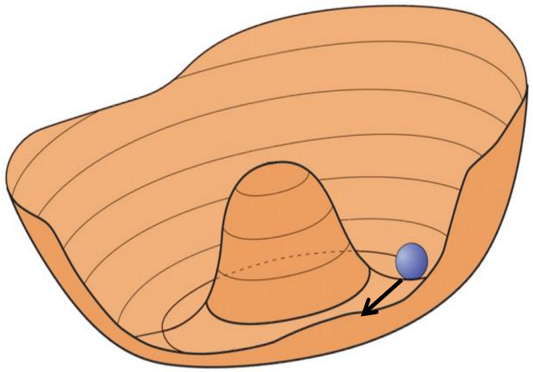
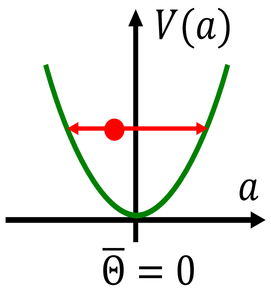
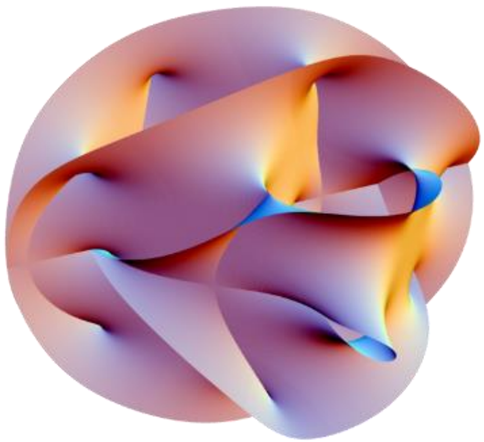
B. Majorovits (bela@mpp.mpg.de)

Dark Matter Axion and ALPs

Where do they come from?





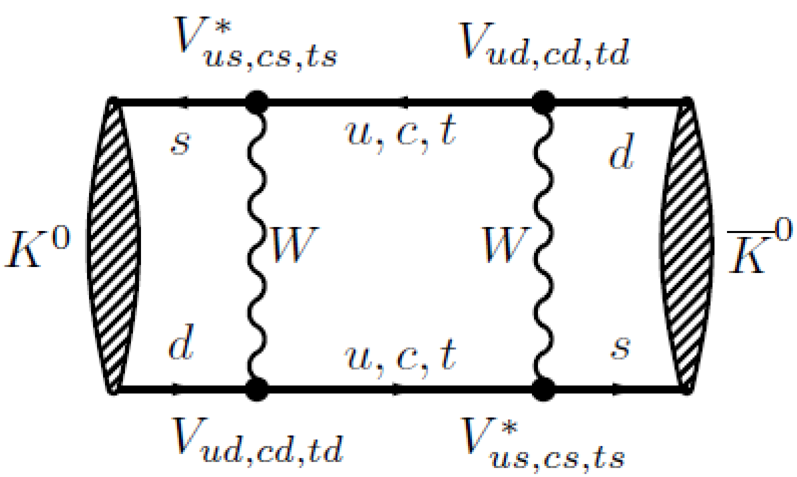


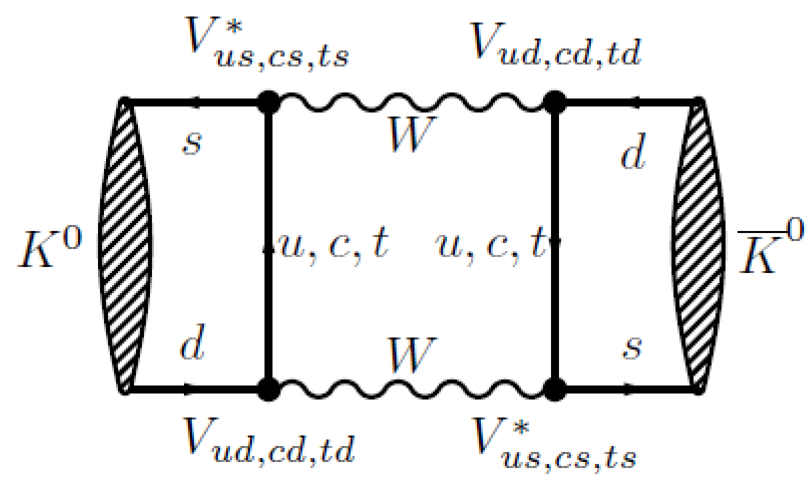
- **CP violation in QCD**
- **The strong CP problem**
- **Peccei Quinn symmetry breaking & the axion**
- **Axion production in the early universe**

CP violation in the quark sector

$K^0 - \overline{K^0}$ Oscillation via quark mixing

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}.$$





CP violation in the quark sector

For Kaons (negative parity):

$$C|\,\boldsymbol{K^0}, \boldsymbol{p}> = \; -|\overline{\boldsymbol{K^0}}, \boldsymbol{p}>$$

$$P|\,\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0}> = \; -|\,\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0}> \quad \text{and} \quad P|\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0}> = \; -|\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0}>$$

Thus:

$$CP|\,\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0}> = \; |\,\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0}> \quad \text{and} \quad CP|\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0}> = \; |\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0}>$$

Thus there are two CP Eigenstates:

$$|\boldsymbol{K^0_{1/2}}, \boldsymbol{p} = \boldsymbol{0}> = \frac{1}{\sqrt{2}}\{|\,\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0}> \pm |\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0}>\}$$

With

$$CP|\boldsymbol{K^0_{1/2}}, \boldsymbol{p} = \boldsymbol{0}> = \; \pm|\boldsymbol{K^0_{1/2}}, \boldsymbol{p} = \boldsymbol{0}>$$

$\boldsymbol{K^0_1}$ ALWAYS has to decay into states with *CP=1*
$\boldsymbol{K^0_2}$ ALWAYS has to decay into states with *CP=-1*

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CP violation in the quark sector

Experimentally two states observed:

$K_S^0 \rightarrow \pi\pi$ and $K_L^0 \rightarrow \pi\pi\pi$

$\tau_S = 0.9 \cdot 10^{-10} s, \quad \tau_L = 0.5 \cdot 10^{-7} s$

corresponding to (CP states)

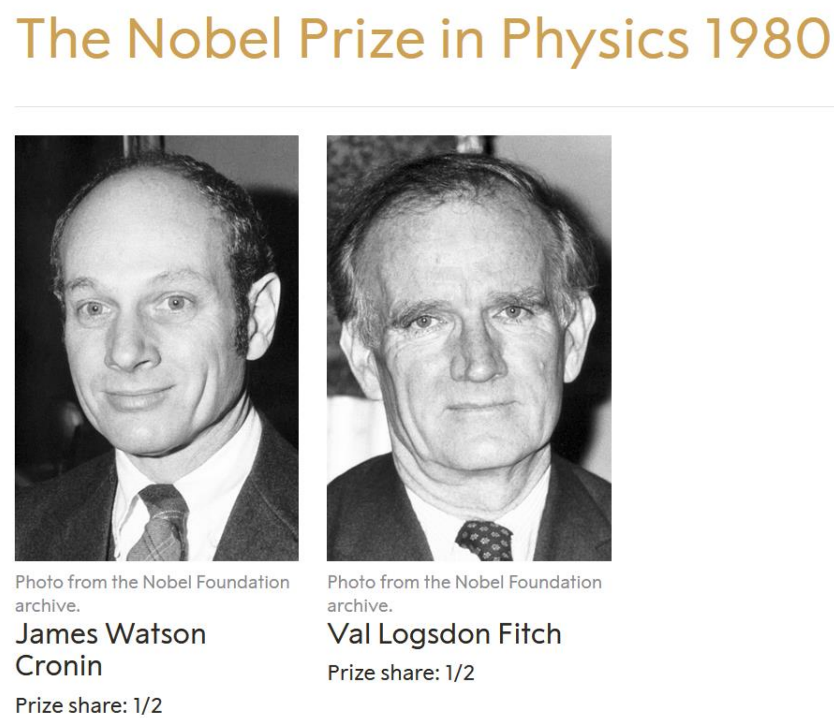
$K_L^0 = K_2^0$ and $K_S^0 = K_1^0$

1964: Christenson, Cronin, Fitch and Turlay at Brookhaven national Lab also **observed**:

→ $K_L^0 \rightarrow \pi\pi$

This is a CP violating decay!
(similar CP violating decays appear in b-mesons: BELLE/Babar)

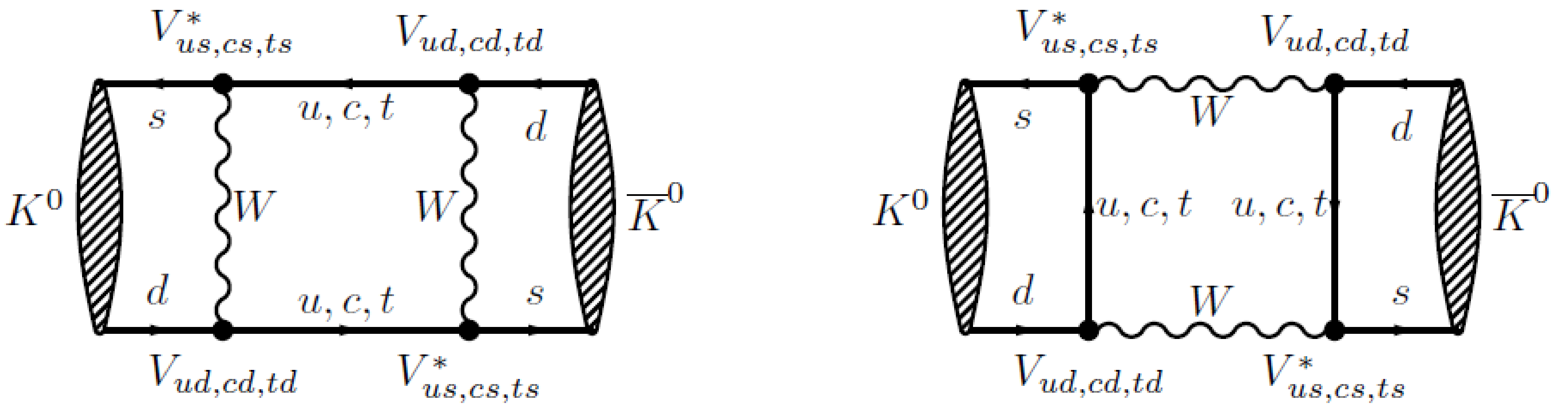
→Nobel Prize 1980



CP violation in the quark sector

$K^0 - \overline{K^0}$ Oscillation

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}.$$



$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{12} = 13.04 ± 0.05°, θ_{13} = 0.201 ± 0.011°, θ_{23} = 2.38 ± 0.06°, and δ_{13} = 1.20 ± 0.08 radians.

CP violation in the QCD vacuum

QCD gauge group $SU(3)_c$ is a **non-Abelian**:
gauge transformations of the Lie group are **not commutative**!

Consequence: QCD has "large gauge transformations", which come with gauge in-equivalent **ZERO energy states** $|\boldsymbol{n}\rangle$, separated by potential barrier.

→No single $|n\rangle$ (including $|0\rangle$) can be a stable vacuum state due to quantum tunelling

Physical ground state of QCD vacuum is defined by **gauge invariant superposition** of vacuum states:

$$|\boldsymbol{\theta}\rangle = \sum_n e^{in\theta} |\boldsymbol{n}\rangle$$

For couplings this means: Need to evaluate "possible amplitudes"

→ **NEED** to add a general CP violating term to the QCD Lagrangian:

$$\Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu}$$

CP violation in QCD

→ There are **two INDEPENDENT sources for CP violation** in QCD.

Physically only one CP violating phase will appear:

$$\theta_{eff} = \bar{\theta} = \theta - (phase\ of\ CKM\ matrix)$$

leading to additional CP violating term in the QCD Lagrangian:

$$\overline{\Theta}\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$$

With α_s the strong coupling constant and
$G_{\mu\nu a}$ and $\tilde{G}_a^{\mu\nu}$ the gluon field and its dual.

Electric Dipole Moment (EDM)

Nonzero EDMs imply P and T (and CP) violation if the system has a non-degenerate ground state. This can be seen as follows:

$$\vec{d} = \left|\vec{d}\right| \frac{\vec{\sigma}}{|\sigma|} \rightarrow \Delta E = \left|\vec{d}\right| \frac{\vec{\sigma}}{|\sigma|} \cdot \vec{\mathrm{E}}$$

$$P\left(\vec{\sigma} \cdot \vec{\mathrm{E}}\right) = -\left(\vec{\sigma} \cdot \vec{\mathrm{E}}\right)$$

$$T\left(\vec{\sigma} \cdot \vec{\mathrm{E}}\right) = -\left(\vec{\sigma} \cdot \vec{\mathrm{E}}\right)$$

EDM energy Eigenstates are neither P nor T conserving

→ Together with CPT theorem:
Non vanishing dipole moment is CP violating!

→ Consequence of non-vanishing cp violating $\bar{\theta}$:

Finite **electric dipole moment (EDM)** of elementary particles

The strong CP problem:

CP violation in QCD should induce EDM in neutron

$$\boldsymbol{d_n = \bar{\theta} \cdot 10^{-16} e\, cm}$$

Experimental limit: $d_n < 3 \cdot 10^{-26}\mathrm{e\ cm}$

$$\rightarrow \boldsymbol{\bar{\Theta} = \Theta - \arg\det M_q < 10^{-10}}$$

Why do **two INDEPENDENT sources for CP violation** eliminate each other to 1 in 10^{10}?

Anthropic principle does not help!

Universe would look the same with $\boldsymbol{\bar{\Theta} \sim 0.001}$

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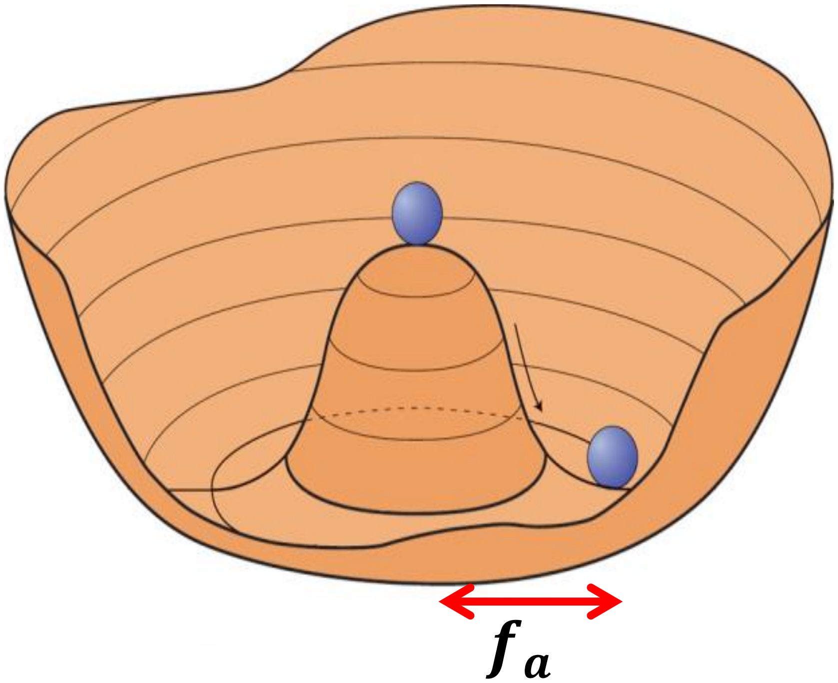
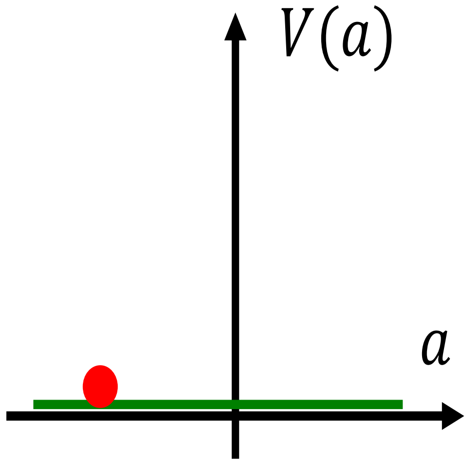
The Peccei Quinn mechanism

“Make $\overline{\Theta}$ a field that is dynamically driven to 0”

