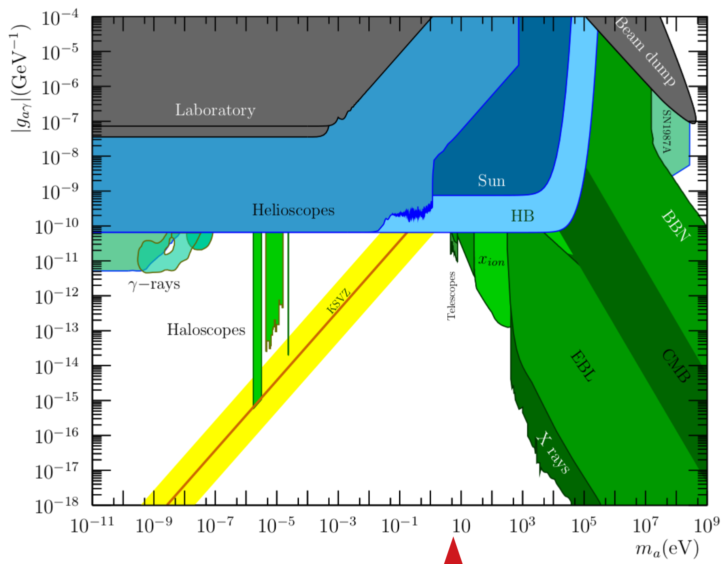
Search for ultra low-mass dark matter

Outline

Laurent Chevalier university Paris-Saclay
Exploring The Dark Side of the universe
Guadeloupe 25-29 June 2018

Search for ultra low-mass dark matter



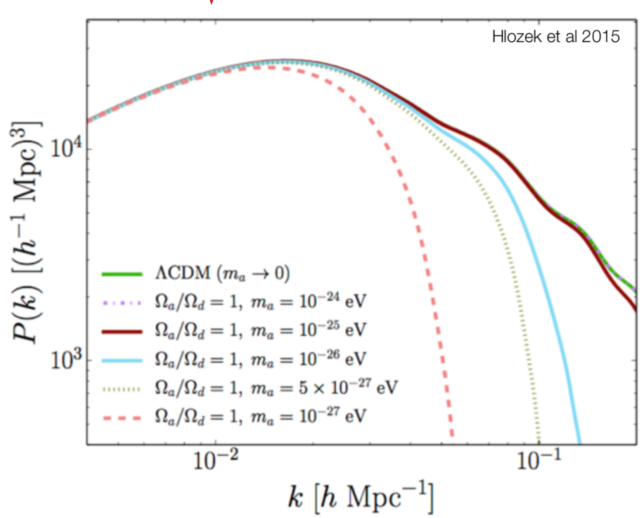
Scope of this talk

Axions
Axions-like-particles (ALPs)
Hidden (or Dark) photons

Ultra-low mass dark matter

$\sim 10^{-24}$eV → ~ 1eV

light neutral
(pseudo) scalar boson
weakly couple



Remarks

- CMB exclude masses < 10^{-24}eV
- Dwarf galaxy structure formation →

$$\frac{\lambda_{\mathrm{dB}}}{2\ \mathrm{kpc}} \sim \left(\frac{10^{-22}\ \mathrm{eV}}{\mathrm{m_a}}\right)\left(\frac{10\ \mathrm{km/s}}{\mathrm{v}}\right)$$

Search for ultra low-mass dark matter

Remarks:

dark matter candidates → light dark matter must be bosons

$$N_{particles} \sim \frac{10^{12} M_{\odot}}{m} \qquad N_{cells} \sim \frac{\frac{4\pi}{3} p_{max}^3 \frac{4\pi}{3} R^3}{(2\pi\hbar)^3}$$

$$\frac{N_{particles}}{N_{cells}} \sim \left(\frac{100 \ \frac{\mathrm{eV}}{\mathrm{c}^2}}{m} \right)^4$$

Search for ultra low-mass dark matter

Problem: missing matter of the universe

Dark matter predictions from astrophysics and cosmology

- **CMB**
- Velocity dispersion in galaxy cluster
- Bullet cluster
- Galaxy rotation curve
- Galaxy without dark matter

Main dark matter candidates

- Standard model
- WIMPS
- LSP susy $\tilde{\chi}^0$
- Axions
  - Axions-like-particles (ALPs)
  - Hidden (or Dark) photons

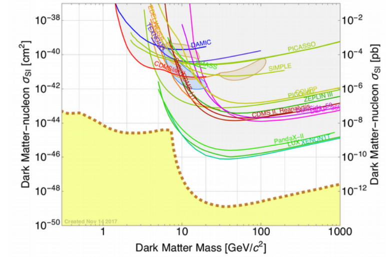
LHC: ATLAS, CMS, LHCB results

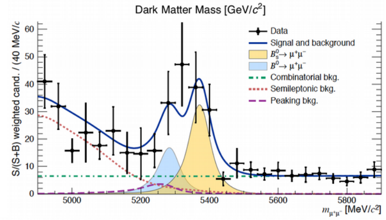
1/ $B_s \to \mu^+\mu^-$ purely SM

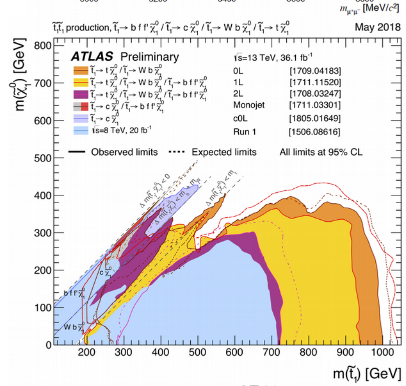
2/ $m_{top} \ll m_{\tilde{t}}$

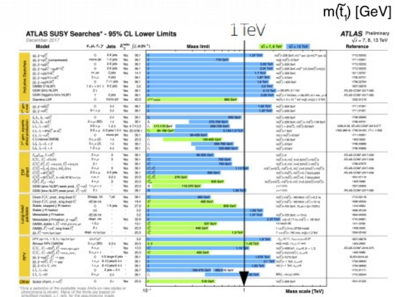
3/ no other susy clues

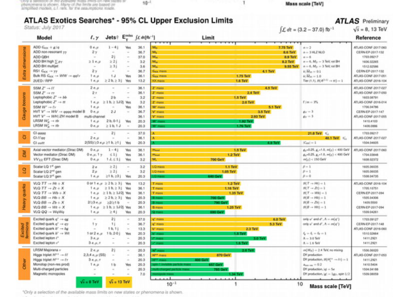
4/ neither exotics process











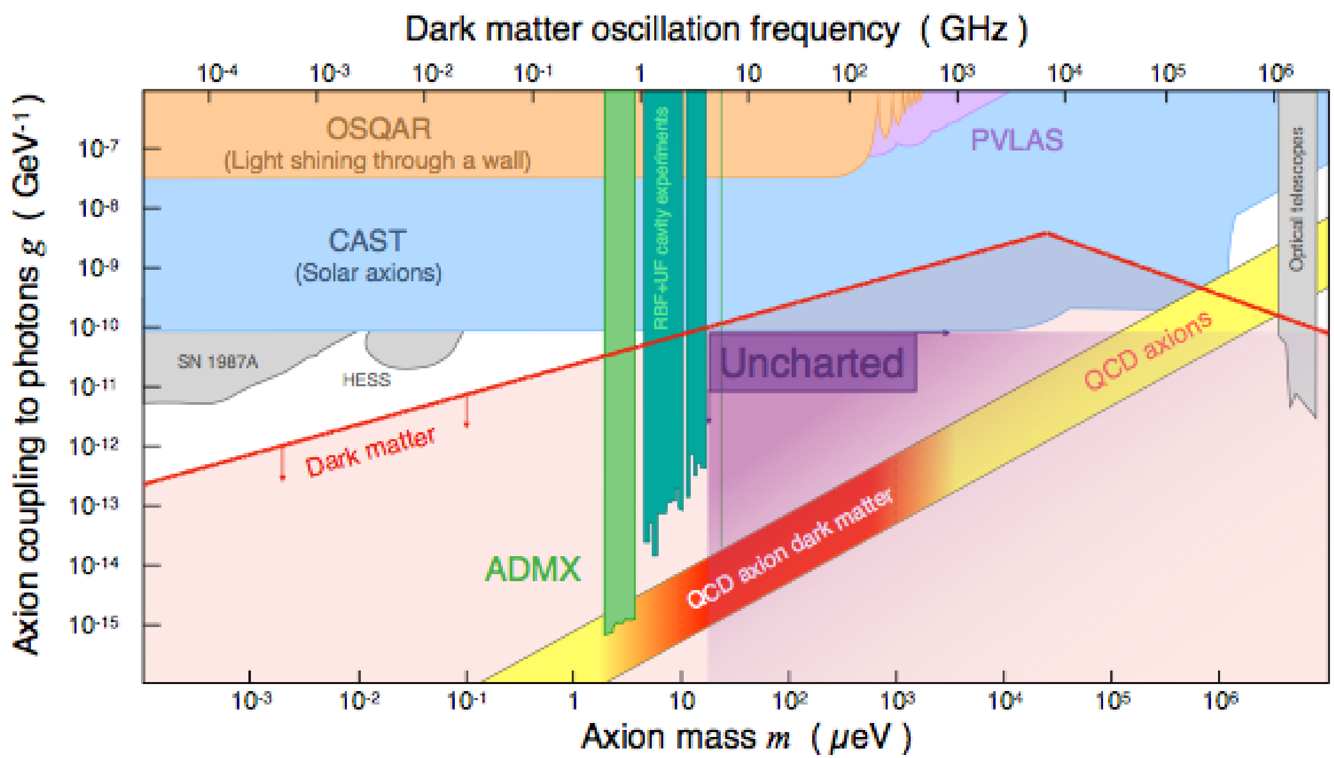
Search for ultra low-mass dark matter

Problem: missing matter of the universe

Dark matter candidates

- Standard model — no ?
- WIMPS — no clues
- LSP susy $\tilde{\chi}^0$ — no clues
- Axions — no clues neither
  - Axions-like-particles (ALPs)
  - Hidden (or Dark) photons

But large unexplored mass domain



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CP-strong problem:

EW interaction : 6 quarks → CKM matrix →
3 mixing angles
1 CP-violating complex phase : $\theta_{\text{weak}} = \text{Arg}(\det(\text{CKM}))$

QCD vacuum structure & QCD gauge invariance →
1 CP_strong violating term θ_{strong}

SM Lagrangian: → $$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{EW}} + \mathcal{L}_{\text{QCD}} + \theta_{total} \frac{\alpha_s}{8\pi} G\tilde{G}$$

with $\theta_{total} = \theta_{\text{strong}} + \theta_{\text{weak}}$

T-violating quantity

Remarks:

- this term reflect the topological properties of the QCD vacua
- strong CP violation is predicted
- induces a large neutron Electric Dipole Moment (←T-violation)
- non-zero EDM necessarily violates CP
- for the neutron $d_n \to \theta_{total}\ e\ m_q/m_n^2 \to \theta_{total}\ 10^{-16}$ e cm

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CP-strong problem:

The experimental limit on $d_n < 10^{-26}$ e cm $\rightarrow \theta_{total} < 10^{-10}$ e cm

issues:

- why this free parameter θ_{total} is so small?
- $\theta_{weak} \sim 10^{-4}$ & $\theta_{total} = \theta_{strong} + \theta_{weak}$ $\rightarrow$ cancellation ?
- unexpected fine tuning

solutions:

- θ_{total} is small ! (Anthropic solution)
- there is new global spontaneously chiral-symmetry breaking
- other ...

