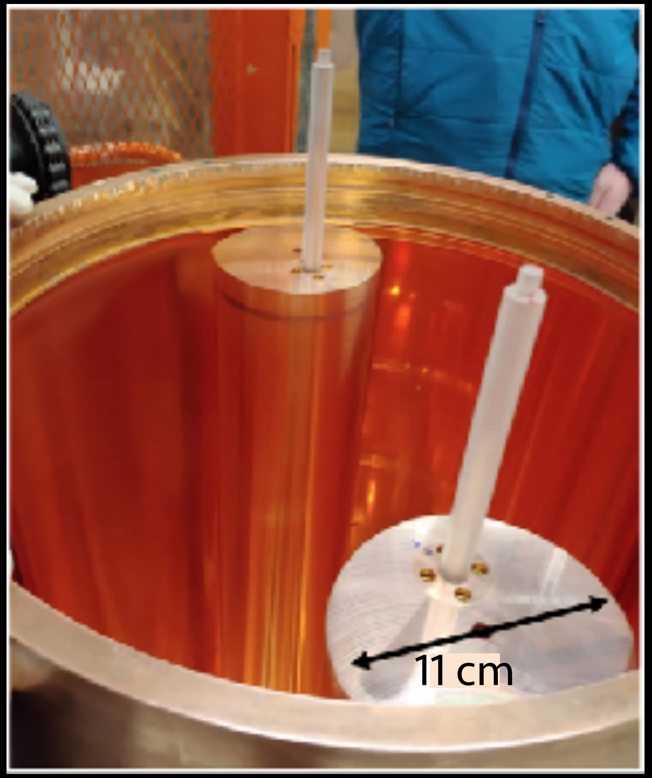
ADMX

ADMX: example among many of a resonant cavity

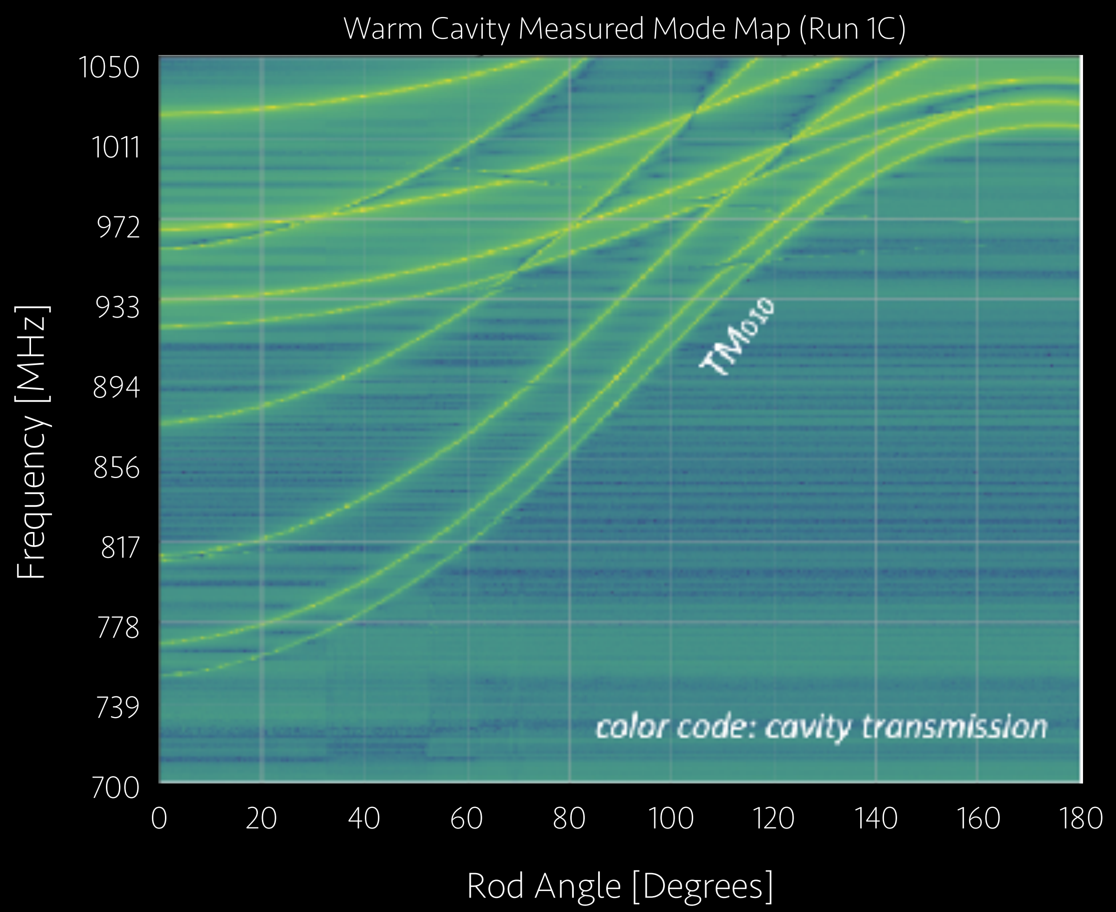
Magnetic field: 7.6 T

Cryostat w/ cavity

Cavity & tuning rod



Cavity resonant modes

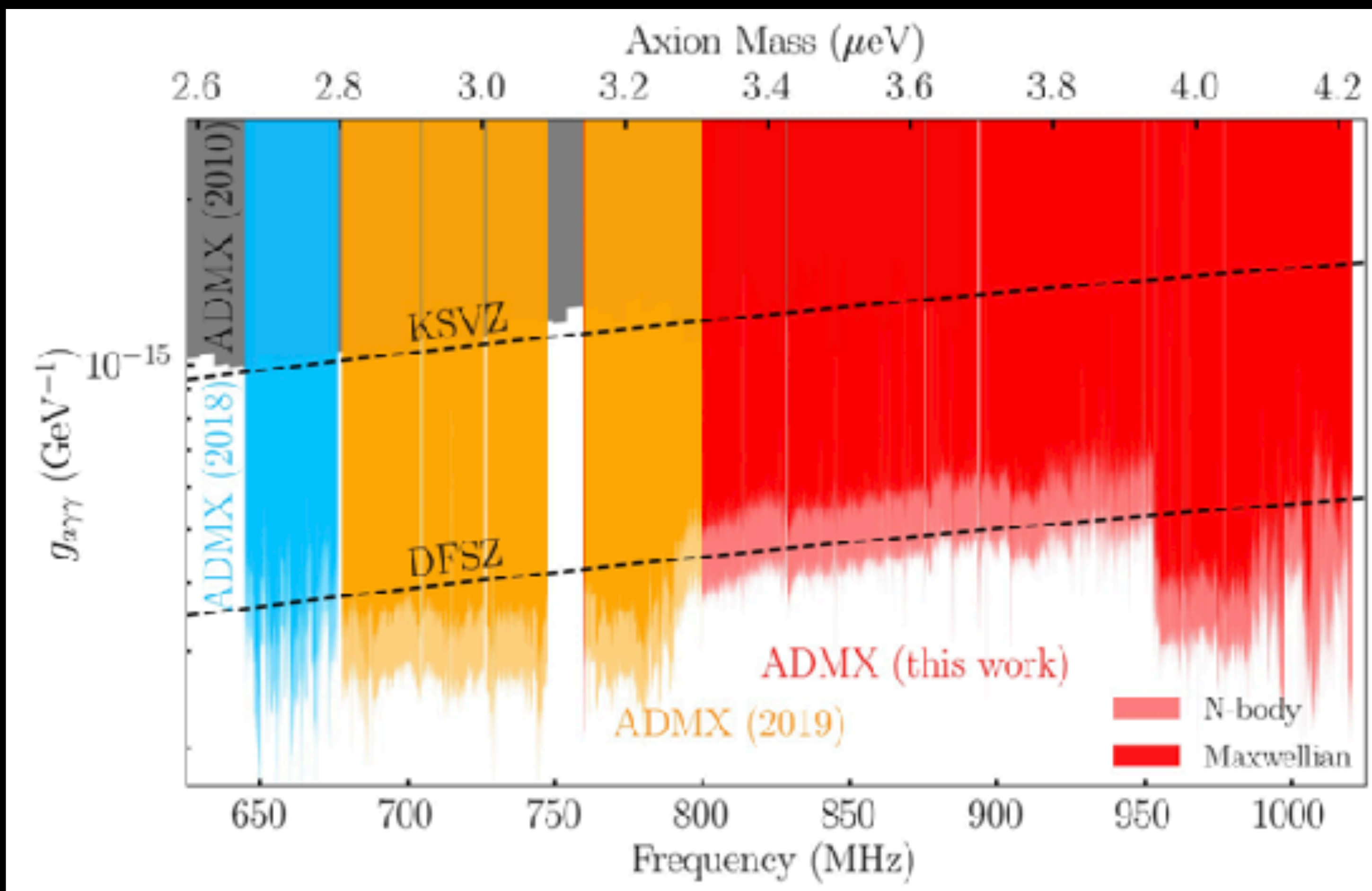


Talk by E. Daw this morning

Figures from S. Knirck

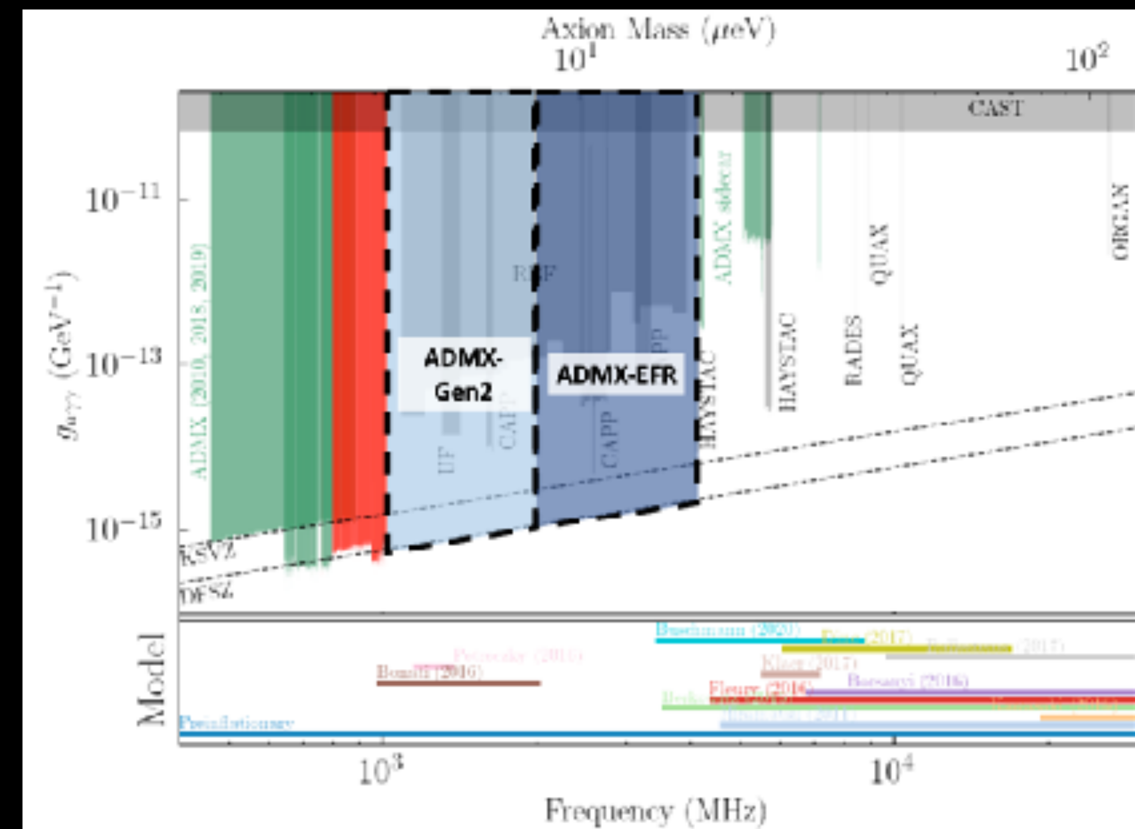
ADMX exclusion curves

2022 run : ~50 days $T_{\text{sys}} \sim 0.5\ \text{K}$



ADMX collab., PRL 127 (2021)

