Axion dark matter

Matière noire : candidats au-delà des WIMPs

Annecy

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Outline

- ⋆ Axions
  - Motivations in brief
  - Relevant mass range, an educated guess
- ⋆ Local axion field
- ⋆ Experimental strategies
  - From narrow to broad band
  - Ideas and prospects

Biased talk:
personal interests
photon coupling
French connection

General QCD lagrangian

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

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

q quark matt, real

phase of Yukawa coupling

angle [-***π***, ***π***]

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

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

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

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

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

Constraints on the $\boldsymbol{\theta}$ factor

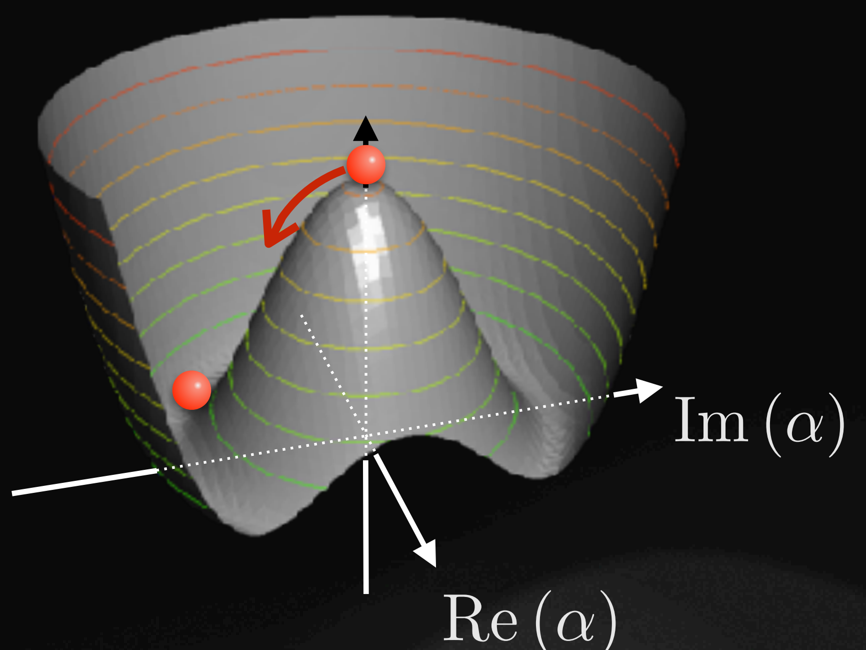
- $\theta \neq 0 \Rightarrow$
  - $\eta \longrightarrow \pi^+\pi^-$
  - Neutron electric dipole moment $d_n = 4.5\ 10^{-5}\ \theta\ e\text{cm}$
- Measurements :
  - $BR\left(\eta \to \pi^+\pi^-\right) < 1.5 \times 10^{|5}$
  - $|d_n| < 2.9 \times 10^{-26}\ e\text{cm}$

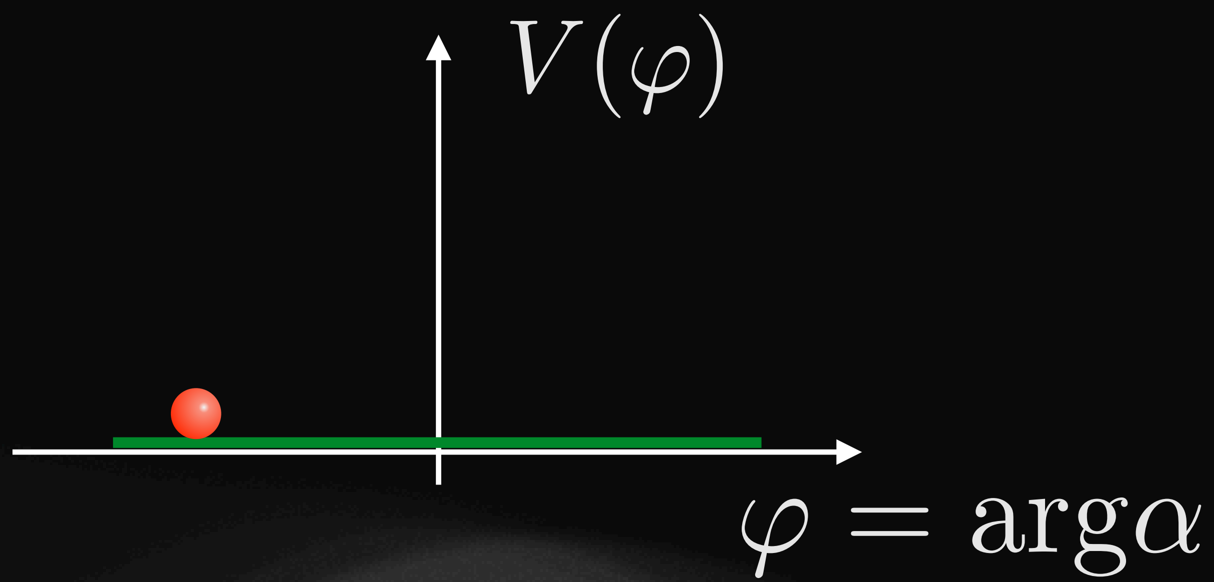
$$\theta < 10^{-11}$$

Textbook-case of a fine-tuning problem

Peccei-Quinn and the axion

- ⋆ New symmetry: U(1) Peccei-Quinn
- ⋆ $U(1)_{PQ}$ spontaneously broken at some high scale f_a

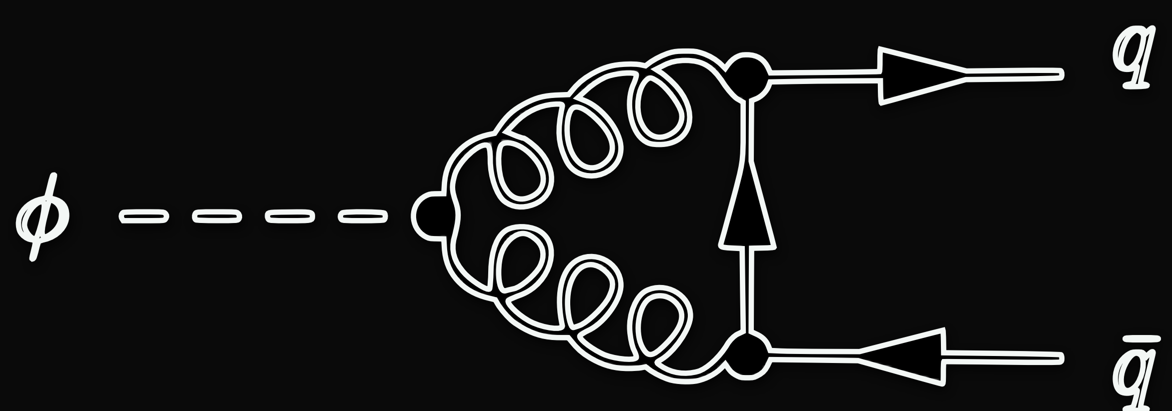




- ⋆ Goldstone boson: **the axion**
- ⋆ Axion $\boldsymbol{\varphi}$ is introduced massless

Generating the axion mass

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



Axion-π^0 mixing

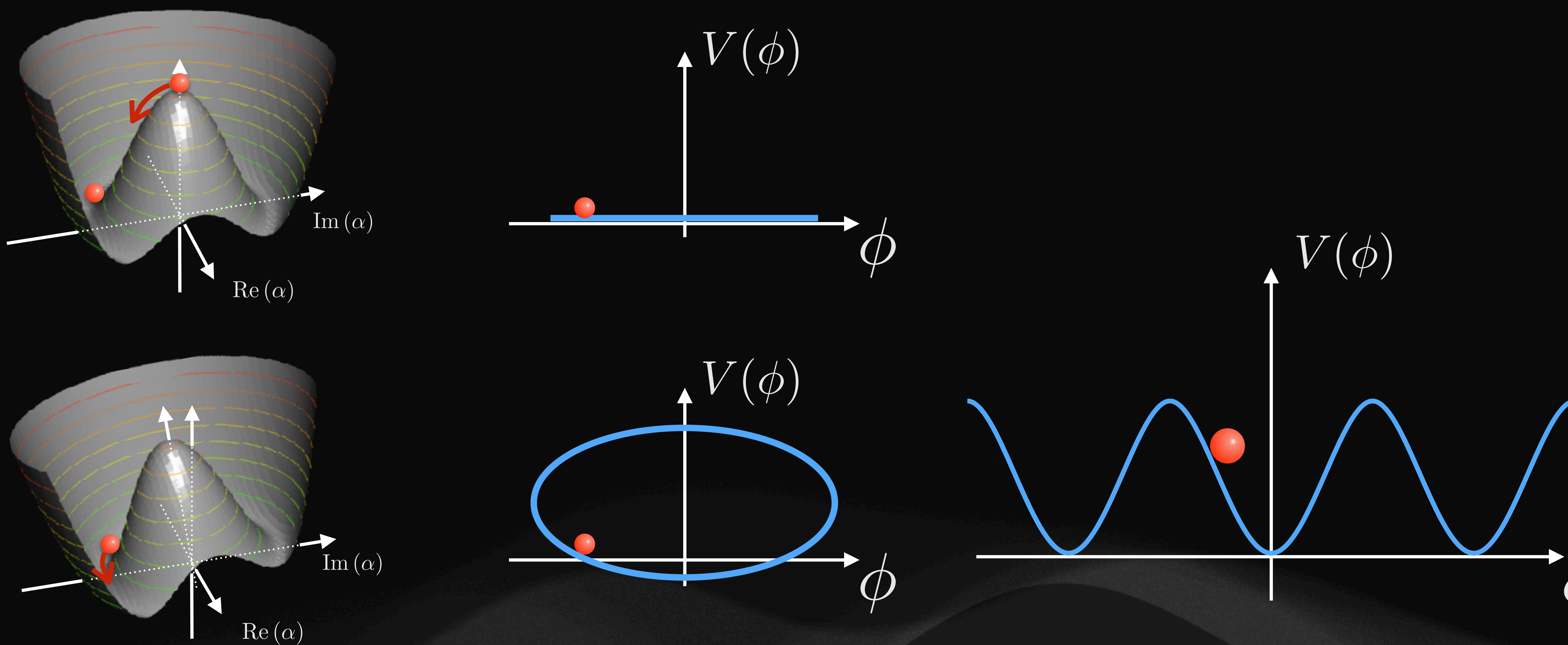
$$m \sim \frac{m_\pi f_\pi}{f_a}$$

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

(ϕ is shifted φ)

lowest order

Generating the axion mass

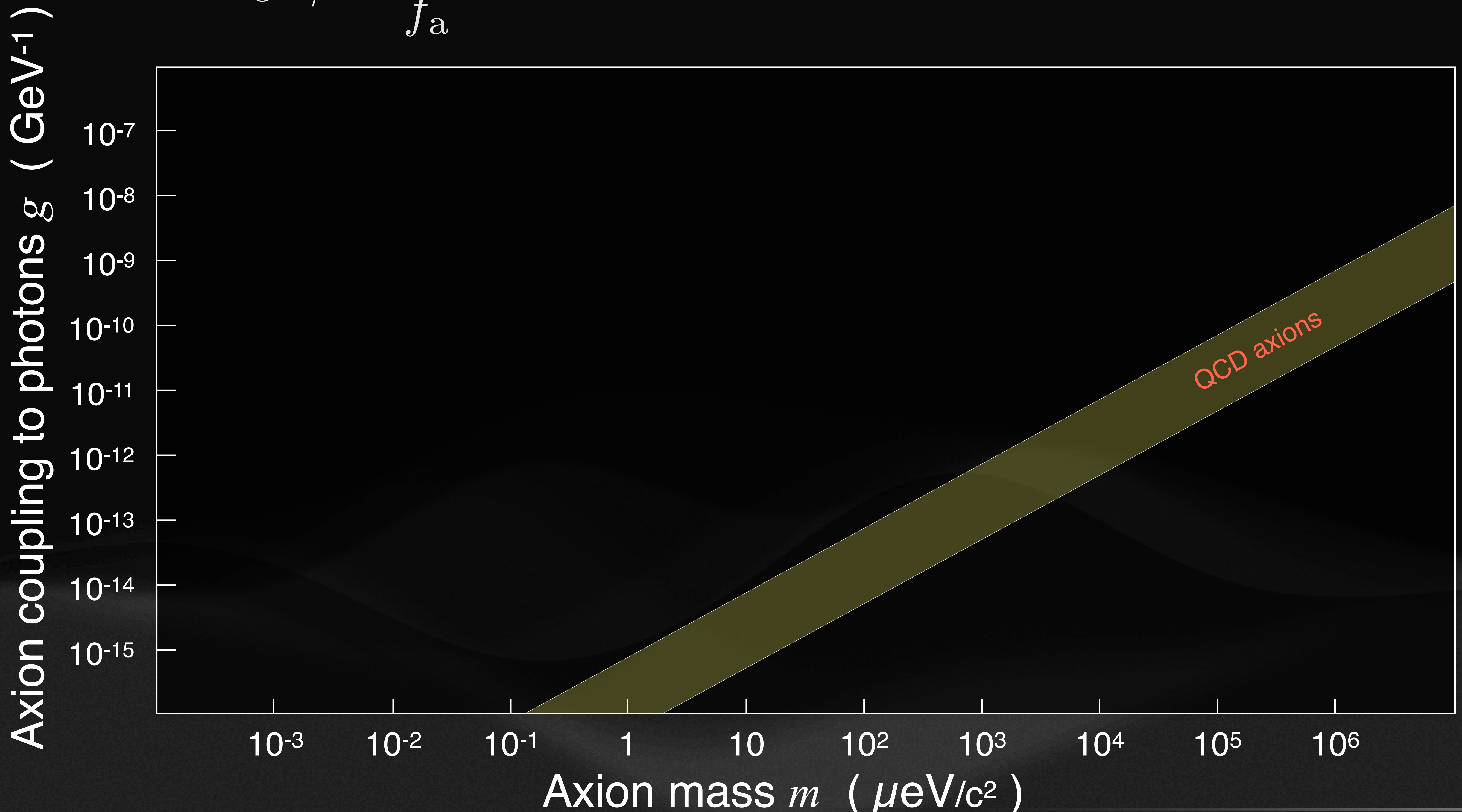


$$V_{QCD}(\theta) = \chi_0 \left(1 - \cos\theta\right)$$

$$\theta = \frac{\phi}{f_a}$$

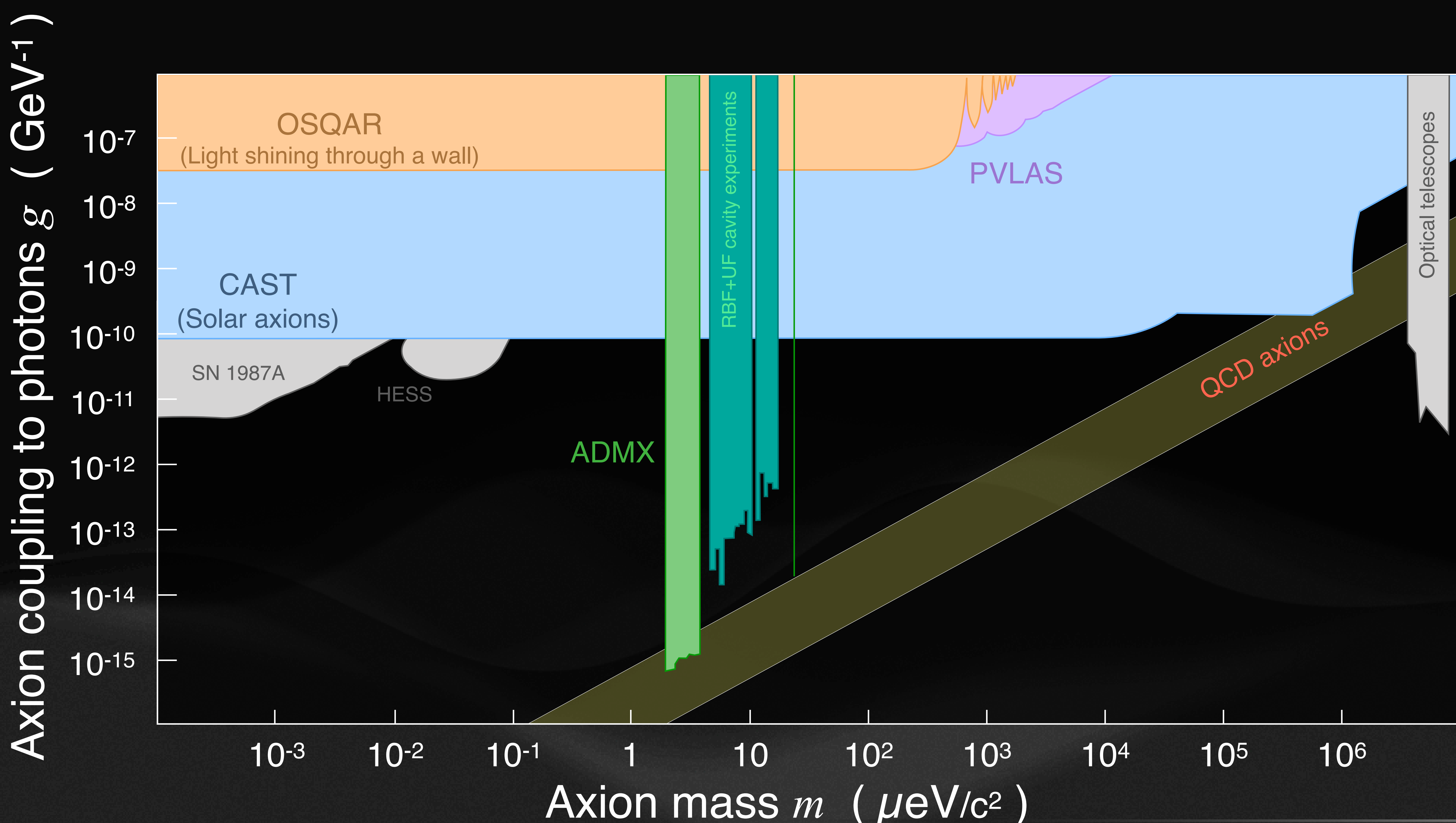
Axion-photon parameter space

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



Examples of constraints

Astrophysics / dedicated observations / laboratory experiments



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

Evolution of $\boldsymbol{\theta}$, w/ $\boldsymbol{\phi = f_a \theta}$:

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

drives the dynamics

QCD vacuum susceptibility: $m^2 f_a^2 = \dfrac{\partial^2 V_{\rm QCD}}{\partial \phi^2} \equiv \chi$

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

gives the mass at lowest order in $\boldsymbol{\theta}$:

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

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

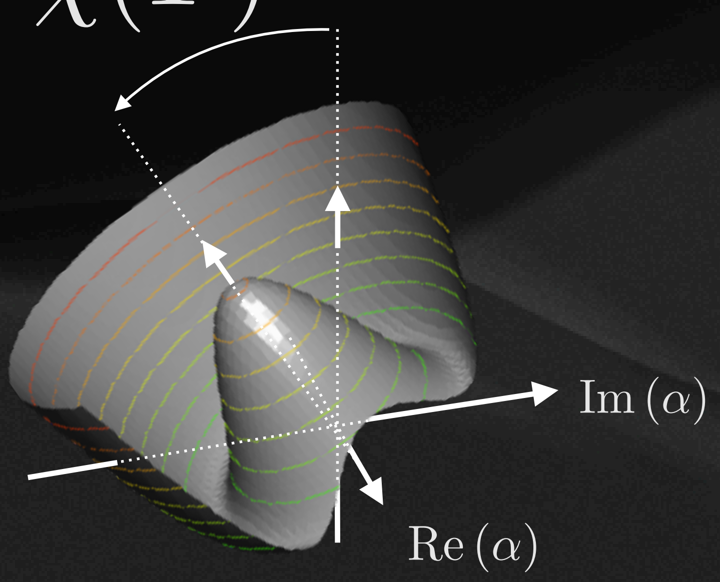
Homogeneous evolution

For the $\boldsymbol{k = 0}$ mode :

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

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

$\chi(T)$



$\longrightarrow$ $H(t)$ 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

Mass: T-dependance

Parametrization of simulations:

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

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

T=0 value similar from lattice QCD and NNLO

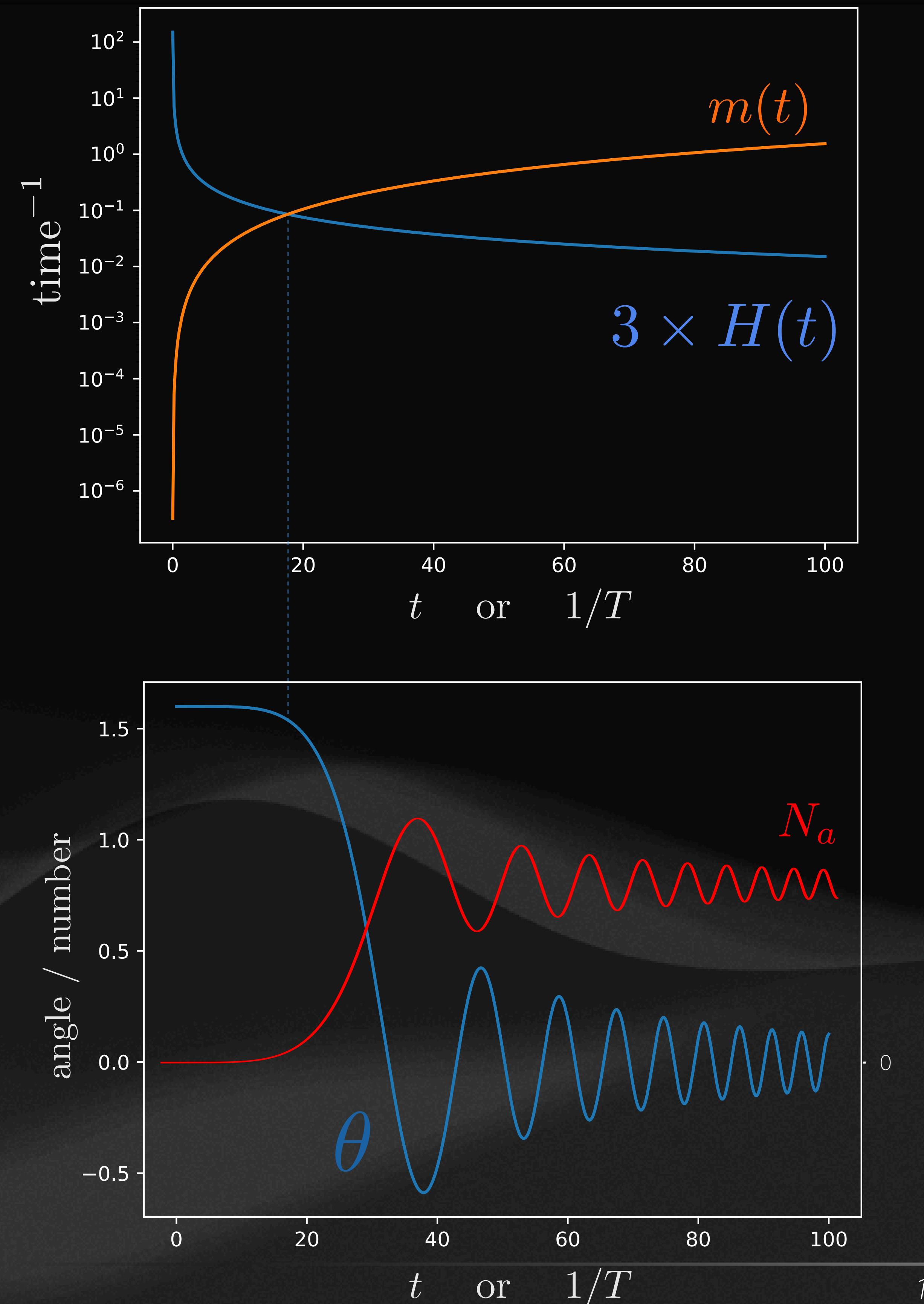
NB : same order of magnitude as KSVZ :

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

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

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

★ Transition temperature: $m \sim 3H$

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

$$\Downarrow$$

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

Axion number conservation

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

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

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

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

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

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

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

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

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

Mass-initial θ relation

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

Cosmological parameters

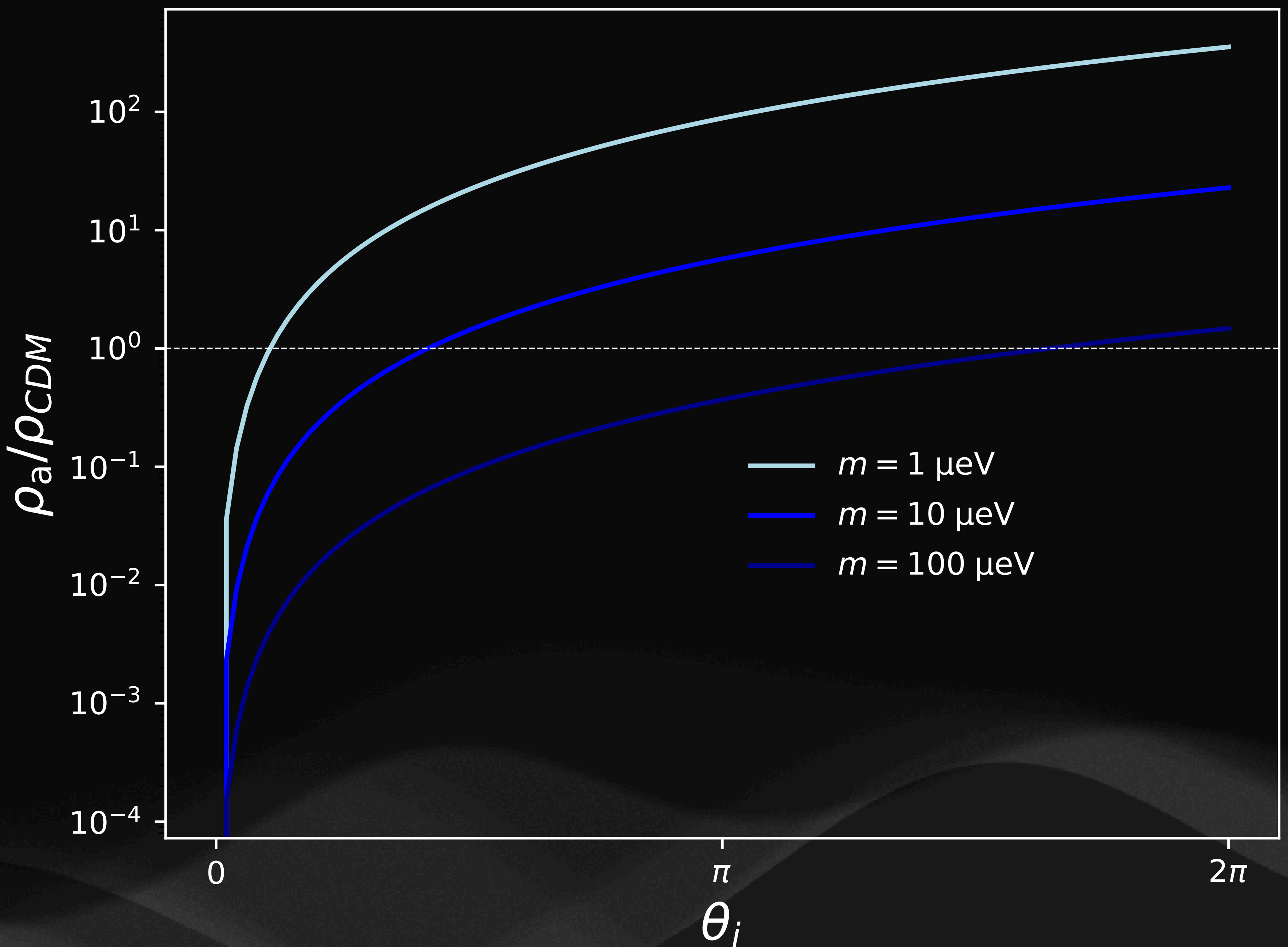
Dark matter density: $\rho_{\rm CDM} \simeq 0.84 \times 0.3 \times \frac{3m_{\rm Pl}^2 H_0^2}{8\pi} = 10^{-47}\ {\rm GeV}^4$