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CP-strong problem → solution

New global spontaneously chiral-symmetry breaking: $U(1)_{pq}$

- R.D.Peccei & H.Quinn proposed the first prototype chiral solution
- many other similar mechanism exist today, that I did not explore

New SSB → new Nambu-Goldstone boson field

- S.Weinberg & F.Wilczek proposed a new field : axion → a(x)
- $U(1)_{pq}$ degree of freedom θ_{total} is replaced by this field a(x)
- scale of the $U(1)_{pq}$ spontaneously symmetry breaking: f_a

$T \sim \Lambda_{QCD}$ → explicit chiral-symmetry breaking

- axion become a pseudo-Nambu-Goldstone boson
- a(x) dynamically relax to 0 → no more apparent CP-violation

$$\mathcal{L}_\theta = \theta_{total} \frac{\alpha_s}{8\pi} G\tilde{G} \rightarrow \mathcal{L}_\theta = \frac{a(x)}{f_a} \frac{\alpha_s}{8\pi} G\tilde{G}$$

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CP-strong problem → solution

Remarks:

- non-pertubative QCD effect at $T \sim \Lambda_{QCD}$ → ESB
- axion at weak scale: $f_a \sim 246$GeV → 100keV resonance
  → ruled out by beam dump experiment $K^+ \to \pi^+ a$, $\pi^+ \to e^+ \nu a$ …
- but the $U(1)_{pq}$ symmetry breaking could be higher: $f_a \gg 246$ GeV

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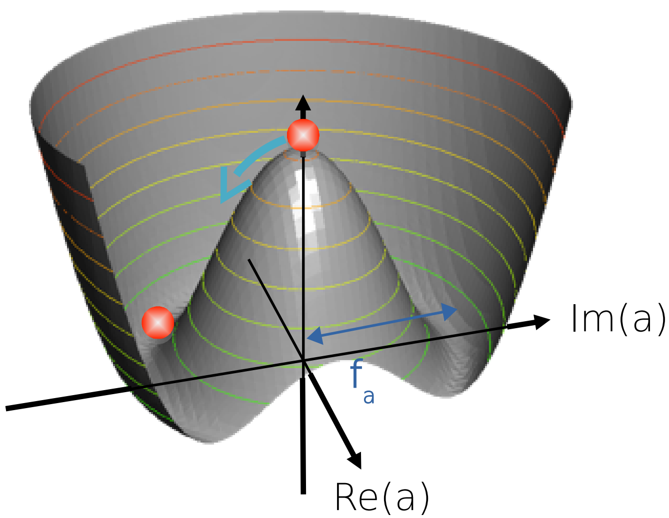
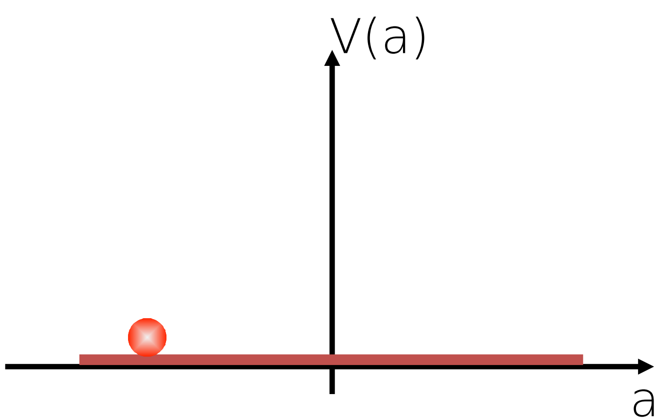
$$T = f_a \gg \Lambda_{QCD}$$

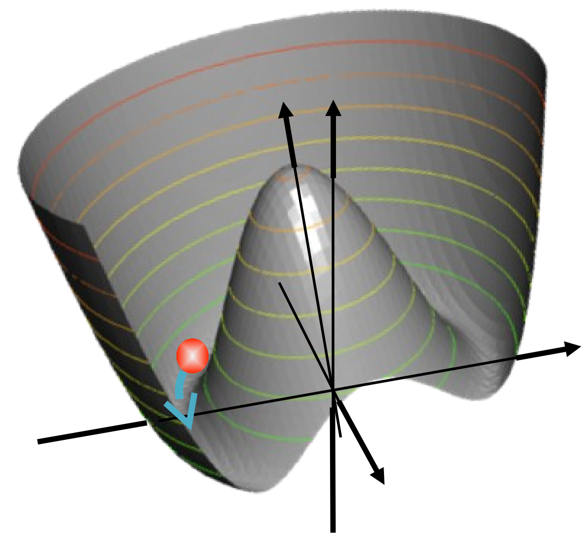
$U(1)_{pq}$ spontaneous symmetry breaking

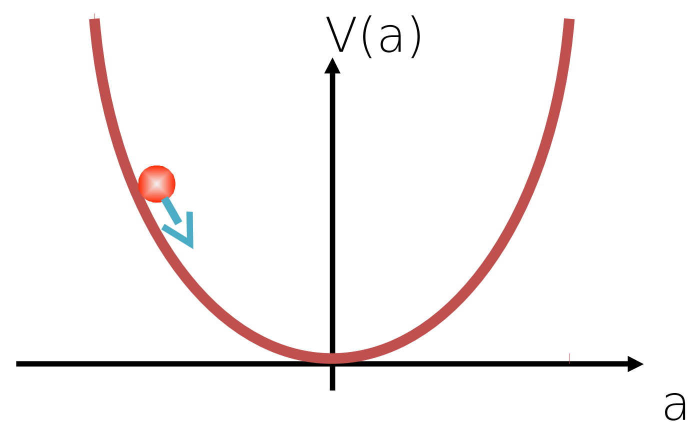




$$T \sim \Lambda_{QCD}$$

$U(1)_{pq}$ explicit symmetry breaking





axion gets mass

Misalignment mechanism
axion → CDM

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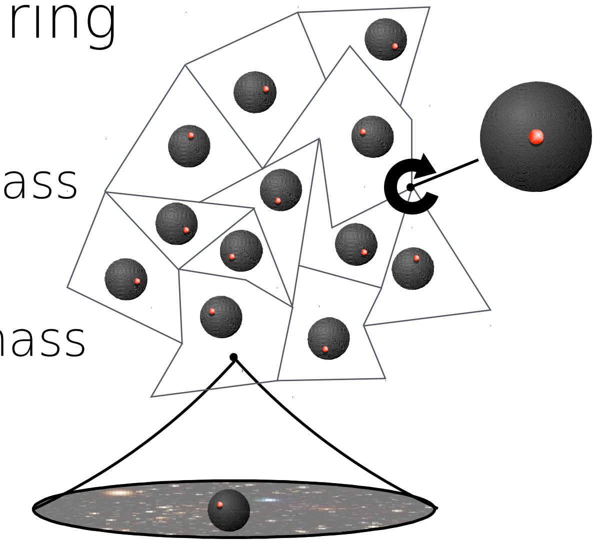
Two scenarios: PQ symmetry is broken during