Future reach



Mass predictions

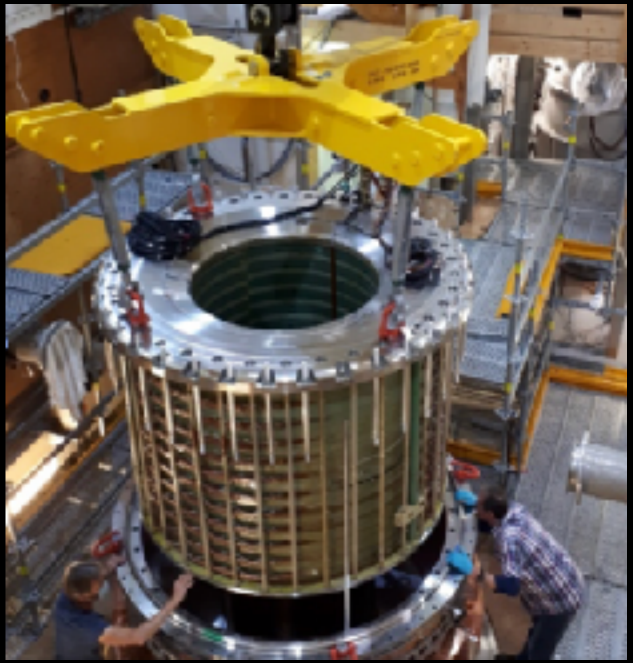
Should we try more broadband methods in // ?

Think of particle colliders : ⟷ Discovery ↓ Precision physics

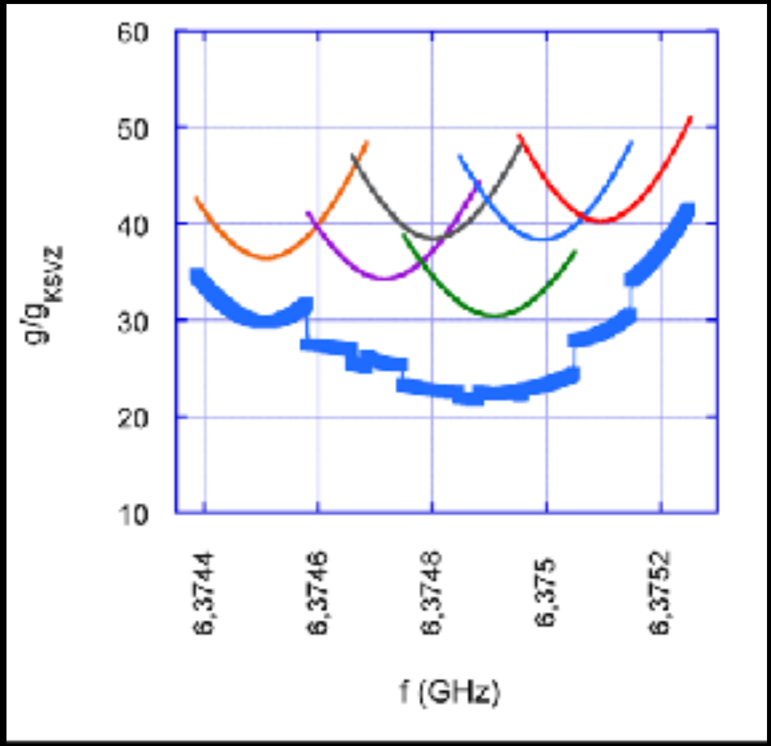
Towards higher masses

Challenge: smaller cavities
On example: GaHal in Grenoble

14 T	Q= 37 000
Ø 36 mm	6 days
6.375 GHz	$T_{\mathrm{sys}} \sim \mathrm{few\ K}$



Superconducting magnet



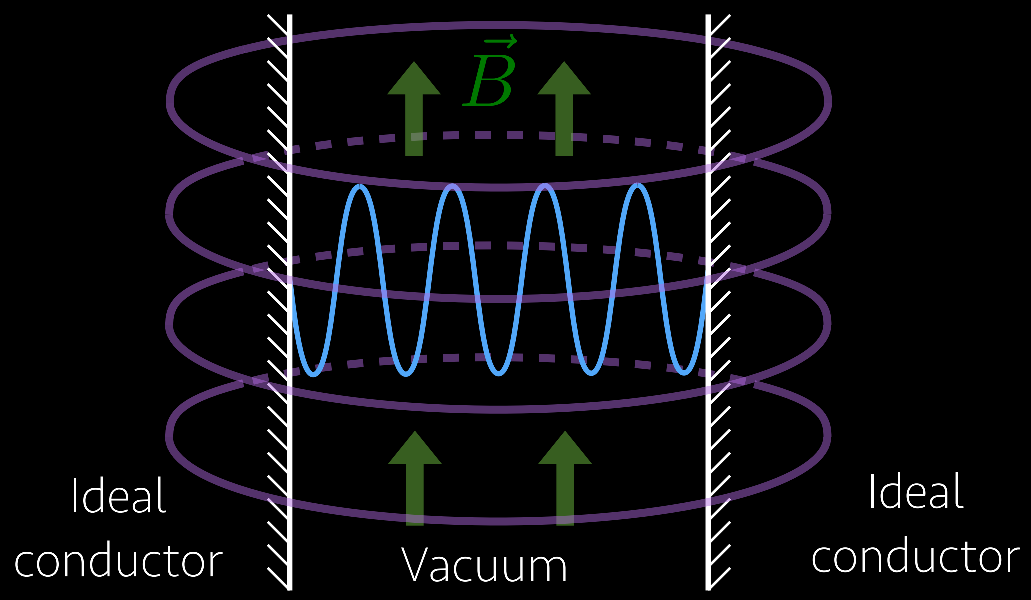
GraHal collab., arXiv:2110.14406
GraHal-CAPP, *Front.in Phys.* 12 (2024) 1358810

Future: collaboration with CAPP: Plan to 8mm / 42 T / 100 mK

Will reach QCD sensitivity at 12.78 GHz / 52.5 μeV

Even shorter distances...