Introduce U(1) symmetry with $\overline{\Theta}$ the complex phase





Potential is degenerate in $\overline{\Theta}$

U(1) symmetry is sponatneously borken at Peccei Quinn scale f_a
(f_a also sometimes called axion decay constant)

→ **Massless Nambu-Goldsonte-Boson** $\mathbf{a(x)} = \overline{\Theta}(x) \cdot f_a$

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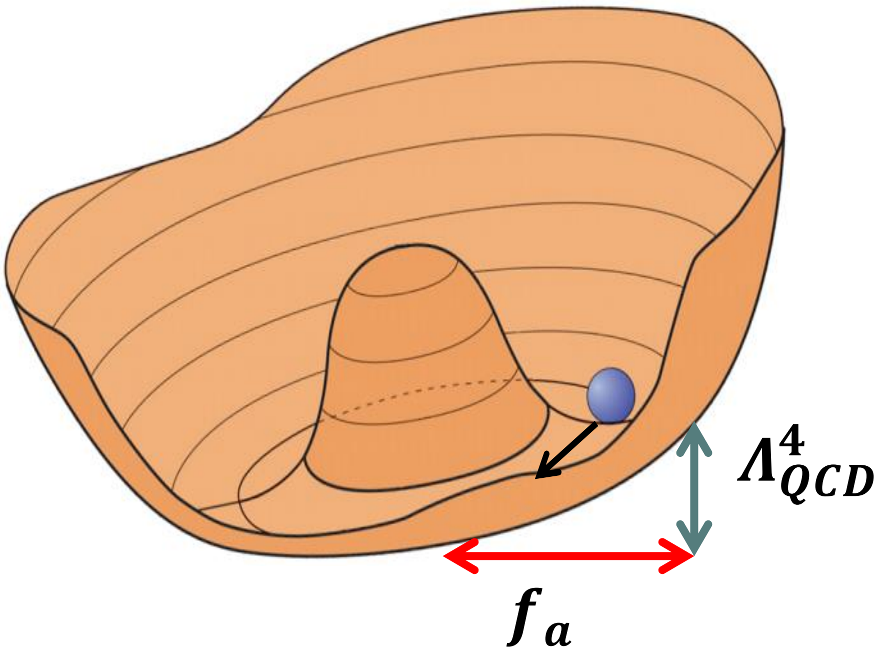
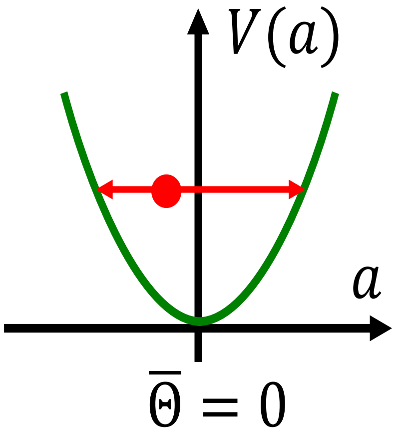
The Peccei Quinn mechanism

→ Explicit symmetry breaking during QCD phase transition



Potential develops minimum:



„Topological susceptibility" of QCD vacuum :
dependence of term $G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a}$ on $\bar{\Theta}$

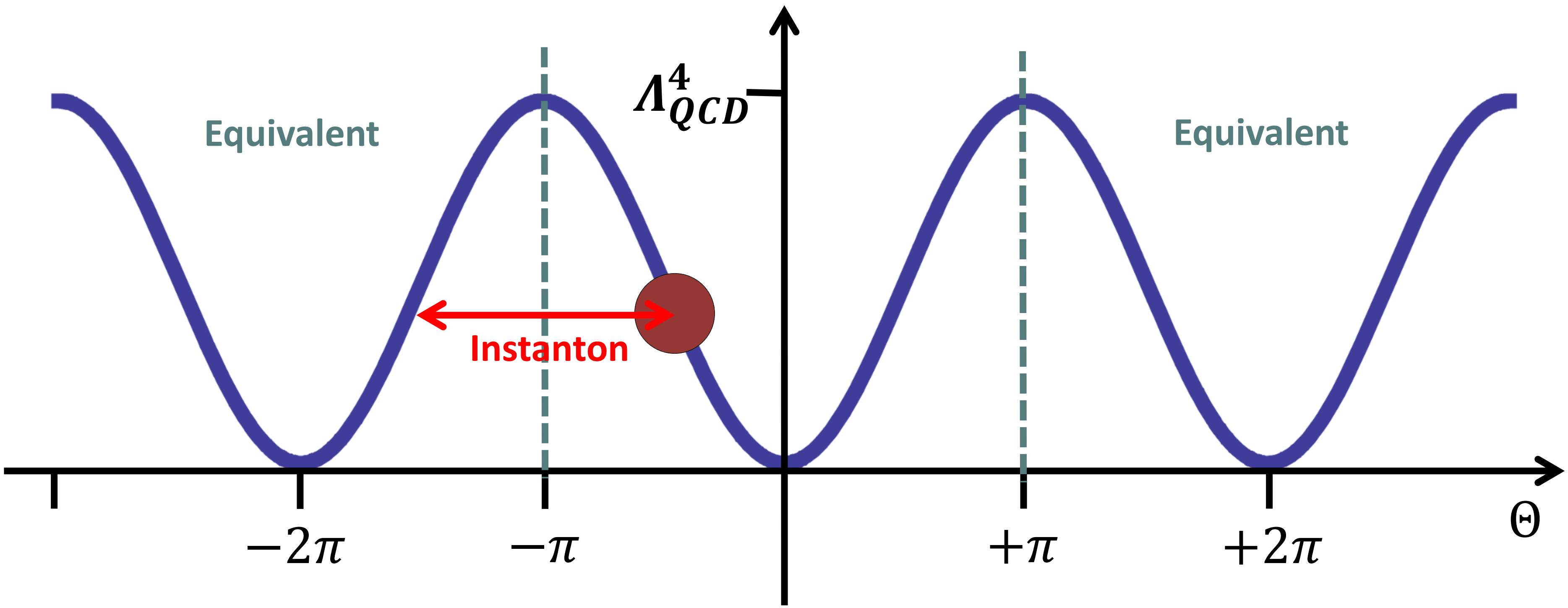
→ Dependence of field potential on $\bar{\Theta}$:

→ **Potential minimum at $V(\bar{\Theta} = 0)$** due to "Instanton dynamics"

→ **Massive pseudo Nambu-Goldsonte-Boson**

The Peccei Quinn mechanism

"Make $\overline{\Theta}$ a field that is dynamically driven to 0"



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Axion as massive pseudo Nambu-Goldsonte-Boson

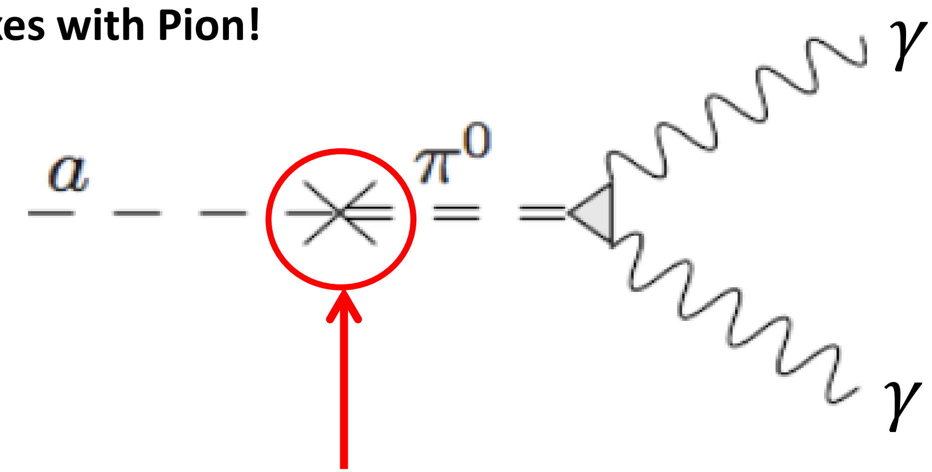
→ generation of mass by chiral symmetry breaking
(mass: second derivative of potential at minimum)

$$m_a = 5.7\mu eV \left(\frac{10^{12}}{f_a}\right)$$

Correlated to f_a by QCD

Chiral symmetry breaking is process giving π^0 its mass!!
→ Mass generation by "mixing with mesons!"

→ Axion mixes with Pion!

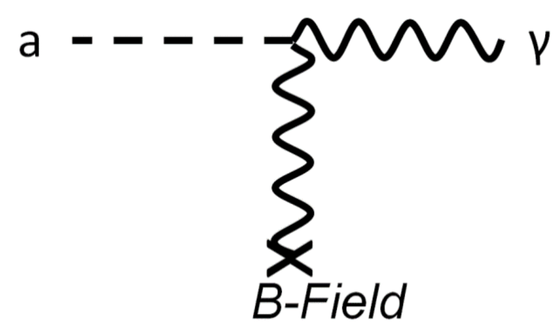


Coupling to Photons: $g_{a\gamma\gamma} \propto 1/f_a$

Axion Photon mixing

→ Axion photon conversion in external B-field

Inverse Primakoff effect



Coupling to Photons: $g_{a\gamma\gamma} \propto 1/f_a$

In general: Presence of axion field modifies Maxwell's equations:

$$\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho - g_{a\gamma} \mathbf{B} \cdot \nabla a \,, \\
\nabla \times \mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma} \left(\mathbf{B}\, \dot{a} - \mathbf{E} \times \nabla a \right) \,, \\
\nabla \cdot \mathbf{B} &= 0 \,, \\
\nabla \times \mathbf{E} + \dot{\mathbf{B}} &= 0 \,, \\
\ddot{a} - \nabla^2 a + m_a^2 a &= g_{a\gamma} \mathbf{E} \cdot \mathbf{B} \,.
\end{aligned}$$

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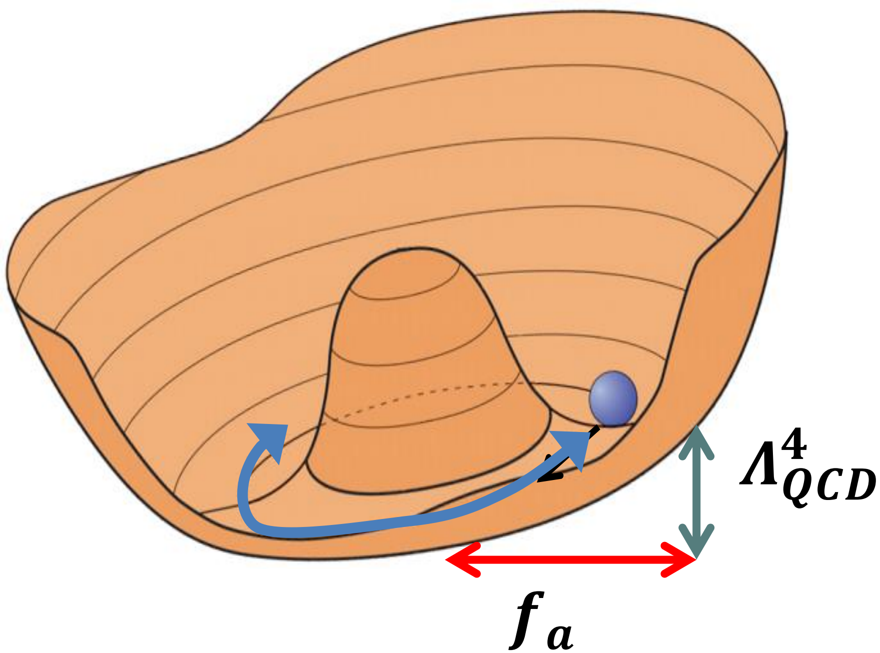
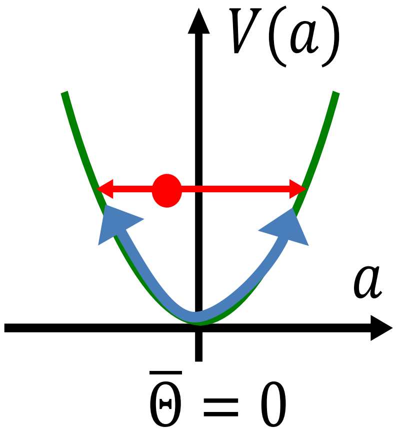
Axions in the early universe

Axions are produces as **NON-THERMAL local field oscillations,**

→ particle population without initial momentum → NON RELATIVISTIC!





After phase transition: axion field oscillations:
frequency proportional to axion mass
Quantization of oscillations → huge particle density
→ Ideal cold Dark Matter candidate

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Axions in the early universe

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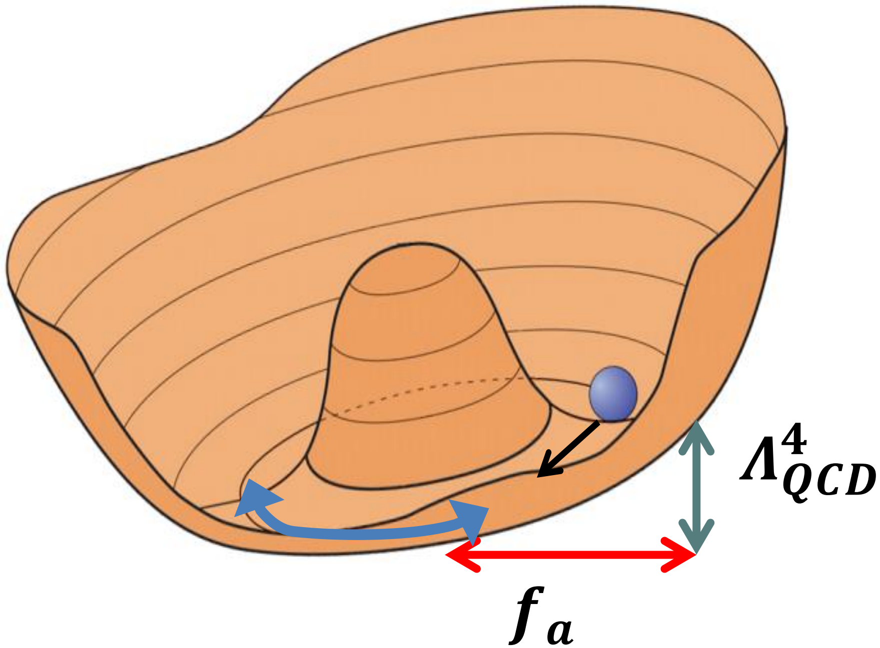
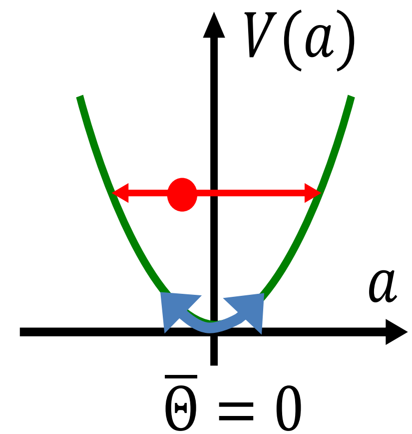


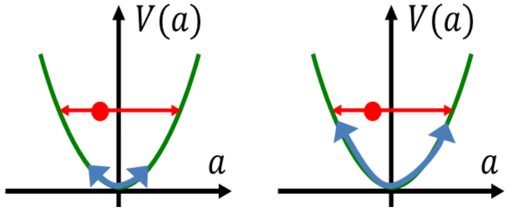


Energy stored, i.e. particle number density:
depends on initial alignment of $\bar{\Theta}_i$ after symmetry breaking.
Assume: Axions make up all dark matter:
If we can calculate axion relic density → prediction for their mass!

Axions in the early universe

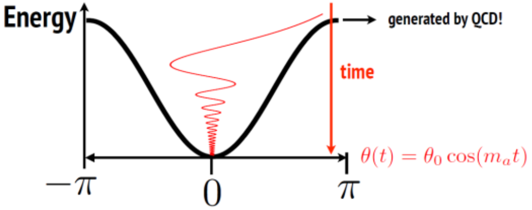
Axion relic density depends on:

- Initial misalignment $\overline{\boldsymbol{\Theta}_i}$



- **Damping of oscillation** amplitude due to **Hubble expansion** of universe during QCD phase transition:
  Damping: proportional to ratio between Hubble expansion rate and axion field oscillation frequency (mass)

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



- Energy scale of $\boldsymbol{f_a}$: Peccei-Quinn symmetry breaking before or after inflation?