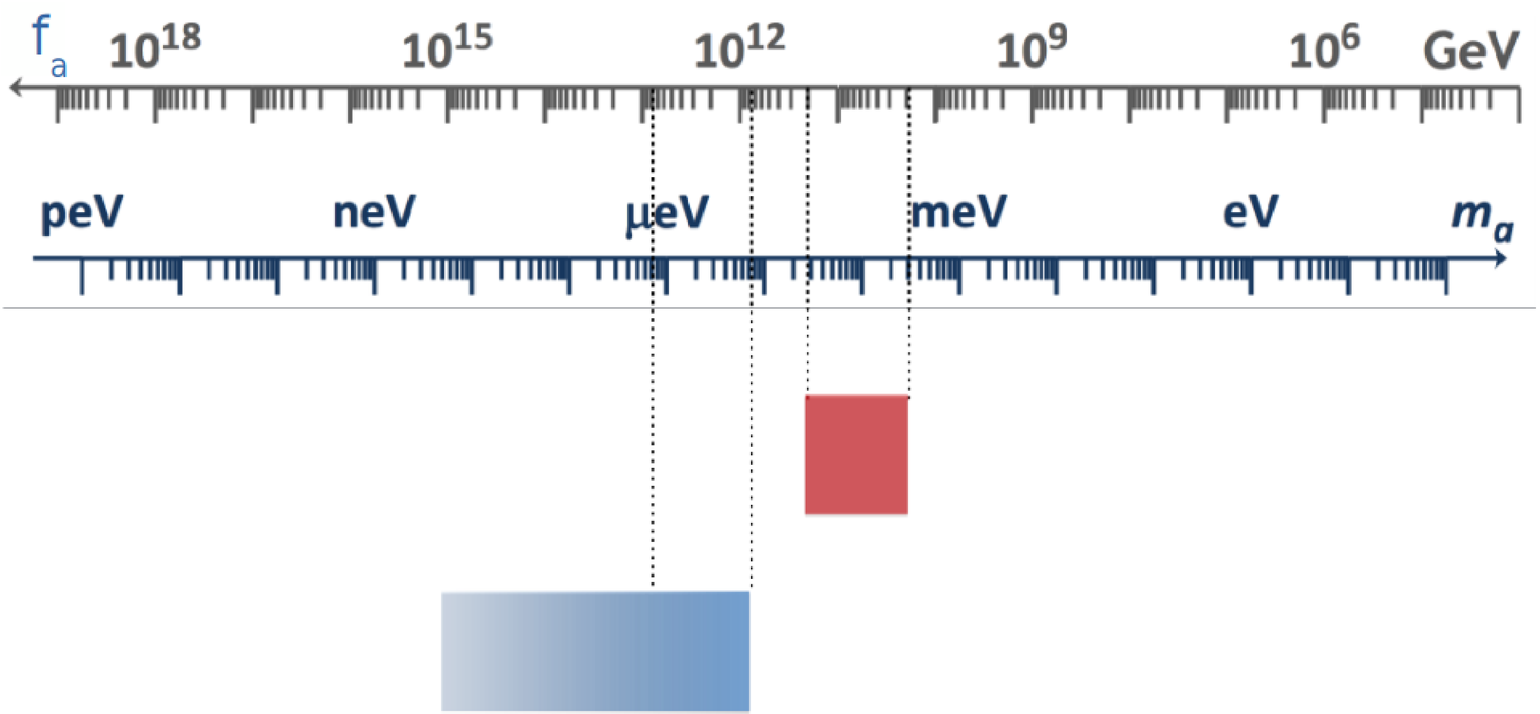
pre inflation: Misalignment

→ light constraints on axion mass

post inflation: decay of topological defects

→ hard constraints on axion mass





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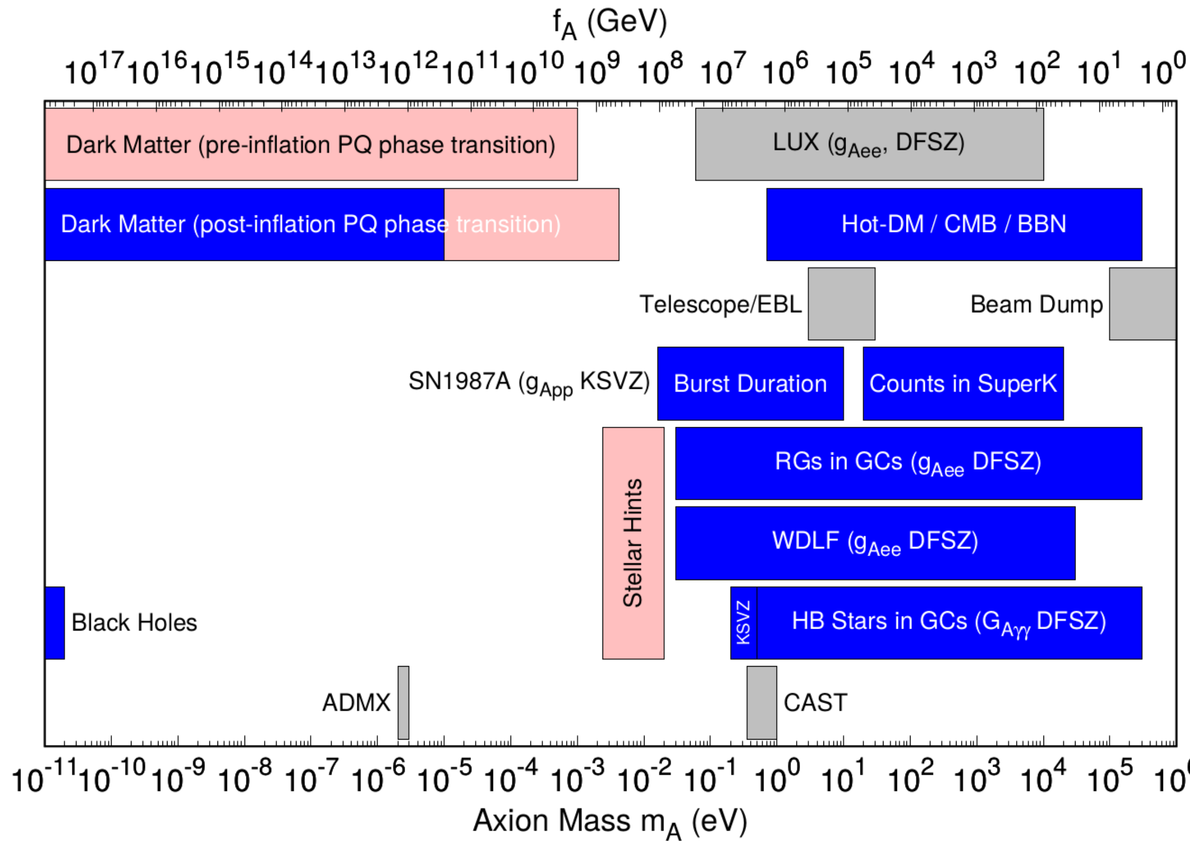
Effective models

Kim-Shifman-Vainshtein-Zakharov: KSVZ (I,II,III)
a complex SM singlet scalar a(x) and color triplet exotic (heavy) quark Q

Dine-Fischler-Srednicki-Zhitnitsky: DFSZ (I,II)
a complex SM singlet scalar a(x) and two Higgs doublets

Astrophysical constraints

$$f_a \geq\sim 10^9 \mathrm{GeV}$$



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Axion or Axion-Like-Particles

- Observations via electromagnetic interaction:Primakoff effect
- Adding to the QCD Lagrangian a new effective term

$$\mathcal{L}_a^{eff} = -\frac{1}{2}\partial_\mu\partial^\mu a + \frac{1}{2}m^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

$$g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi}\frac{C_{a\gamma}}{f_a}$$

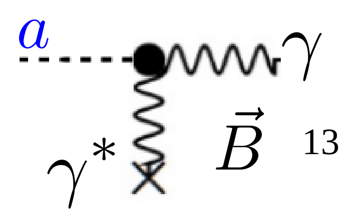
Remarks:

axion

axion-like-particle

$$\left.\right\} F_{\mu\nu}\tilde{F}^{\mu\nu} \propto \vec{E}.\vec{B} \quad \boxed{\rightarrow m_a \propto \frac{1}{f_a}}$$

Primakoff effect →



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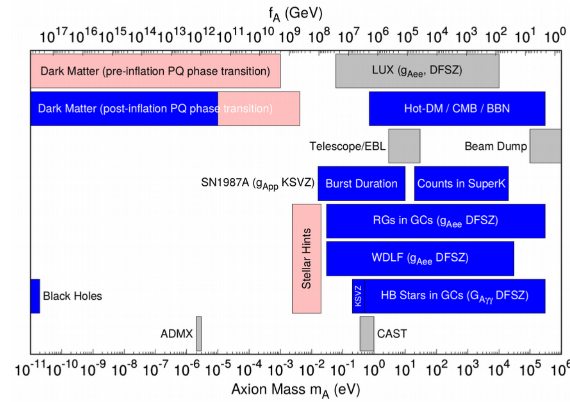
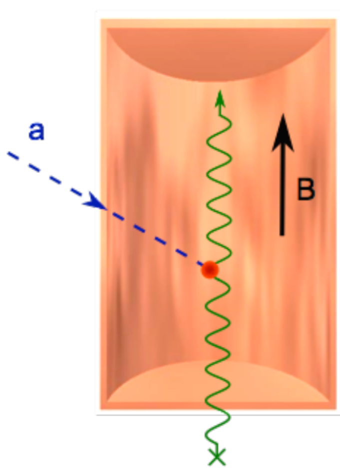
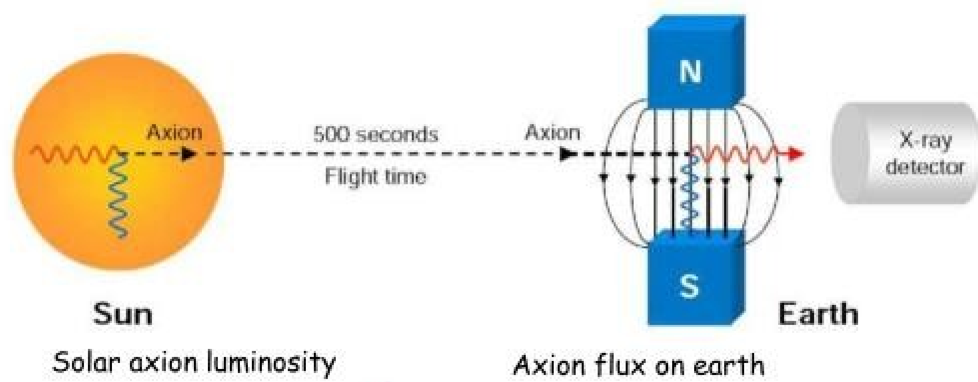


Search strategies and current limits

- Astrophysical bounds (see slide 16)
  - Star evolution
- Laboratory
  - Haloscopes
    resonance condition
    high sensitivity → small bandwidth exploration
  - Helioscopes
    big volume and High B-field
    less sensitive → large bandwidth exploration
  - Dish antenna
  - Light Shining though Walls





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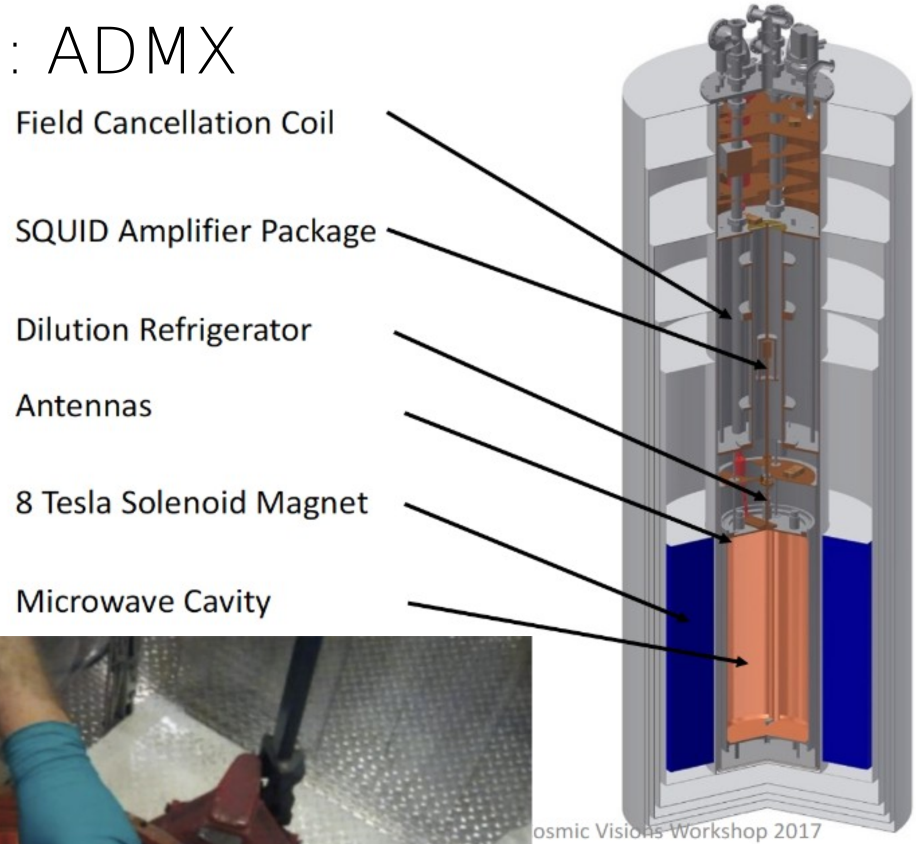
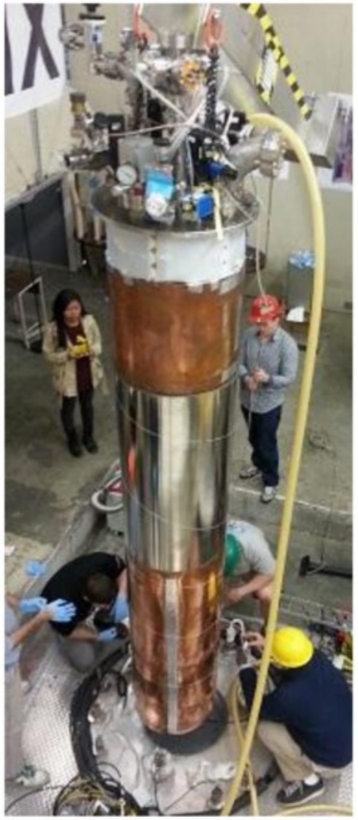
Haloscope: ADMX