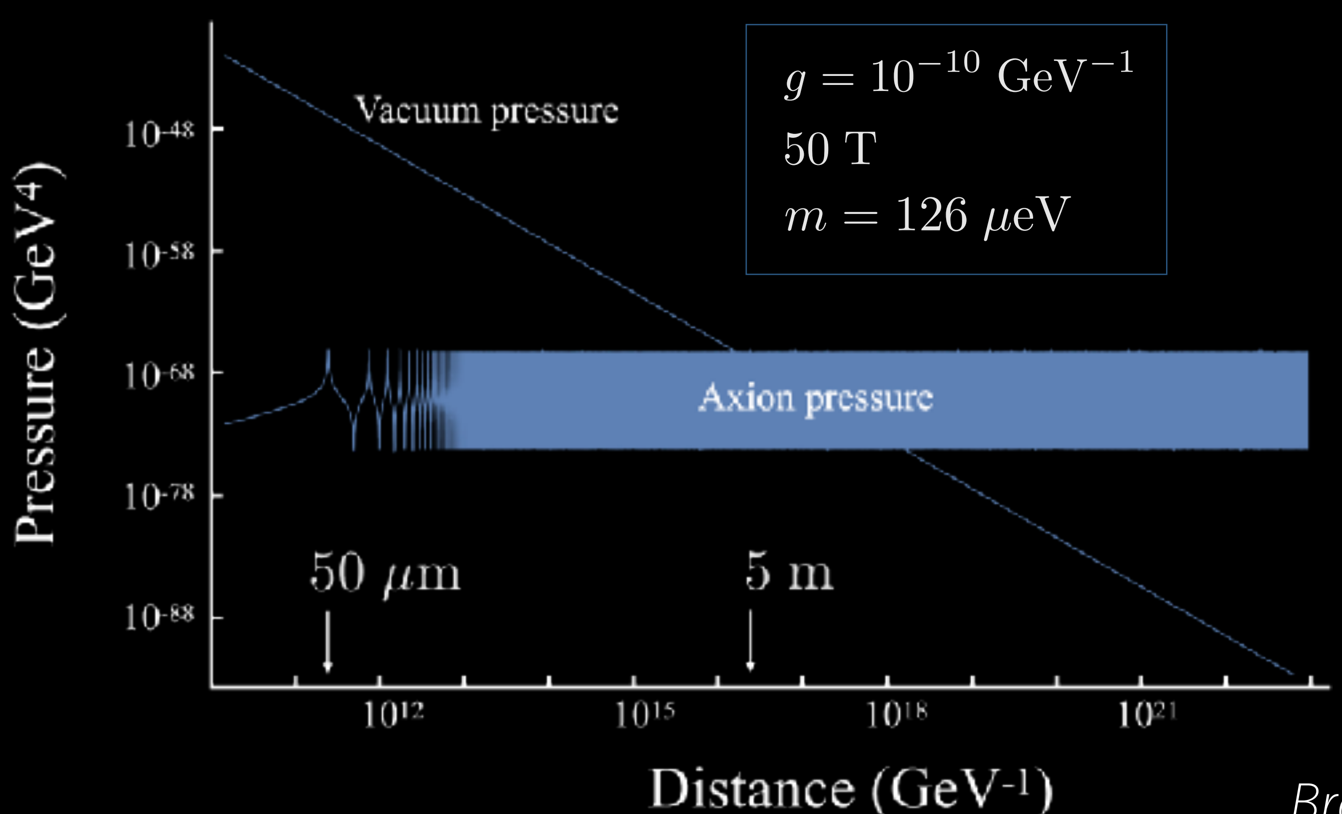
An empty cavity has Casimir pressure

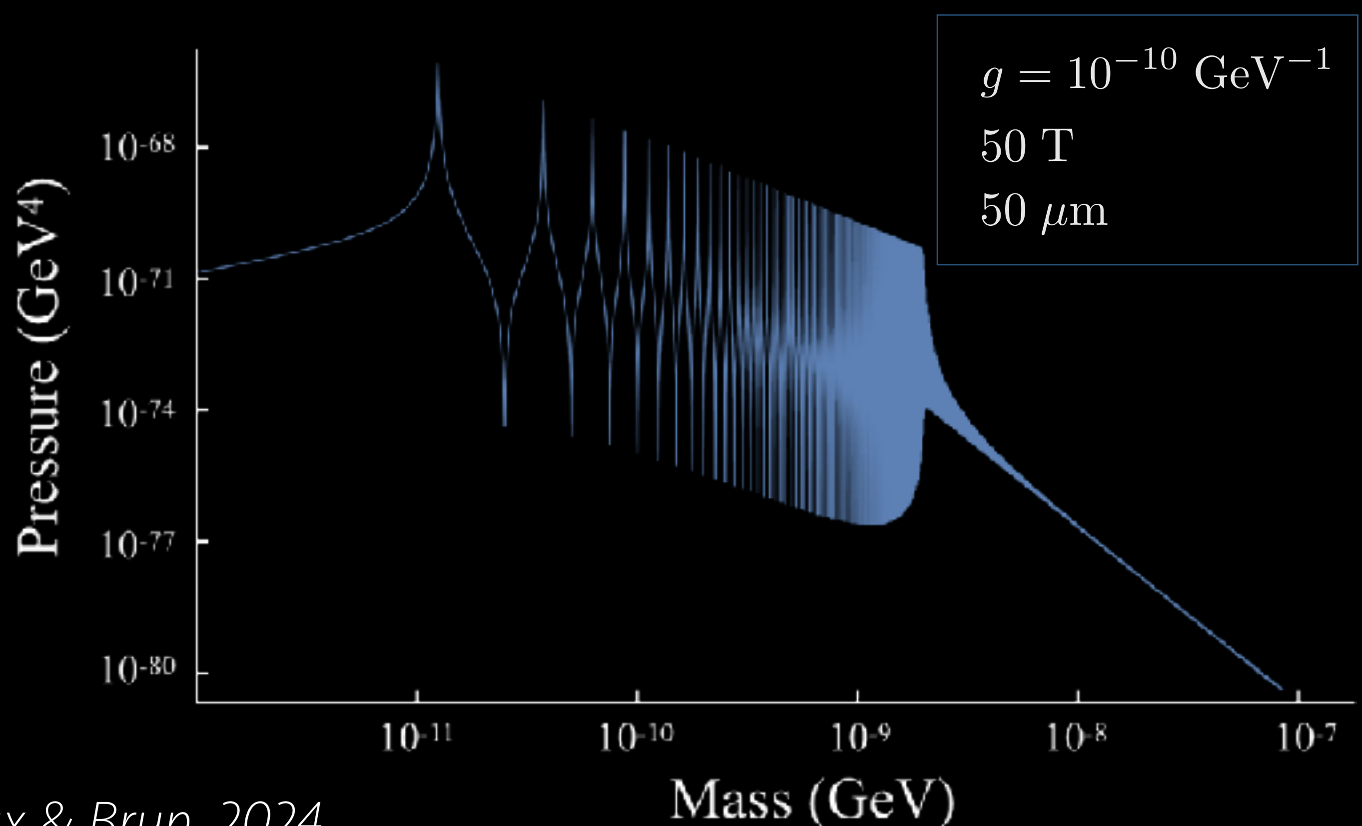


Axion / vacuum modes coupling leads to resonances for distances:

$$d_n = \frac{(2n+1)\pi}{m}$$

Resonances regularized by dissipation

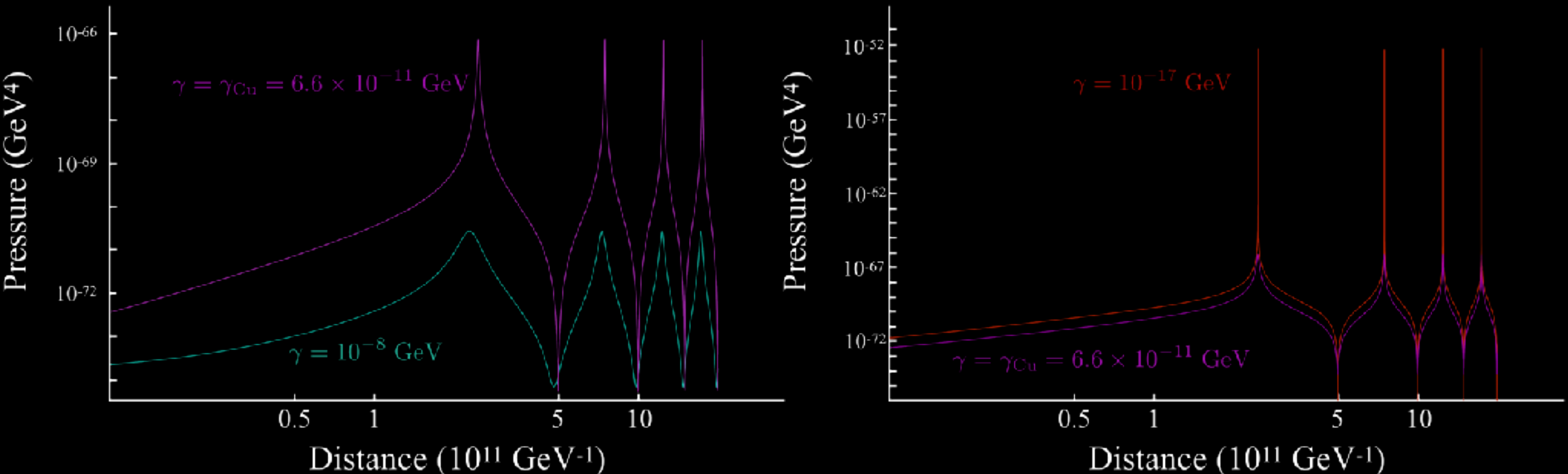




Brax & Brun, 2024

Axions & Casimir pressure

Resonances can be made very narrow w/ right material

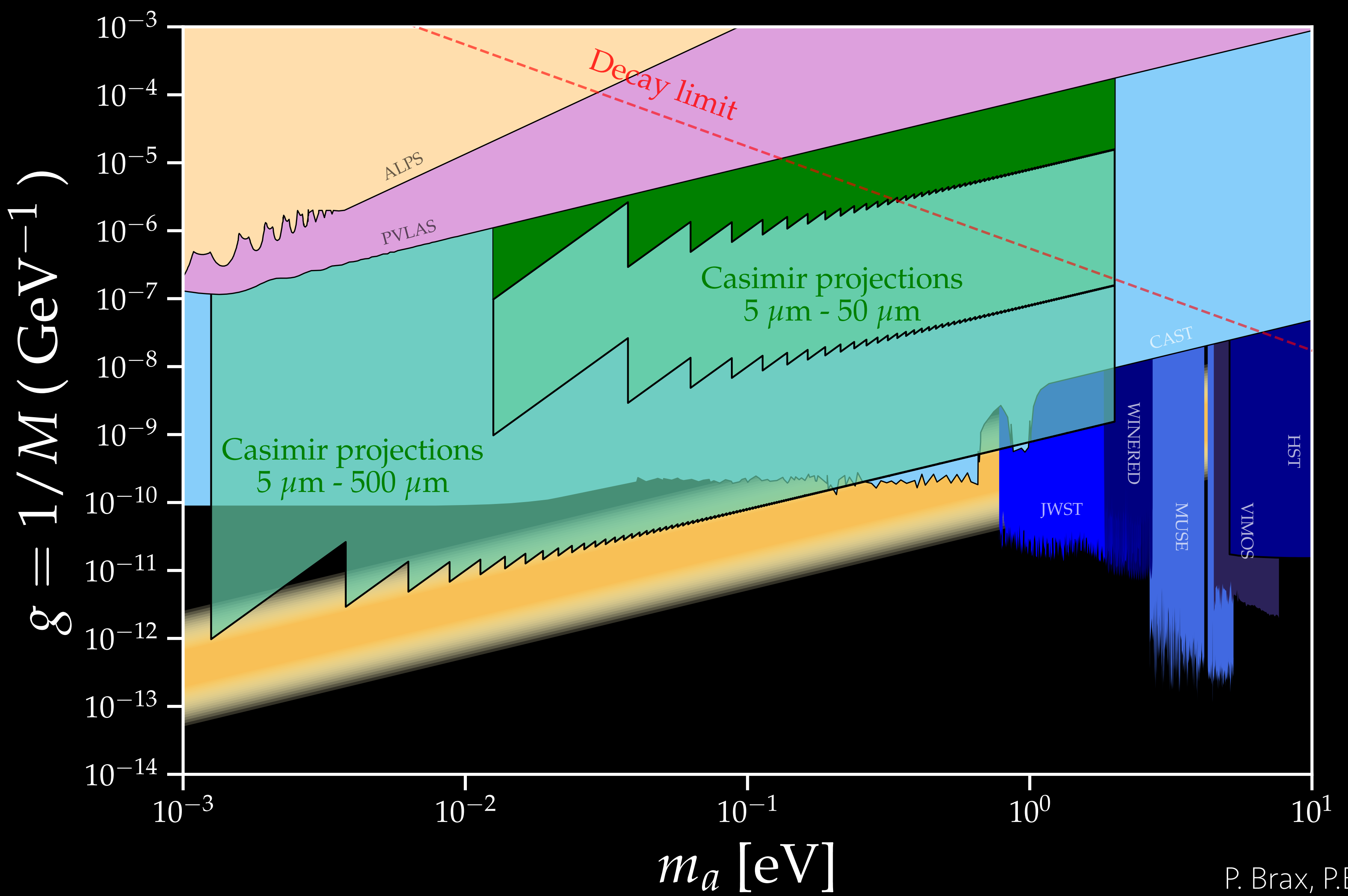


γ : damping factor in the plaque $\quad \gamma = \dfrac{\omega^2_{\text{plasma}}}{\sigma}$

Axions & Casimir pressure

Some (optimistic) prospects...

50 T $\qquad \dfrac{P_{\text{axion}}}{P_{\text{vacuum}}} = 1\%$

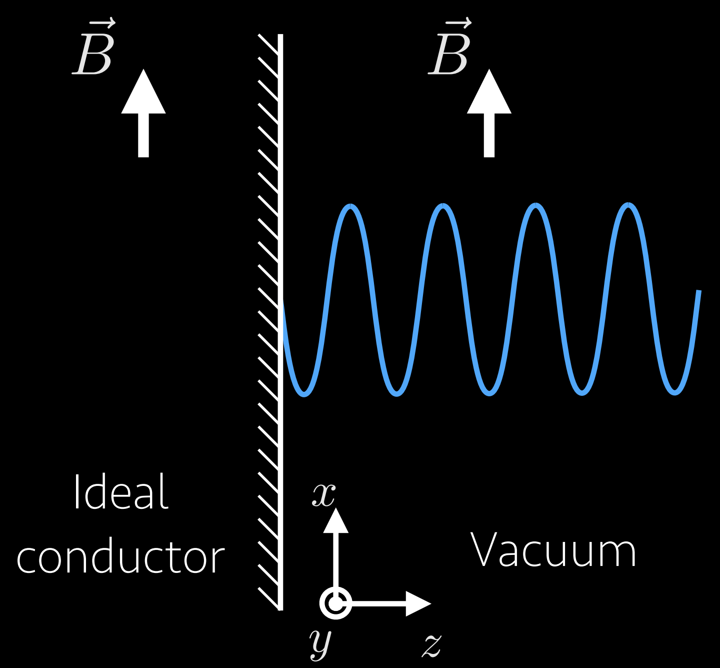


P. Brax, P.B., PRD 127 (2024)

P. Brax, P.B., PRD 112 (2025)

Work in progress w/ P. Brax & A. Alachkar

Towards broadband searches



Axion = long wavelength ($\boldsymbol{k} \sim \mathbf{0}$) excitation

$$\vec{E} = i\phi_0\, g_\gamma\, B_x\, e^{-imt} \vec{e}_x$$

Field must cancel on the interface:

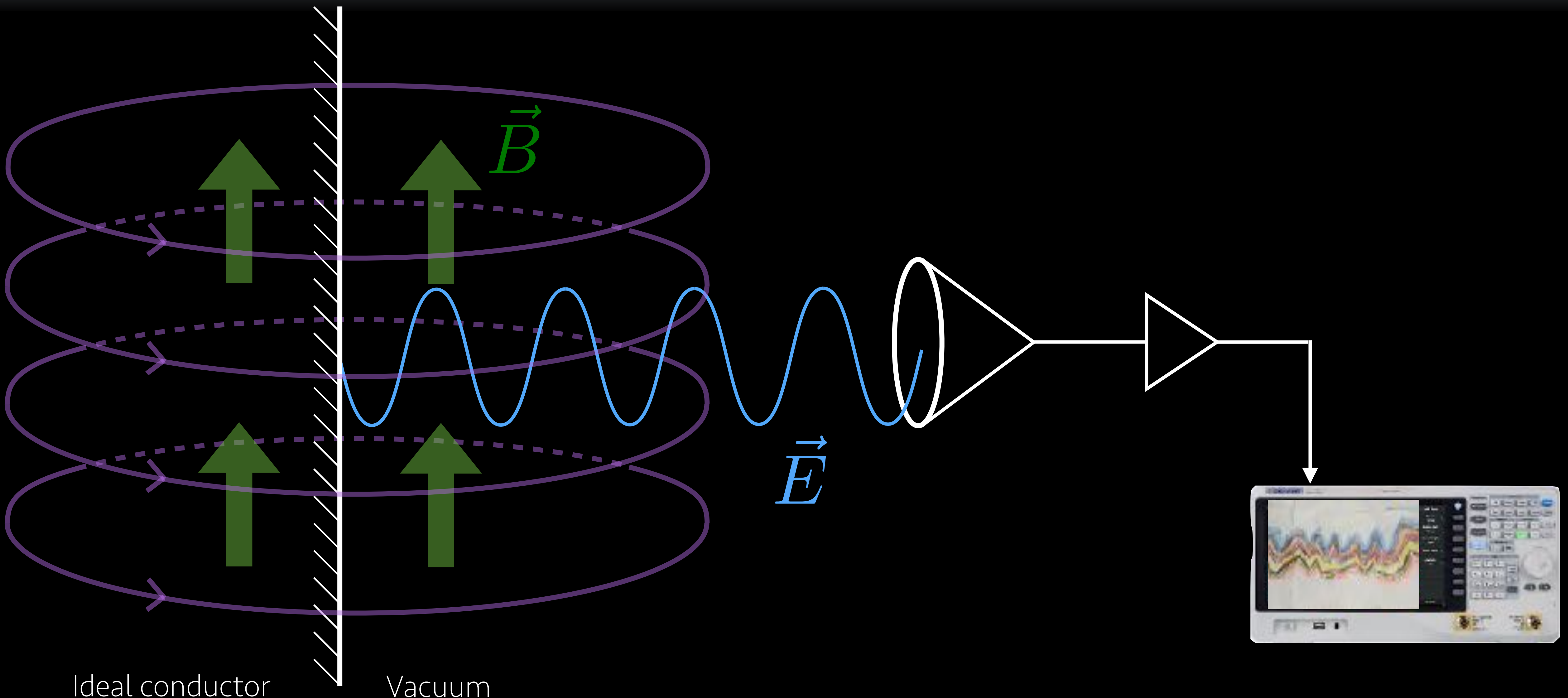
$$\vec{E}_{\text{total}} = \vec{E} + \vec{E}_{out}$$

$\Rightarrow$ emitted signal: $\vec{E}_{out} = -i\phi_0\, g_\gamma\, B_x\, e^{-i(mt-kx)} \vec{e}_x$

Output power:

$$\Pi = 2.76\times10^{-30}\ \mathrm{W/m^2} \left(\frac{\rho_{\mathrm{CDM}}}{\mathrm{GeV/cm^3}}\right) \left(\frac{\mathrm{B}}{1\ \mathrm{T}}\right)^2 \left(\frac{\mathrm{m}}{100\ \mu\mathrm{eV}}\right)^{-2} \left(\frac{\mathrm{g}}{10^{-14}\ \mathrm{GeV}^{-1}}\right)^{-2}$$

Towards broadband searches

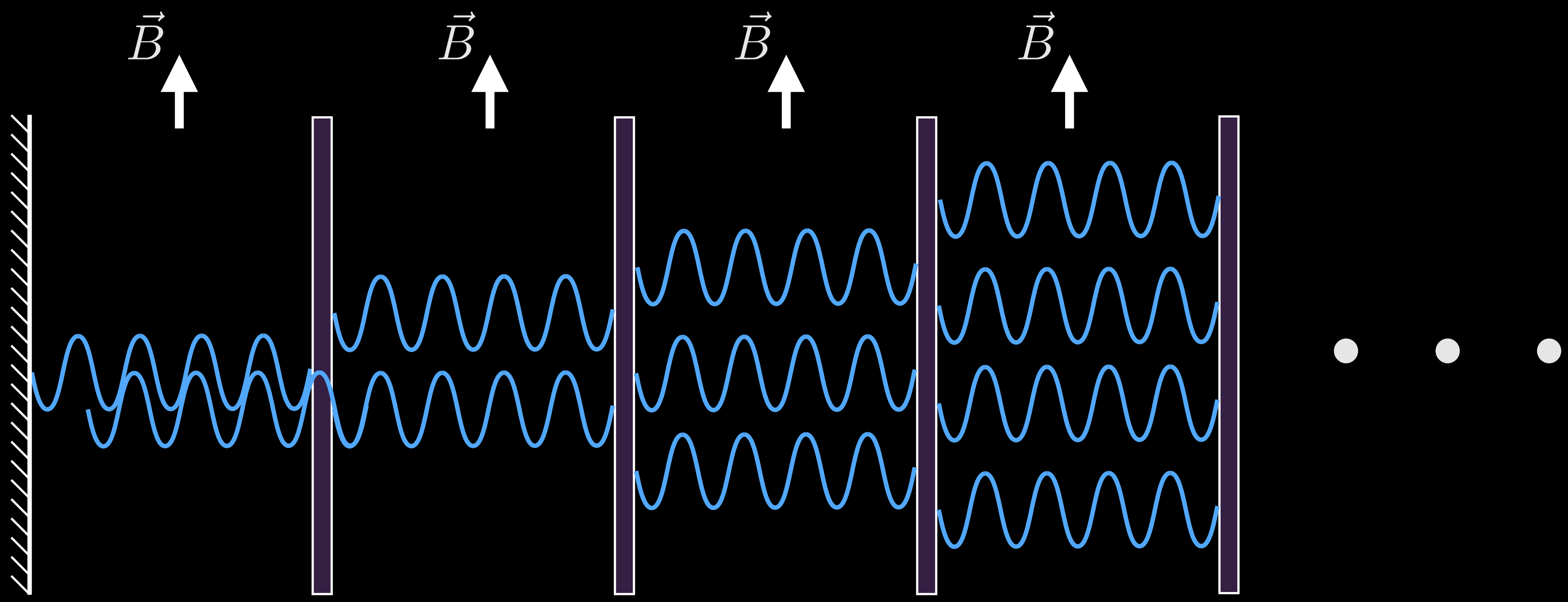


Weak signal, no quality factor:

need a way to boost the signal

MadMax

Principle: semi-transparent materials used to increase signal



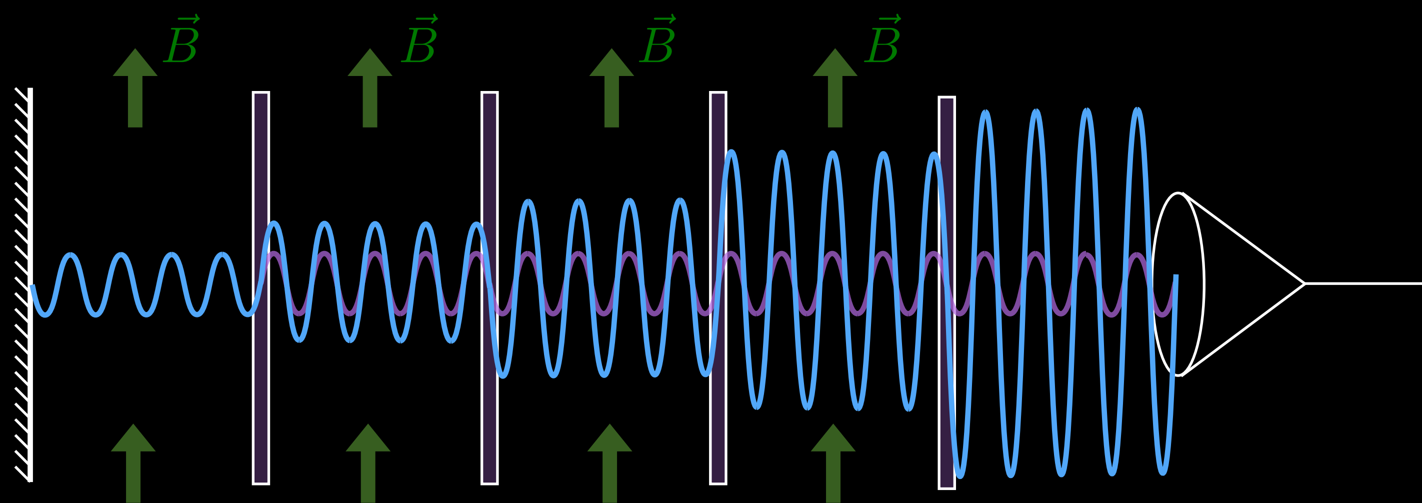
Boost depends on spacing: adjustable broadbandness

Expected boost factor up to 10^5

Talk by D. Leppla-Weber this morning

MADMAX

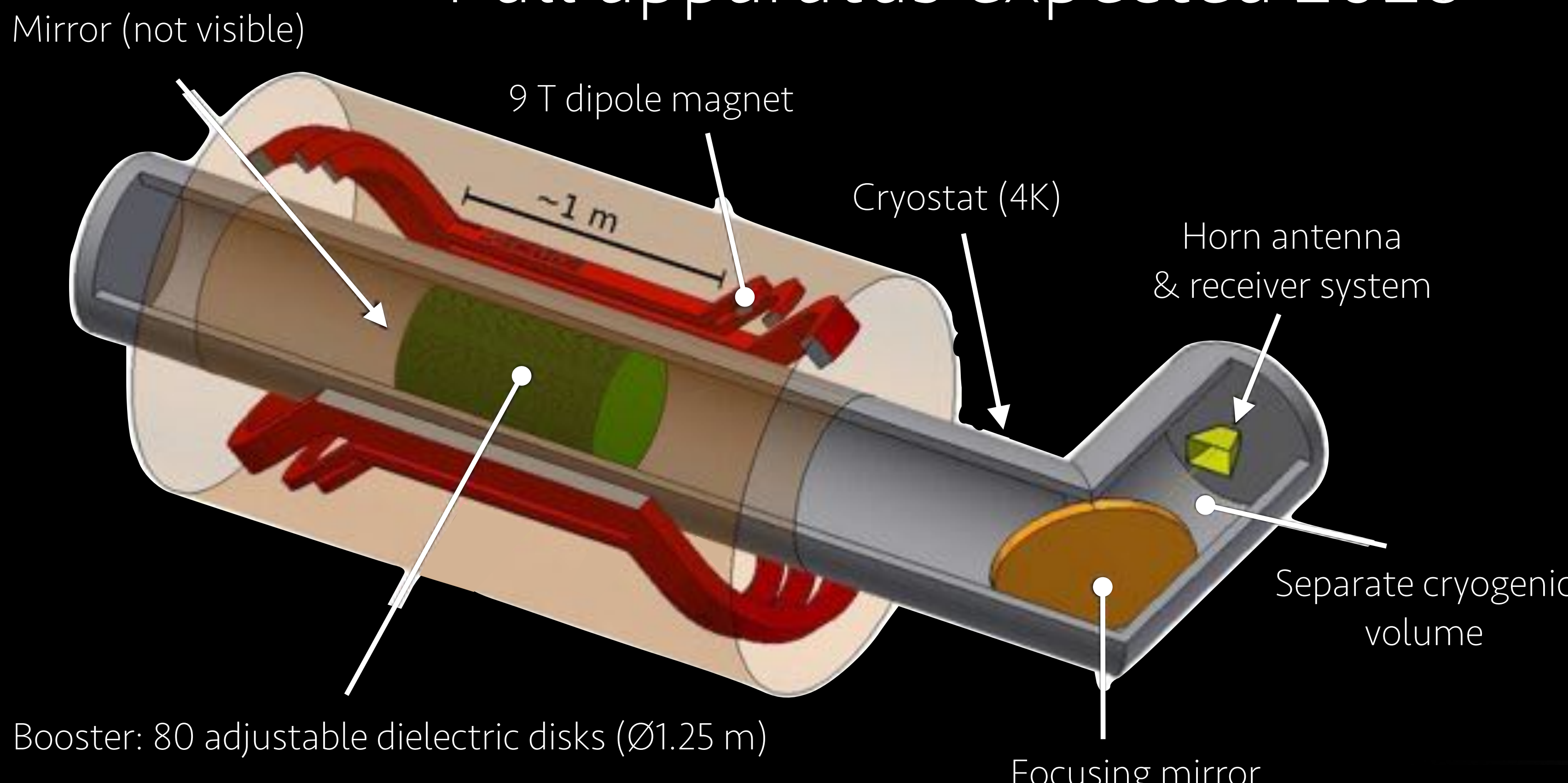
Principle: semi-transparent materials used to increase signal