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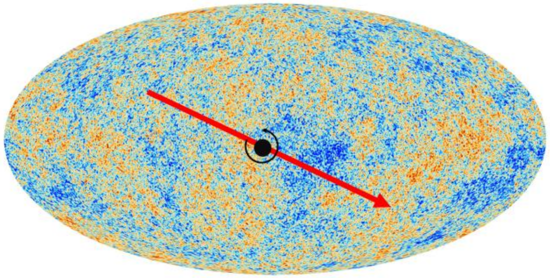
Axions in the early universe

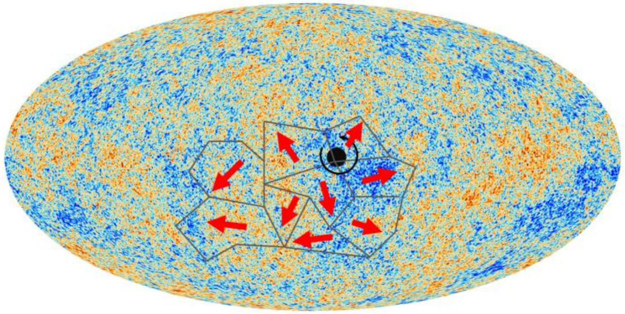
Pre-inflationary scenario: Peccei Quinn symmetry breaking occurred before inflation: $\overline{\boldsymbol{\Theta}_i}$ the same everywhere in the observable universe → $0 < \left|\overline{\boldsymbol{\Theta}_i}\right| < \pi$



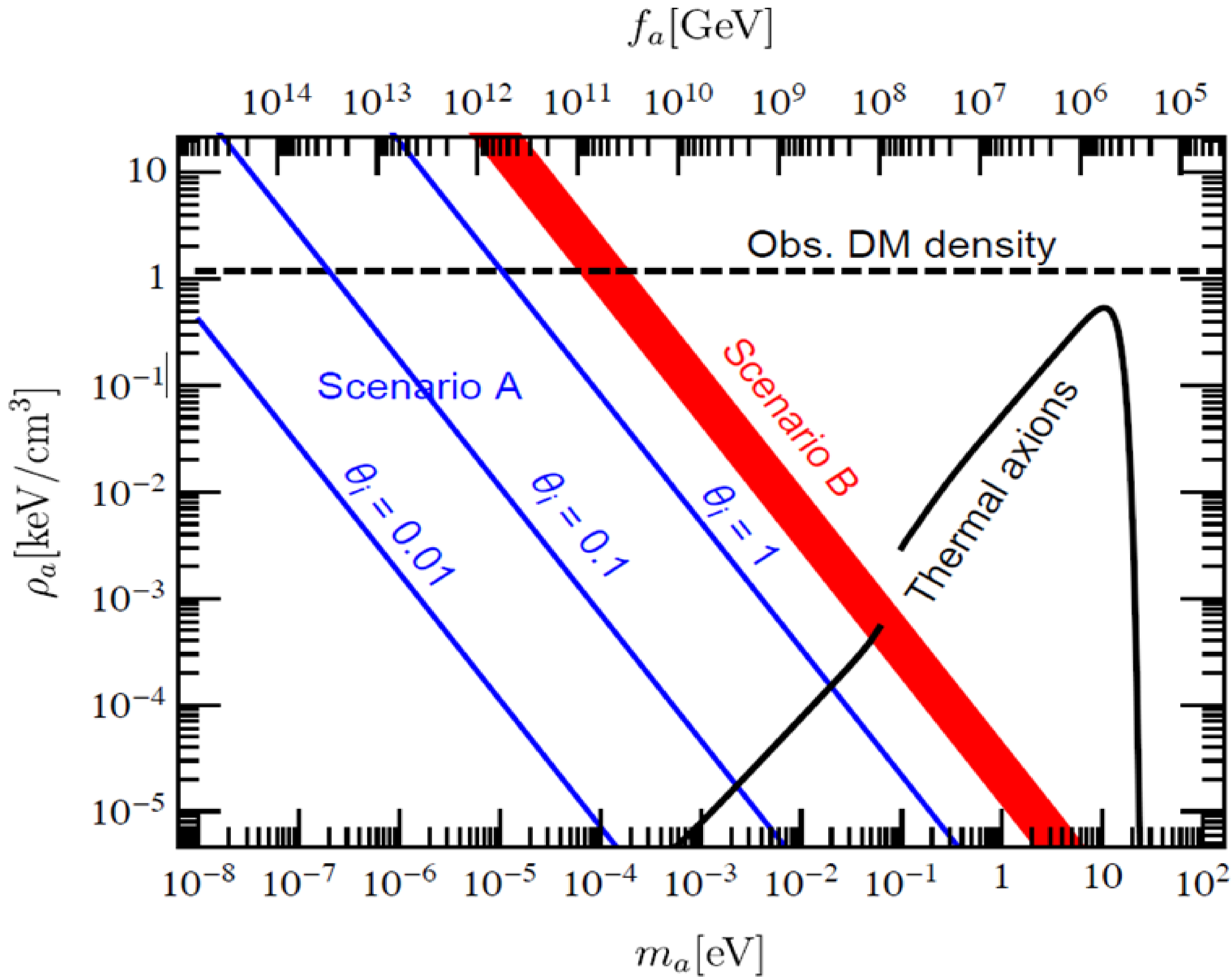
Post-inflationary scenario: Observable universe consists of many patches not in causal contact during Peccei Quinn symmetry breaking

→ Today we see average of all $\overline{\boldsymbol{\Theta}_i}$ from many patches now in causal contact

→ $\left|\widehat{\overline{\boldsymbol{\Theta}_i}}\right| \sim \pi/2$!



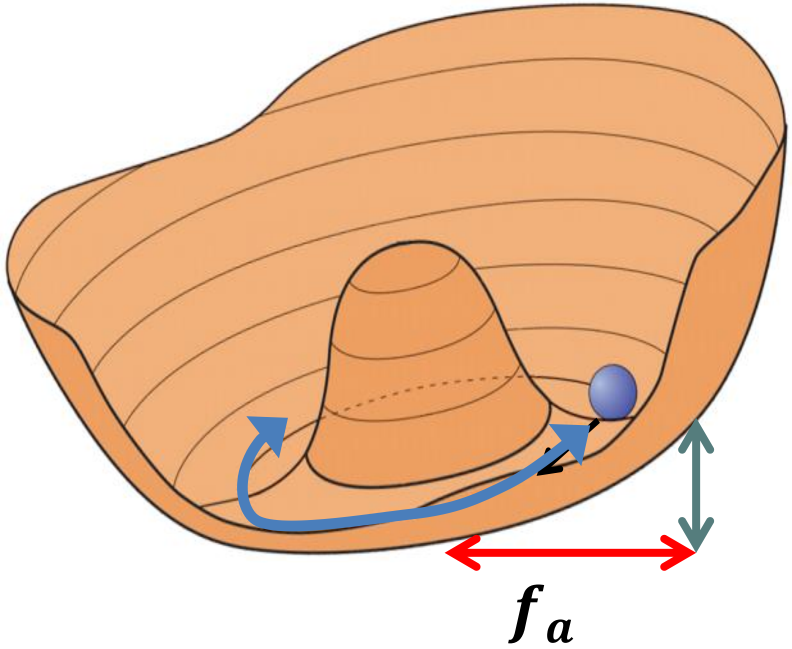
Problem: Topological defects lead to additional axion population → large uncertainties

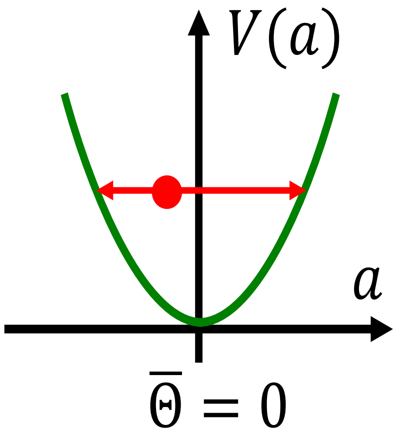

f_a[GeV]
10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
ρ_a[keV/cm^3]
Obs. DM density
Scenario A
Scenario B
Thermal axions
$\theta_i = 0.01$
$\theta_i = 0.1$
$\theta_i = 1$
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2}
m_a[eV]

Axion Like Particles (ALPs)

Any spontaneously broken U1 symmetry with explicit symmetry breaking:
Pseudo Nambu Goldstone Boson
→ **Axion like particle**

For axion:
mass correlated by QCD to spontaneous symmetry breaking energy scale f_a





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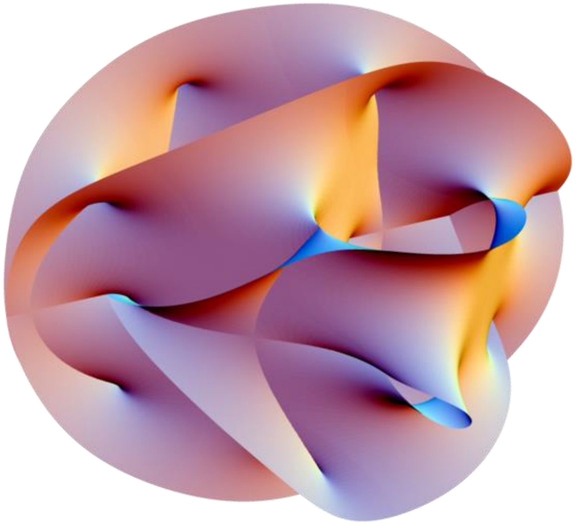
Axion Like Particles (ALPs)

Many other pNGBs:
→ The **Axiverse** from string theory arising from compactification of dimensions (Calabi-Yau manifold of extra dimensions)!
→ No correlation between energy scale of spontaneous symmetry breaking and mass, but coupling to photon suppressed by energy scale of spontaneous symmetry breaking

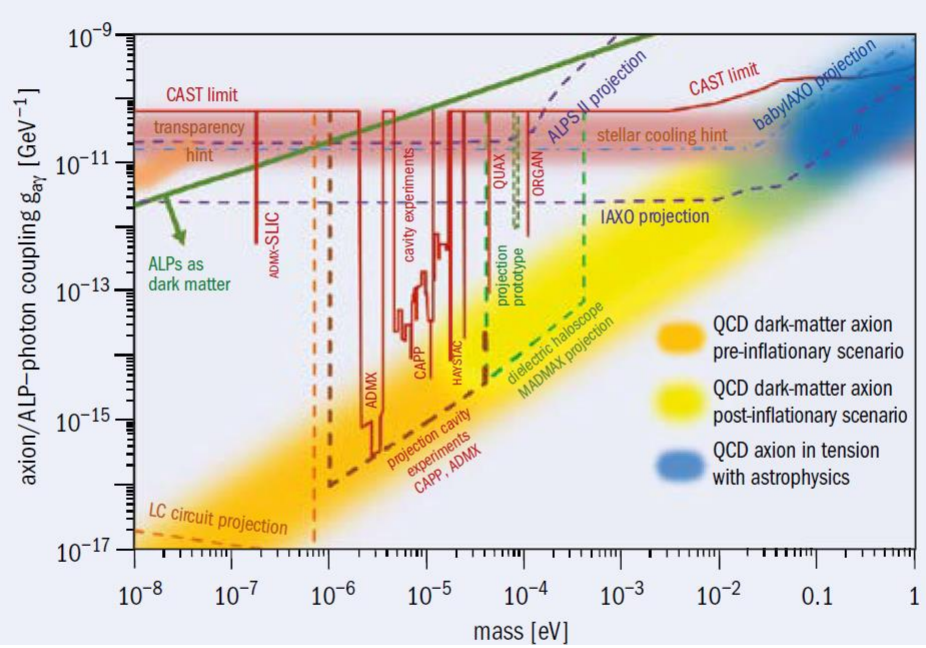
→ Same mechanism of ALP photon mixing and Primakoff effect!
→ Axion searches also good for ALP searches

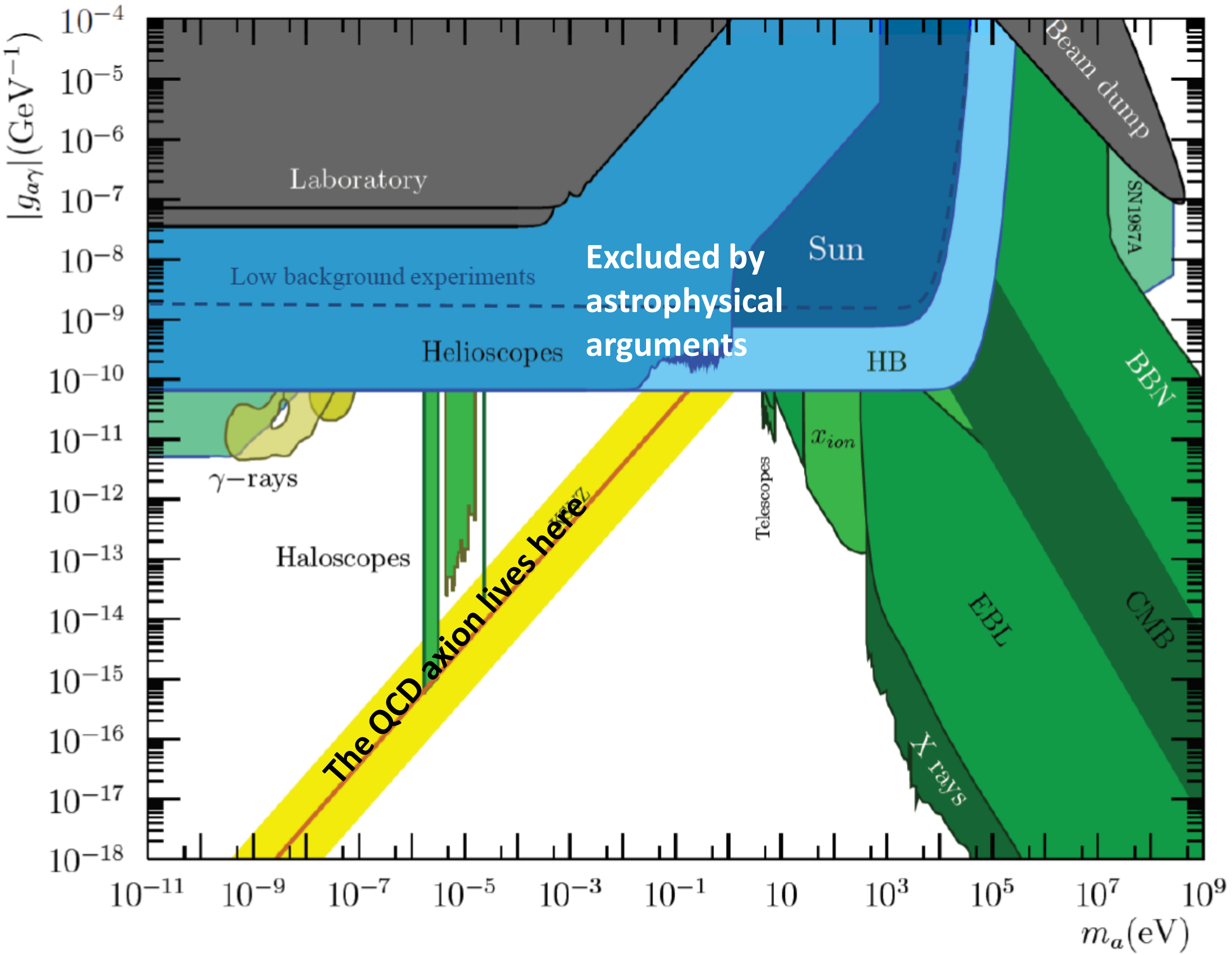


Dark Matter Axion and ALPs

How to detect them?