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

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

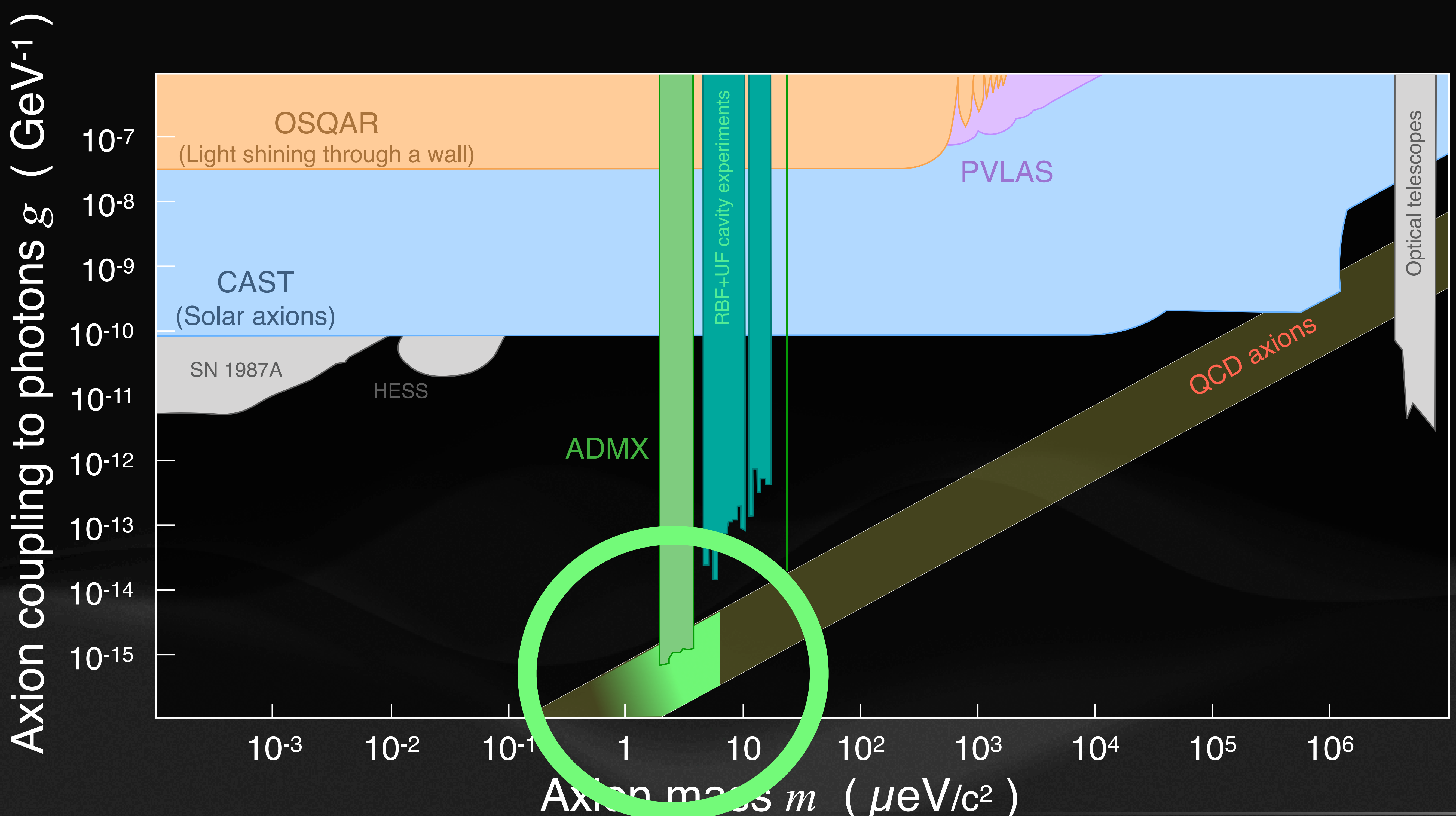


$\theta_i \sim 1$ gives an upper limit on the mass: $m \lesssim 6\ \mu\text{eV}$

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

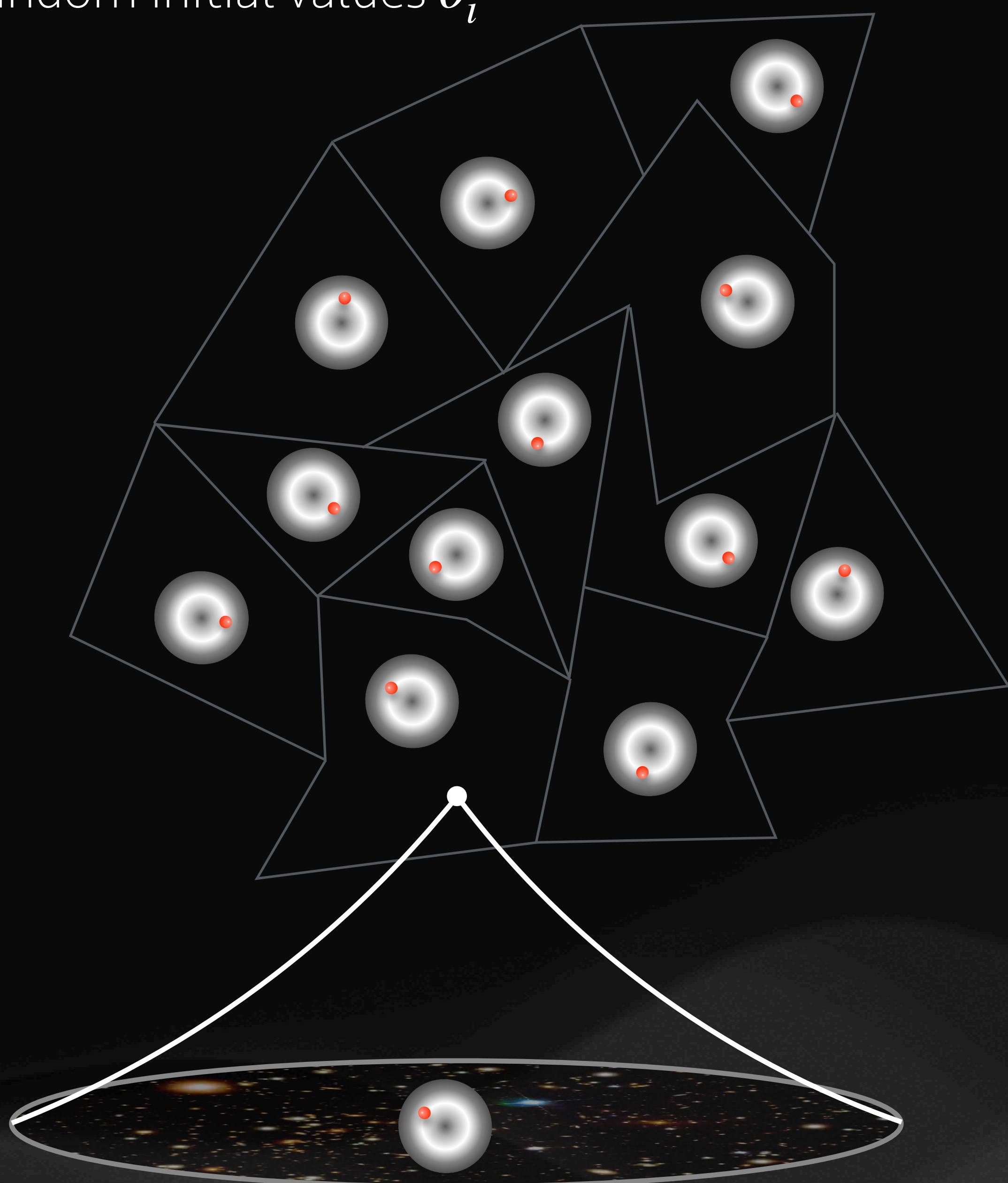
Preferred mass range

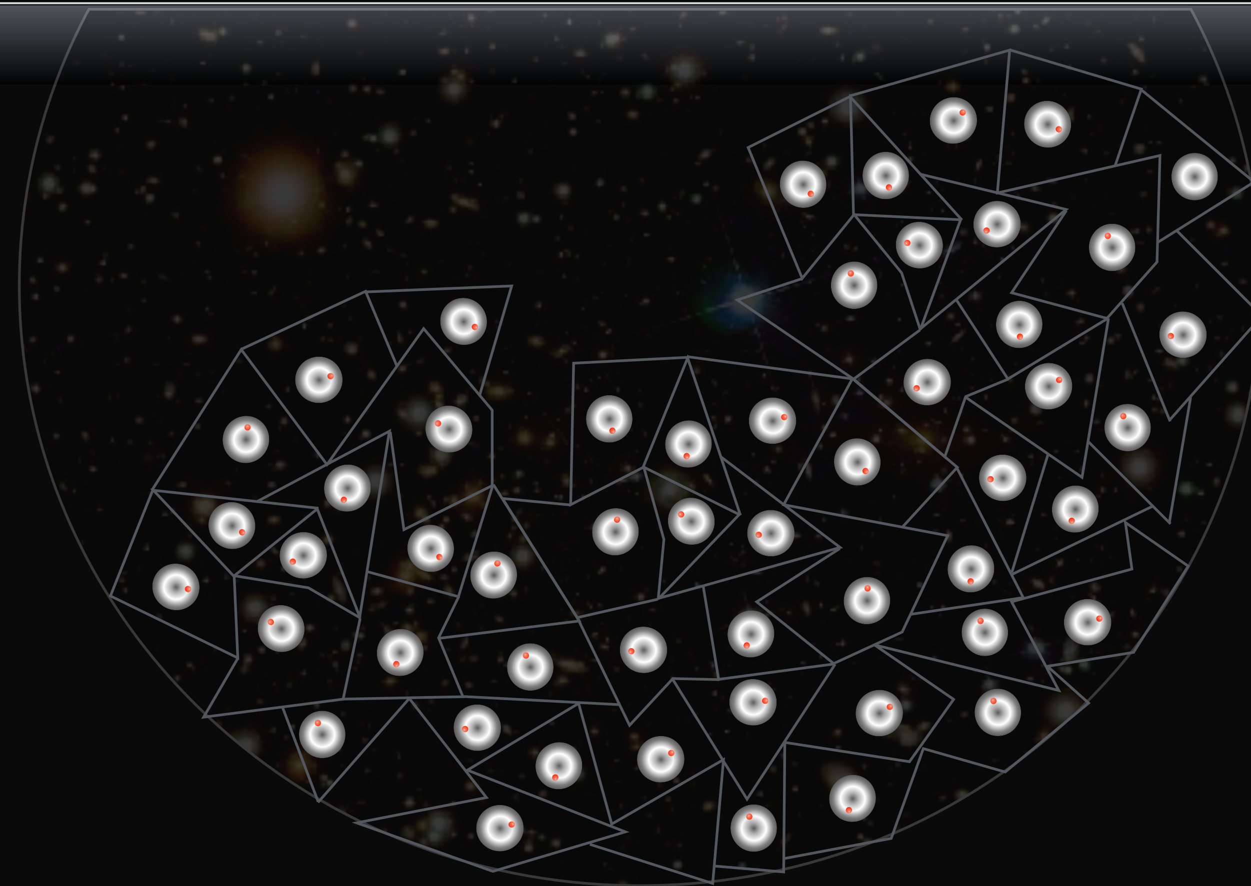
« pre-inflation scenario »



How many initial conditions?

Random initial values θ_i





High-energy inflation

- θ_i picked up *after* infllation
- Our Hubble radius contains many θ_i

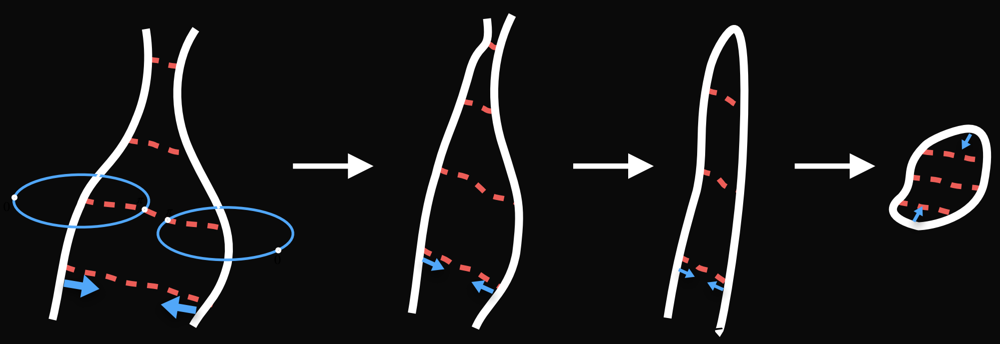
Low-energy inflation

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

Axions from topological defects

New contributions:

- ★ Misalignment (same as previous)
- ★ Cosmic strings rearrangements
- ★ decay of domain walls



$$\rho_{\mathrm{a}} = \rho_{\mathrm{mis.}} + \rho_{\mathrm{strings}} + \rho_{decay}$$

3 same-order contributions

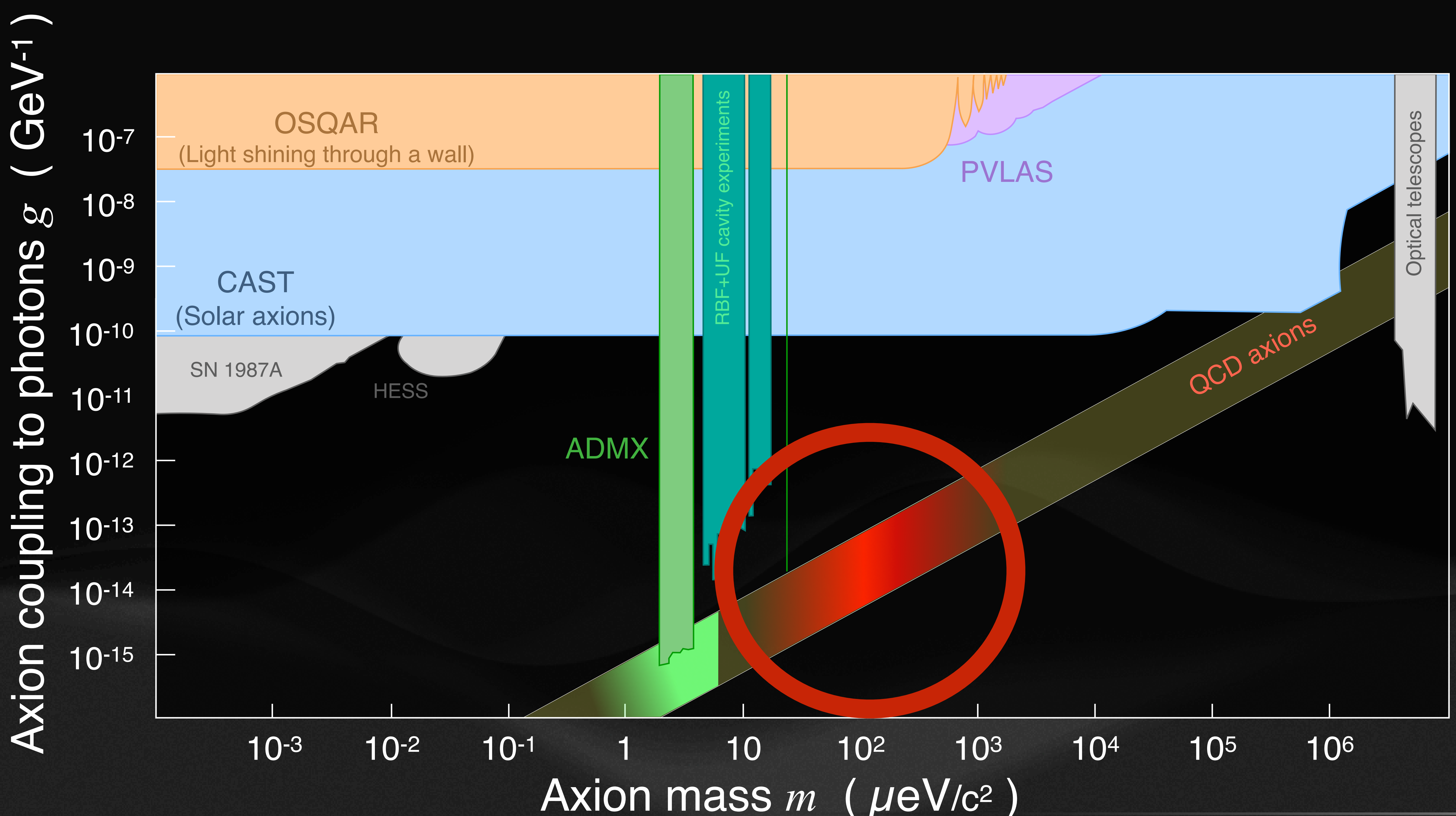
Examples of numerical predictions:

$$m = 115 \pm 25\ \mu\mathrm{eV}$$ *Kawasaki et al. 2015*

$$m = 26.2 \pm 3.4\ \mu\mathrm{eV}$$ *Klaer & Moore 2017*

Preferred mass range

« post-inflation scenario »



A Galactic halo of axions

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

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

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

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

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

→ Classical field

Mass-frequency relation

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

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

- ⋆ Oscillation frequency set by axion mass

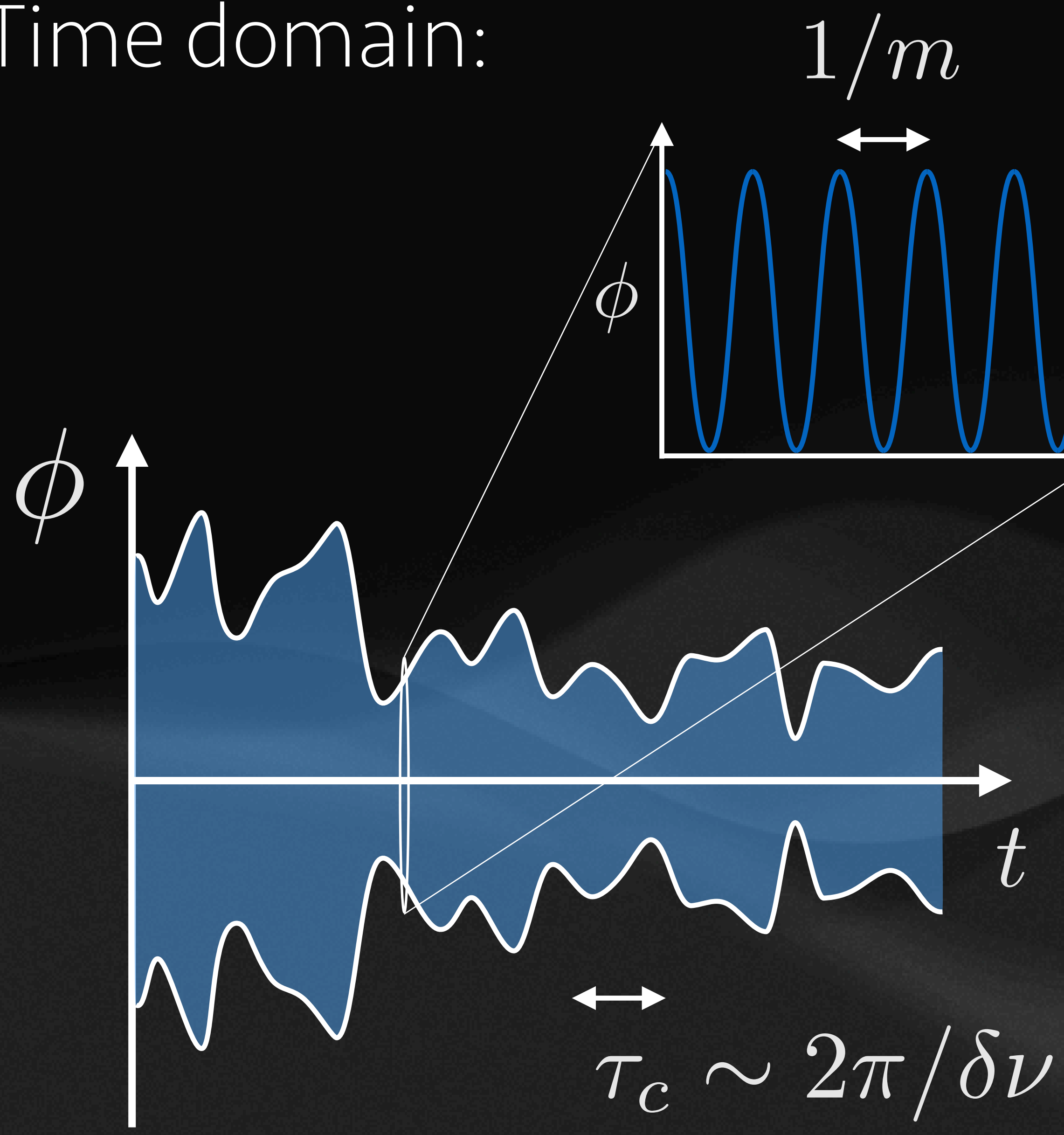
$$k = 0 \Rightarrow \omega = \frac{mc^2}{\hbar} \qquad \nu = \frac{mc^2}{2\pi\hbar} \qquad \boxed{\nu = 2.4 \text{ GHz} \times \frac{m}{10\ \mu\text{eV}}}$$