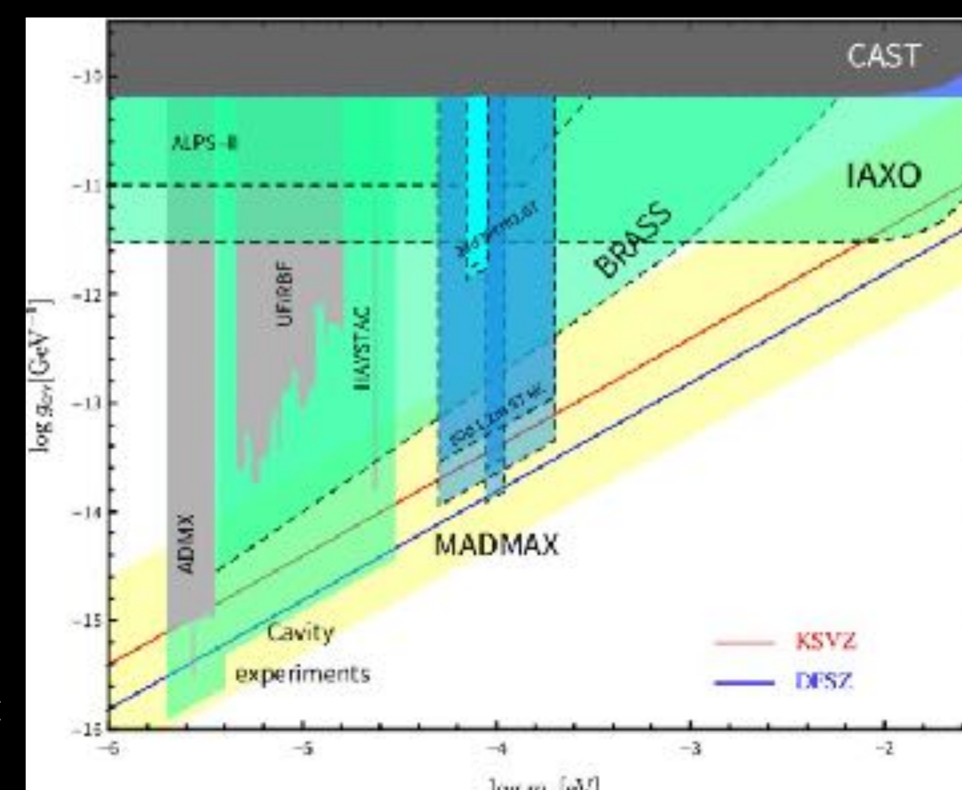


Boost depends on spacing: adjustable broadbandness

Expected boost factor up to 10^5

Full apparatus expected 2028





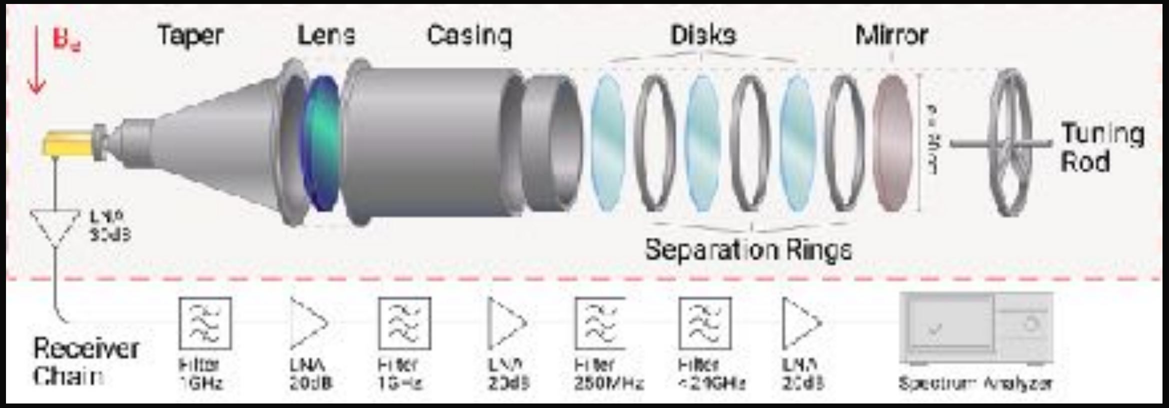
MADMAX collab., Eur.Phys.J.C 79 (2019)