- **Axion couplings and sources**
- **Cavity experiments**
- **Dielectric haloscopes**
- LC circuits
- NMR experiments
- **Solar axion search**
- **Light shining through the wall**
- **Some astrophysical constraint**



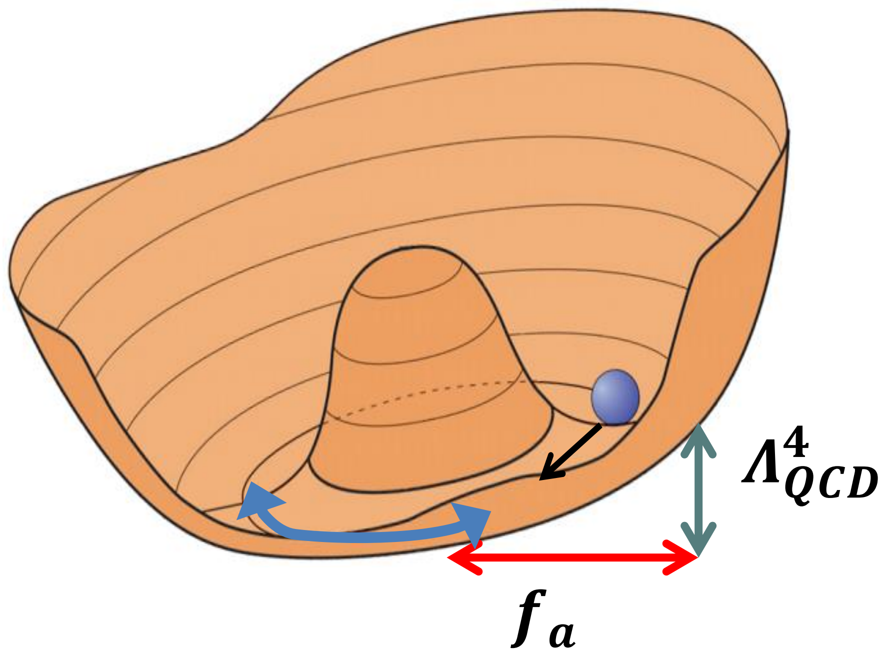

Laboratory
Low background experiments
Helioscopes
Sun
HB
Excluded by astrophysical arguments
γ−rays
Haloscopes
The QCD axion lives here
Telescopes
x_{ion}
Beam dump
SN1987A
BBN
EBL
CMB
X rays
$|g_{a\gamma}|(\mathrm{GeV}^{-1})$
$m_a(\mathrm{eV})$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10
10^{3}
10^{5}
10^{7}
10^{9}

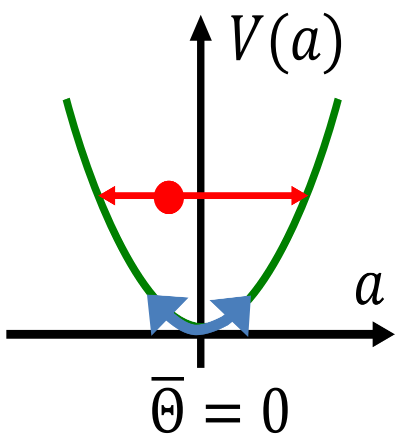
Axion production in the early universe

Axions are produces as **NON-THERMAL local field oscillations,**

→ particle population without initial momentum → NON RELATIVISTIC!
→ Production by misalignment as relic-oscillation of $\overline{\Theta}_i$

$$\langle v_{DM} \rangle = 10^{-3} c$$





Axion as massive pseudo Nambu-Goldsonte-Boson

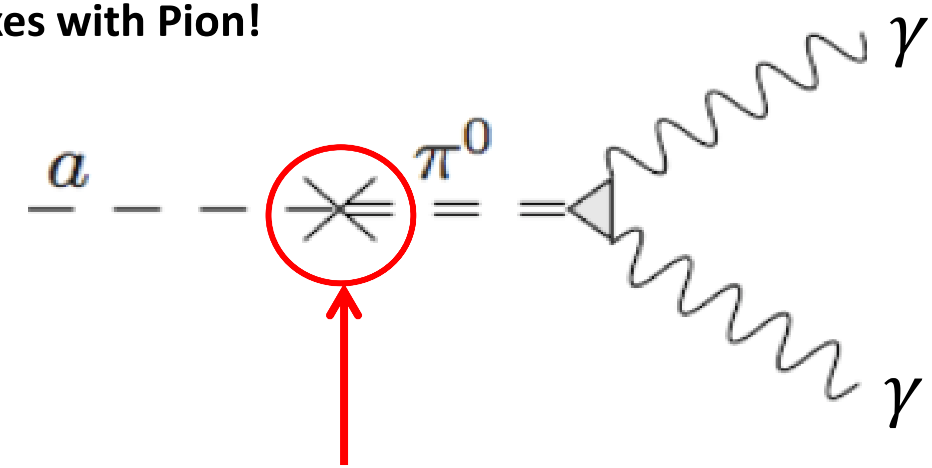
→ generation of mass by chiral symmetry breaking
(mass: second derivative of potential at minimum)

$$m_a = 5.7\mu eV \left(\frac{10^{12}}{f_a}\right)$$

Correlated to f_a by QCD

Chiral symmetry breaking is process giving π^0 its mass!
→ Mass generation by "mixing with mesons!"

→ Axion mixes with Pion!



Coupling to Photons: $g_{a\gamma\gamma} \propto 1/f_a$

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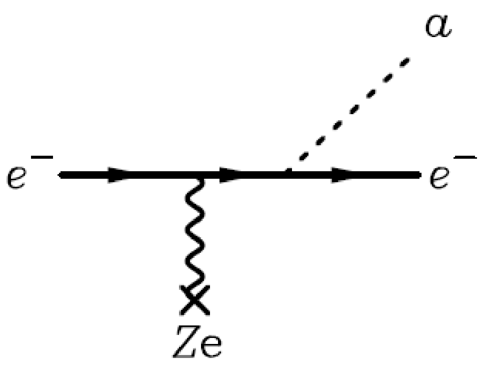
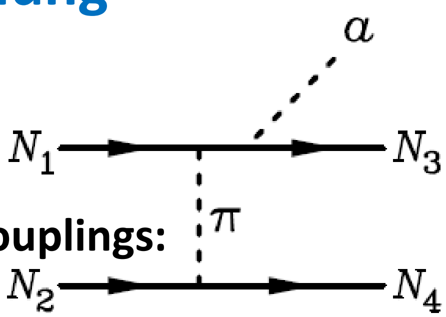
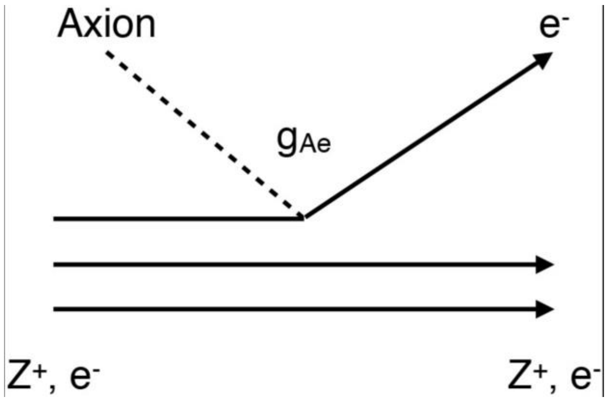
Other axion couplings $\propto 1/f_a$:

Axion Bremsstrahlung





Axioelectrif effect



Oscillating EDM

$$d_n = \bar{\theta} \cdot 10^{-16} e\ cm$$

→ $\frac{\partial \bar{\theta}}{\partial t}$ leads to $\dot{d}_n$

→ Spin coupling $\propto \boldsymbol{\sigma} \cdot \boldsymbol{E}$

Axion Photon mixing

In general: Presence of axion field modifies Maxwell's equations:

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma} \mathbf{B} \cdot \nabla a \,,$$
$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma} \left(\mathbf{B} \dot{a} - \mathbf{E} \times \nabla a \right) \,,$$
$$\nabla \cdot \mathbf{B} = 0 \,,$$
$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0 \,,$$
$$\ddot{a} - \nabla^2 a + m_a^2 a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} \,.$$

$\dot{a}$ Oscillation of axion field

∇a Gradient in axion field

→ $\dot{a}$ **Sources E – field oscillation!**

Primakoff Effect:

Real photon

$$E = mc^2 = h\boldsymbol{\nu}$$

$$C_{a\gamma} \propto g_{a\gamma} \cdot f_a$$

B-Field

$$\mathcal{L}_{a\gamma} = \frac{\alpha}{2\pi} C_{a\gamma} \frac{a(t)}{f_a} \boldsymbol{E} \cdot \boldsymbol{B}$$

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(Werner-Heisenberg-Institut)
MAX-PLANCK-GESELLSCHAFT

„Waves on water surface“

„Field of water waves couples“ to air

→ Sound!

Higher air pressure:
→ stronger coupling to air

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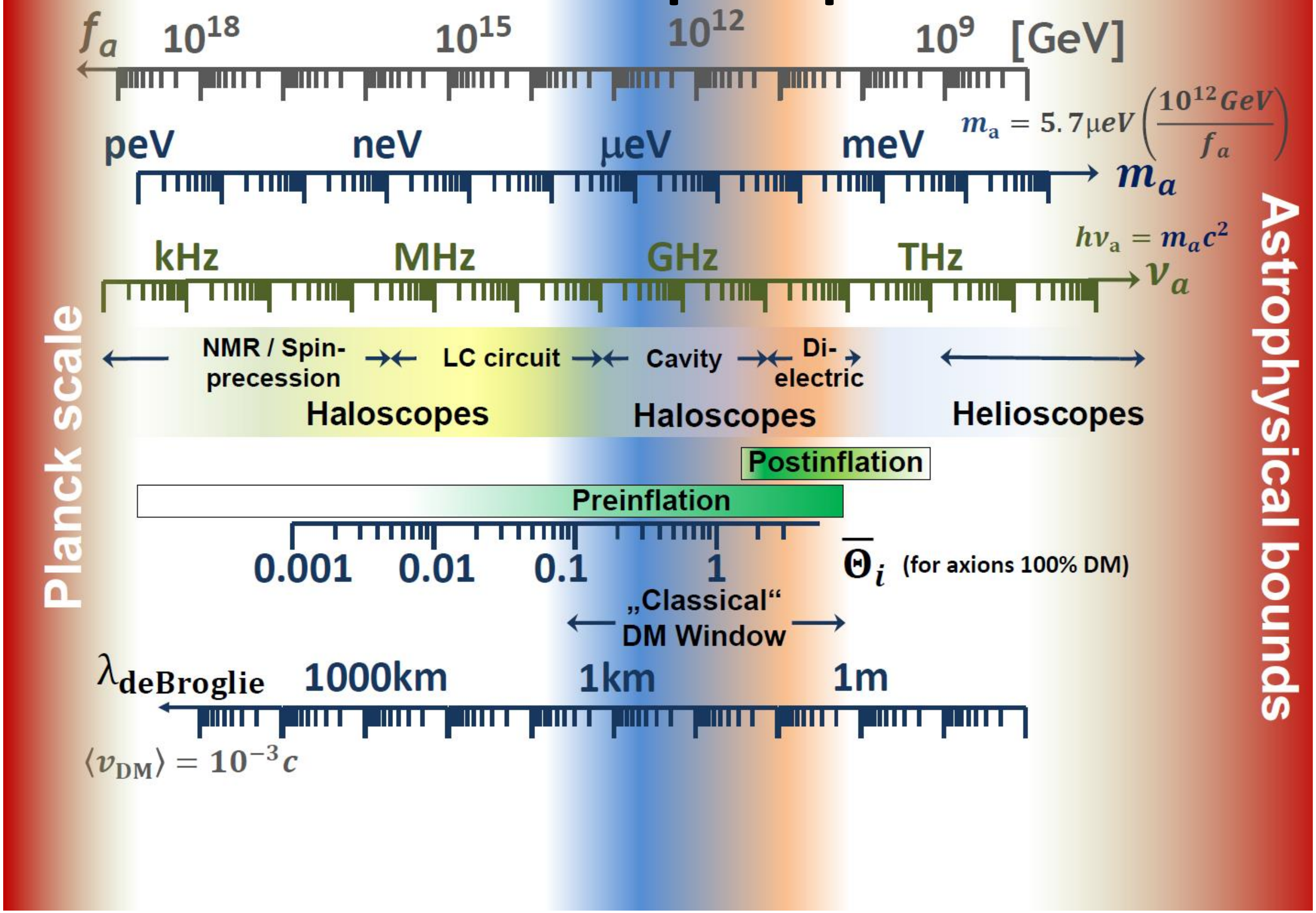
Axions in persepctive



Axion and ALPs experiments: categorization in source of axions

DM axions: Haloscopes

Detect axions from galactic DM Halo

Model dependence:

→Assume axions make up DM (100%)

→Halo density distribution

→Velocity distribution

Solar axions: Helioscopes

Production of axions/ALPs in the sun:

Inverse Primakoff effect → thermal distribution depends on solar modeling

Production in lab: Laboratory experiments

Use photon sources (lasers) to measure effects

Axion "size":

Local DM velocity distribution

$$\langle v_{DM} \rangle = 10^{-3} c$$

De Broglie wavelength:

$$\lambda_{deBroglie} = \frac{h}{p}$$

$$\lambda_{deBroglie} = \frac{h}{p} \sim \frac{h}{m_a \langle v_{DM} \rangle} \sim \frac{h}{\frac{h\nu_a}{c^2} 10^{-3} c}$$

$$= 10^3 \frac{c}{\nu_a} = \frac{3 \cdot 10^{11} m/s}{\nu_a} =$$

$$300m \cdot \left(\frac{1\ GHz}{\nu_a} \right) \sim 75m \cdot \left(\frac{\mu eV/c^2}{m_a} \right)$$

→ **Experiment fits into particle!**

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Axion-experiment "coherence time":

Local DM velocity distribution

$$\langle v_{DM} \rangle = 10^{-3} c$$

axion mass vs. frequency

$$m_a = \frac{h\nu_a}{c^2}$$

Interaction time of axions for experiment determined by $\lambda_{deBroglie}$**:**

$$dt \sim \frac{\lambda_{deBroglie}}{\langle v_{DM} \rangle} \sim \frac{300\ m}{10^{-3} c} \cdot \left(\frac{1\ GHz}{\nu_a}\right) = 10^{-3} s \cdot \left(\frac{1\ GHz}{\nu_a}\right)$$

→Number of oscillation phases during propagation through experiment:

$$\boldsymbol{dt \cdot \nu_a \sim 10^6}$$

→ Many oscillations periods during transition

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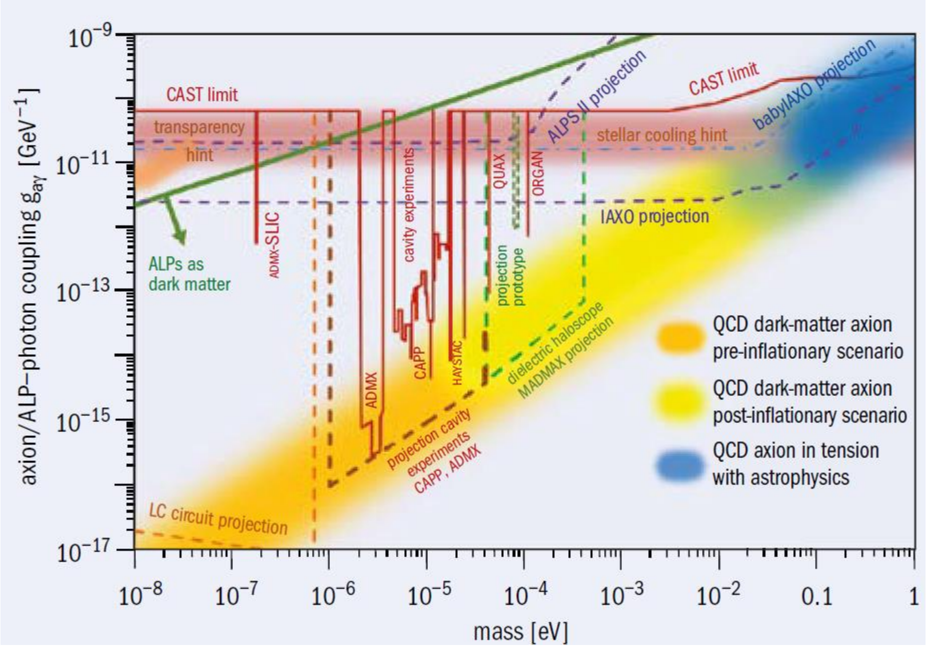
Dark Matter Axion and ALPs
How to detect them?