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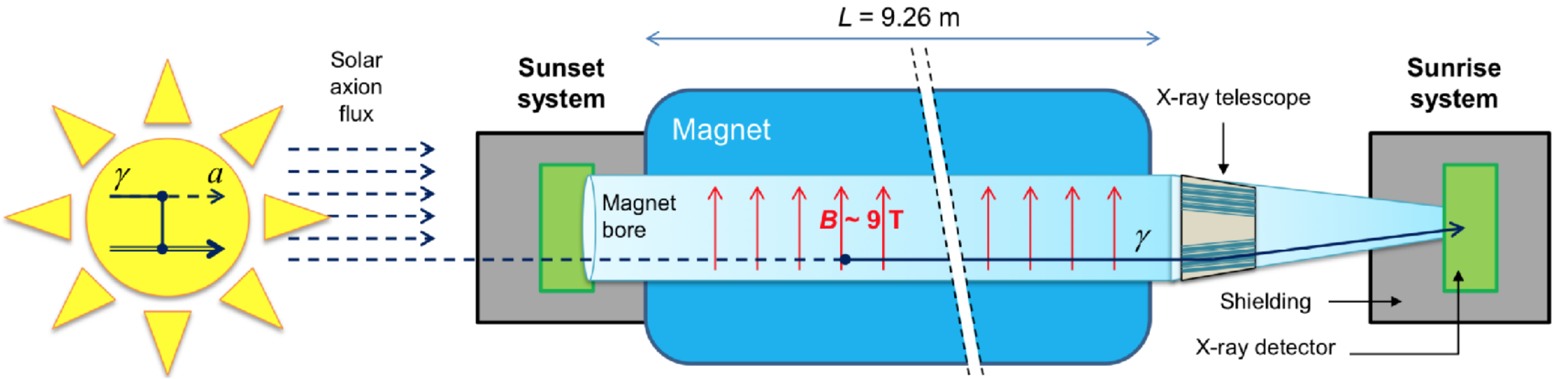
Helioscope CAST



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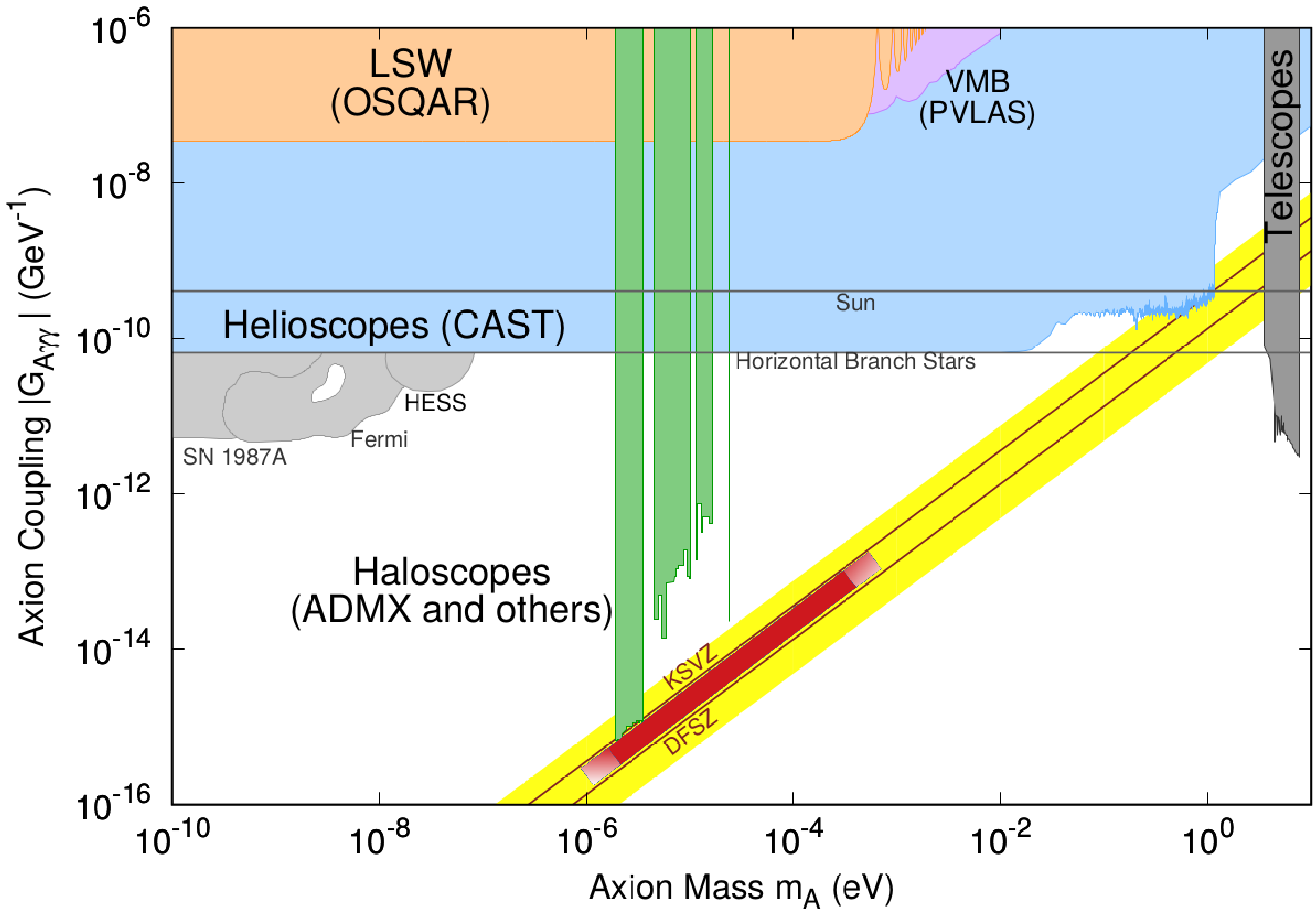
Axions & ALPs current limits



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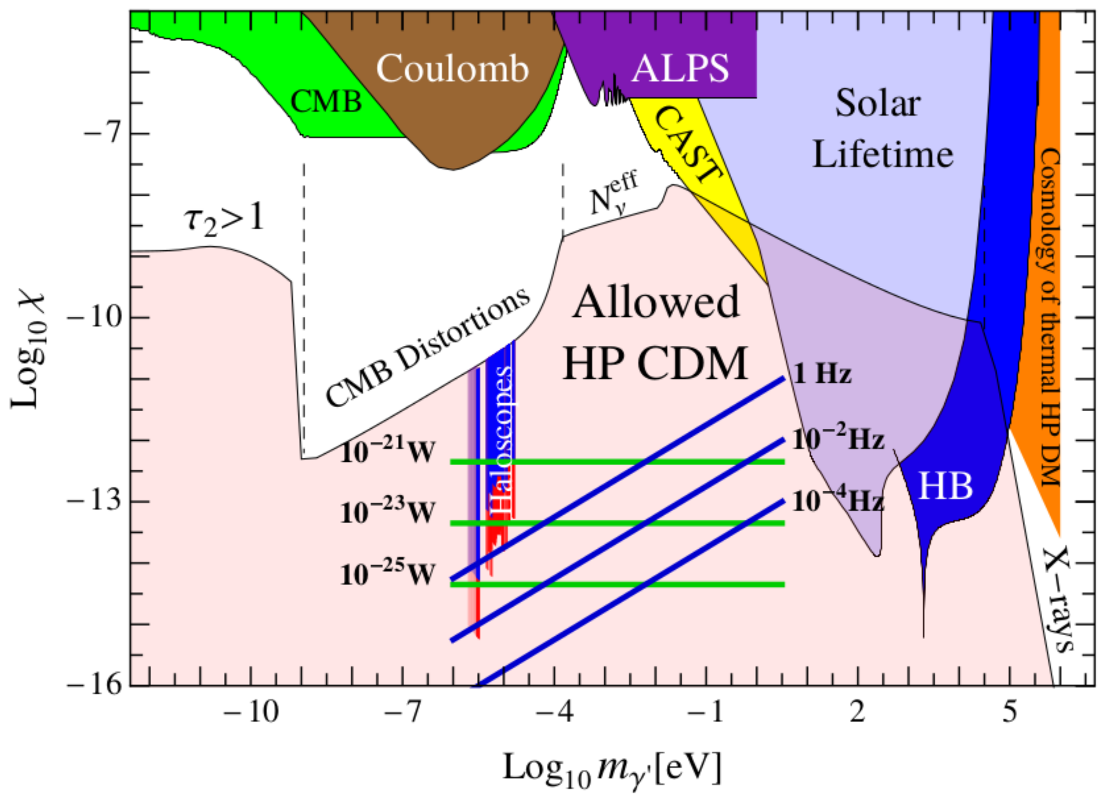
Hidden photon current limits

- Observations without electromagnetic interaction
- Adding to the QCD Lagrangian a new effective term

$$\mathcal{L}_{HP}^{eff} = -\frac{1}{2}\tilde{\chi}_{\mu\nu}\tilde{\chi}^{\mu\nu} + \frac{1}{2}m^2\tilde{\chi}_{\mu}\tilde{\chi}^{\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\chi F_{\mu\nu}\tilde{\chi}^{\mu\nu}$$



Search for ultra low-mass dark matter

Future experiments

- MadMax
- IAXO
- ALP-II
- Orpheus
- Quax
- Cultask
- CASPER
- Shuket
- ....