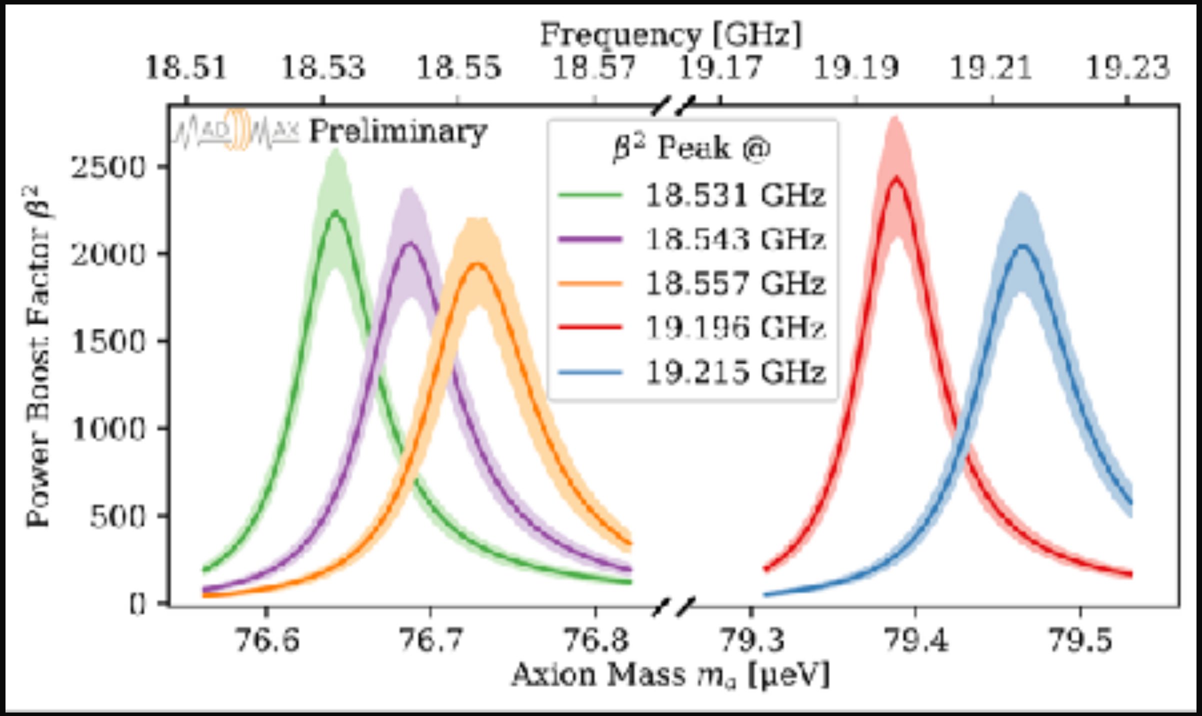
MADMAX run at CERN

Test run in a 1.6 T magnet

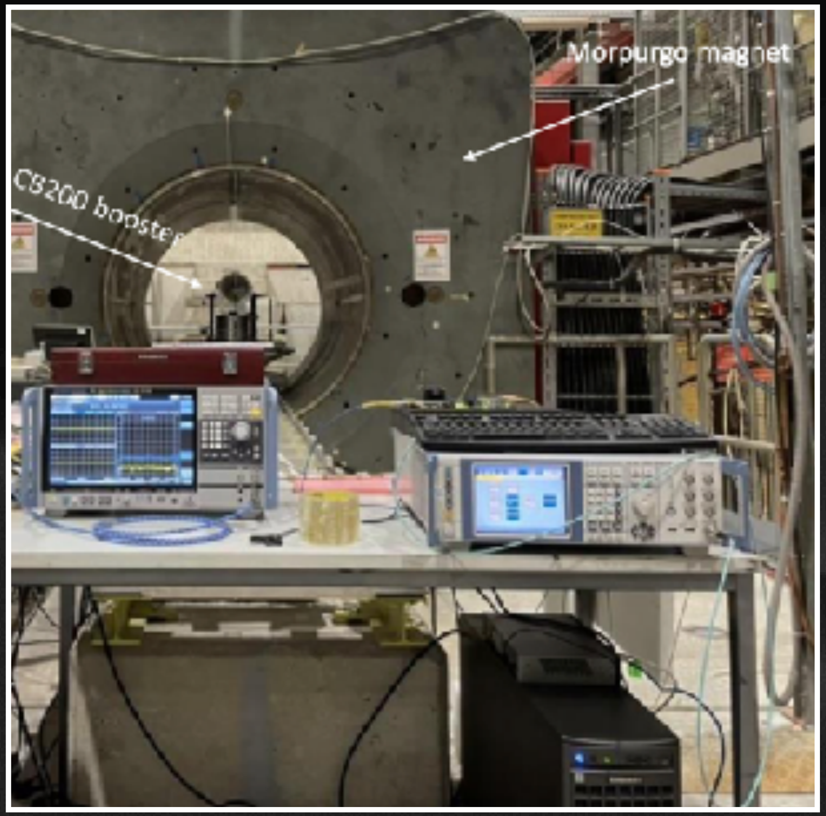
Ø 200 mm

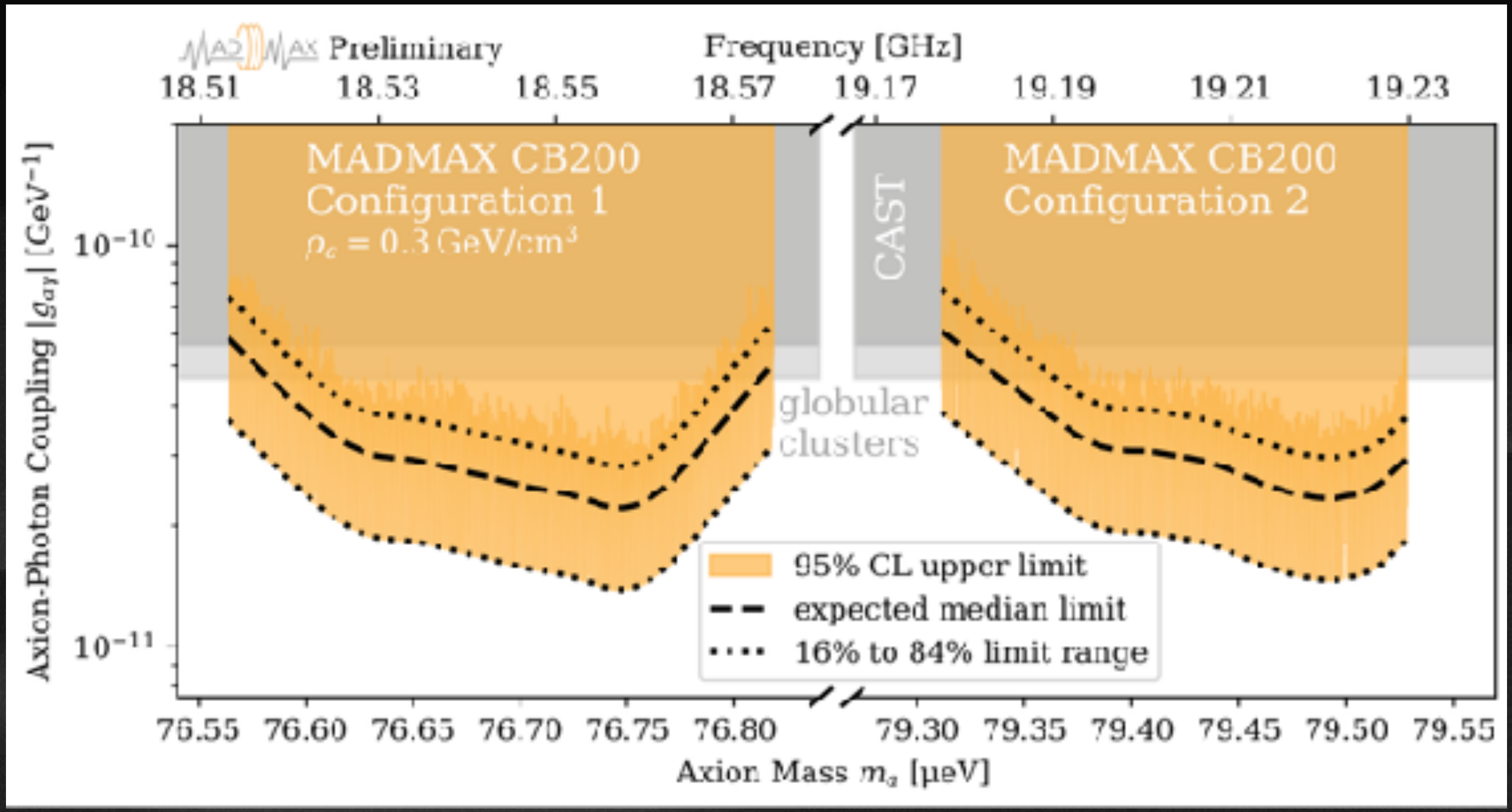
14.5 days $T_{\mathrm{sys}} = 530\ \mathrm{K}$





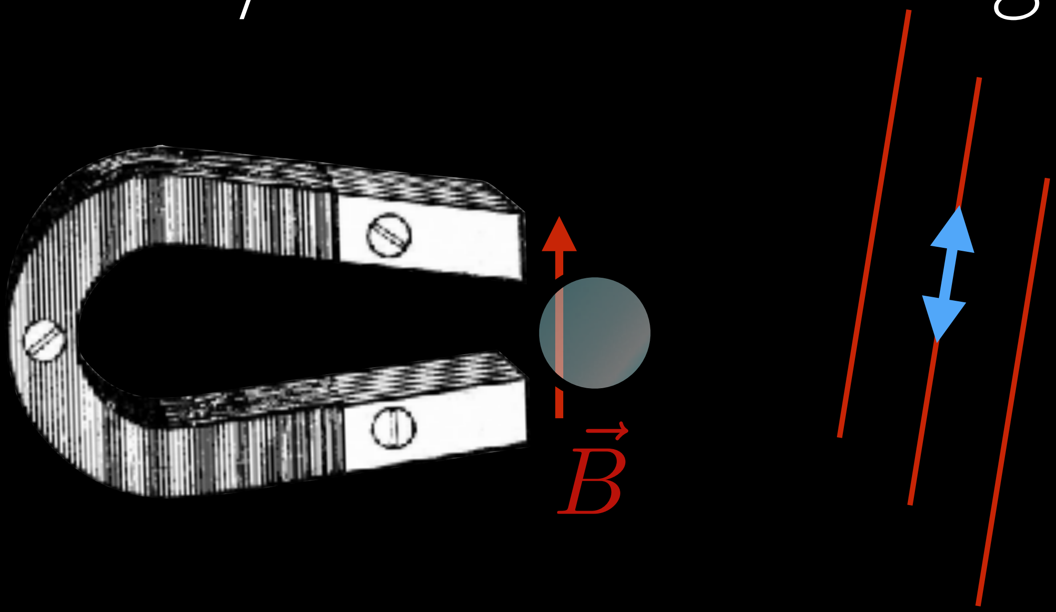
MADMAX collab., arXiv:2409.11777





Broadband concentrators

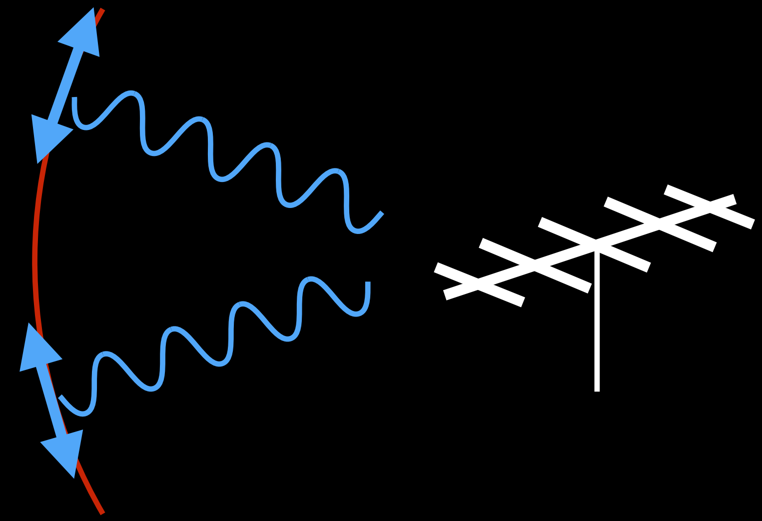
Everywhere in the background : $\phi = \phi_0 e^{-imt}$



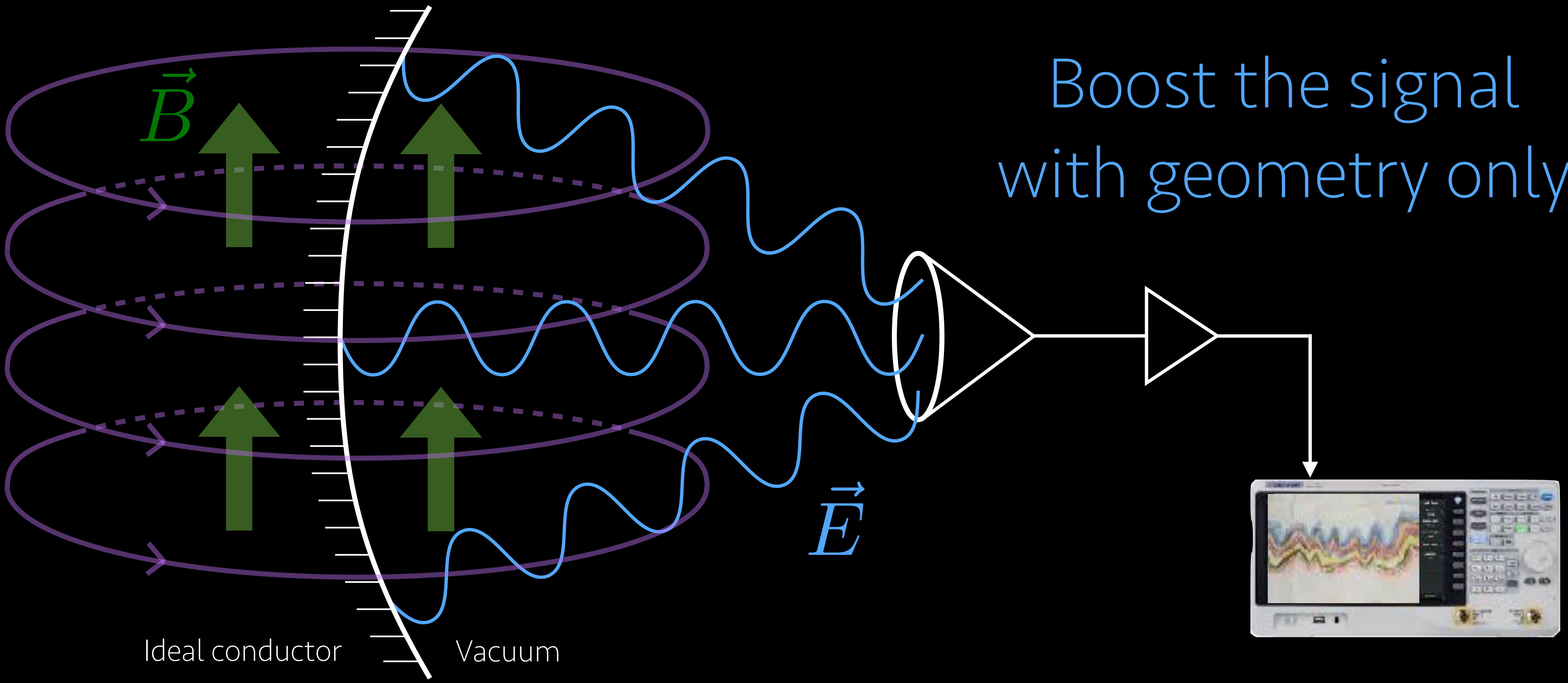
$$g_\gamma \, \phi \, F_{\mu\nu} \tilde{F}^{\mu\nu} \propto g_\gamma \, \phi \, \vec{E} \cdot \vec{B}$$