- **Axion couplings and sources**
- **Cavity experiments**
- **Dielectric haloscopes**
- LC circuits
- NMR experiments
- **Solar axion search**
- **Light shining through the wall**
- **Some astrophysical constraint**



Axion local DM number density:

Local DM density

$$\rho_{DM} \sim 0.3\,\frac{GeV/c^2}{cm^3}$$

De Broglie wavelength:

$$\lambda_{deBroglie} \sim 7500\ cm \cdot \left(\frac{\mu eV/c^2}{m_a}\right)$$

$$\lambda^3_{deBroglie} \sim 4 \cdot 10^{12}\ cm^3 \cdot \left(\frac{\mu eV/c^2}{m_a}\right)^3$$

$$1\ cm^3 \sim 2.5 \cdot 10^{-13}\ \lambda^3_{deBroglie} \cdot \left(\frac{m_a}{\mu eV/c^2}\right)$$

$$N_a = \frac{\rho_a}{m_a} = 0.3\ \frac{(GeV/c^2)/m_a}{cm^3}$$

$$= 0.3\,\frac{(GeV/c^2)/(\mu eV/c^2)}{cm^3}\left(\frac{1\mu eV/c^2}{m_a}\right)$$

$$= \frac{3 \cdot 10^{14}}{cm^3}\left(\frac{\mu eV/c^2}{m_a}\right)$$

$$= 3 \cdot 10^{14}\left(\frac{\mu eV/c^2}{m_a}\right)\frac{4 \cdot 10^{12}}{\lambda_{deBroglie}{}^3}\left(\frac{\mu eV/c^2}{m_a}\right)^3 \sim \frac{10^{27}}{\lambda_{deBroglie}{}^3}\left(\frac{\mu eV/c^2}{m_a}\right)^4$$

Axion-Photon Coupling:

Oscillations of E-Field!

→ Use of resonance effects!

Cavity HALOSCOPES

High Q-factor cavities in strong B-field:

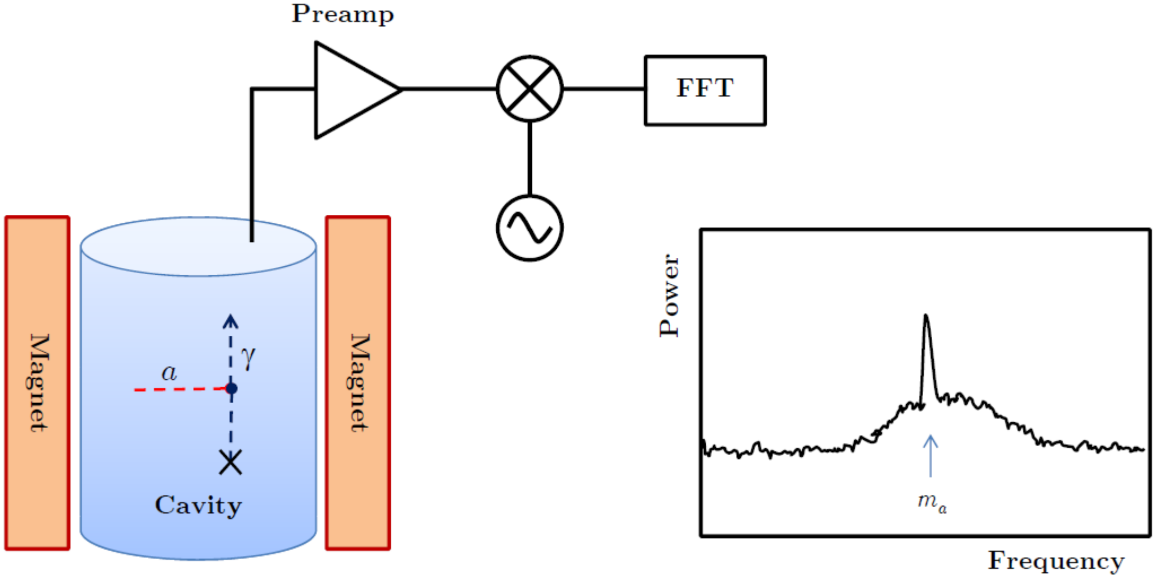
→ **Coherent E-field oscillation**

→ **If at resonant frequency: cavity is "pumped"**

→ **Power can be detected**

$$Q = \frac{Energy\ in\ cavity}{Energy\ dissipated\ in\ walls}$$

$$Q_L = \frac{center\ frequency}{frequency\ bandwidth}$$

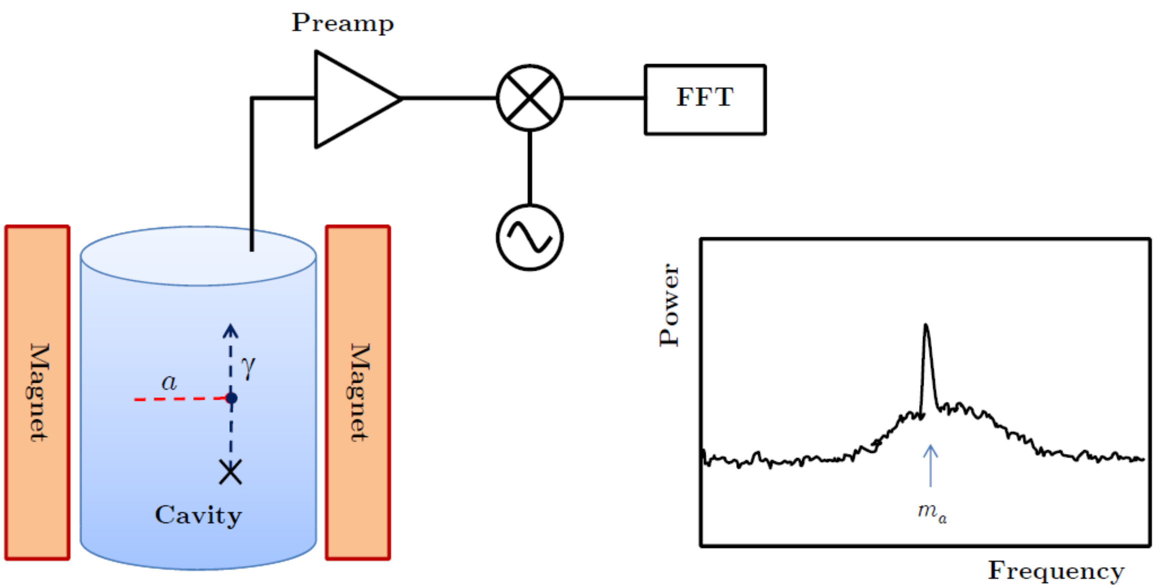


Cavity HALOSCOPES

Total power expected from resonant DM axion to photon conversion:

$$P_{sig} = g_{a\gamma}{}^2 \left(\frac{\rho_a}{m_a}\right) B^2 V Q_L C \qquad C = \frac{\left|\int_V \, d^3x \, \overrightarrow{E(\nu)} \cdot \vec{B}\right|^2}{\int_V \, d^3x \varepsilon \, |E(\nu)|^2}$$

V : Volume of cavity, Q_L: Loaded Quality factor of cavity (if axion signal width narrower), C : Overlap integral of B-field with axion induced E-field of mode

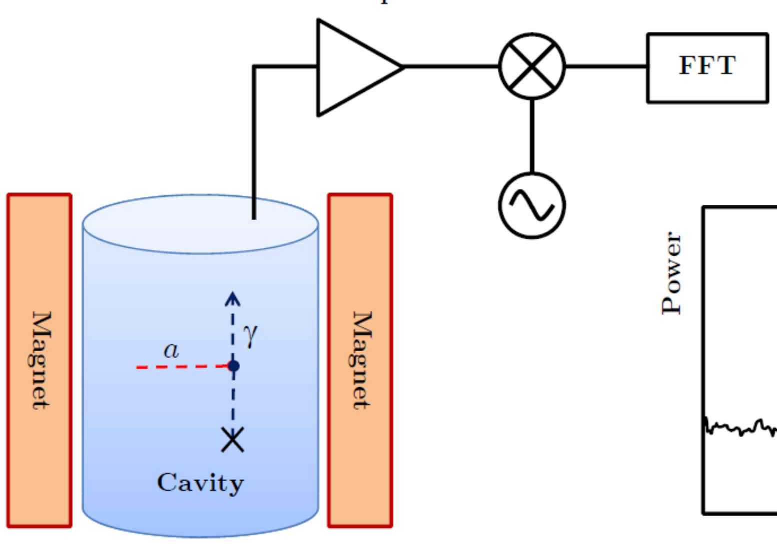


Cavity HALOSCOPES

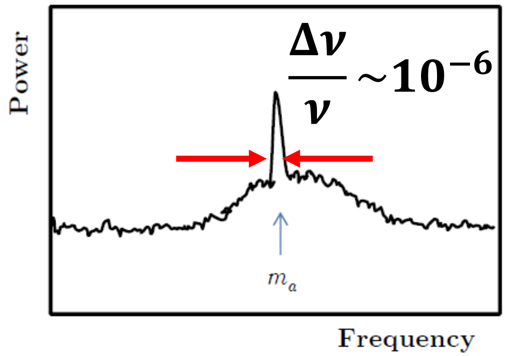
Total power expected from resonant DM axion to photon conversion:

$$P_{sig} = 7 \cdot 10^{-23} W \left(\frac{\mu eV/c^2}{m_a}\right) \left(\frac{B}{8T}\right)^2 \left(\frac{V}{200l}\right) \left(\frac{Q_L}{10^5}\right) \left(\frac{C}{0.35}\right)$$

V : Volume of cavity, Q_L: Loaded Quality factor of cavity (if axion signal width narrower), C : Overlap integral of B-field with axion induced E-field of mode



$\langle v_{DM} \rangle = 10^{-3} c$



Cavity HALOSCOPES

Sensitivity of experiment: Use "**Dickes radiometer equation**":

$$\frac{S}{N} = \frac{P_{sig}}{k_b T_{sys}} \sqrt{\frac{t_{scan}}{\Delta\nu}}$$

$$P_{sens} \sim 10^{-23} W$$

roughly 5σ

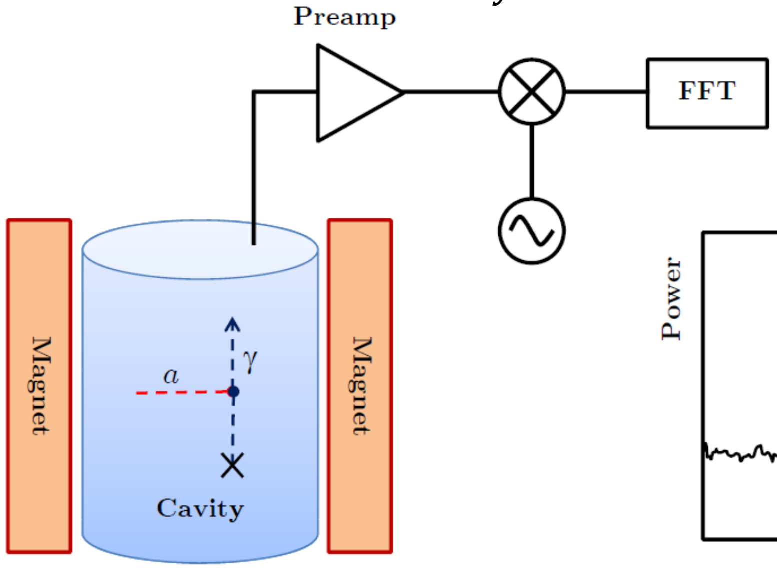
$$\frac{S}{N} \sim 5$$

Dilution fridge + noise temp receiver

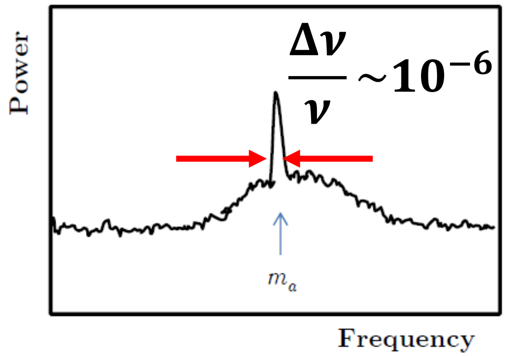
$$T_{sys} \sim 0.2K$$

Many individual measurements!

$$t_{scan} \sim 100\ sec$$



$$\langle v_{DM} \rangle = 10^{-3} c$$



$$\frac{\Delta\nu}{\nu} \sim 10^{-6}$$

Cavity HALOSCOPES

Sensitivity of experiment: Use "**Dickes radiometer equation"**:

Scan rate:

$$\frac{dm_a}{dt} \sim 0.4\ \mu eV/yr \left(\frac{B}{8T}\right)^4 \left(\frac{V}{136l}\right)^2 \left(\frac{Q_L}{3\cdot 10^4}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2 \left(\frac{m_a}{3\mu eV}\right)^2$$

roughly 5σ

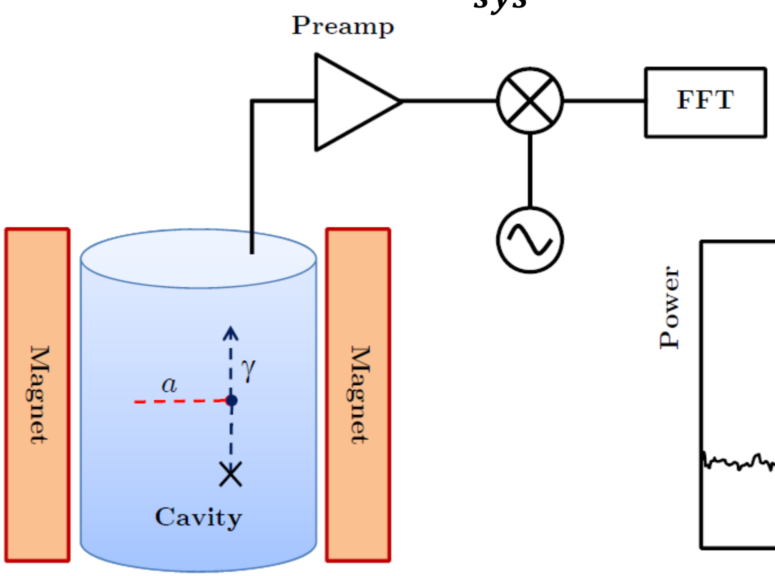
$$\frac{S}{N} \sim 5$$

Dilution fridge + noise temp receiver

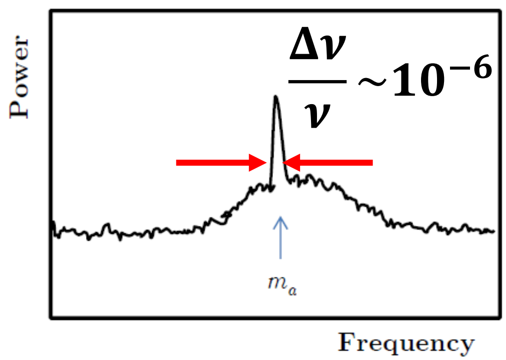
$$T_{sys} \sim 0.2K$$

Many individual measurements!