$\sim 10^{-25}$ Watts

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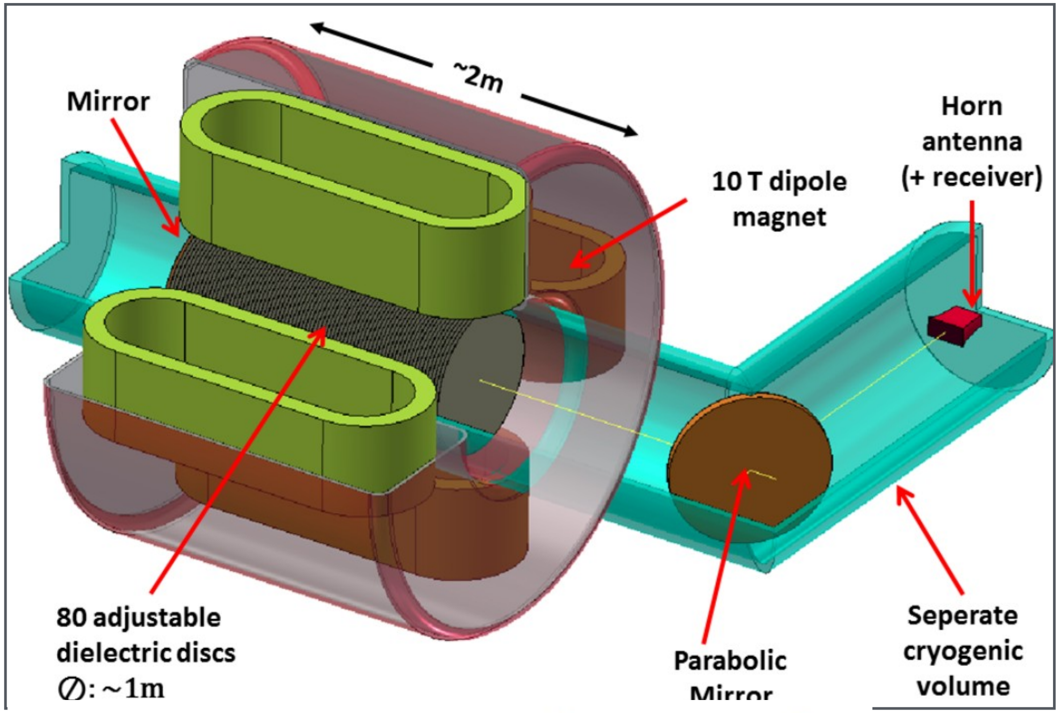
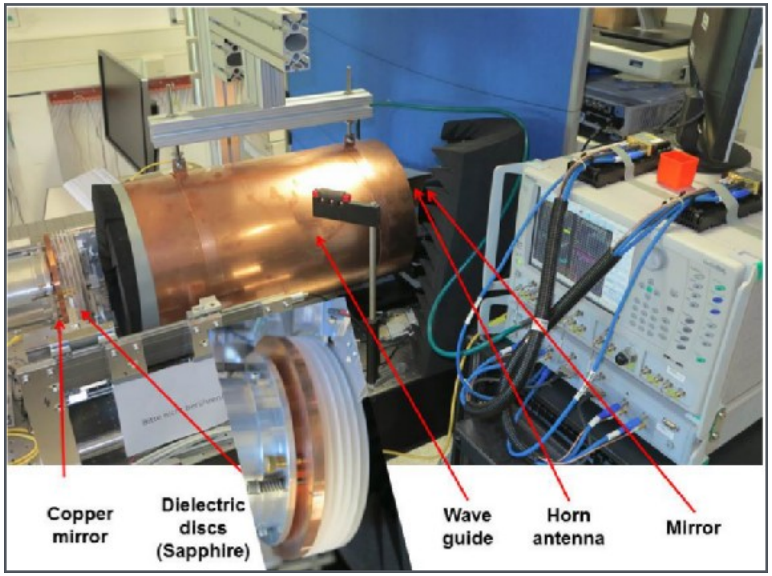
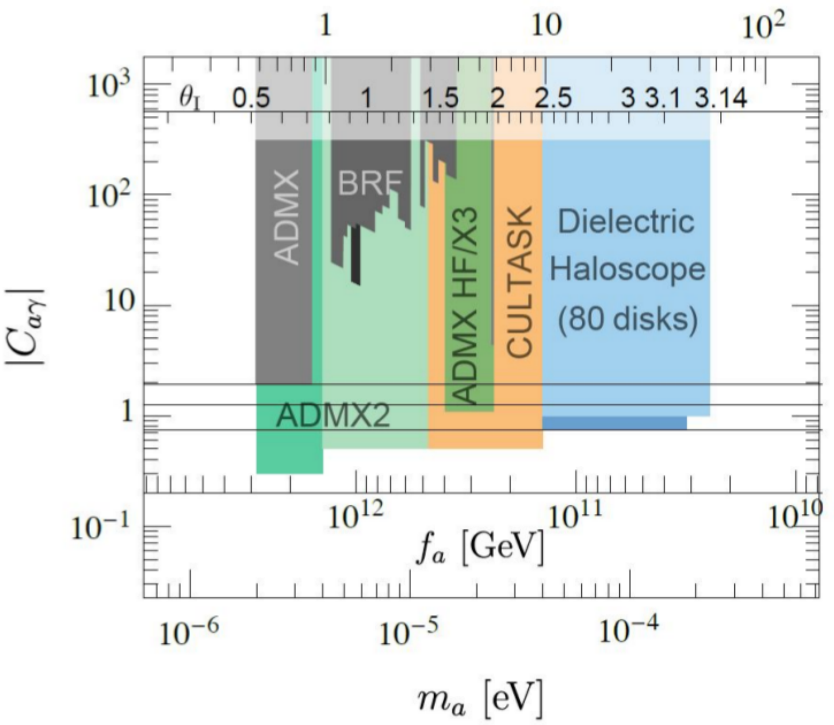
Future experiments: MadMax







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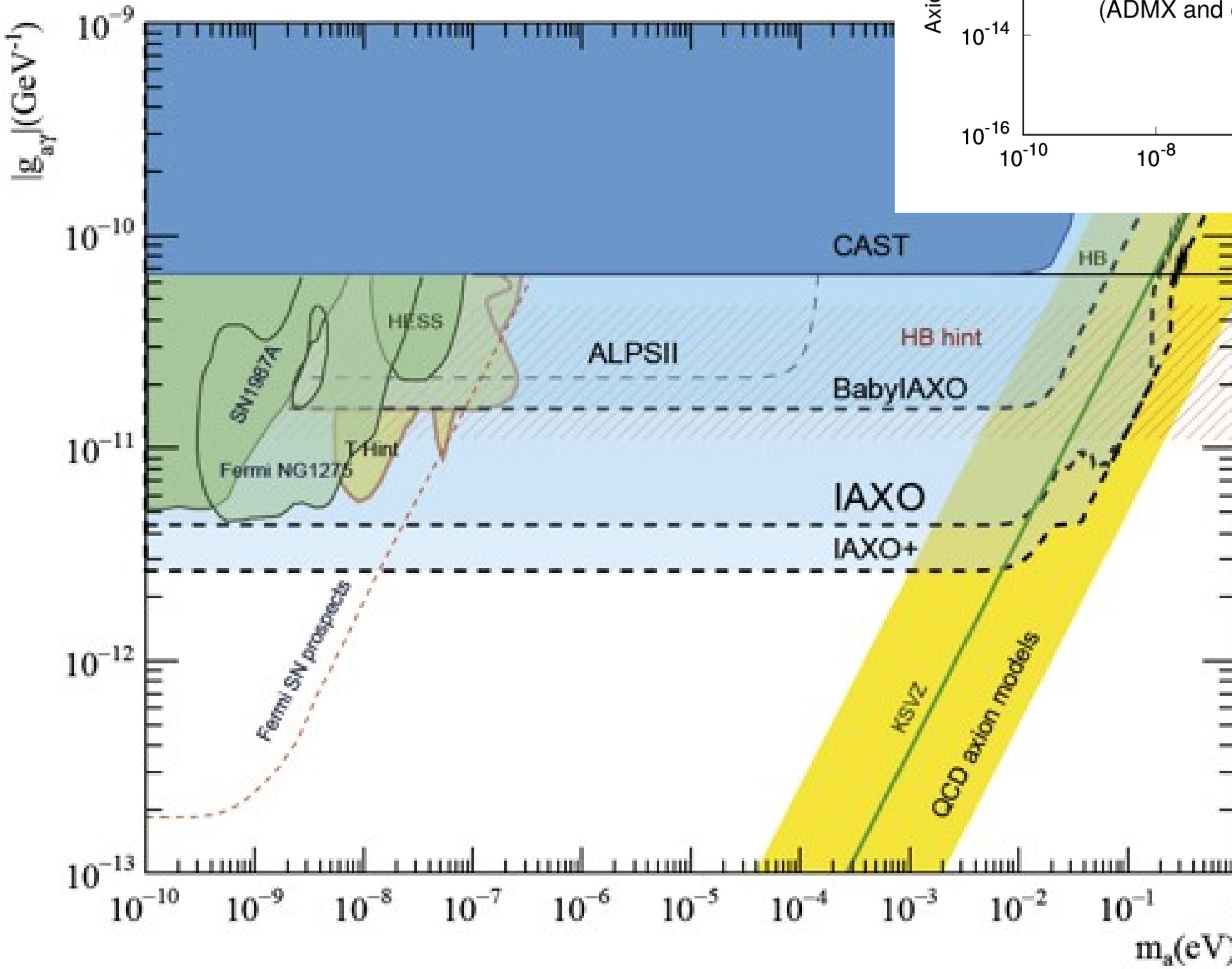
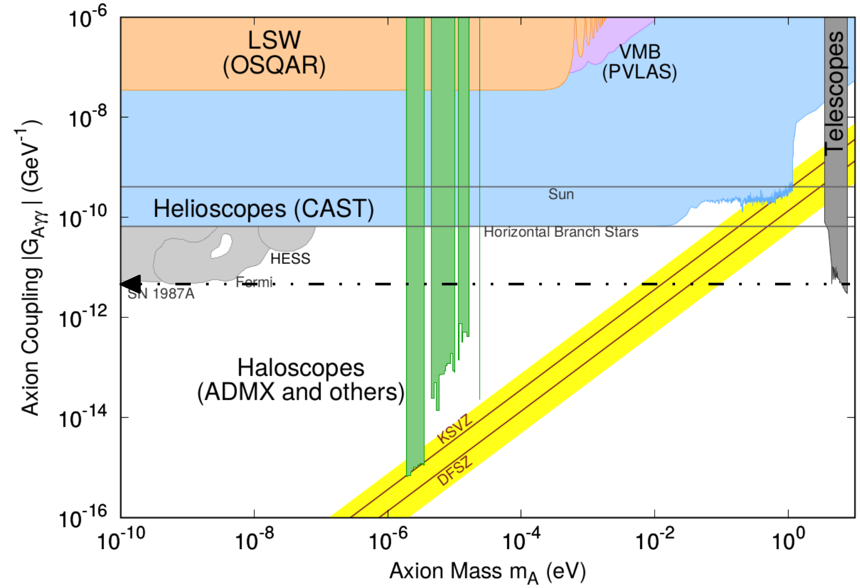
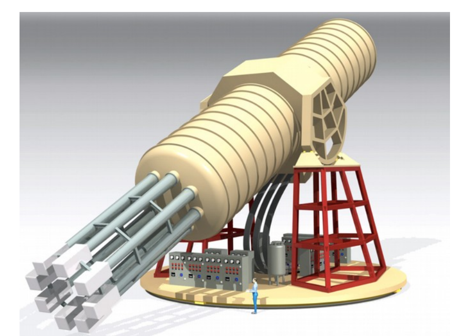
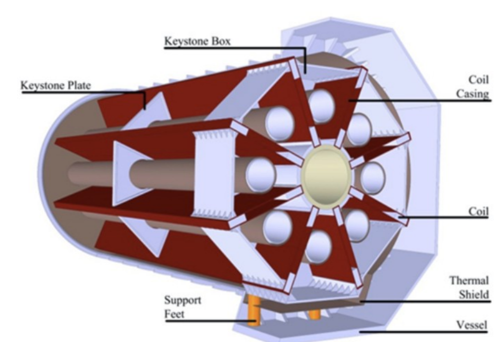
Future experiments: IAXO