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

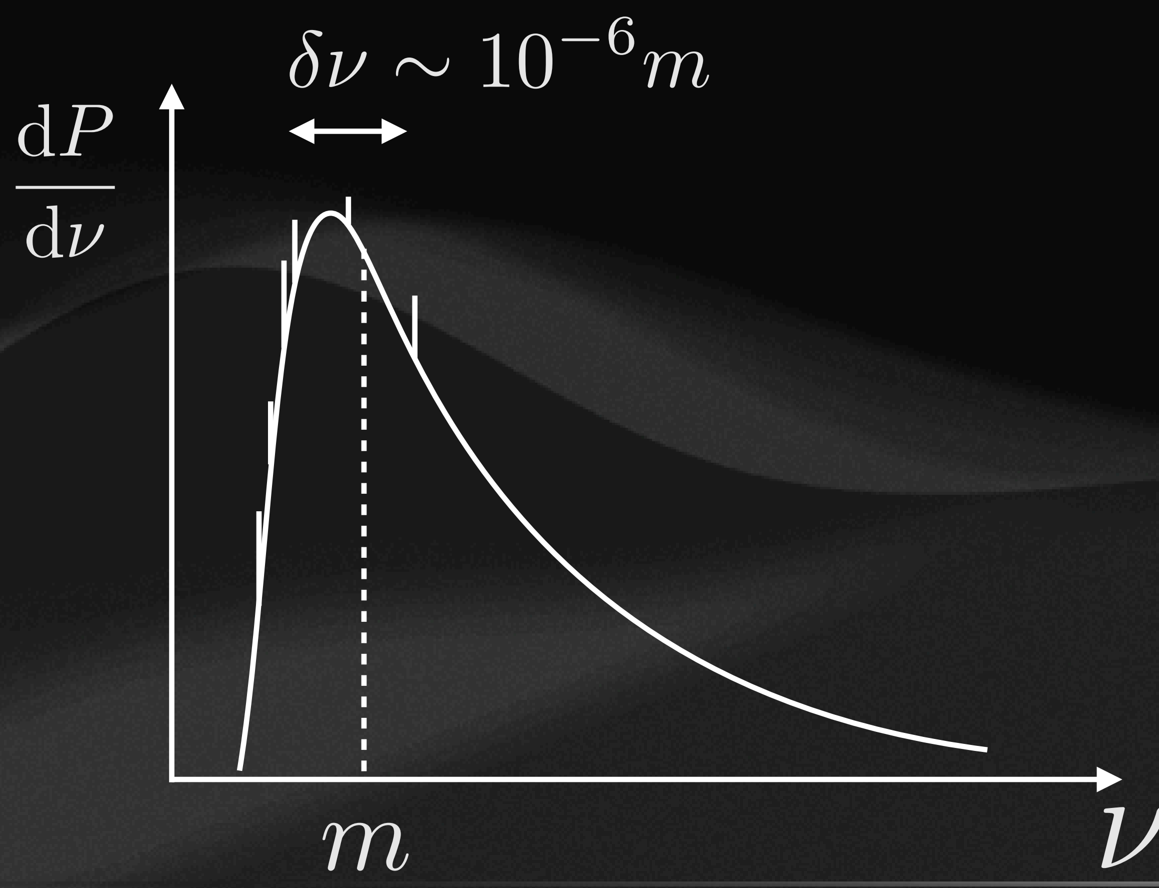
Spectral content

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:



Local phenomenology

Relevant part of the lagrangian:

Use strong magnetic field...

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

...search for new signal

Modified Maxwell's equations:

$$\vec{\nabla}\cdot\vec{B} = 0 \qquad \vec{\nabla}\cdot\vec{E} = \frac{\rho}{\epsilon_0} - g_\gamma\,\vec{\nabla}\phi\cdot\vec{B}$$

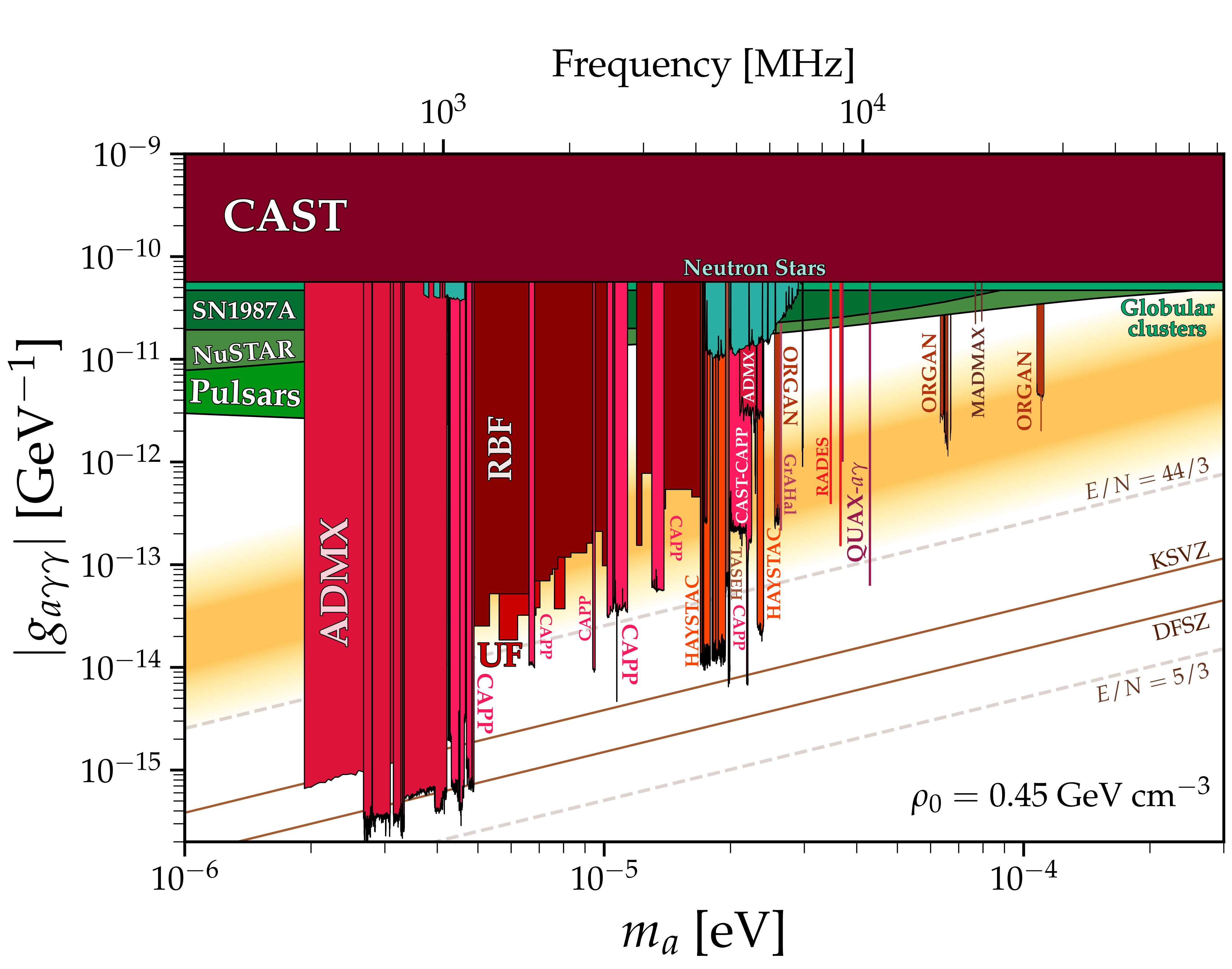
$$\partial_t\vec{B} + \vec{\nabla}\wedge\vec{E} = \vec{0} \qquad \vec{\nabla}\wedge\vec{B} - \partial_t\vec{E} = \mu_0\vec{\jmath} + g_\gamma\,\dot{\phi}\vec{B} + g_\gamma\,\vec{\nabla}\phi\wedge\vec{E}$$

Equations of motion in a $\vec{\boldsymbol{B}}$ background and homogeneous $\boldsymbol{\phi}$:

$$\Box\vec{e} = \frac{1}{f_\mathrm{a}}\ddot{\phi}\left(\vec{B}+\vec{b}\right) + \frac{1}{f_\mathrm{a}}\dot{\phi}\left(\dot{\vec{B}}+\dot{\vec{b}}\right)$$

$$\Box\vec{b} = -\frac{1}{f_\mathrm{a}}\dot{\phi}\,\vec{\nabla}\wedge\left(\vec{B}+\vec{b}\right)$$

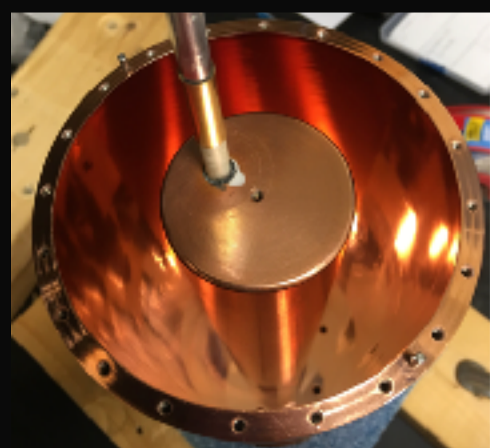
Reduced mass range

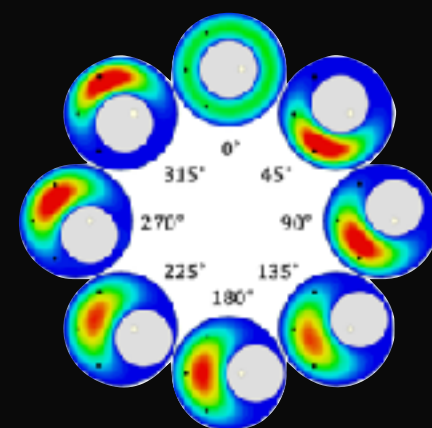


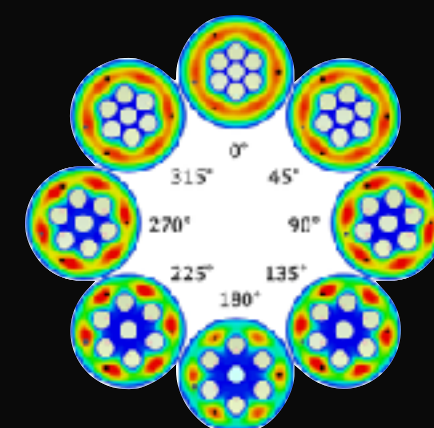
Resonant searches

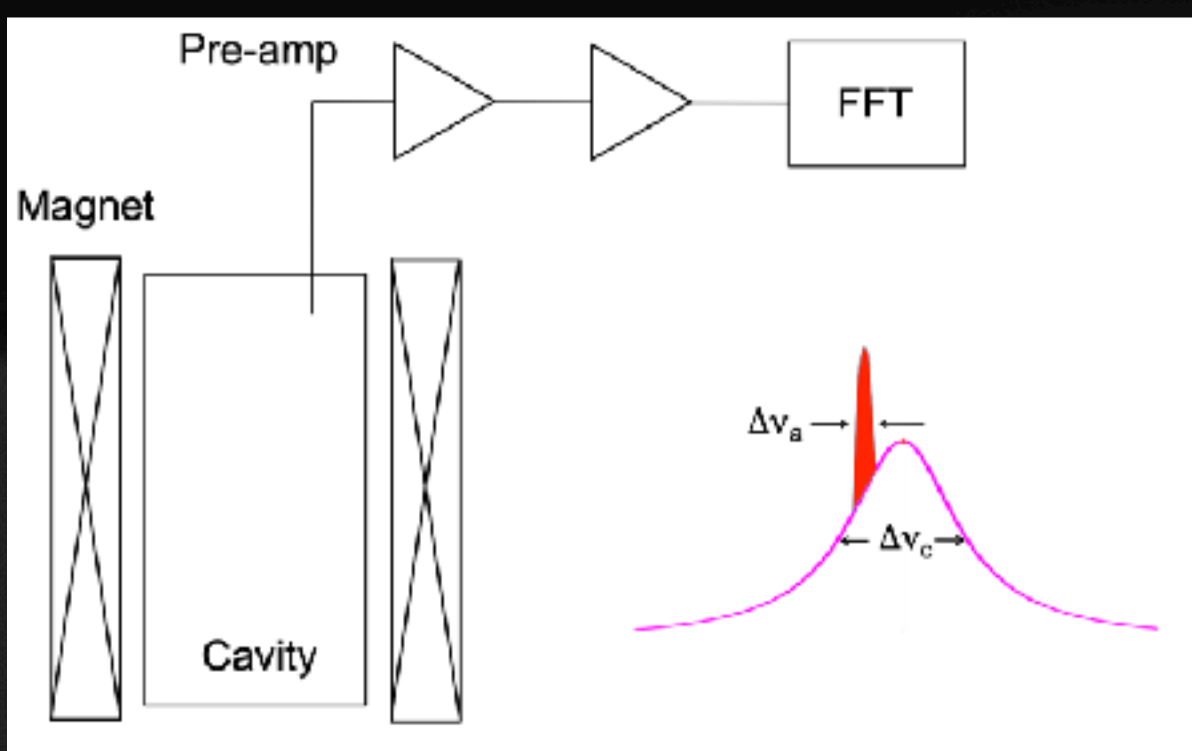
ADMX, CAPP, HAYSTAC (...): use of resonant cavities w/ variable geometry

Example: HAYSTAC, 9.4 T







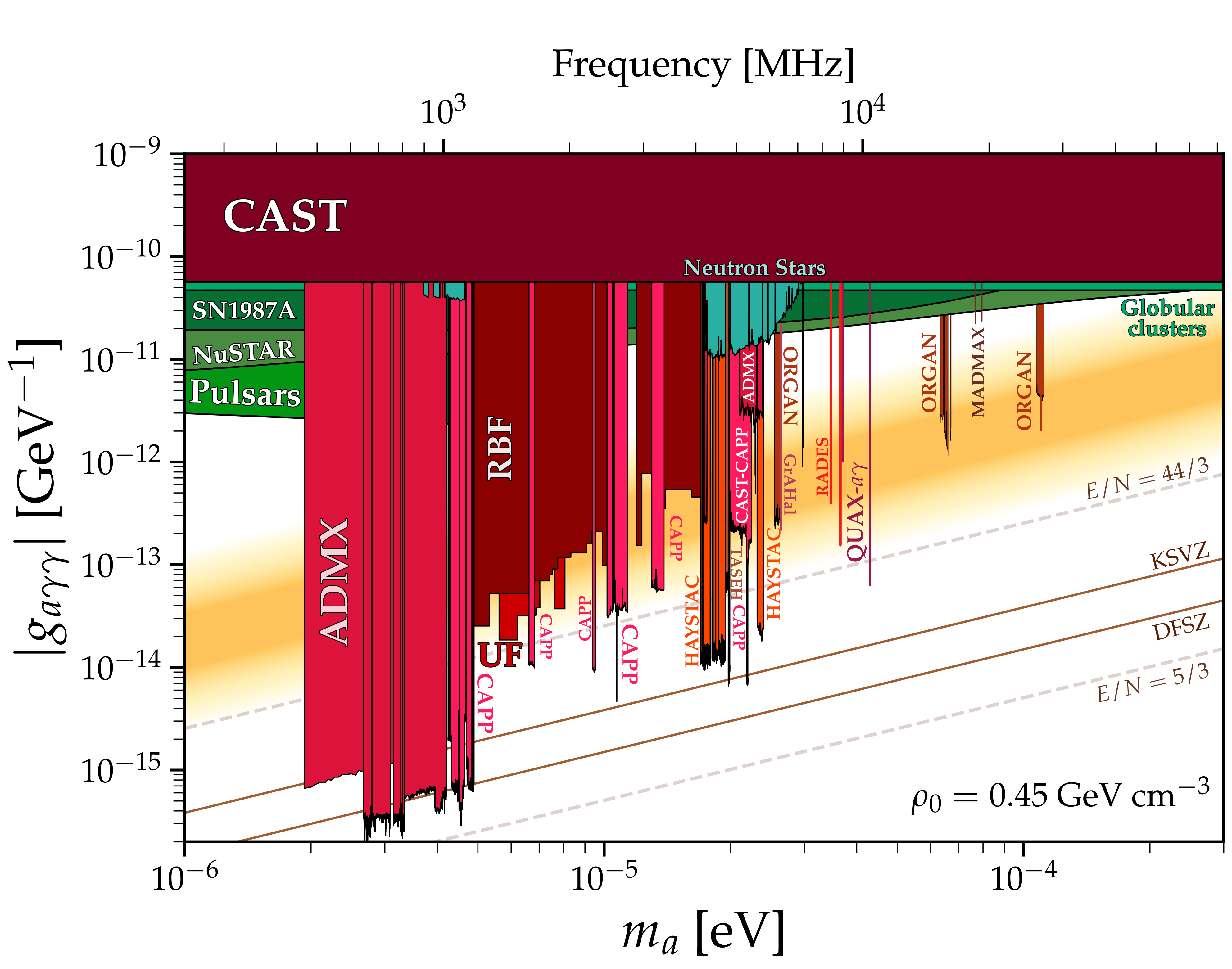


$$P_{\text{signal}} \propto g_\gamma^2 \, \frac{\rho_{\text{a}}}{m} \, B^2 \, V \, Q$$