$$t_{scan} \sim 100\ sec$$



$$\langle v_{DM} \rangle = 10^{-3} c$$

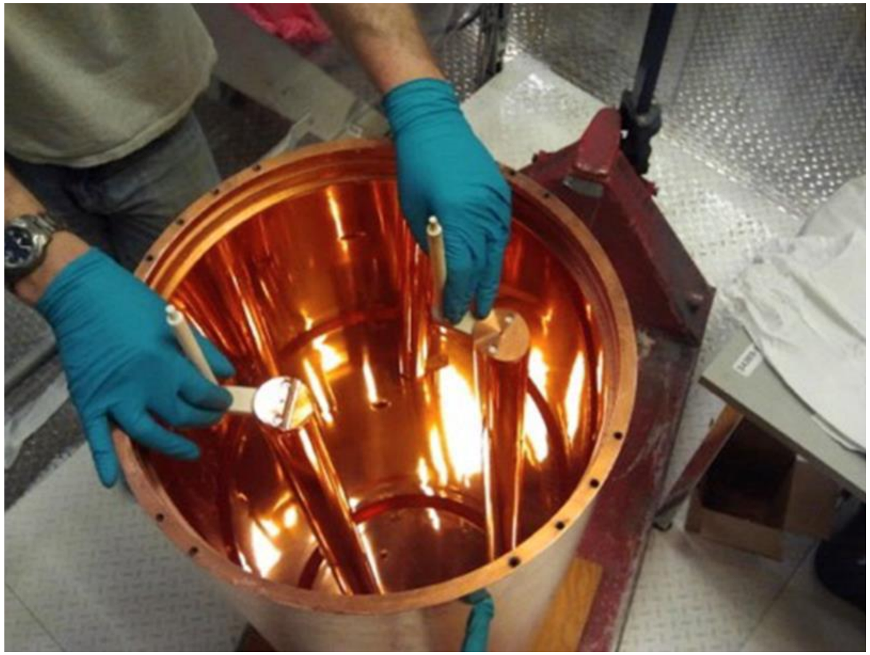


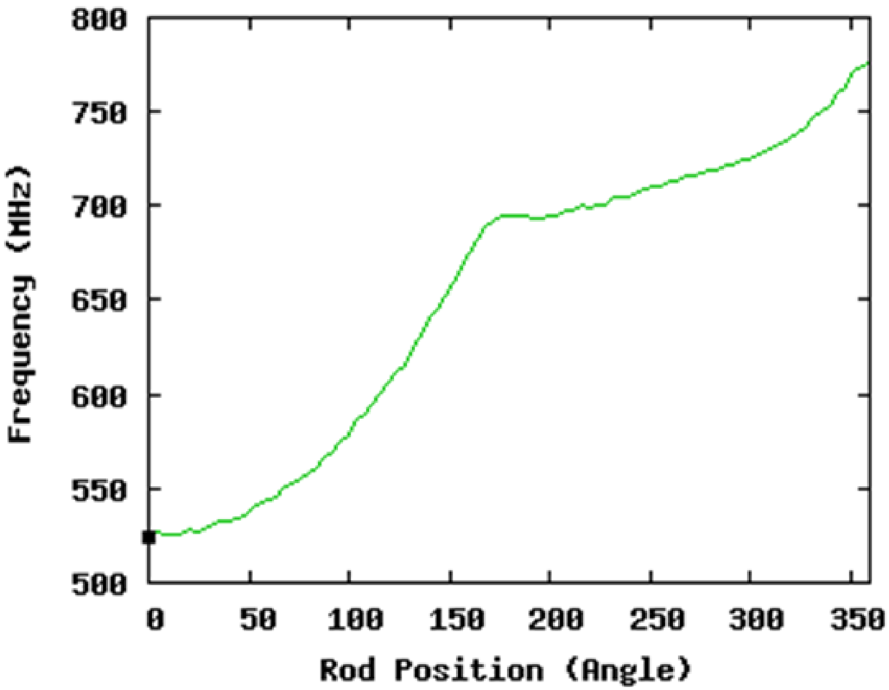
$$\frac{\Delta\nu}{\nu} \sim 10^{-6}$$

Cavity HALOSCOPE: ADMX

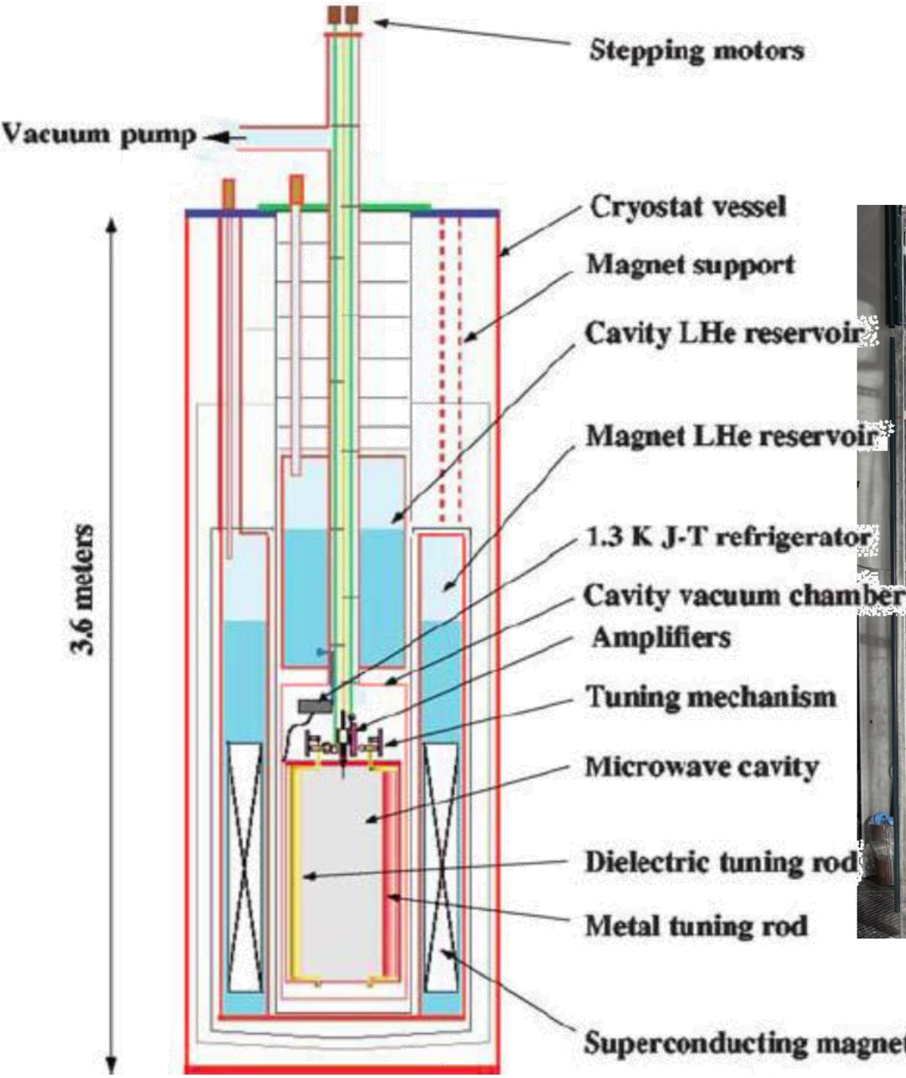
Scan mass range: need to tune

→ Use dielectric low loss tuning rod
→ Change resonance frequency of cavity





Cavity HALOSCOPE: ADMX



Sensitivity range: 0.5 – 2.5 GHz → ~2 – 10 μeV

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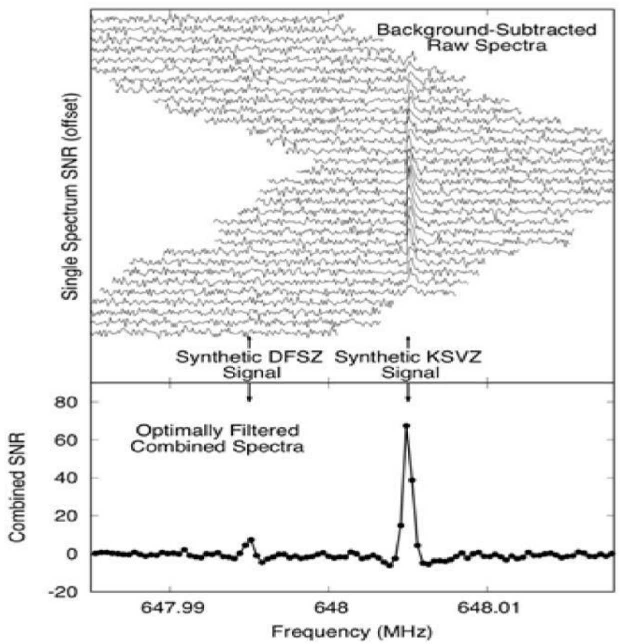
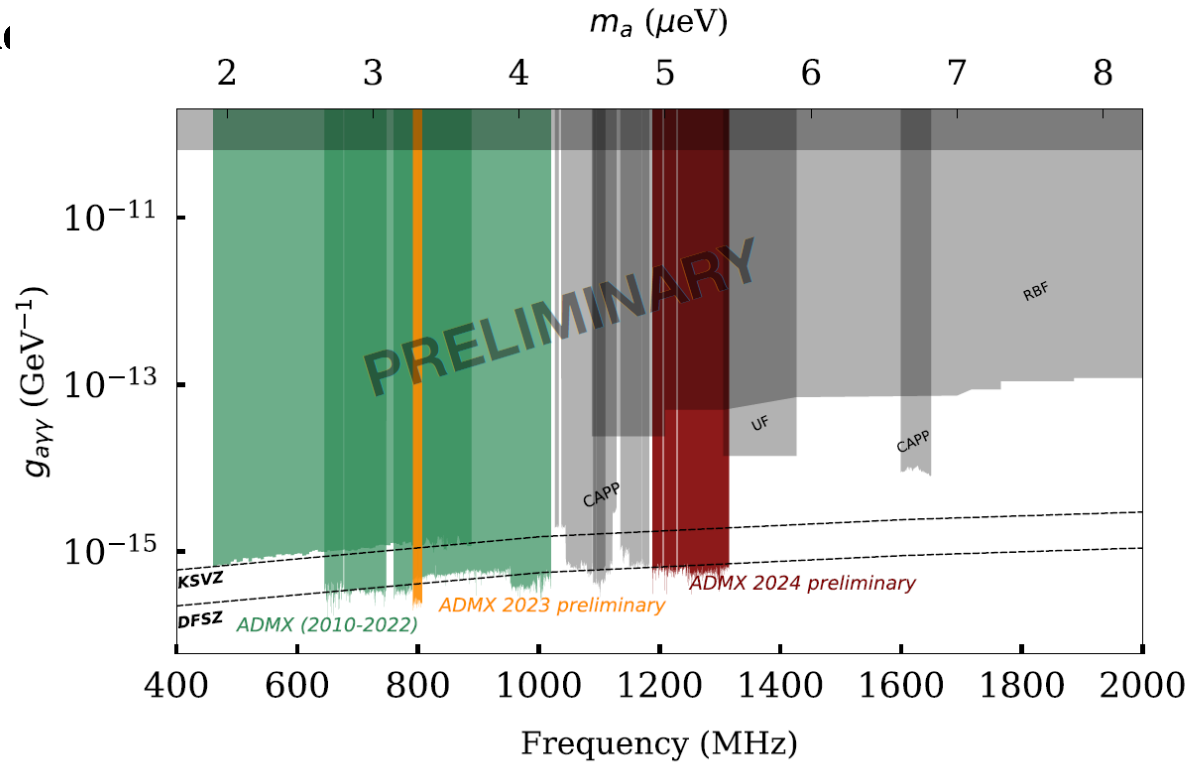
Cavity HALOSCOPE: ADMX

individual ~ 100s measurements
With different tuning rod position



individual measurements
With different tuning rod positiond

No excess signal found



arXiv:2408.15227

Scan rate:

$$\frac{dm_a}{dt} \sim 0.4\ \mu eV/yr \left(\frac{B}{8T}\right)^4 \left(\frac{V}{136l}\right)^2 \left(\frac{Q_L}{3\cdot 10^4}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2 \left(\frac{m_a}{3\mu eV}\right)^2$$

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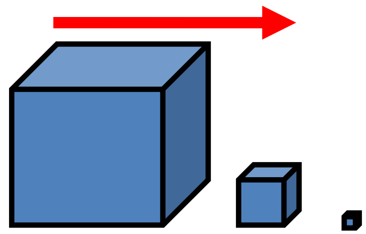
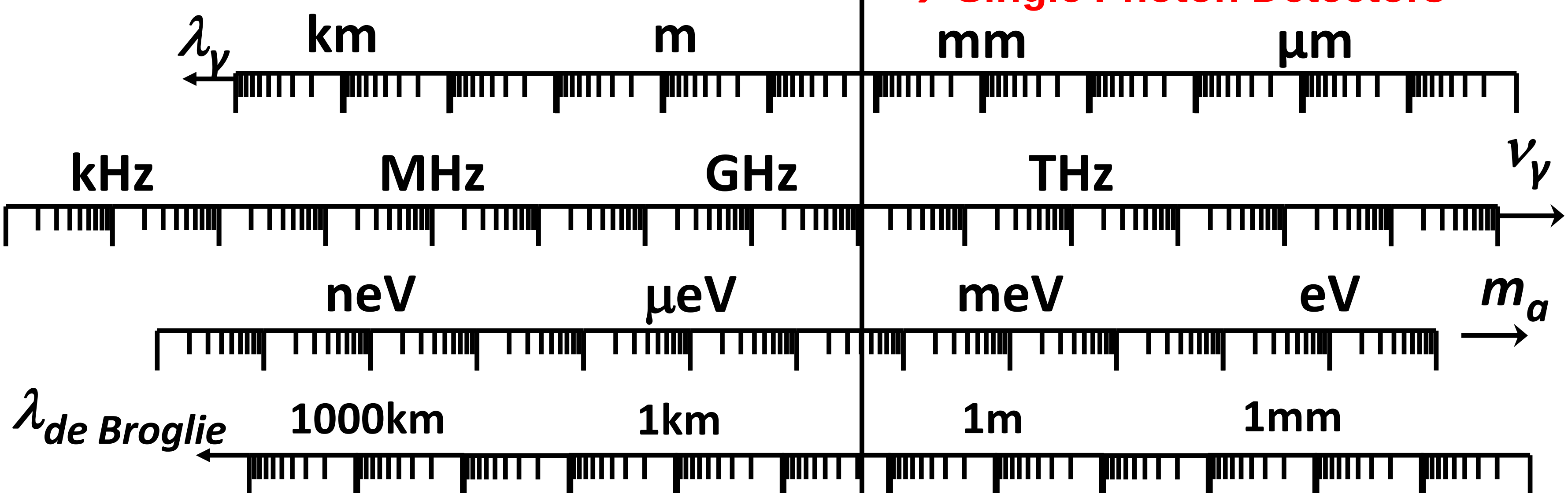
Volume of cavities & Q_L decrease with wavelength



Alternative Approaches:
Coupled & HTS cavities
Dish Antenna
Dielectric Haloscope

Standard Quantum Limit (SQL)
Limit on T_{sys} !
→ Vacuum Squeezing
→ Single Photon Detectors



$$P_{sig} \propto B^2 V\, Q_{cav}$$

$$\frac{S}{N} = \frac{P_{sig}}{k_b T_{sys}} \sqrt{\frac{t_{scan}}{\Delta \nu}}$$

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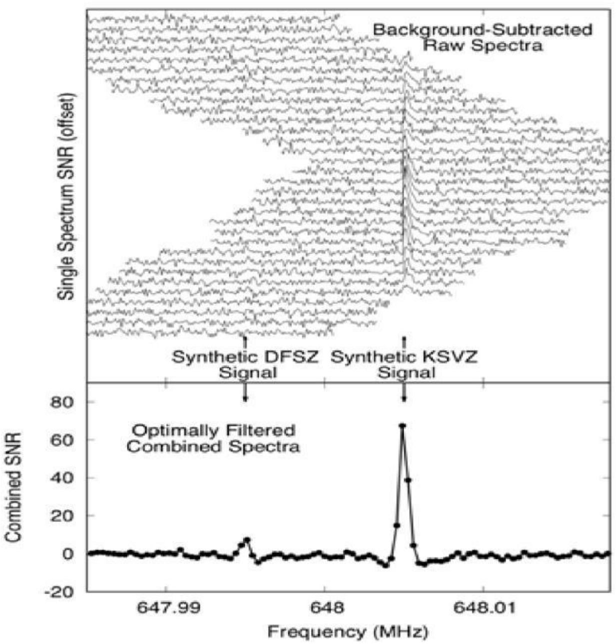
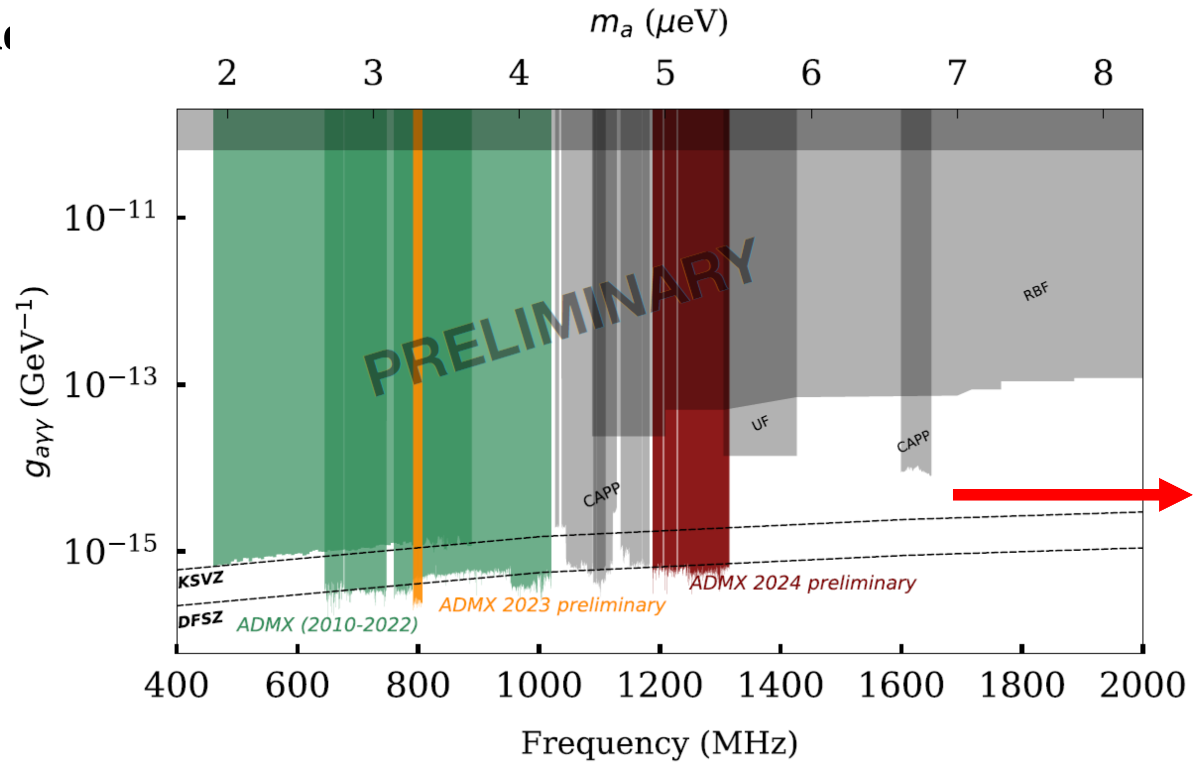
Cavity HALOSCOPE: ADMX

individual ~ 100s measurements
With different tuning rod position



individual measurements
With different tuning rod positiond

No excess signal found



arXiv:2408.15227

Scan rate:

$$\frac{dm_a}{dt} \sim 0.4\ \mu eV/yr \left(\frac{B}{8T}\right)^4 \left(\frac{V}{136l}\right)^2 \left(\frac{Q_L}{3\cdot 10^4}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2 \left(\frac{m_a}{3\mu eV}\right)^2$$