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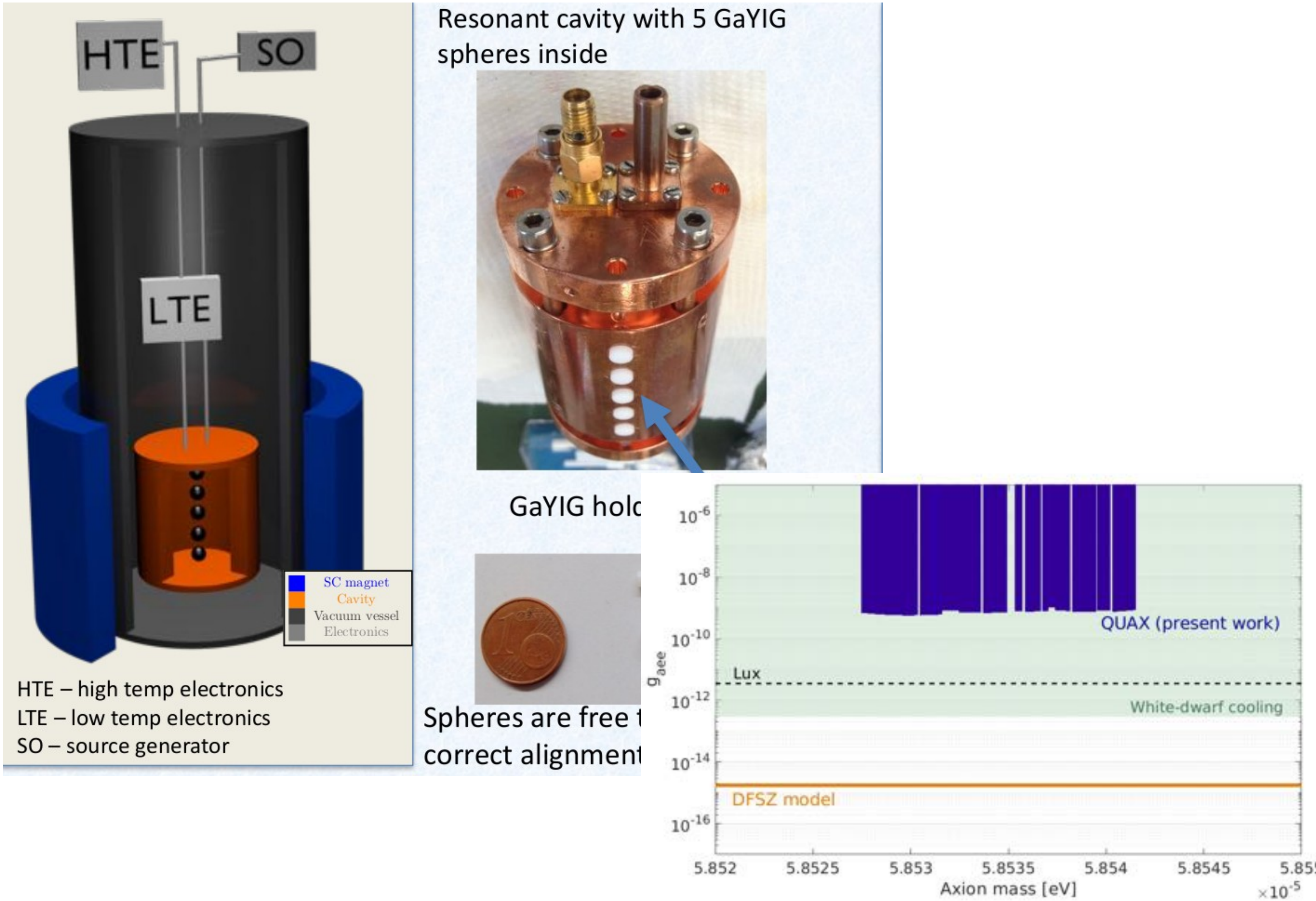
Future experiments: Quax



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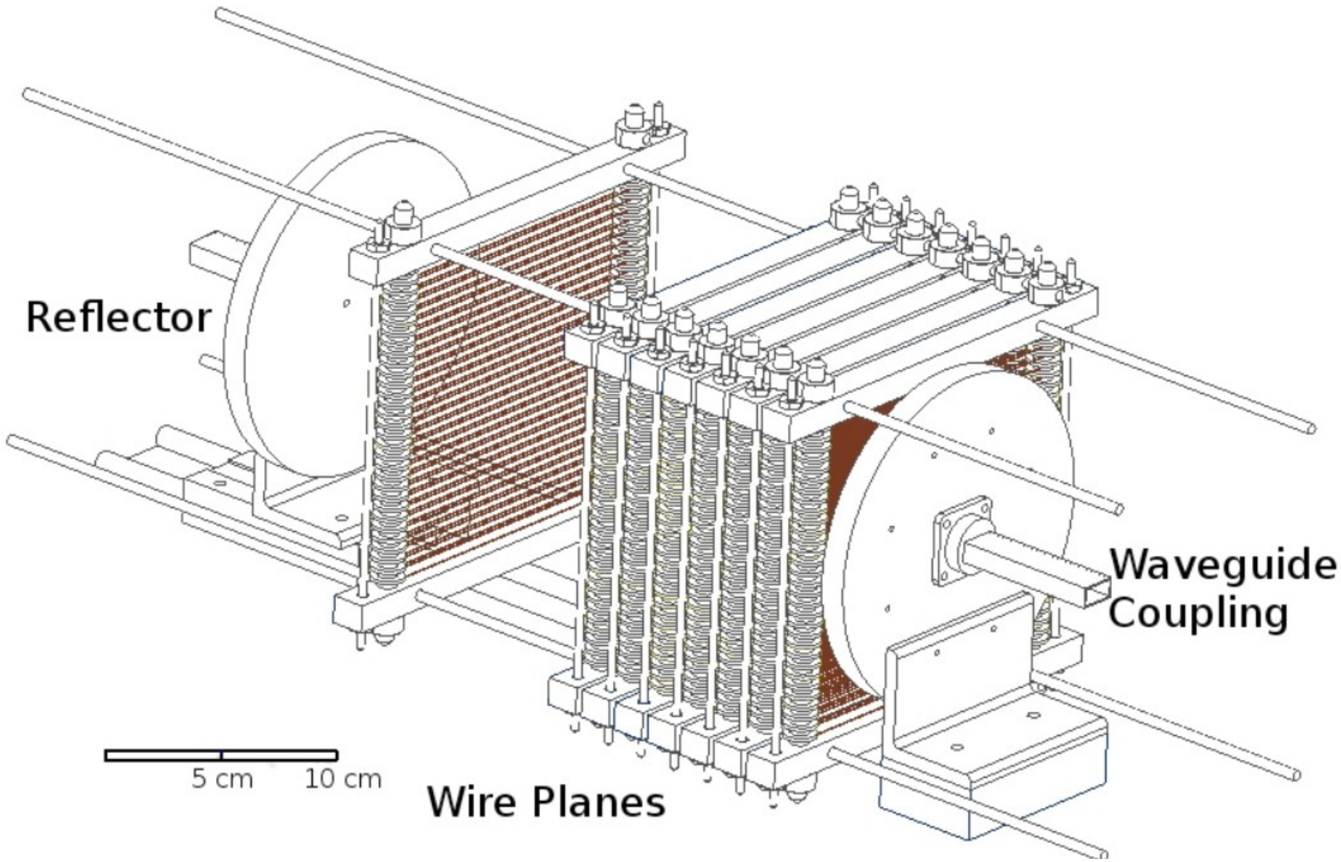
Future experiments: Orpheus

- Open Fabry-Perot resonator and a series of current-carrying wire planes
- Searches for axion like particles in the 68.2-76.5μeV mass range
- Potentially searches in the mass range 40-400μeV in the future
- $g_{a\gamma\gamma}$~1e-14