Mass scan, search for resonances

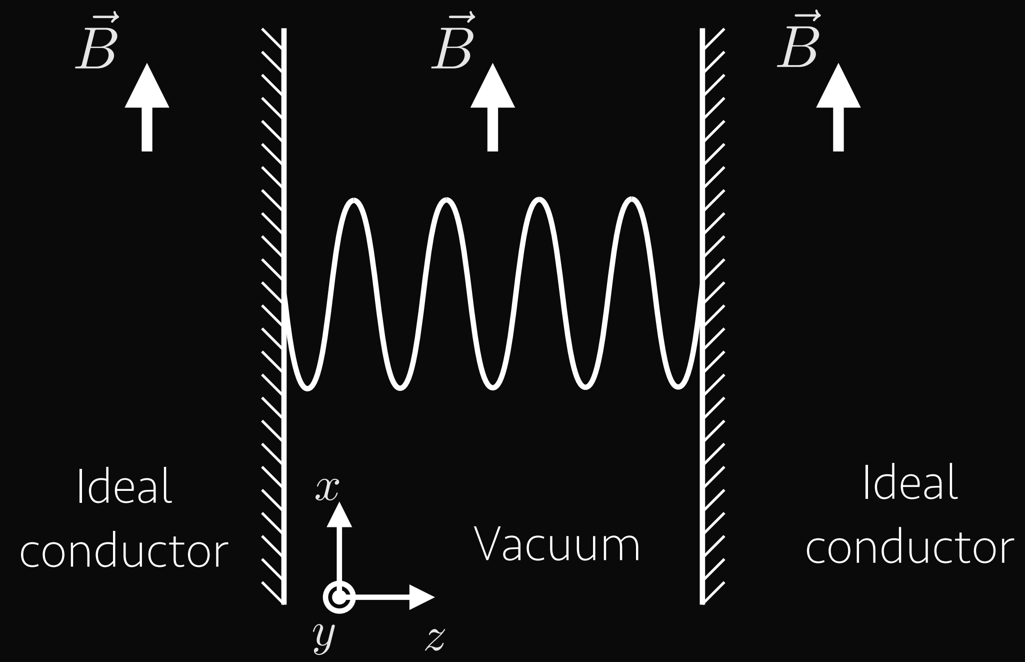
Quality factor of the order of $Q \sim 10^5$

Reduced mass range



A (narrow?) idea…

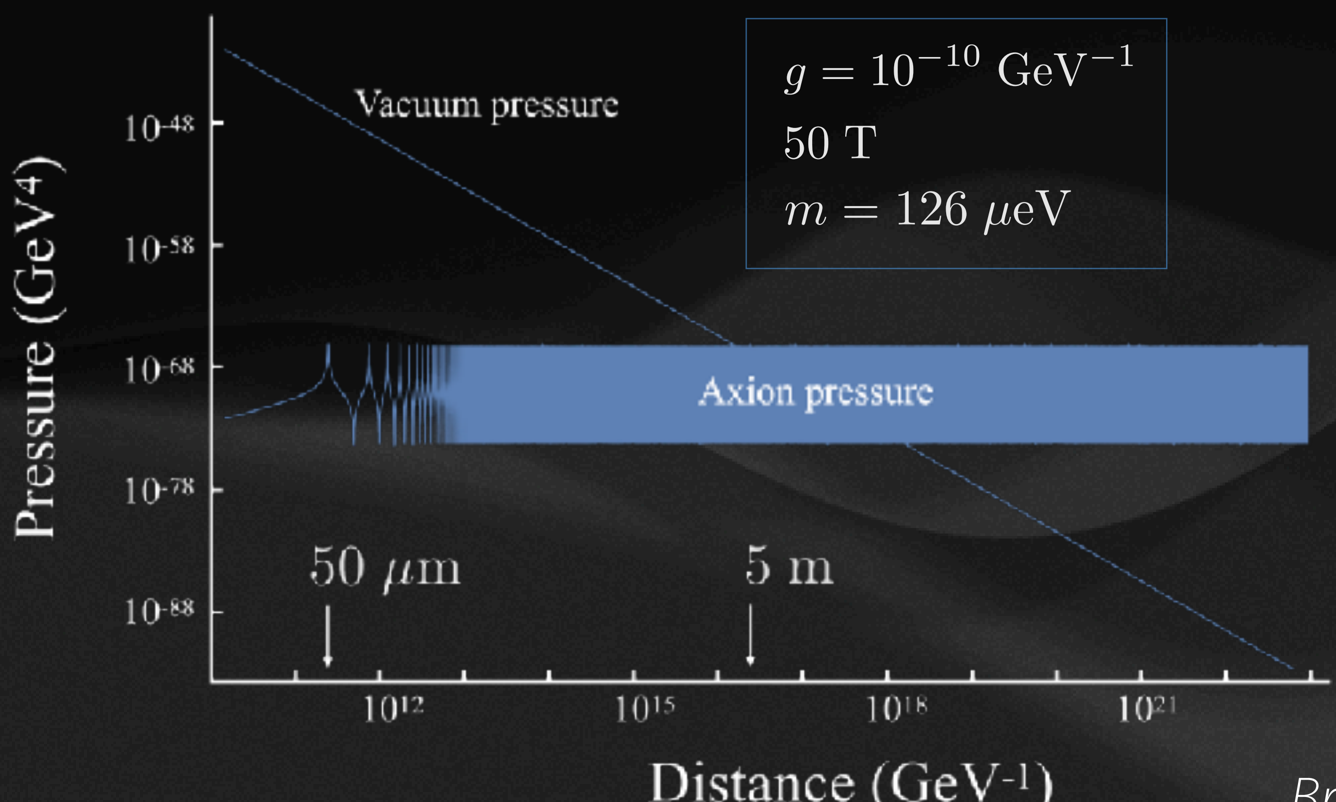
An empty cavity has Casimir pressure

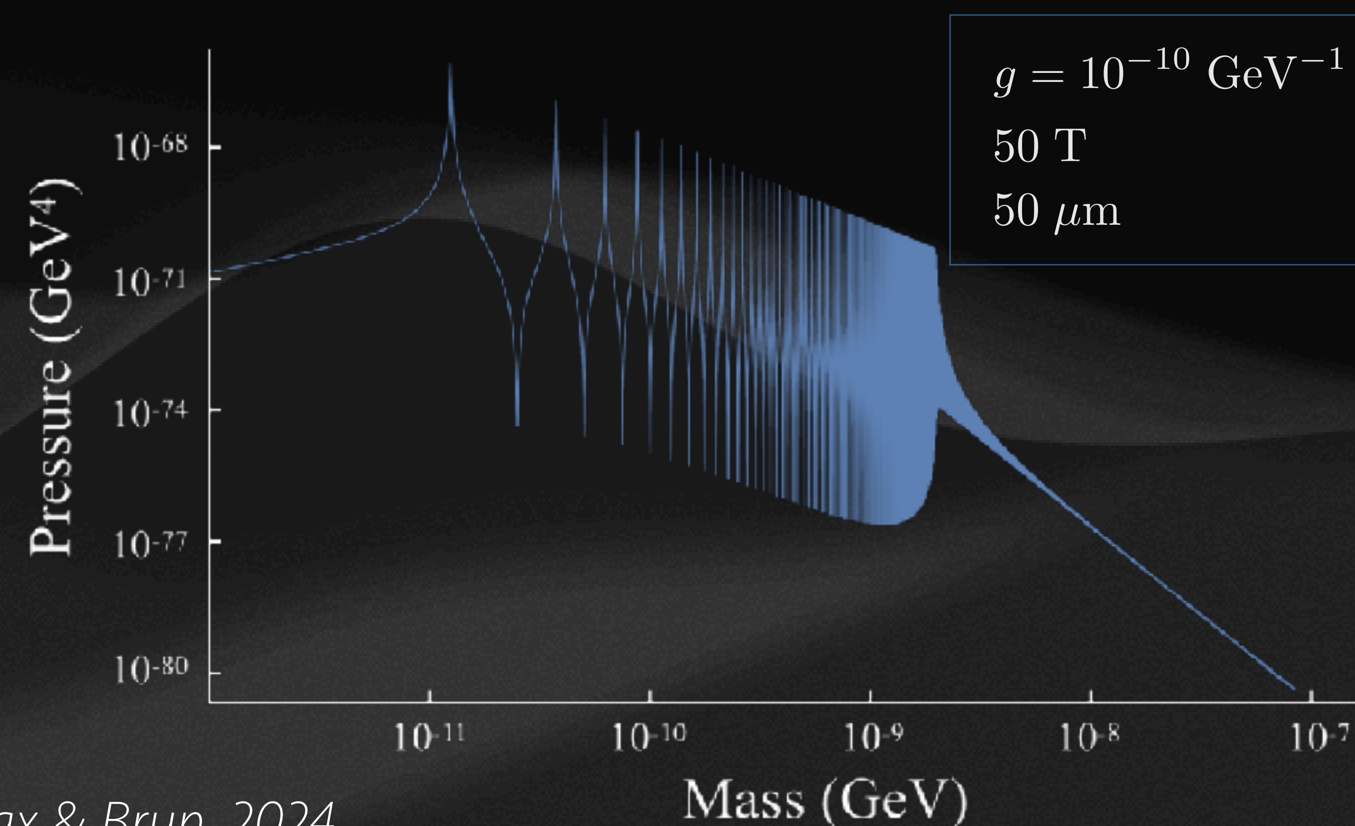


Axion / vacuum modes coupling leads to resonances for distances:

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

Resonances regularized by dissipation

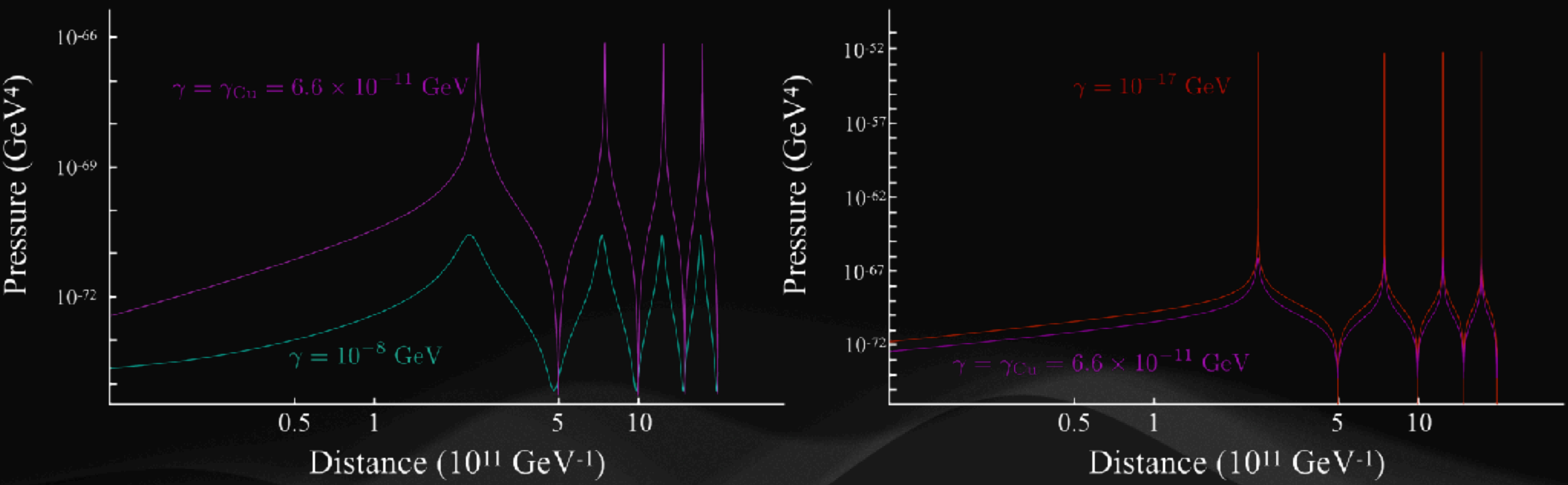




Brax & Brun, 2024

Axions & Casimir pressure

Resonances can be made very narrow w/ right material

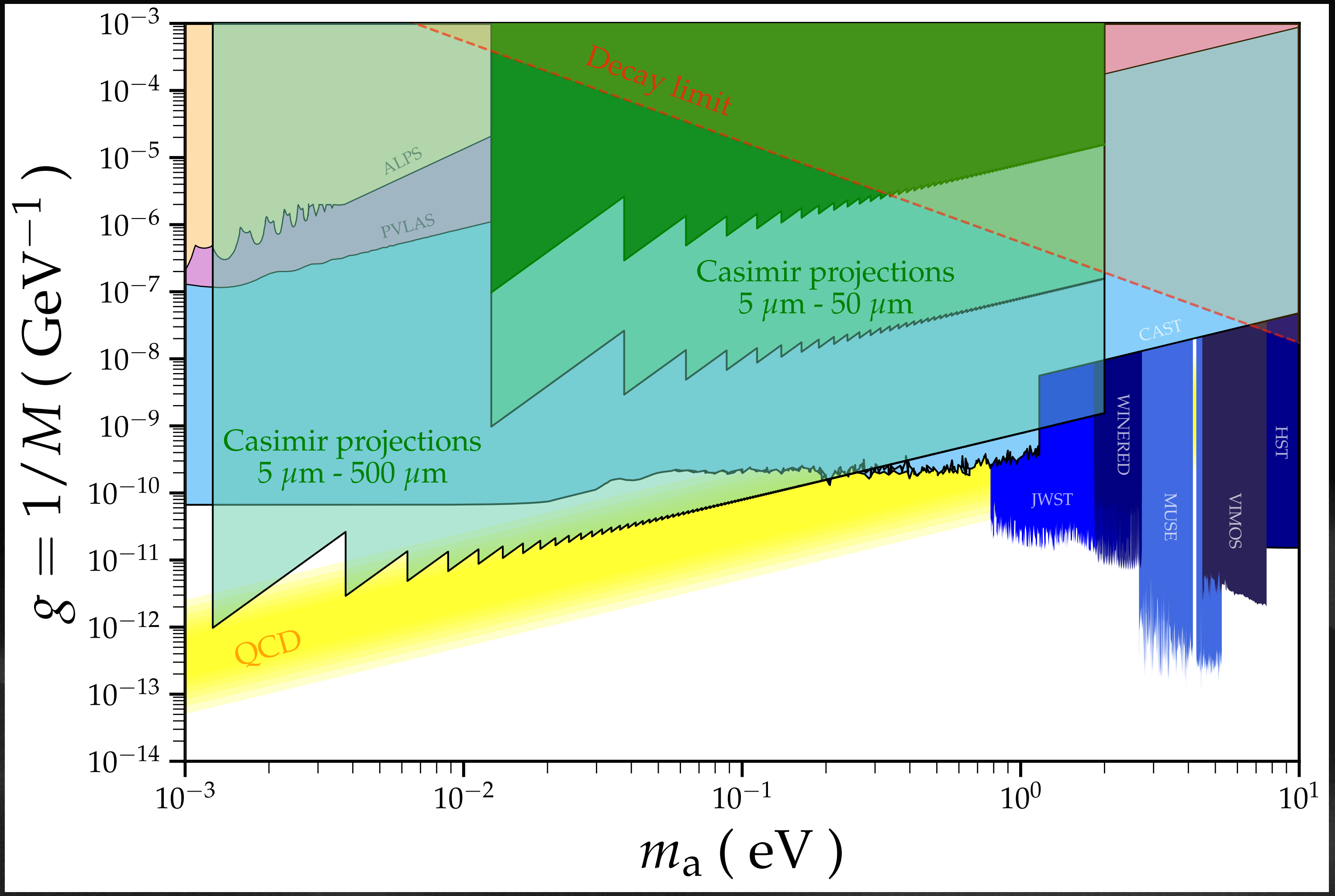


γ : damping factor in the plaque $\quad \gamma = \dfrac{\omega^2_{\rm plasma}}{\sigma}$