small oscillating electric field along each B-field line

Possible lab experiment :
bend field lines,
search for excess power



Broadband concentrators



Boost the signal with geometry only

« dish antenna » setups

D. Horns *et al.*, JCAP04 (2013) 016

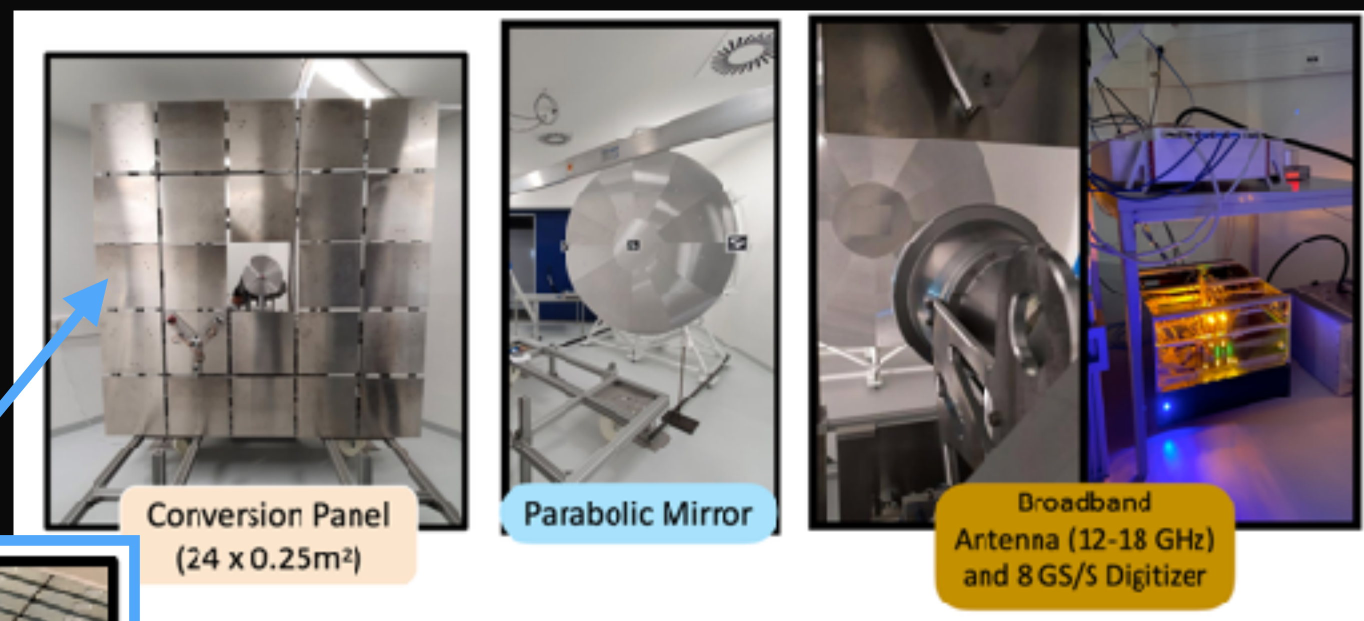
Nice paper on reflector/antenna coupling:
J. Gué *et al.*, Phys.Rev.D 110 (2024)

Same radiometer sensitivity

Signal: $P_{\mathrm{sig}} \propto B^2\ S\ \dfrac{g_{\mathrm{a}\gamma}^2}{m^2}$

BRASS

Broadband Radiometric Axion SearcheS:
Plane of emission + secondary parabolic concentrator