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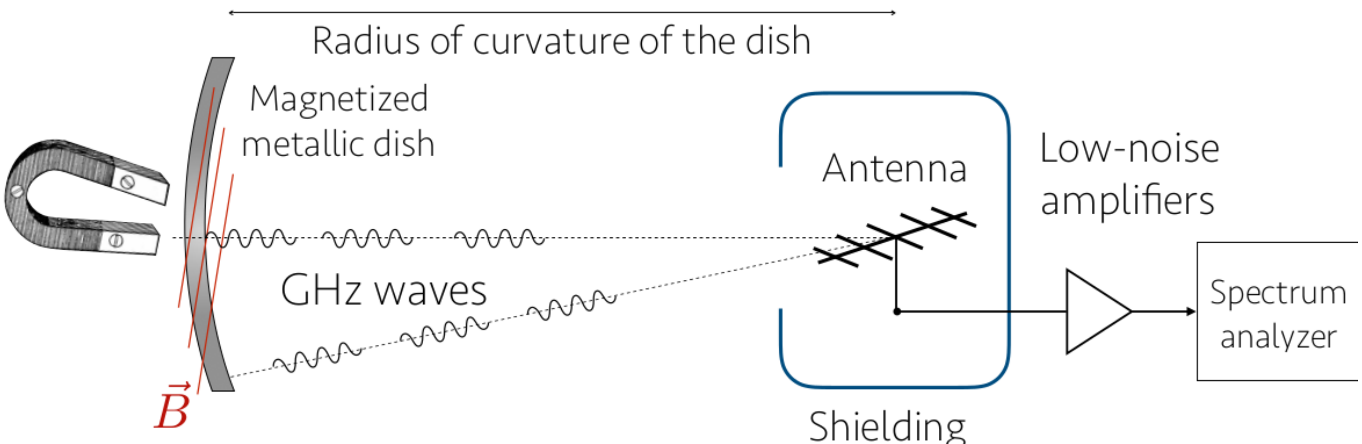
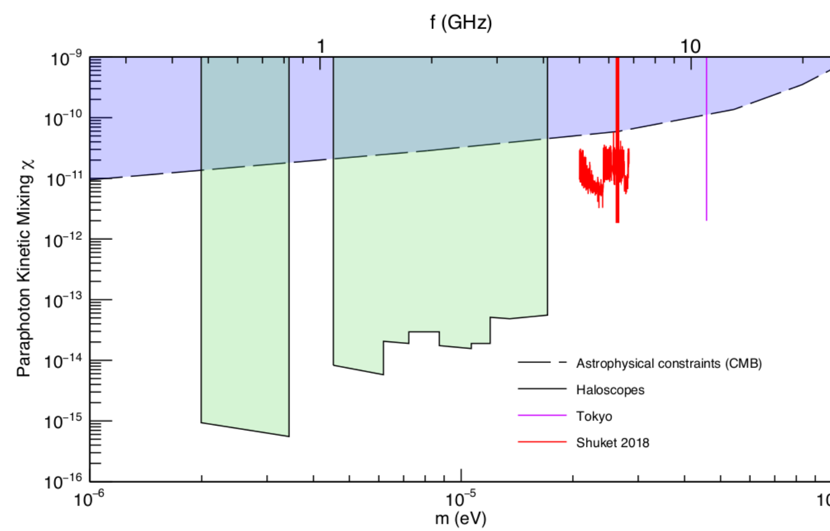
Future experiments: Shuket

(SearcH for extra-U(1) darK matter with a sphErical Telescope)

- dish antenna
- no B field → hidden photon





Search for ultra low-mass dark matter

Conclusion

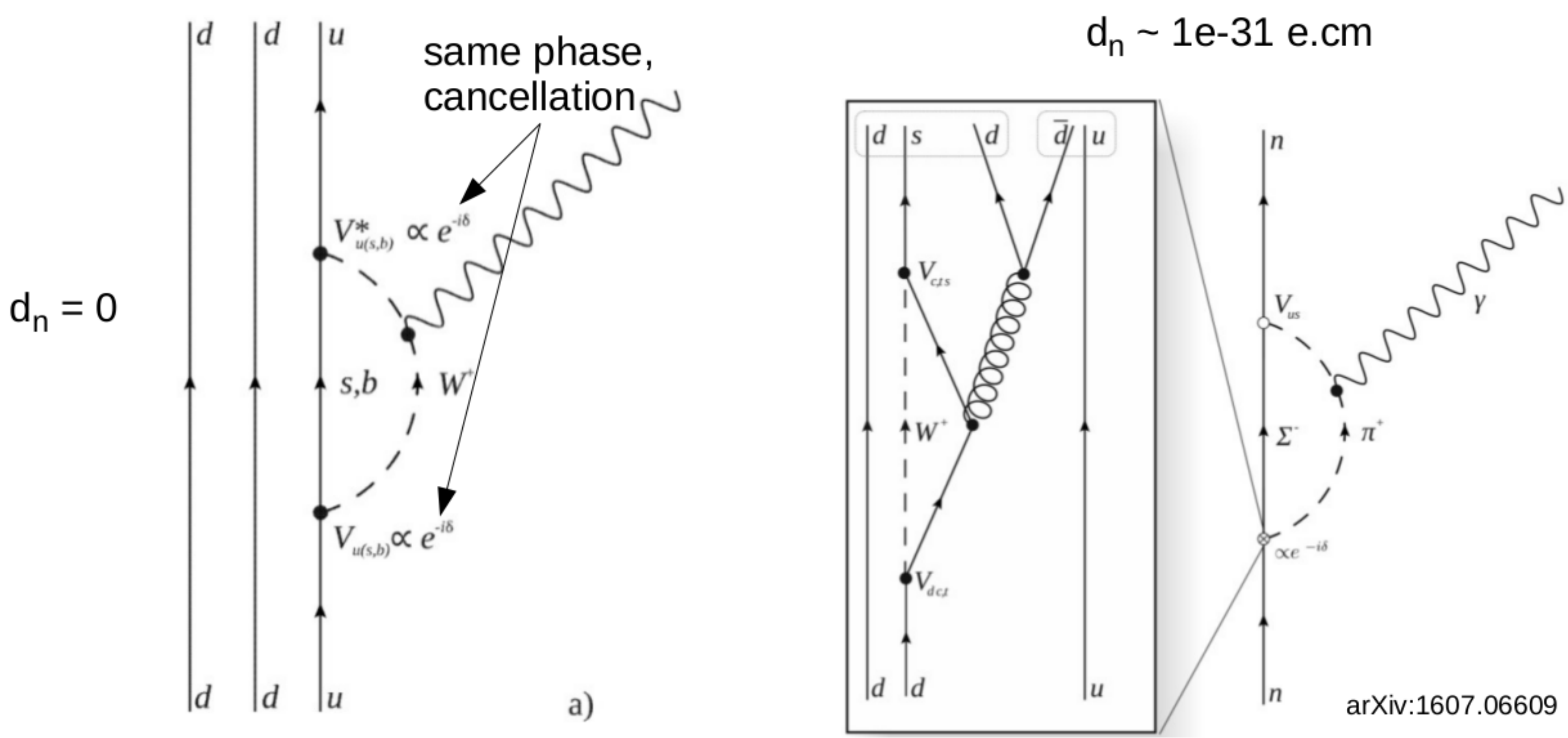
- a very large and technically interesting experimental area is now accessible to constraint axion models.
- many new experiments are starting on this new unexplored mass domain
- the PQ post-inflation scenario with convergence of two clues: dark matter candidate solution of SM CP-strong problem leads to a limited mass region which should be soon covered

Search for ultra low-mass dark matter

Backup

Search for ultra low-mass dark matter

Neutron Electric Dipole Moment (EDM)



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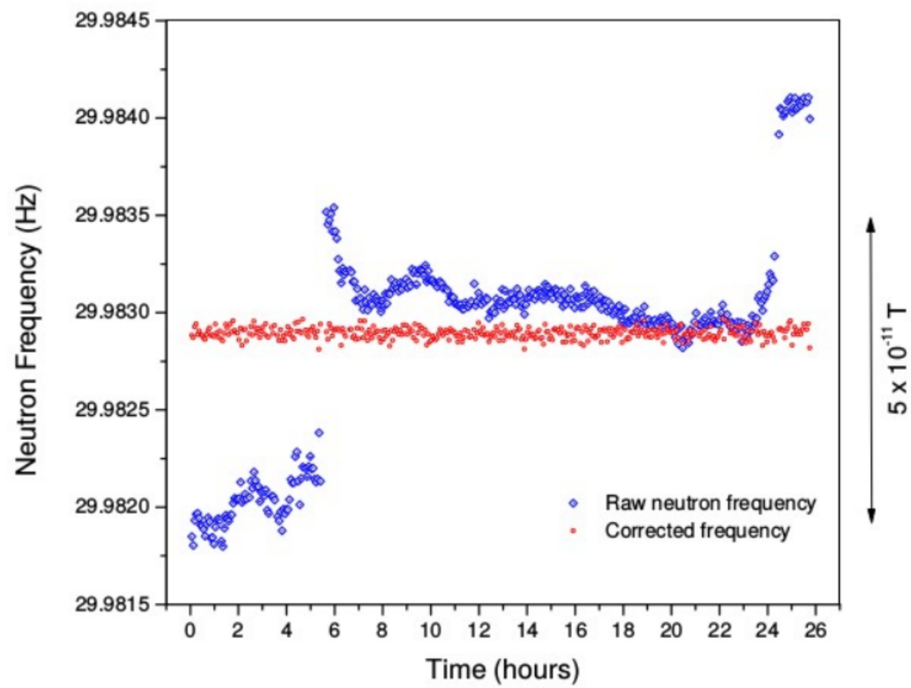
Neutron Electric Dipole Moment (EDM)