Axions & Casimir pressure

Some (very optimistic) prospects…

$$\frac{P_{\text{axion}}}{P_{\text{vacuum}}} = 1\%$$

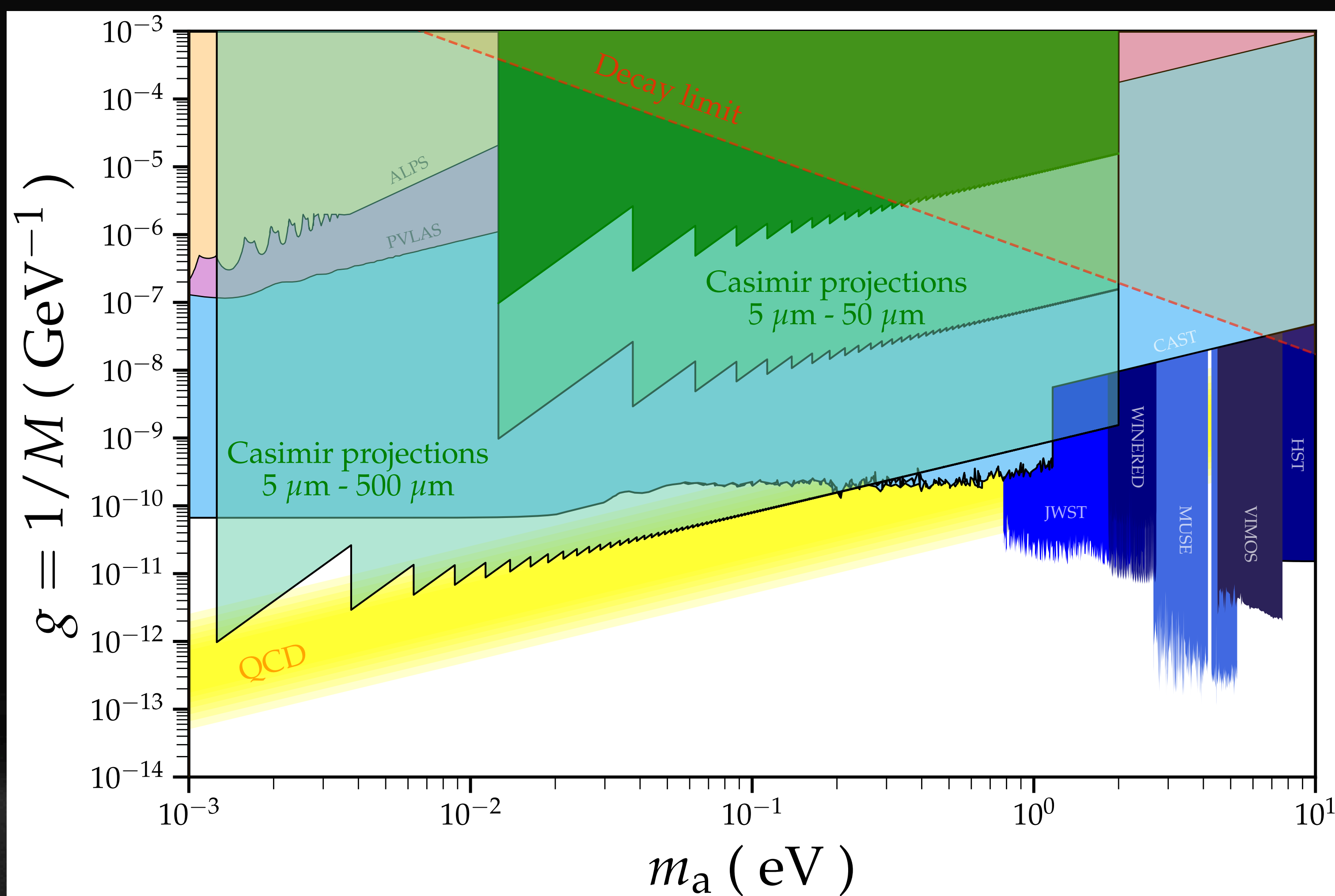


Brax & Brun, 2024

Axions & Casimir pressure

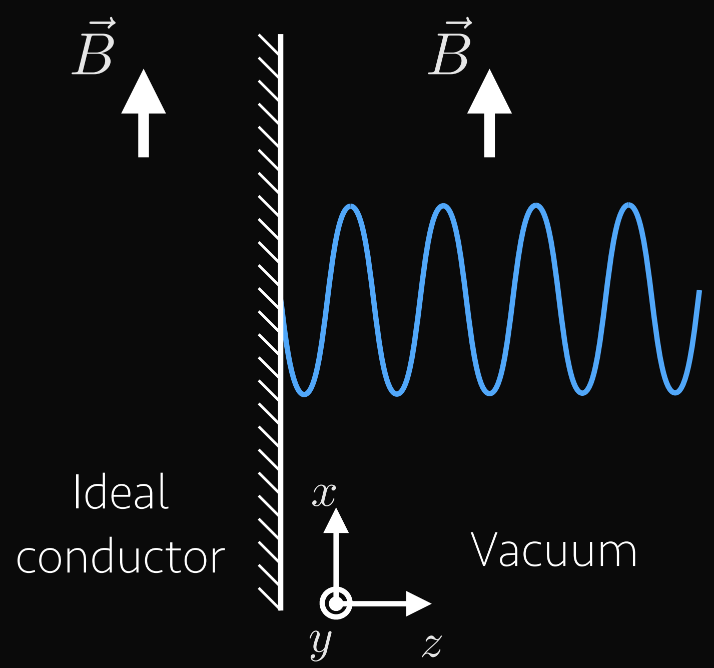
Some (very optimistic) prospects…

$$\frac{P_{\mathrm{axion}}}{P_{\mathrm{vacuum}}} = 1\%$$



Brax & Brun, 2024

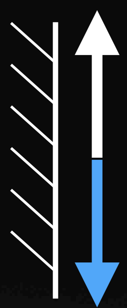
Towards broadband searches



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

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

Field must cancel on the interface:



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

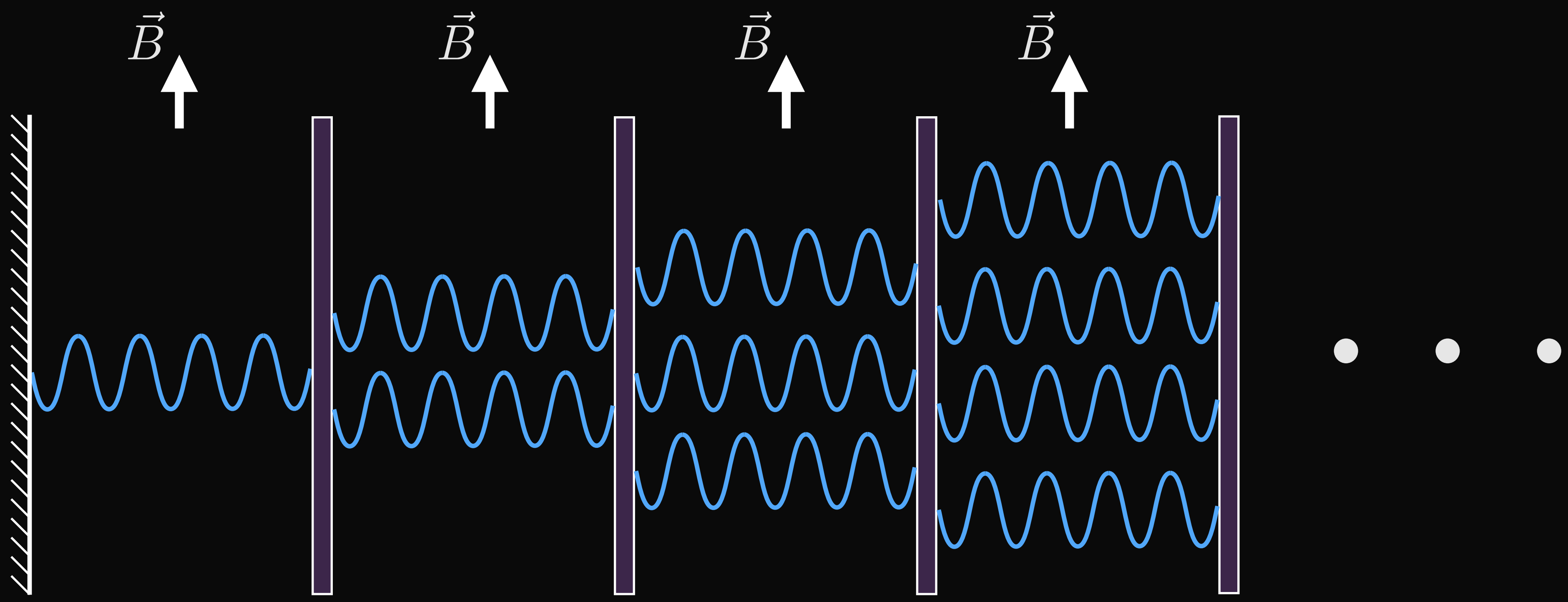
$\Rightarrow$ emitted signal: $\vec{E}_{out} = -i\phi_0 \, g_\gamma \, B_x \, e^{-i(mt - kx)} \vec{e}_x$

Output power:

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

MadMax

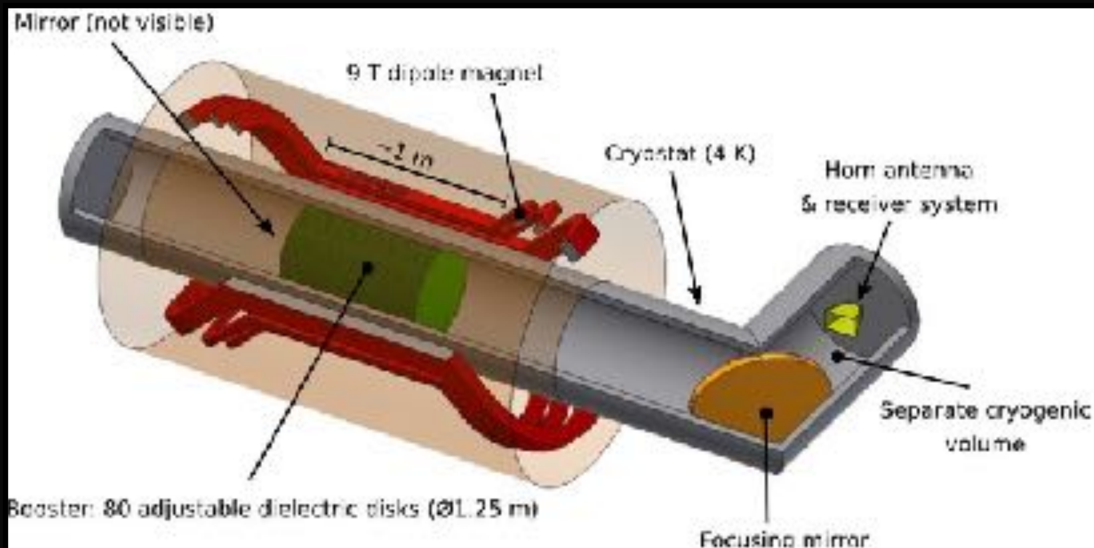
Principle: semi-transparent materials used to increase signal



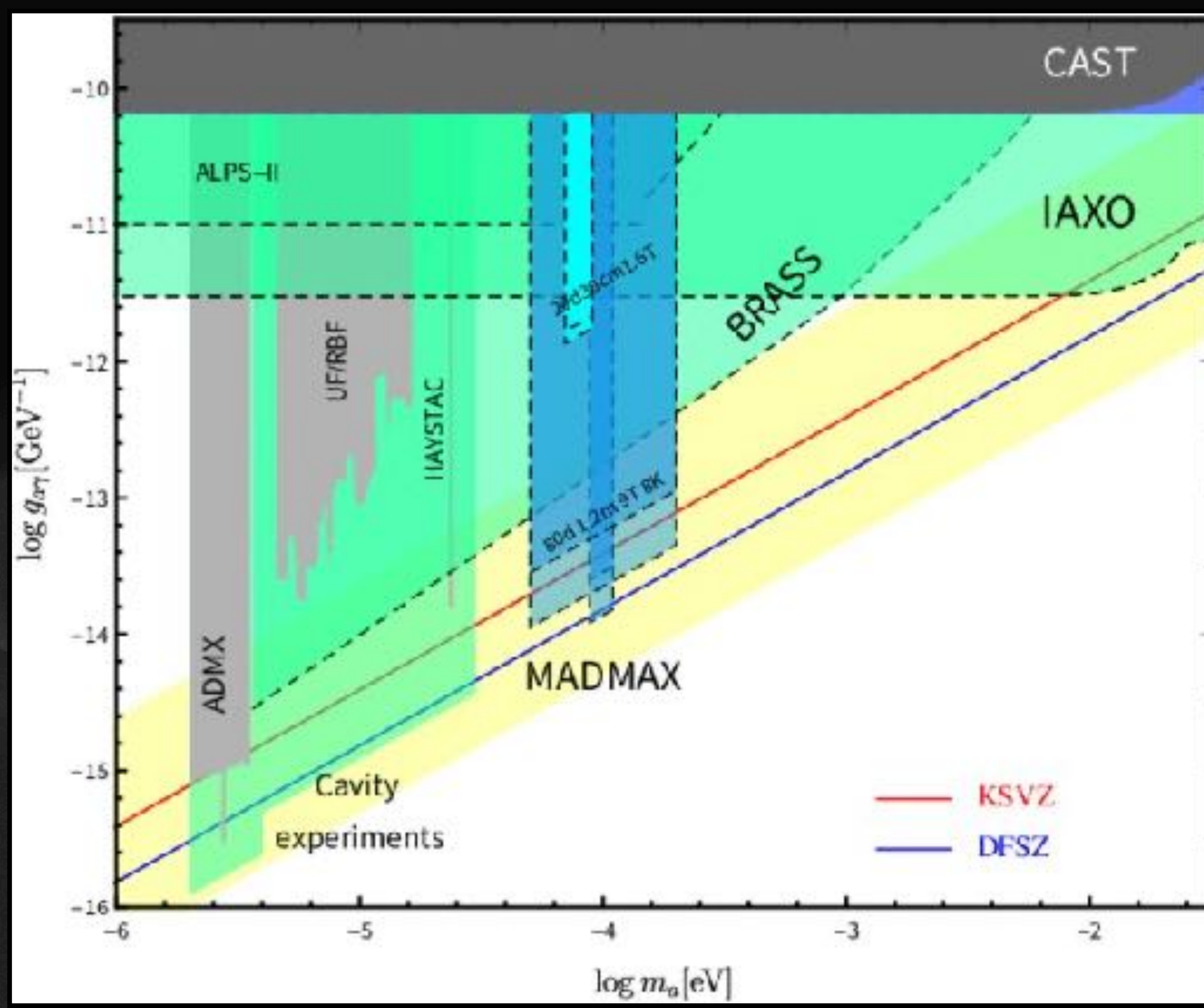
Boost depends on spacing: adjustable broadbandness

Expected boost factor up to 10^5

MadMax setup & prospect

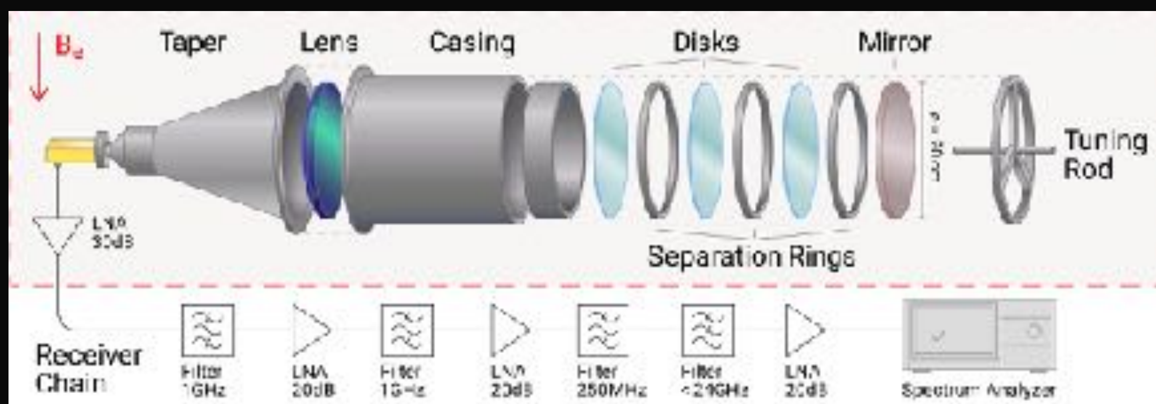


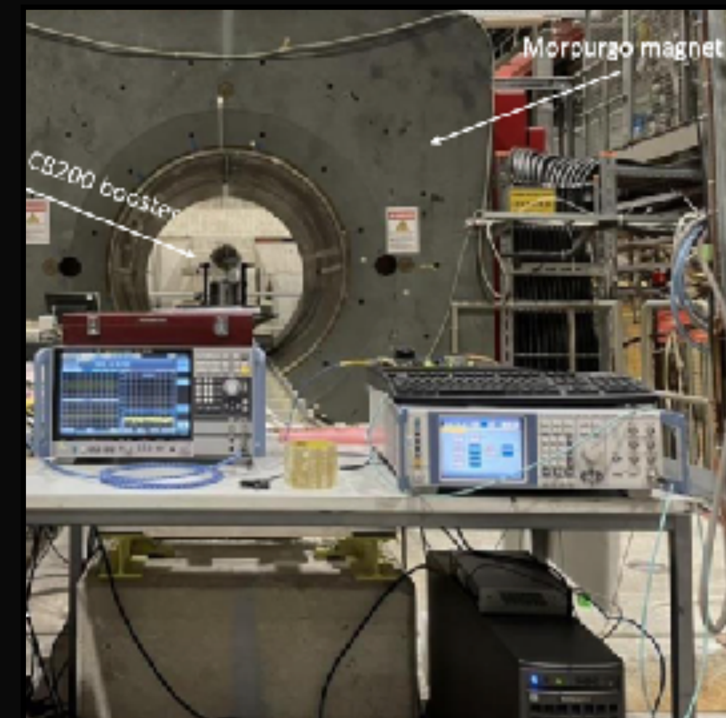
Large dipole magnet
mirror / booster / focusing mirror