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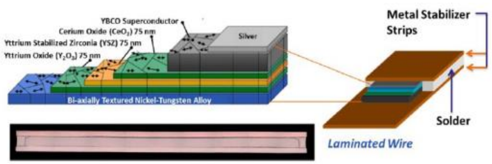
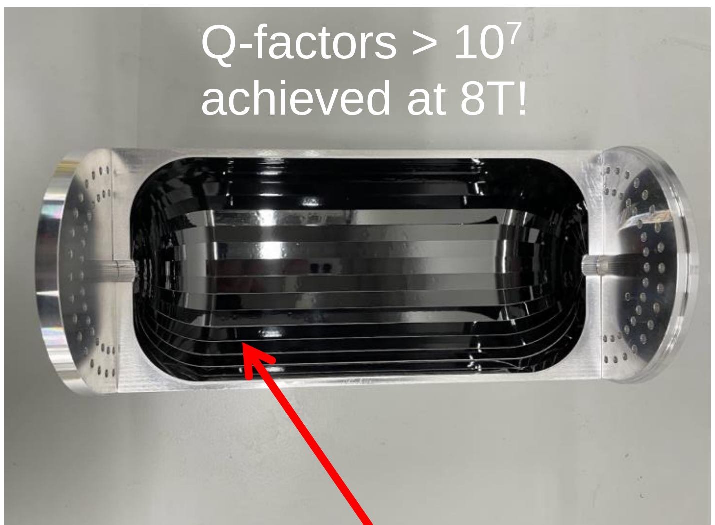
Superconducting and dielectric cavities:

Increase of cavity Q-value:

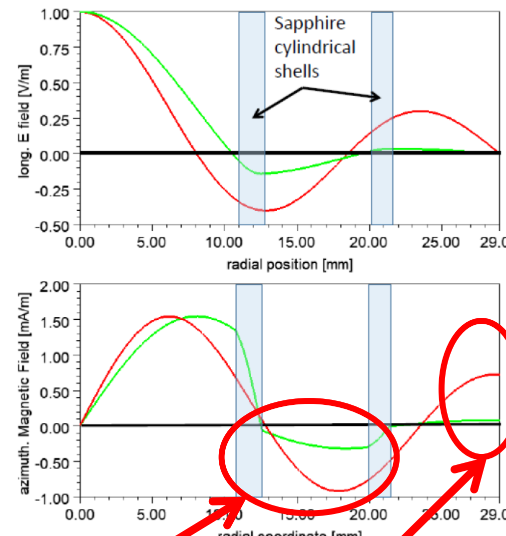
- Avoid high frequency losses:
  use superconducting wall lining.
  → limits B –field → use HTS!
- Minimize field at cavity walls: Use (low-loss) dielectric cylinders

Problem: Superconductor $Tc(B)$





Coating with high
Tc superconductor



Negative field values
→cancellation of coupling

High field values at walls
→ losses

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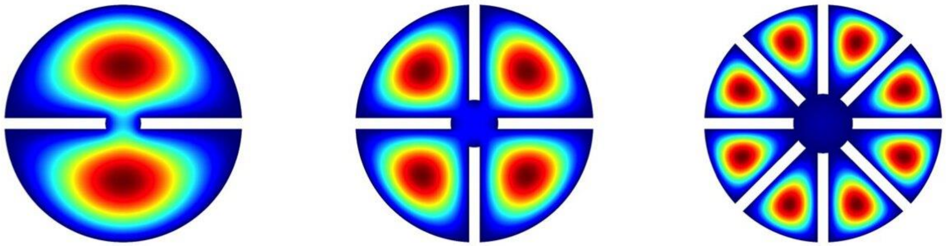
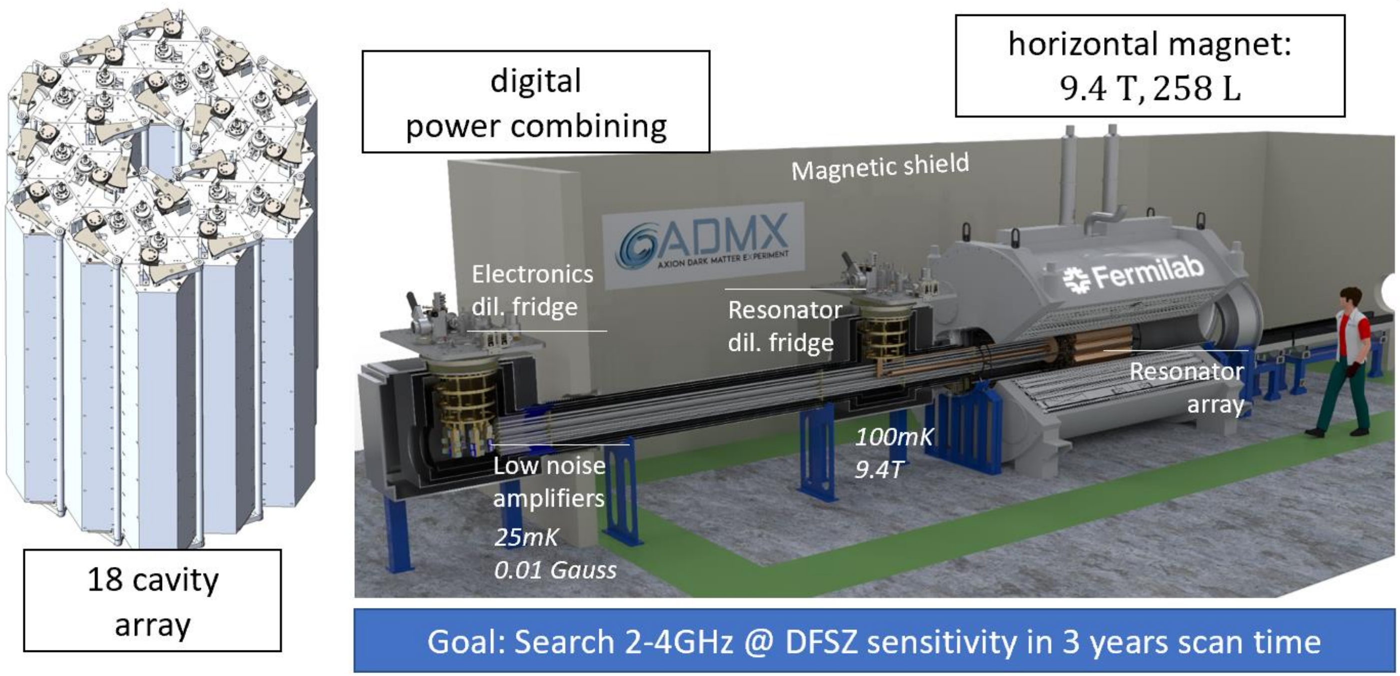
Superconducting and multiple cavities:



Many small cavities
Mode matched

PRL 125, 221302 (2020)

ADMX-EFR (Extended Frequency Range): 2 – 4 GHz (9 – 16 μeV)



S. Knirck at Patras 2024 workshop

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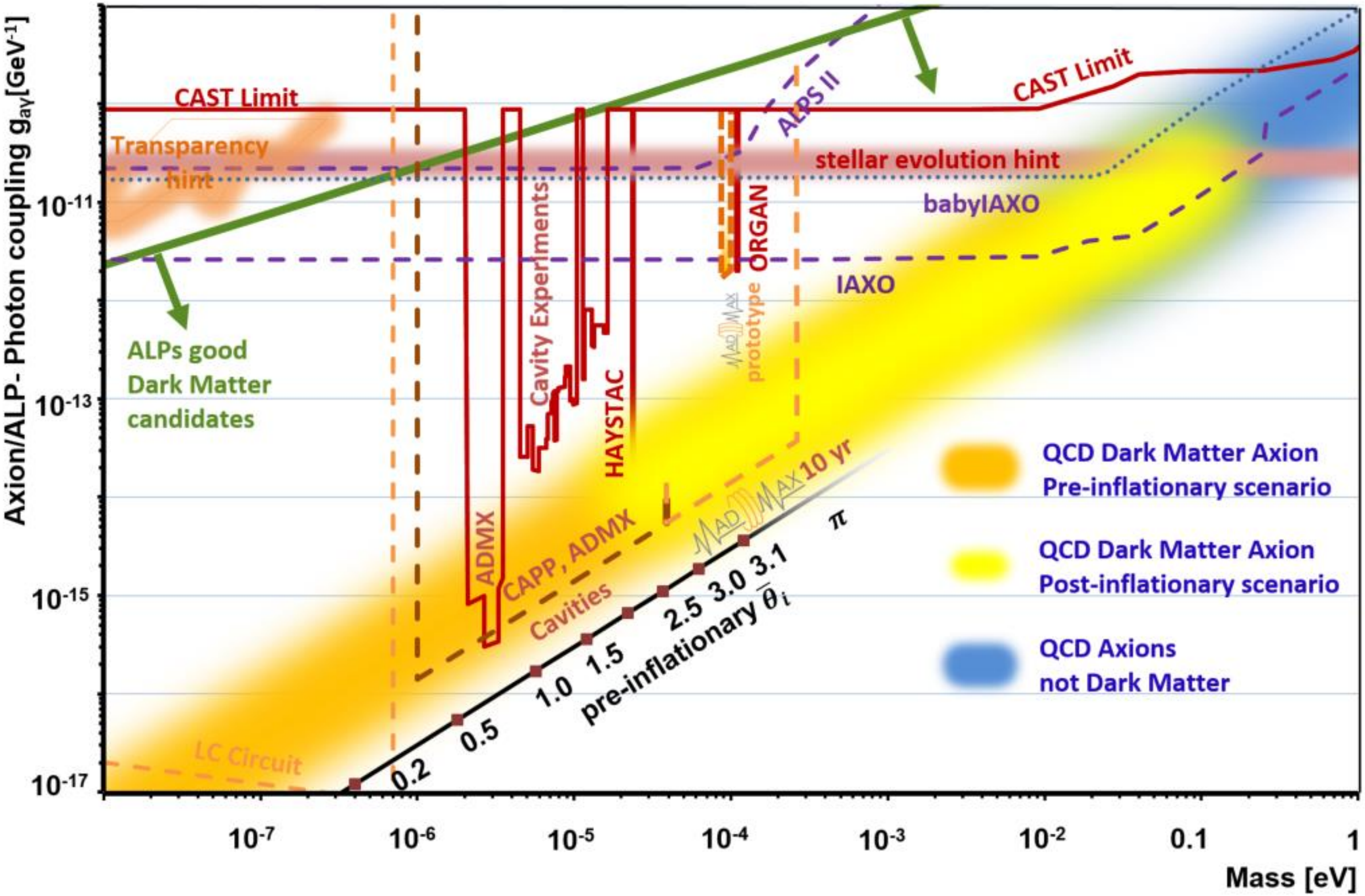
Limits and projections in perspective



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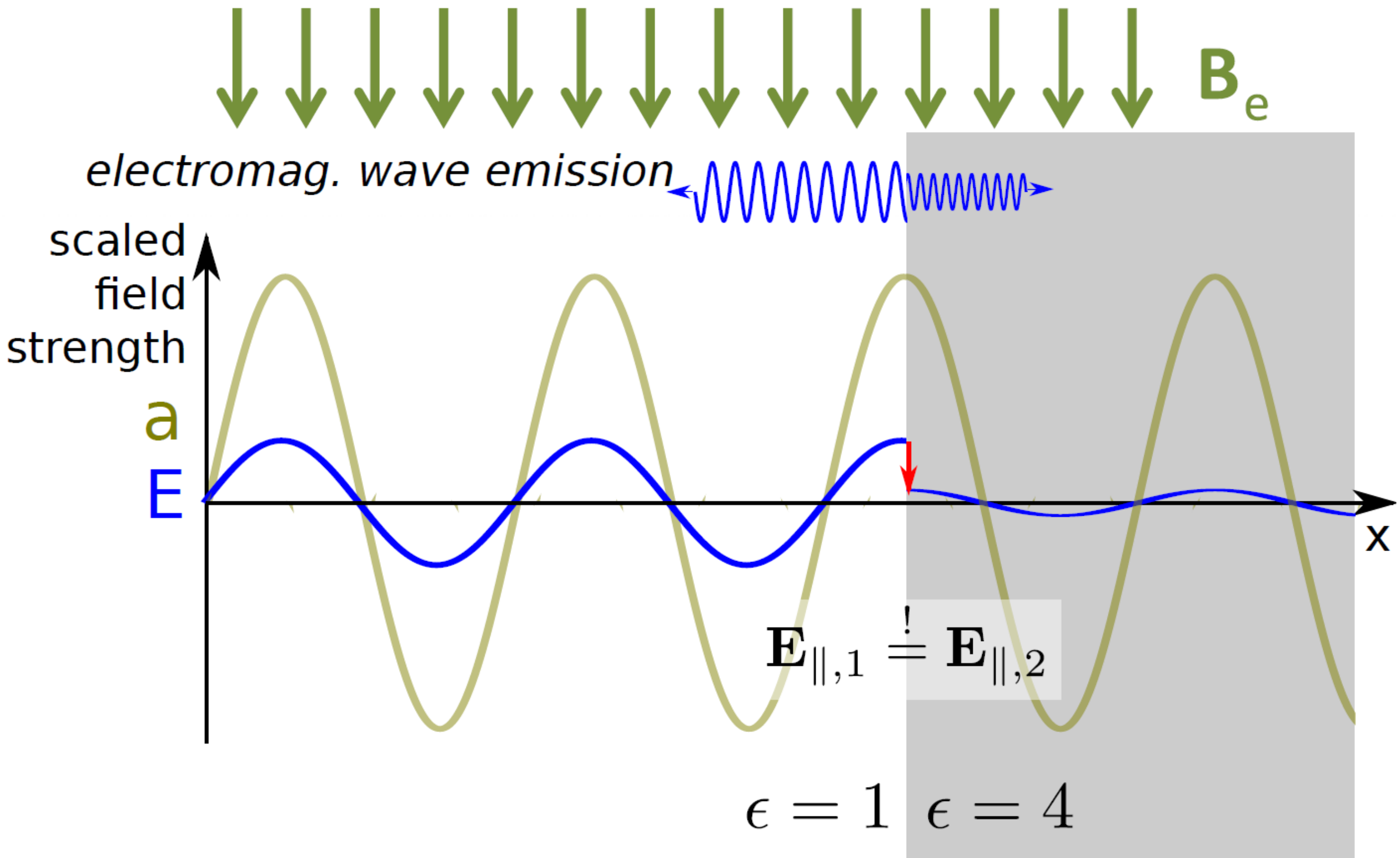
Effect of Dielectric discontinuity