- Measure precession frequency caused by electric field
- Challenge: a tiny magnetic field causes a much faster precession!
- Absolute measurement of precession frequency impossible →
  measure difference of precession with E-field
  parallel or anti-parallel to a given B-field
- Excellent knowledge of B-field stability still required!
- Correct for B-field variations over time by measuring precession of Mercury (Hg) atoms in the same volume

$$h\nu = 2(\mu B \pm d_n E)$$

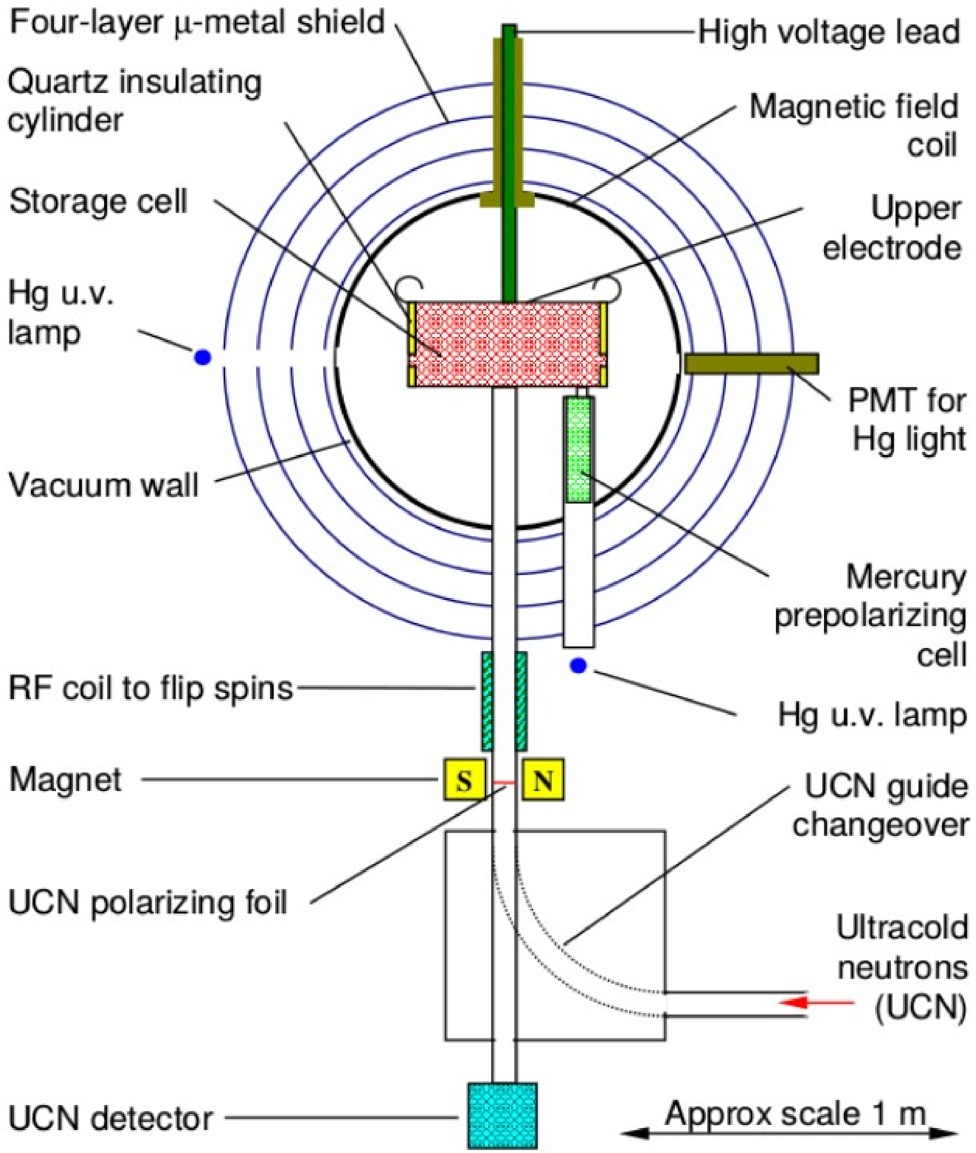
$$\Delta(h\nu) = 4 d_n E$$

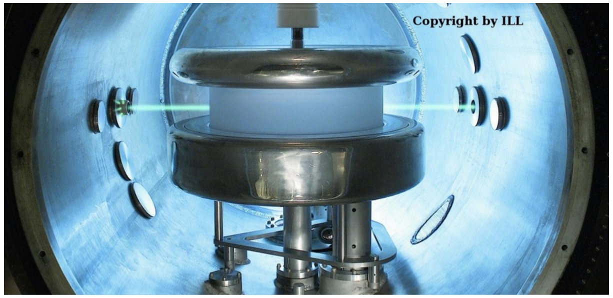


Search for ultra low-mass dark matter

Neutron Electric Dipole Moment (EDM)

ILL (Grenoble)





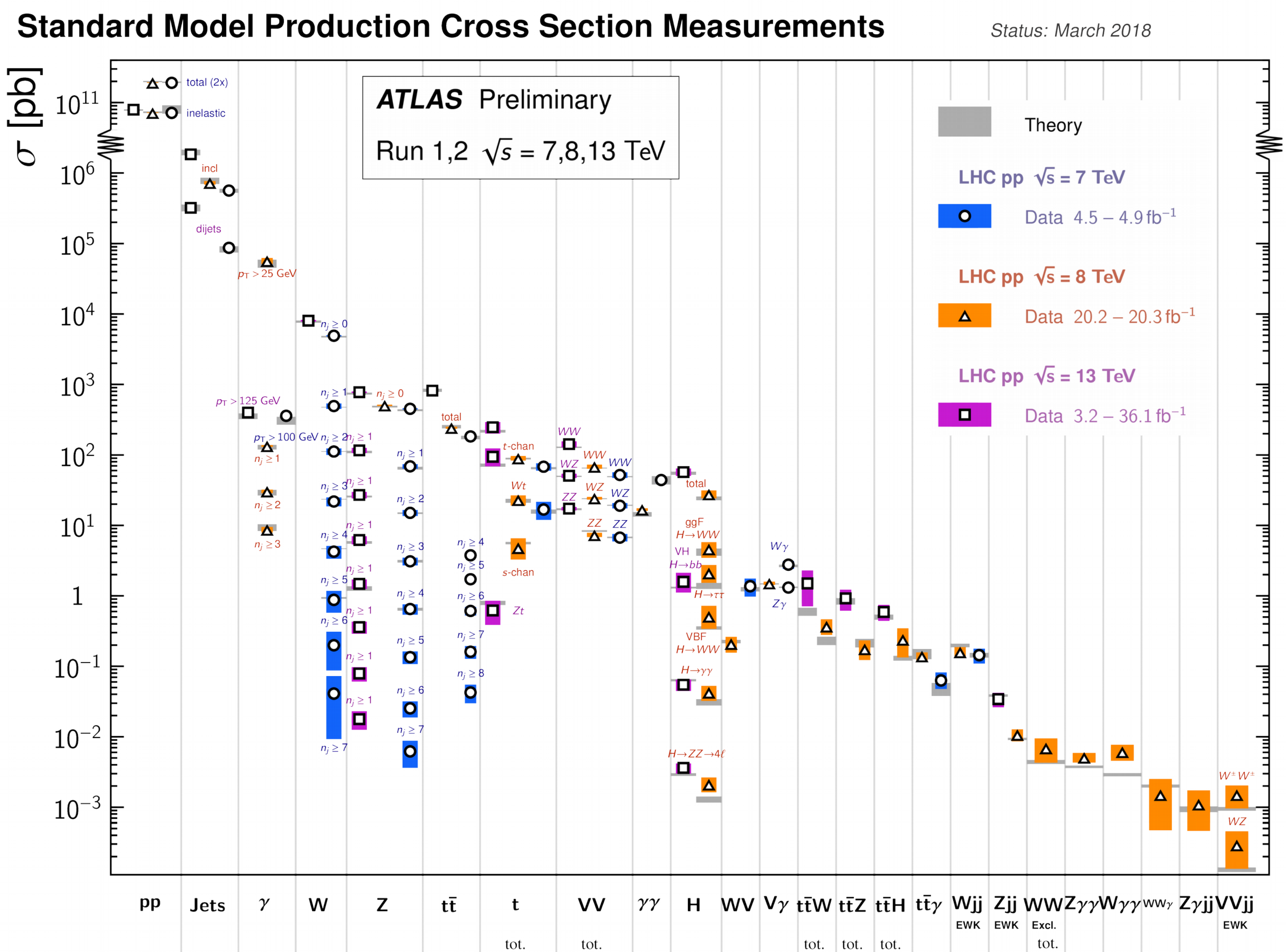
Ultra Cold Neutron

- K ~ 100 neV
- T ~ 2 mK
- speed ~ 5 m/s
- λ ~ 1000 Å
- Gravity not negligible!
  → m.g.h ~ 100 neV / m

Search for ultra low-mass dark matter

Standard model results from LHC experiments:

- very good agreements on large numbers of measurements
- no dark matter candidates (cosmology → neutrinos are not good candidates)



Search for ultra low-mass dark matter

$$N_{particles} \simeq \frac{10^{12}\, M_{\odot}}{m} \simeq 10^{69}\, \frac{1\; Gev/c^2}{m}$$

$$N_{cells} \simeq \frac{(4\pi/3)p_{max}^3(4\pi/3)R^3}{(2\pi\hbar)^3} \simeq 10^{98}\left(\frac{m}{1\; GeV/c^2}\right)^3$$

$$\frac{N_{particles}}{N_{cells}} \simeq \left(\frac{100\; eV/c^2}{m}\right)^4$$

Search for ultra low-mass dark matter

U(1) problem

QCD Lagrangian, with massless quarks, is invariant under chiral symmetry

$$q_{rl} \rightarrow \frac{1}{2}(1 \pm \gamma^5) q_{rl}$$

$$\mathcal{L}_{QCD}^{m_q \rightarrow 0} = \overline{q_r} i \gamma^\mu D_\mu q_r + \overline{q_l} i \gamma^\mu D_\mu q_l - \frac{1}{4} G_{\mu\nu}^{(a)} G^{\mu\nu(a)}$$

But not in agreement with the observation (no $m_{Goldston} \sim \sqrt{3}\, m_\pi$!)

→ QCD vacuum structure is more complex

$$|\Theta > \propto \sum_{n=0}^{\infty} e^{-i\theta n} | n >$$

QCD vacuum is a sum of infinite but countable degenerate vacuum, topologically disconnected

but can be connected by tunnel effect

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To restore the approximate chiral symmetry (Isospin → $SU(N)_F$ results) add full derivative (EoM saved) term to the Lagrangian

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{m_q \to 0} + \mathcal{L}_\theta$$

$$\mathcal{L}_\theta = -\theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^{(a)} \ \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^{\alpha\beta(a)}$$ ← T-violating quantity

$$= -\theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^{(a)} \tilde{G}^{\alpha\beta(a)}$$

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$$\mathcal{L}_\theta = -\theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^{(a)} \tilde{G}^{\alpha\beta(a)}$$

Consequences of this new term:

- conservation of the axial current j_5^μ is restored
- violates T (and P) → CP violation in the strong sector
- add a new free parameter θ , to the SM

Remarks:

one rewriting the QCD Lagrangian with the CP violation from the strong and weak interactions, by a simple transformation

$$q \to e^{-i\gamma^5 \frac{\theta_q}{2}} q$$

$$\mathcal{L}_{QCD} = \overline{q}(i\gamma^\mu D_\mu - m_q e^{i\theta_q})q - \frac{1}{4} G_{\mu\nu}^{(a)} G^{\mu\nu(a)} - \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^{(a)} \tilde{G}^{\alpha\beta(a)}$$

$$= \overline{q}(i\gamma^\mu D_\mu - m_q)q - \frac{1}{4} GG - \theta_{total} \frac{\alpha_s}{8\pi} G\tilde{G}$$

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BACKUP