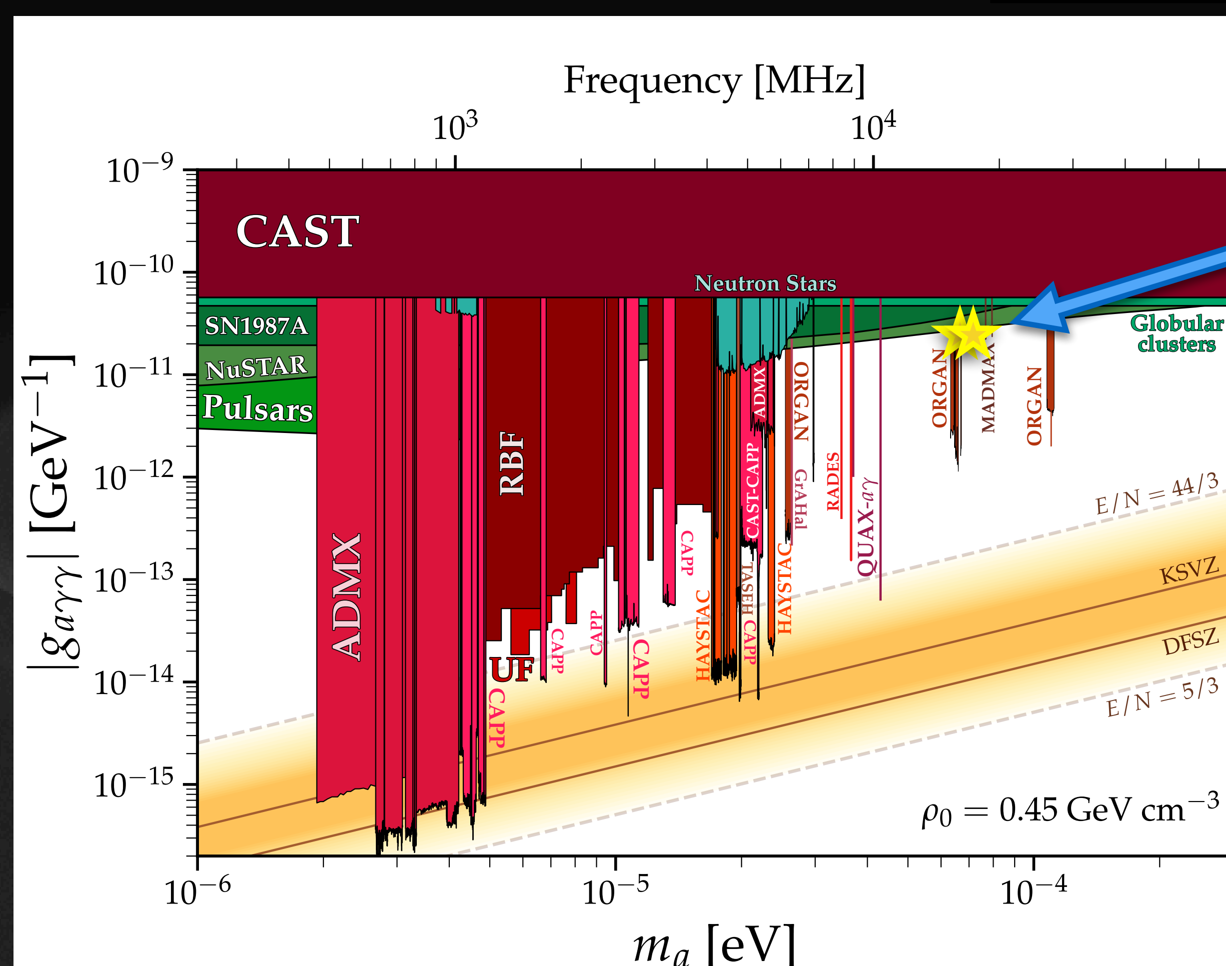


Test run at CERN

Full apparatus expected 2028
Test run in a 1.6 T magnet at CERN



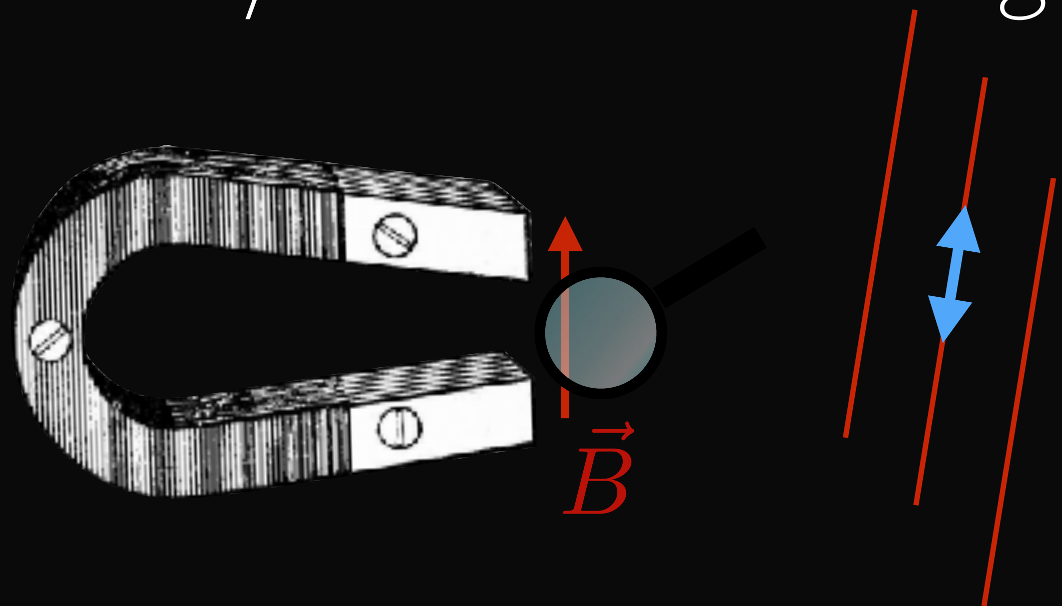




Expected reach

Broadband concentrators

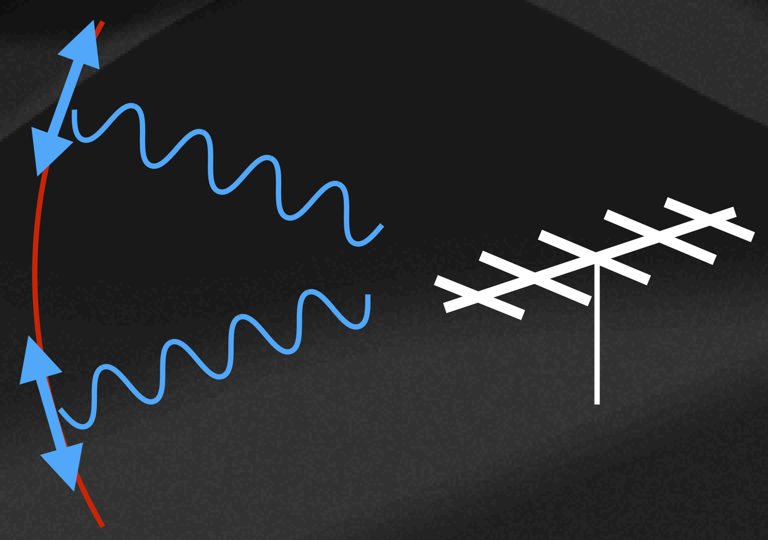
Everywhere in the background : $\phi = \phi_0 e^{-imt}$



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

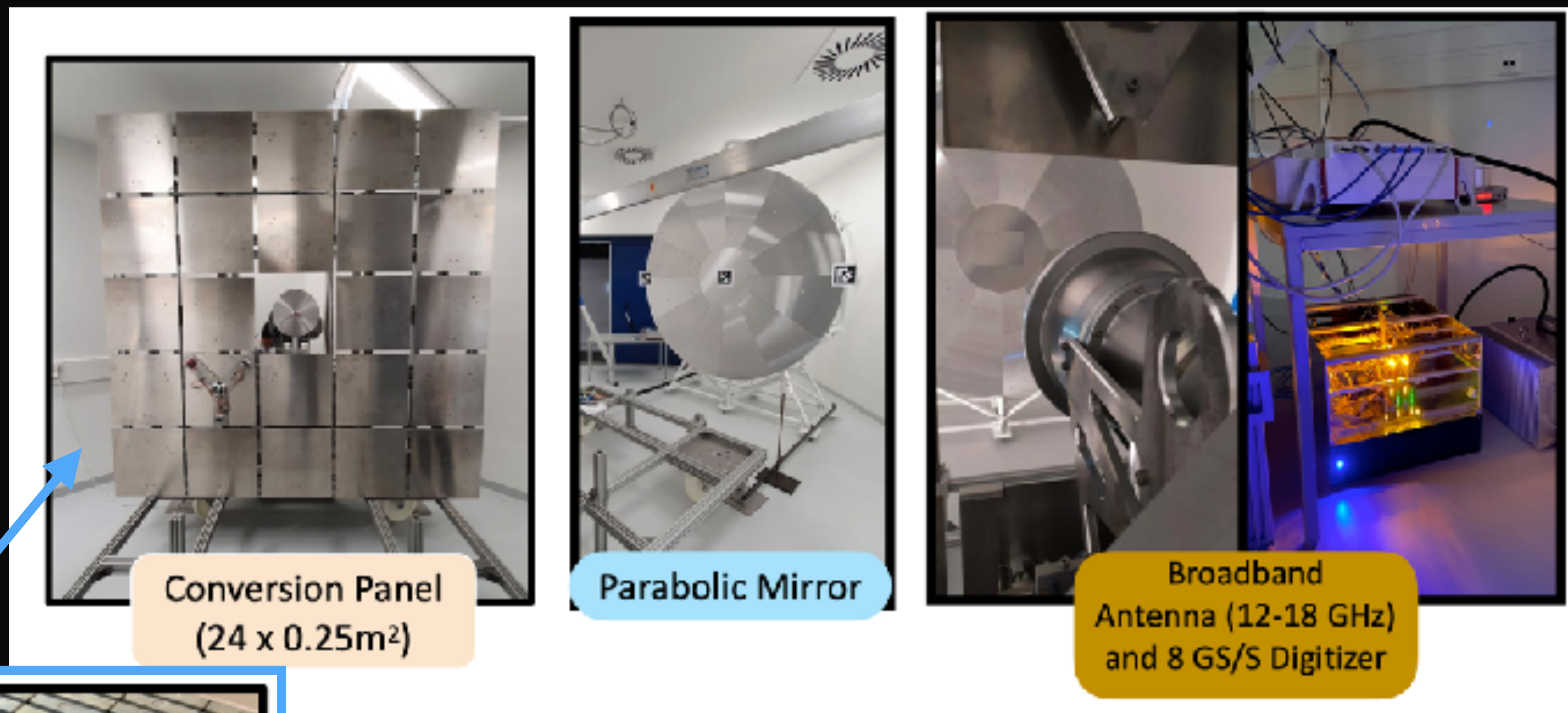
small oscillating electric field along each B-field line