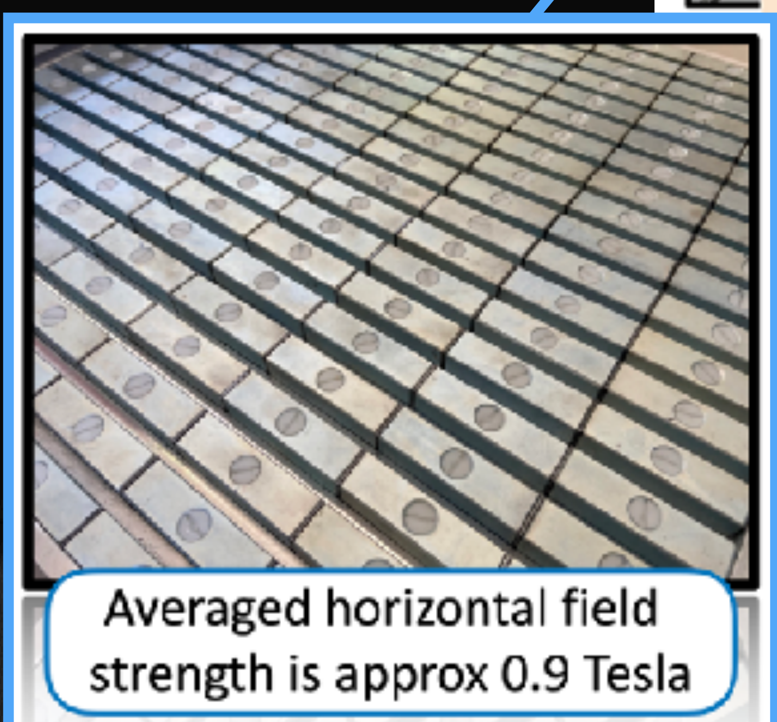


0.9 T magnet

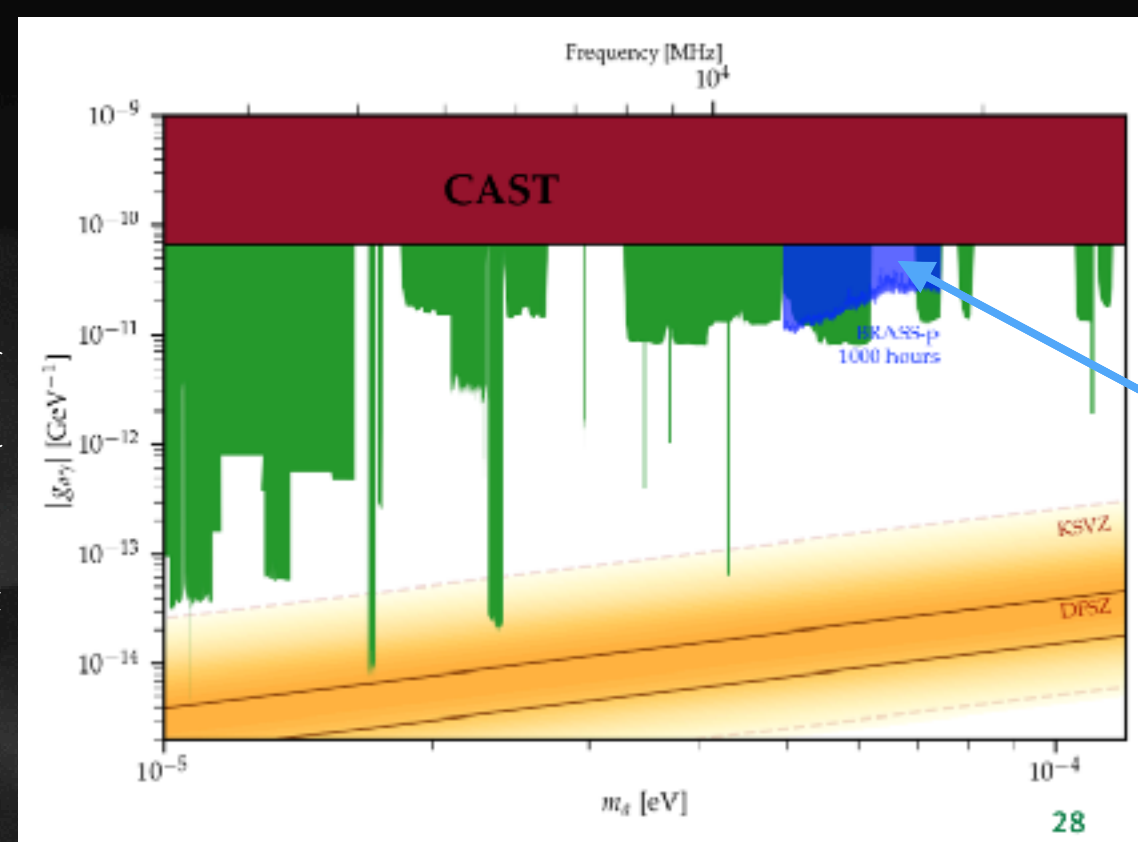
~1.5 m2

$T_{\rm sys} \sim 30$ K

Array of permanent magnets



Nguyen, PATRAS 2022
BRASS collab., JCAP08 (2023) 077



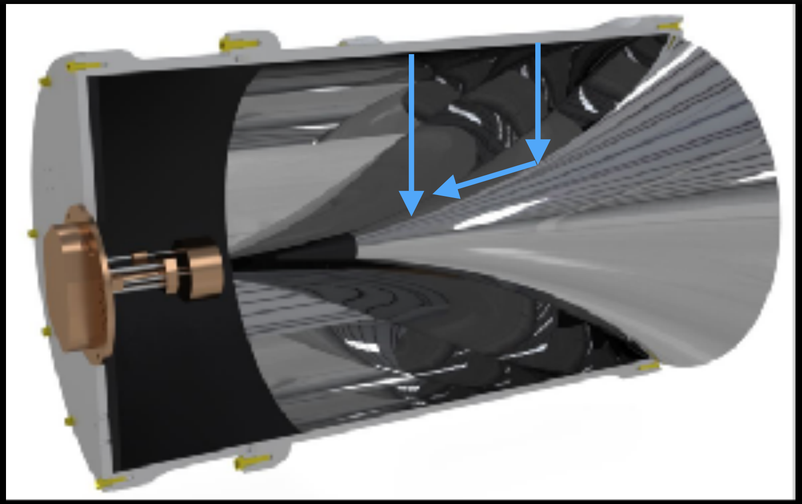
Projection for 1000 h

BREAD

Broadband Reflector Experiment for Axion Detection

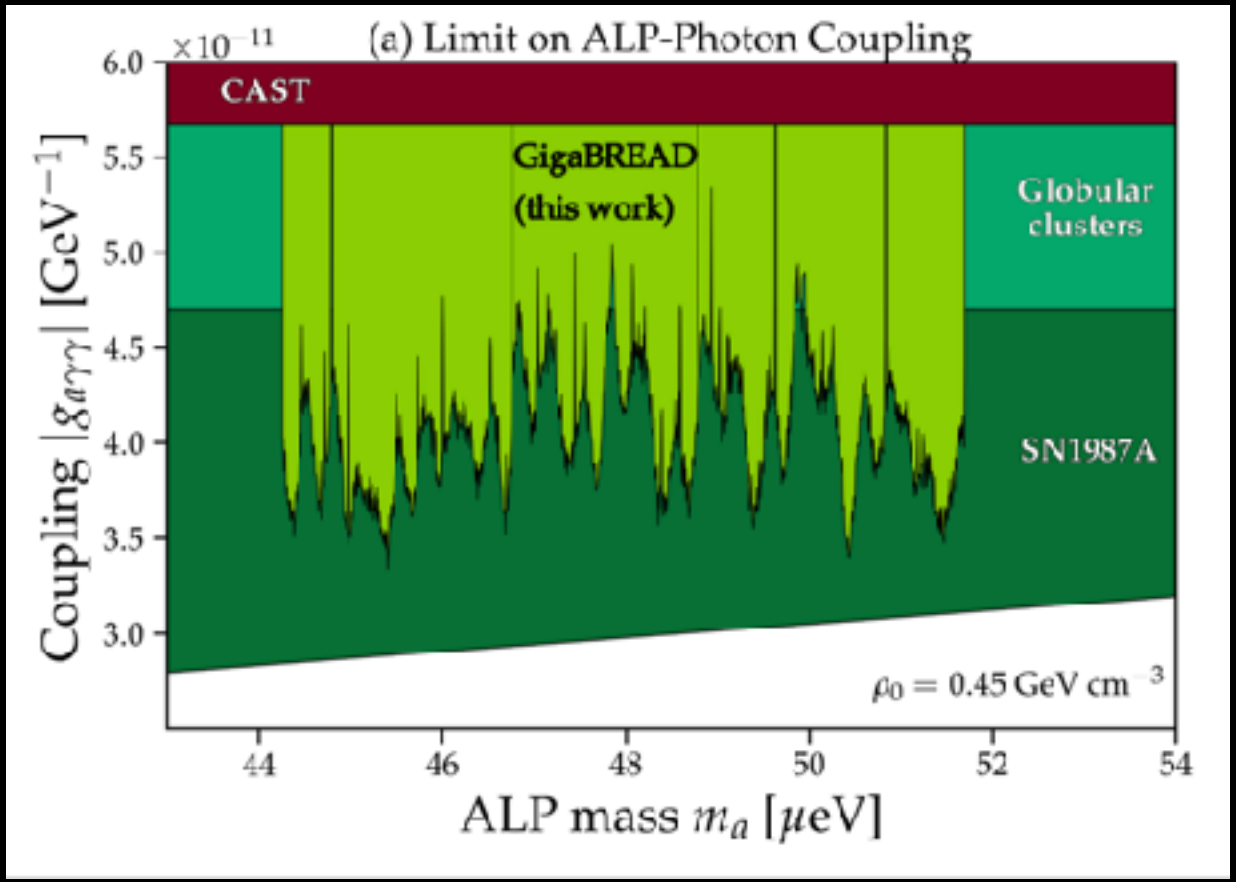
Use of a solenoid magnet

Custom-shaped reflector sends the signal to focus



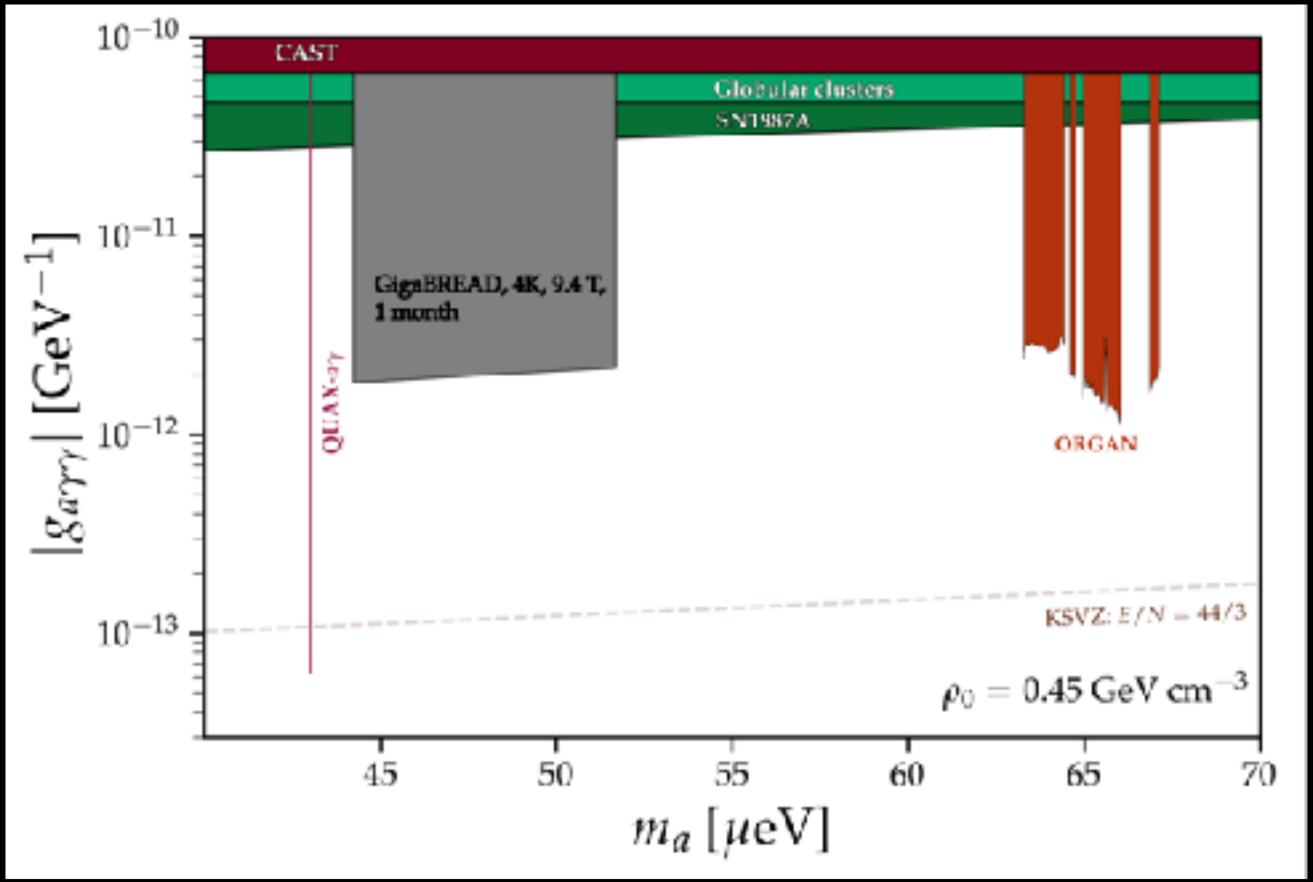
Test run in a 3.9 T MRI magnet

1 month $T_{\rm sys} \sim 600$ K



BREAD collab., arXiv:2501.17119

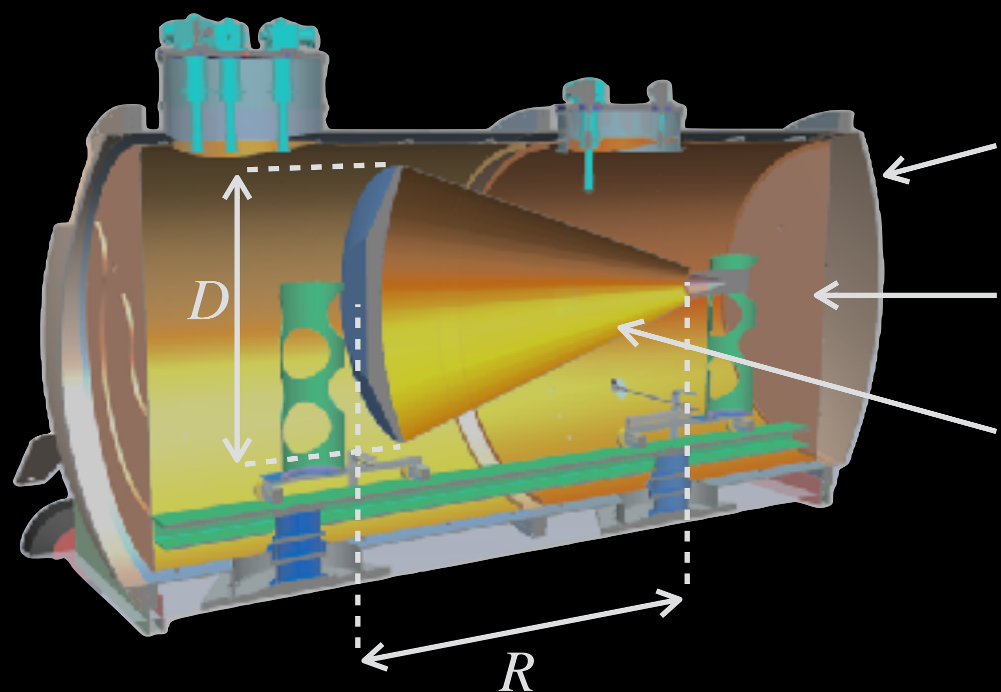
Plans to use a 9.4 T magnet



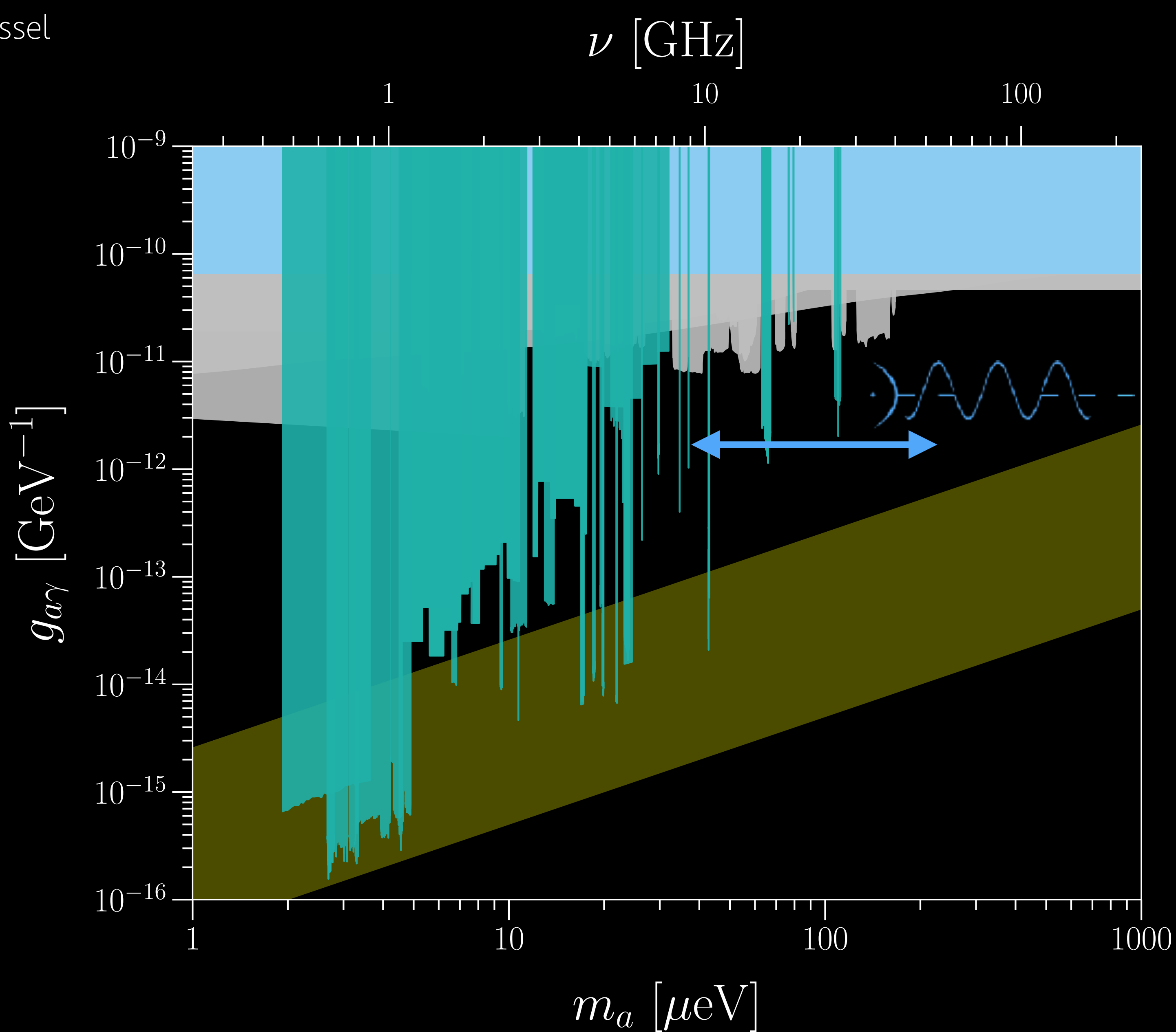
Talk by G. Hoshino this morning

DAWA

Dark Axion Wideband Approach



Potential reach



Ø 1.2 m R = 1.7 m $T_{\text{sys}} \sim 10$ K

Phase 1 : permanent magnets (2025)

Phase 2 : Superconducting magnets

Talk by L. Chevalier this morning

Ideas for discussion

Is the axion a good solution to strong CP ?
What about axion quality problem ?

Are there some strategies to cover wide bands w/ resonators ?

Should experimental efforts focus on non-DM axions (IAXO)

How robust is the post-inflation scenario ?