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

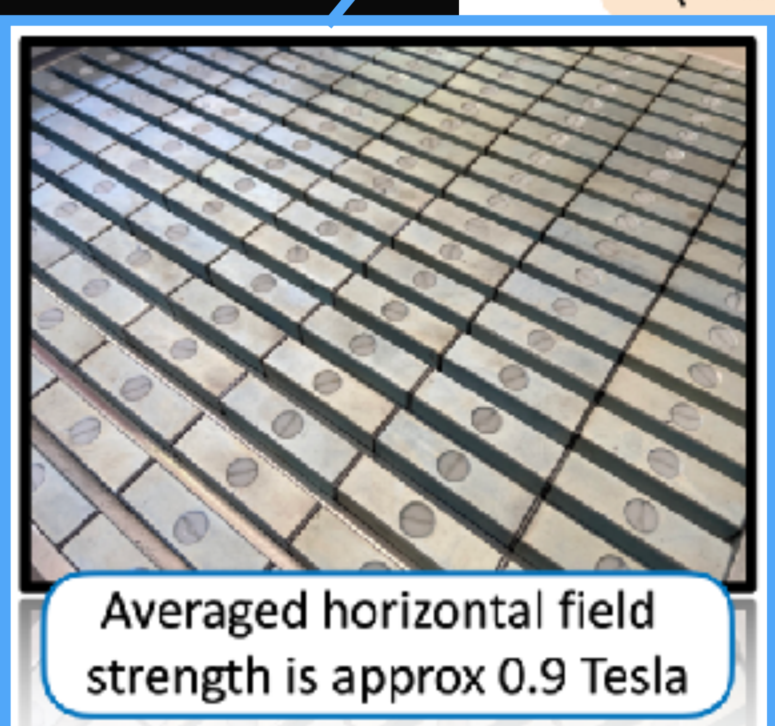


BRASS

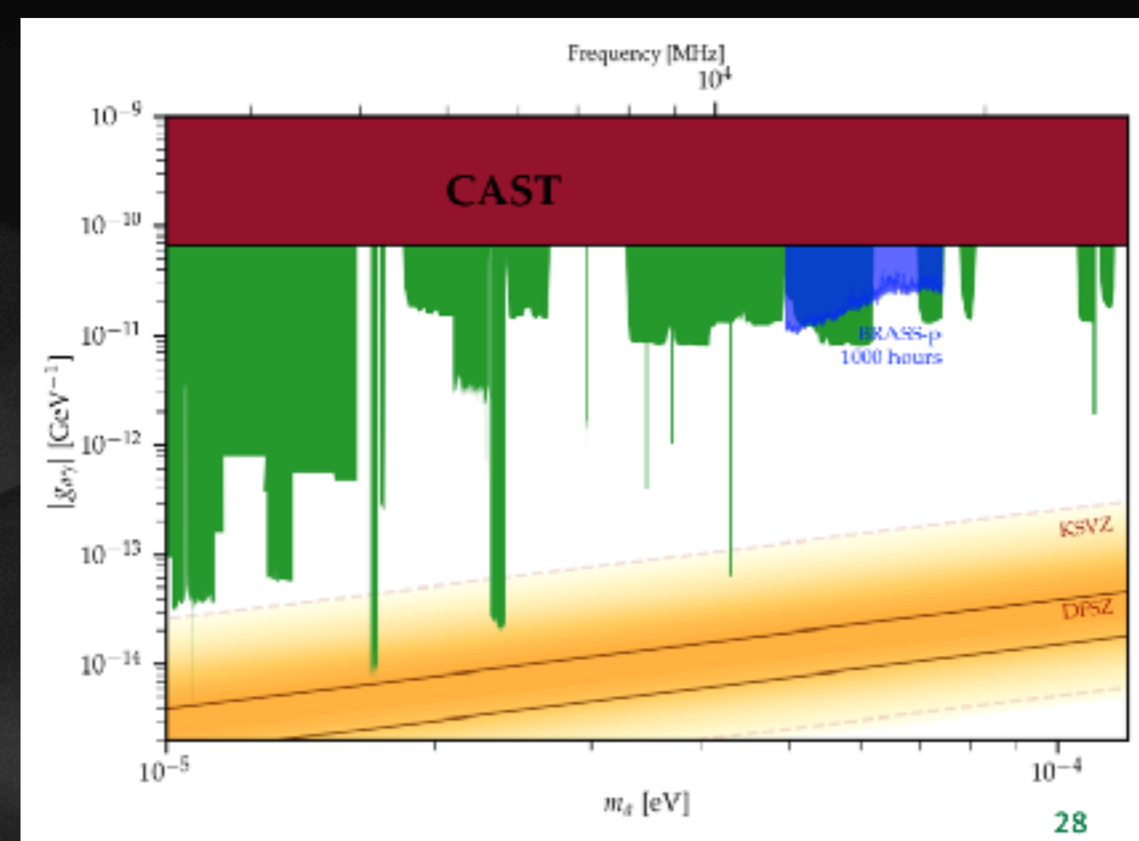
Broadband Radiometric Axion SearcheS



Nguyen, PATRAS 2022

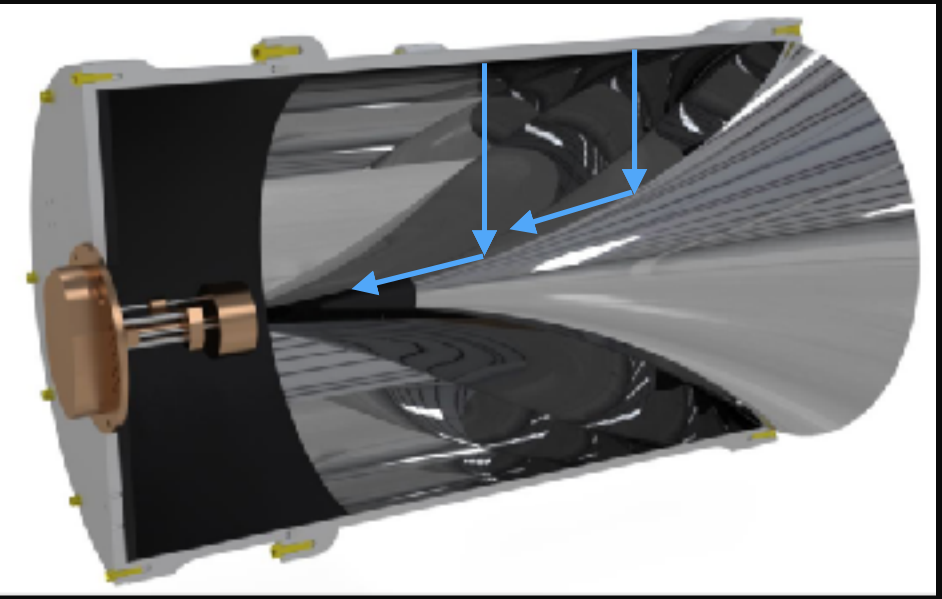


Array of permanent magnets



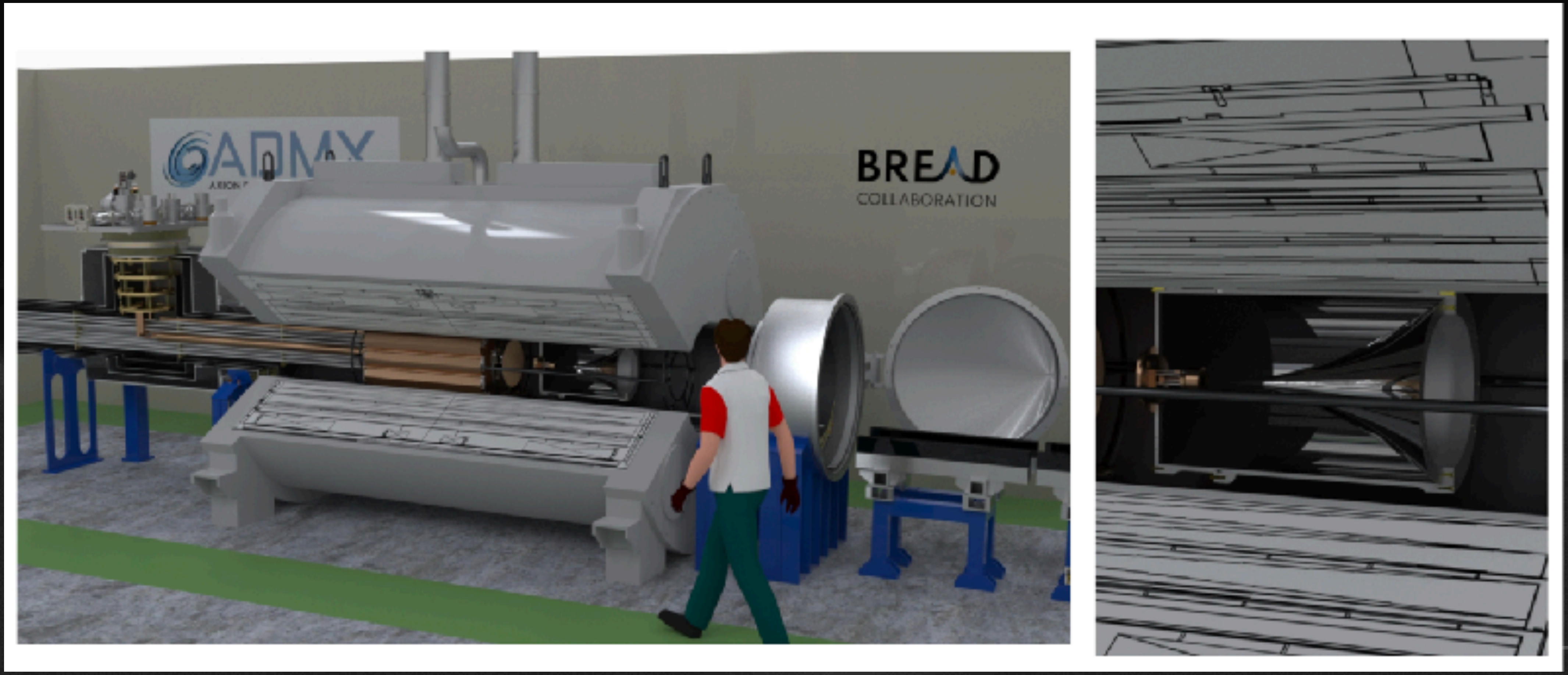
BREAD

Broadband Reflector Experiment for Axion Detection



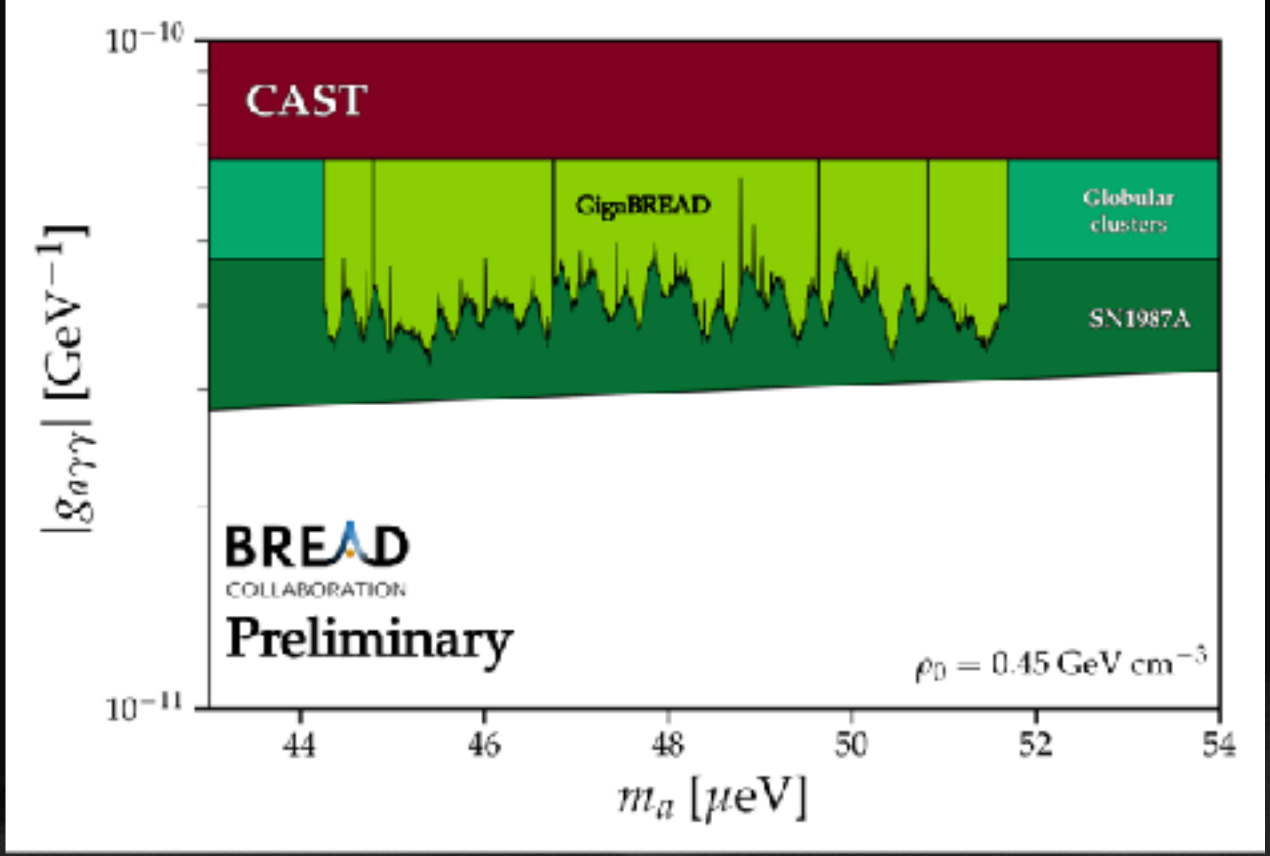
Use of a solenoid magnet

Custom-shaped reflector sends the signal to focus

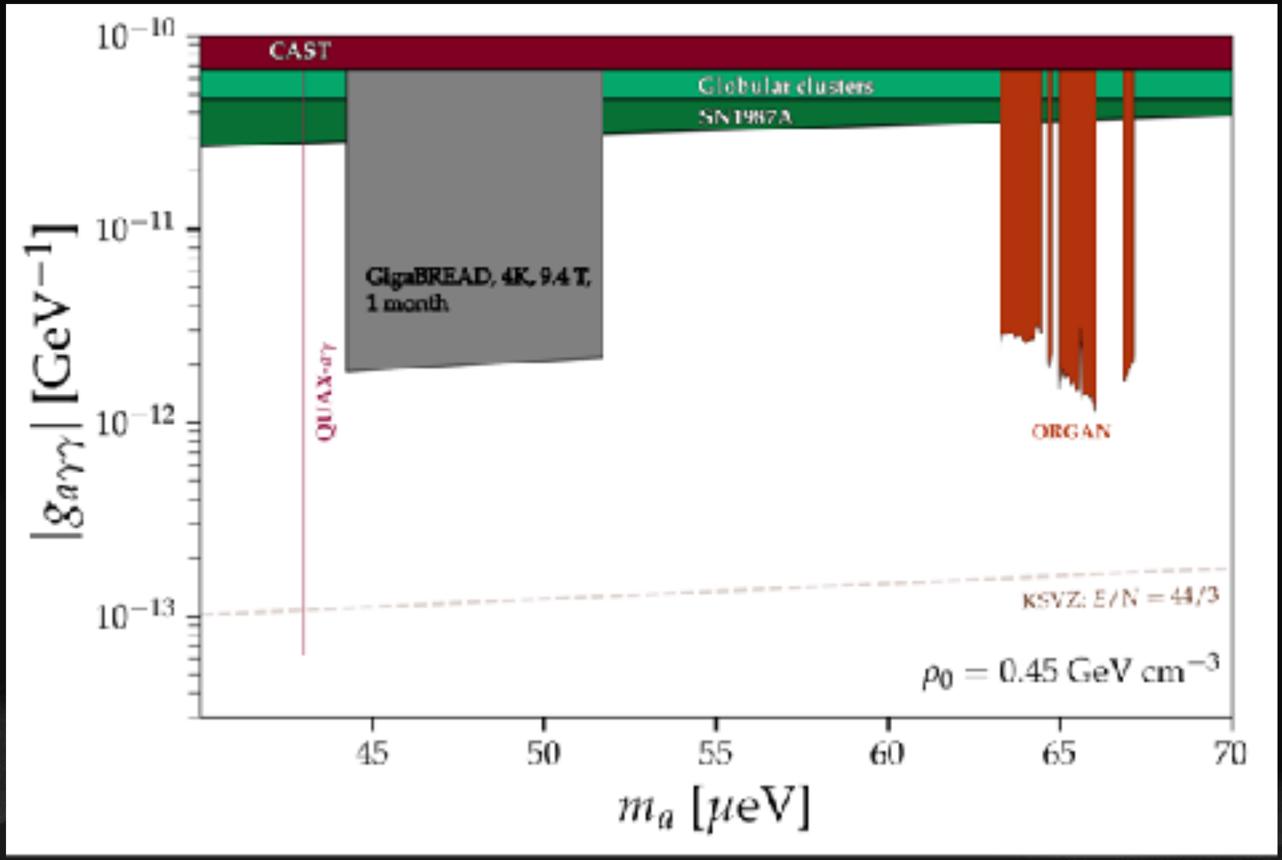


BREAD

Test run in a 3.9 T MRI magnet

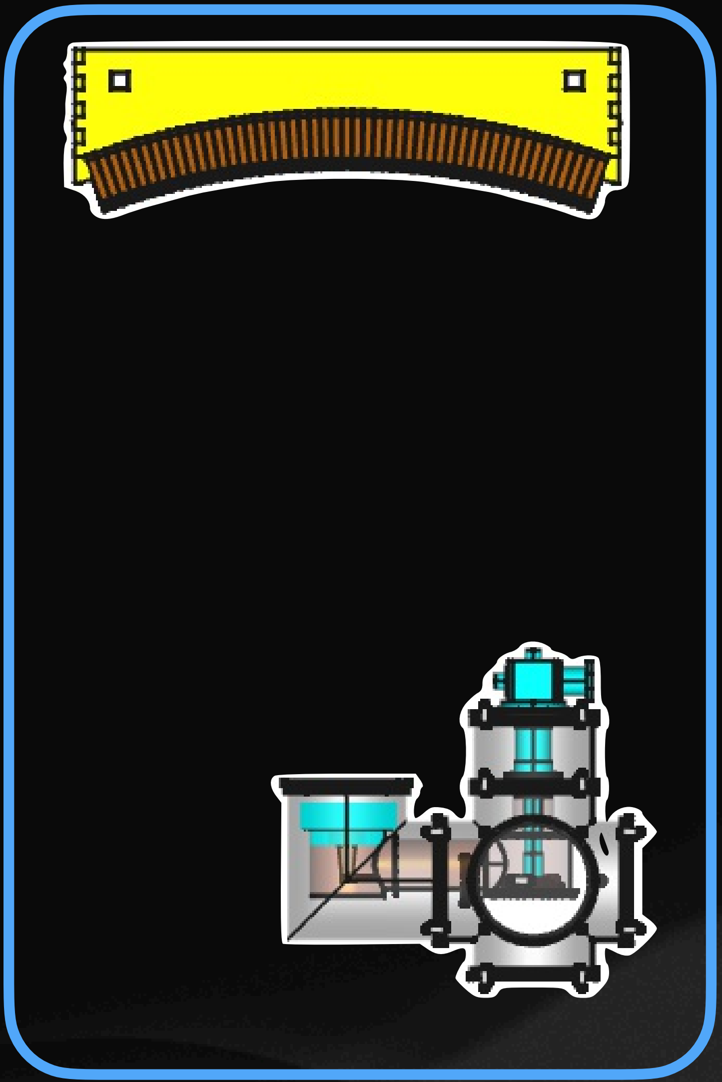


Plans to use a 9.4 T magnet

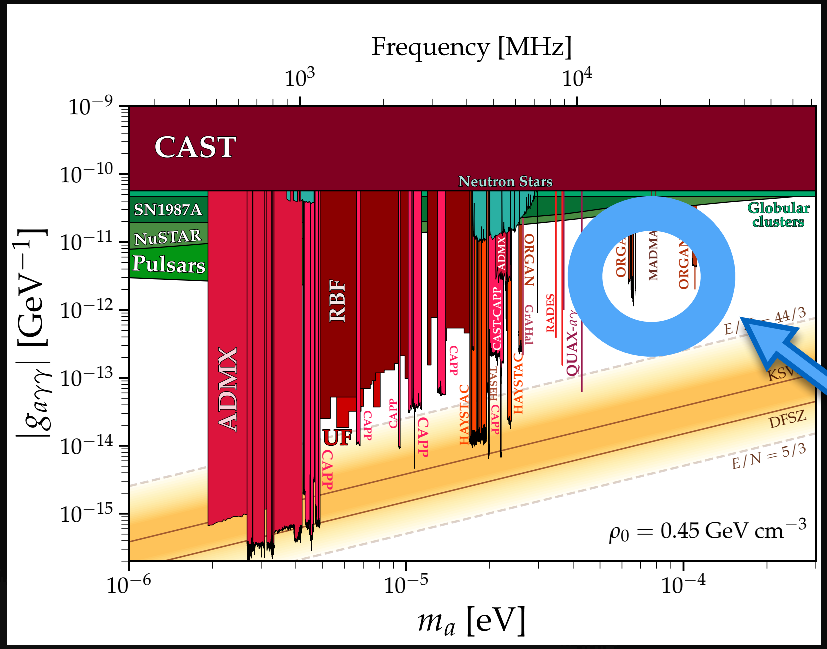


DAWA

Dark Axion Wideband Approach



Array of permanent magnets



Expected reach

Receiver cooled down 4 K

- ★ First fully modular setup
- ★ First axion runs late 2024
- ★ Switch to superconducting magnets late 2025