Discontinuity in ϵ

→ Emission of power Perpendicular to surface

$$\left(\frac{P}{A}\right)_{mirror} \sim 2 \cdot 10^{-27} W \left(\frac{A}{1\ m^2}\right)\left(\frac{B_{||}}{10\ T}\right)^2 (g_{a\gamma\gamma} m_a)^2$$

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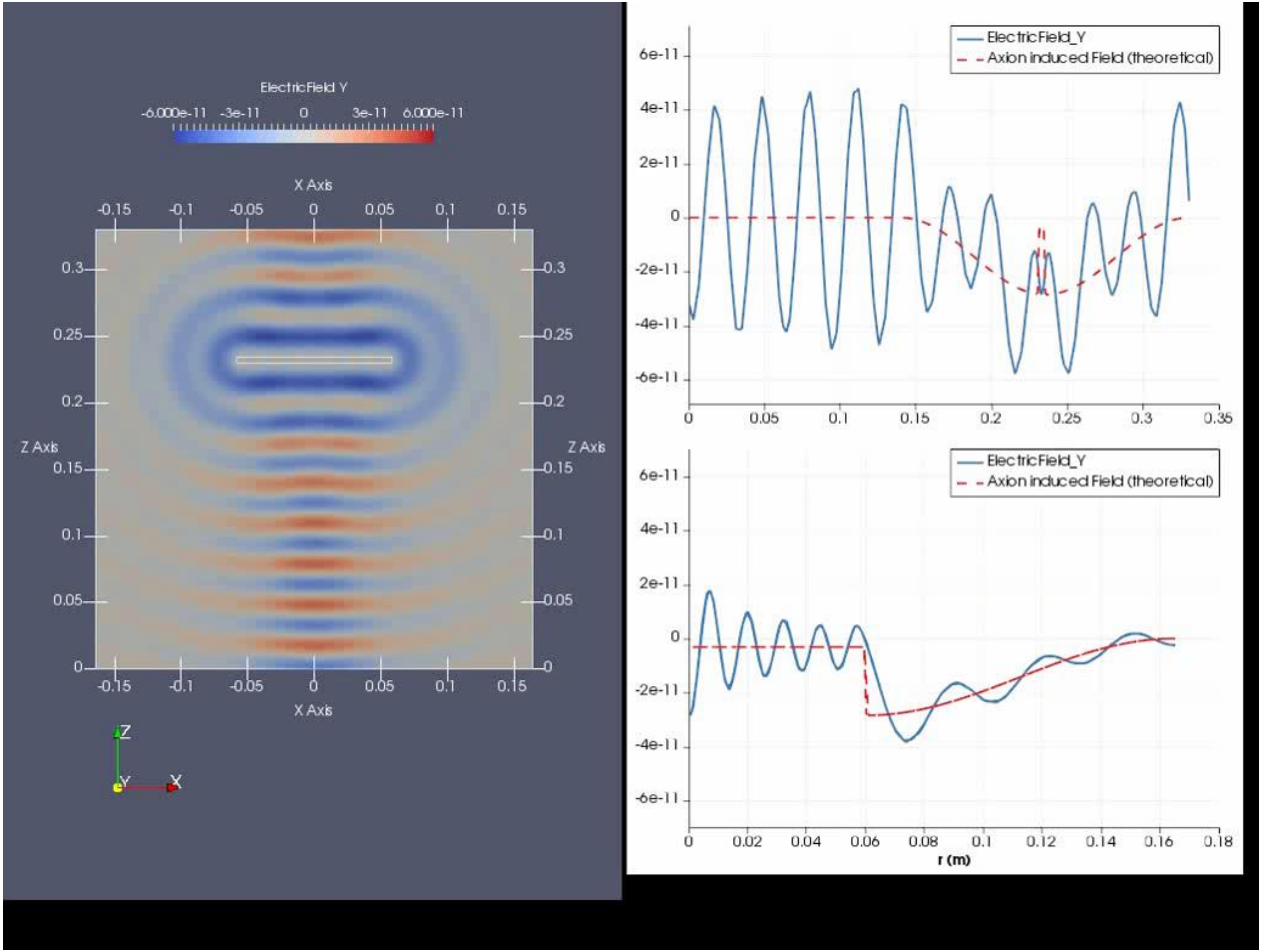

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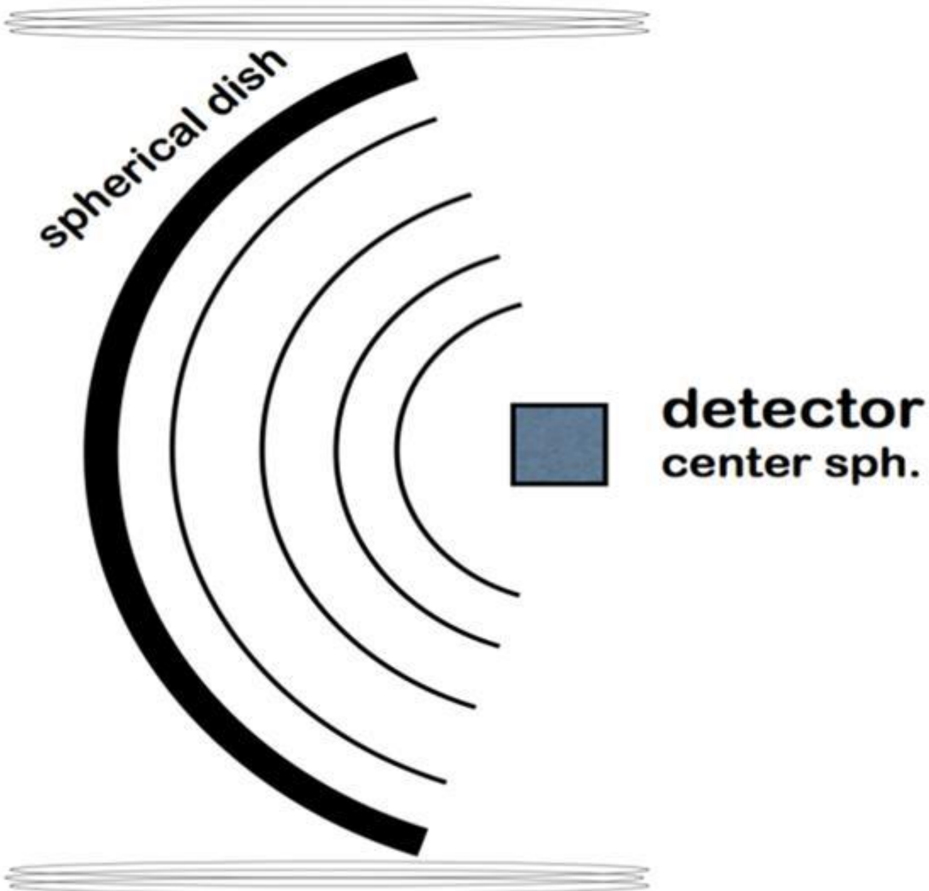
Dish antenna



Broadband approach

Works independent of frequency (axion mass)!

$P_{sig} \sim B^2 A$

For axion search:
Need large area and
Extremely sensitive detector
BRASS @ Uni Hamburg/DESY
BREAD @ Fermilab

B = 10 T

T_{sys} = 8K

P_{sens} = 10^{-23} W

→A=1.000m²

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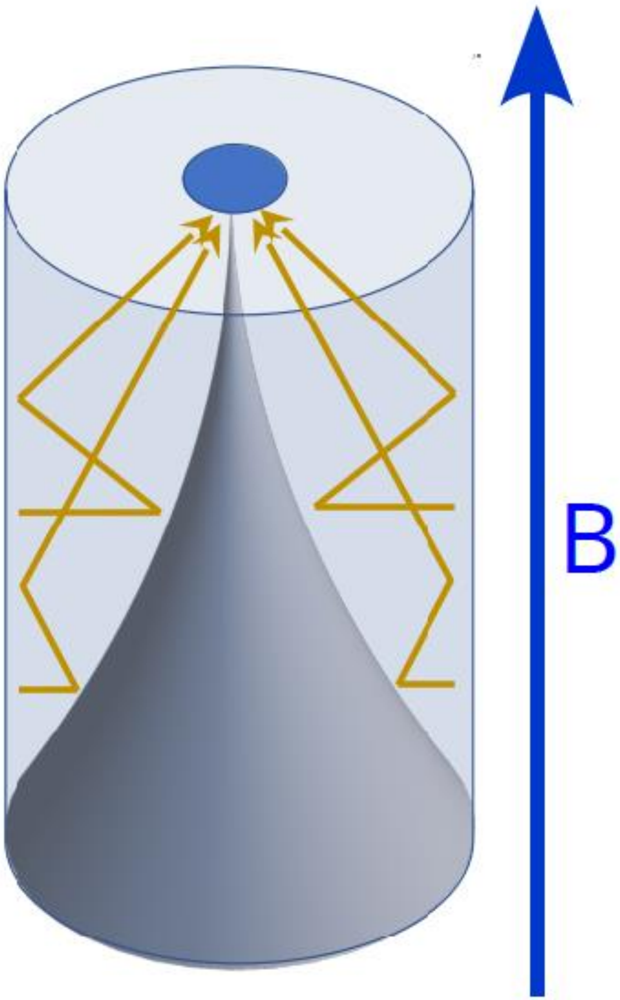
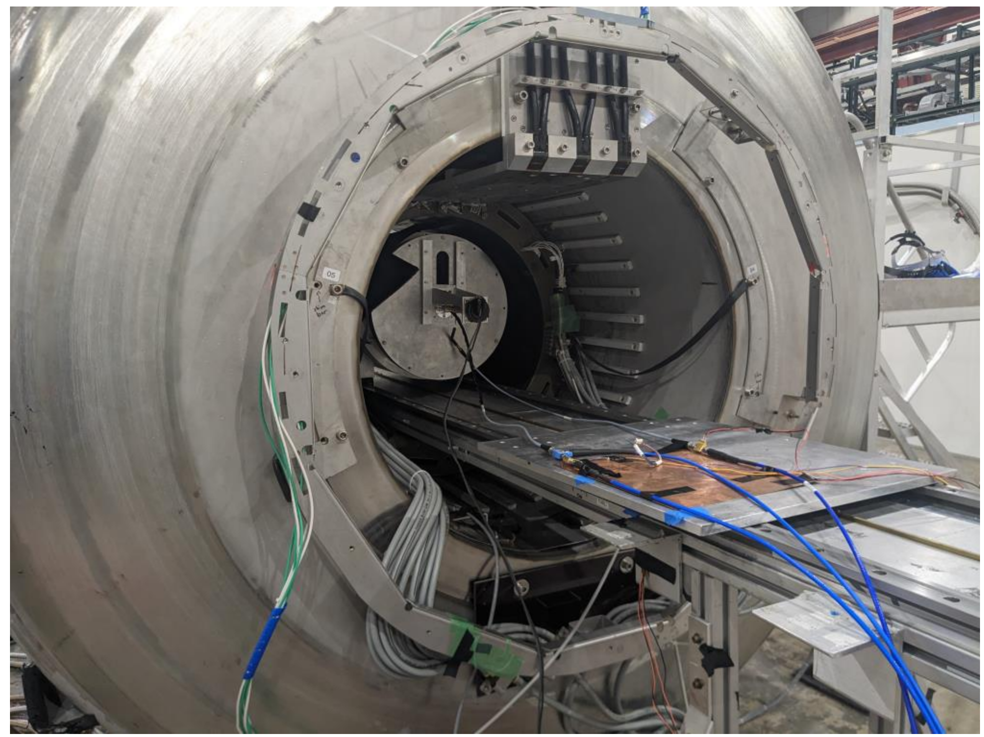
Dish antenna BREAD experiment

Broadband Reflector Experiment for Axion Detection



Use "lighthouse" geometry

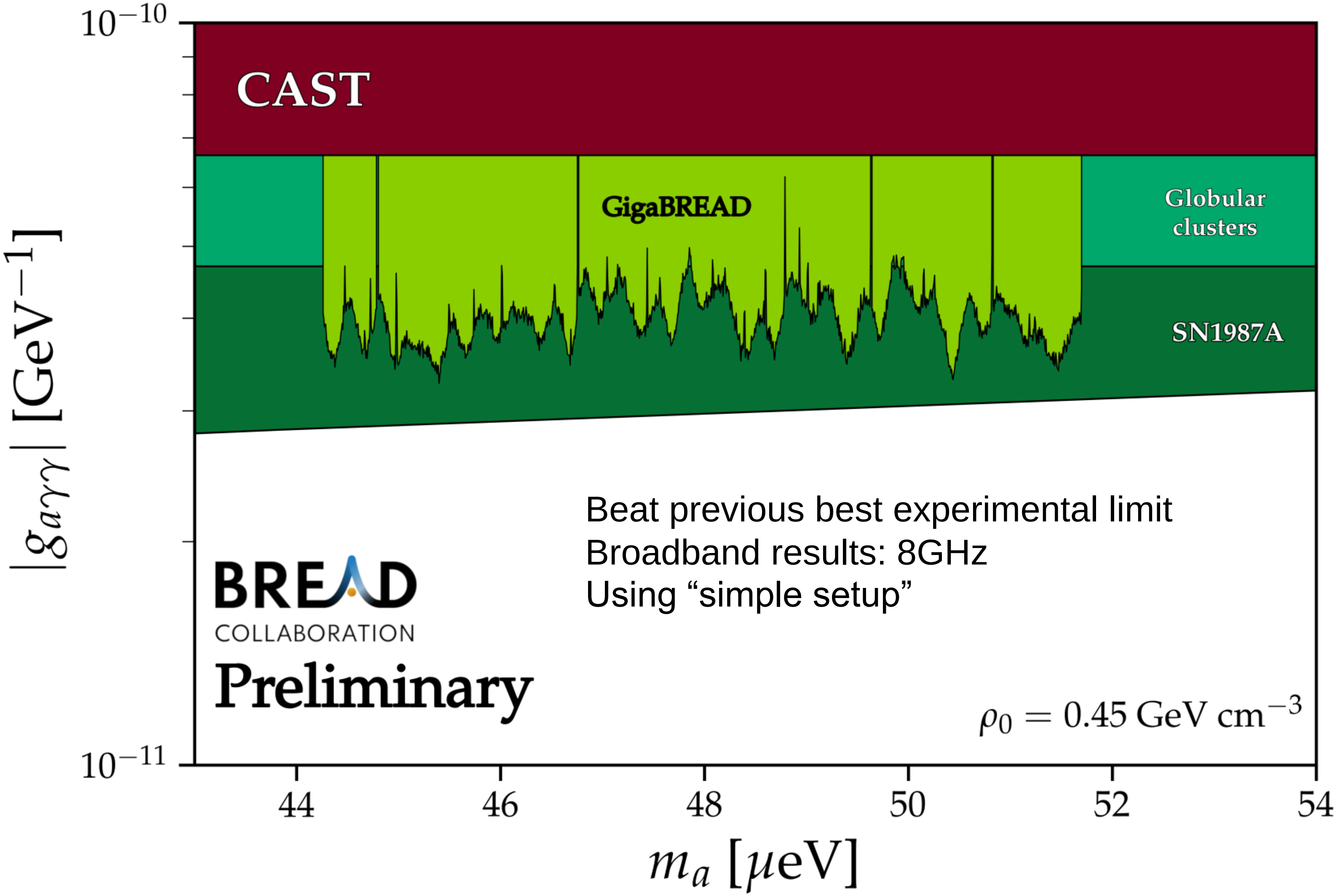
Photon emission from cylinder walls
→ Fits into solenoid magnet



A=0.5 m², B=3.9 T, T_{sys}= 400 to 600 K, t ~ 30 days

Dish antenna BREAD experiment

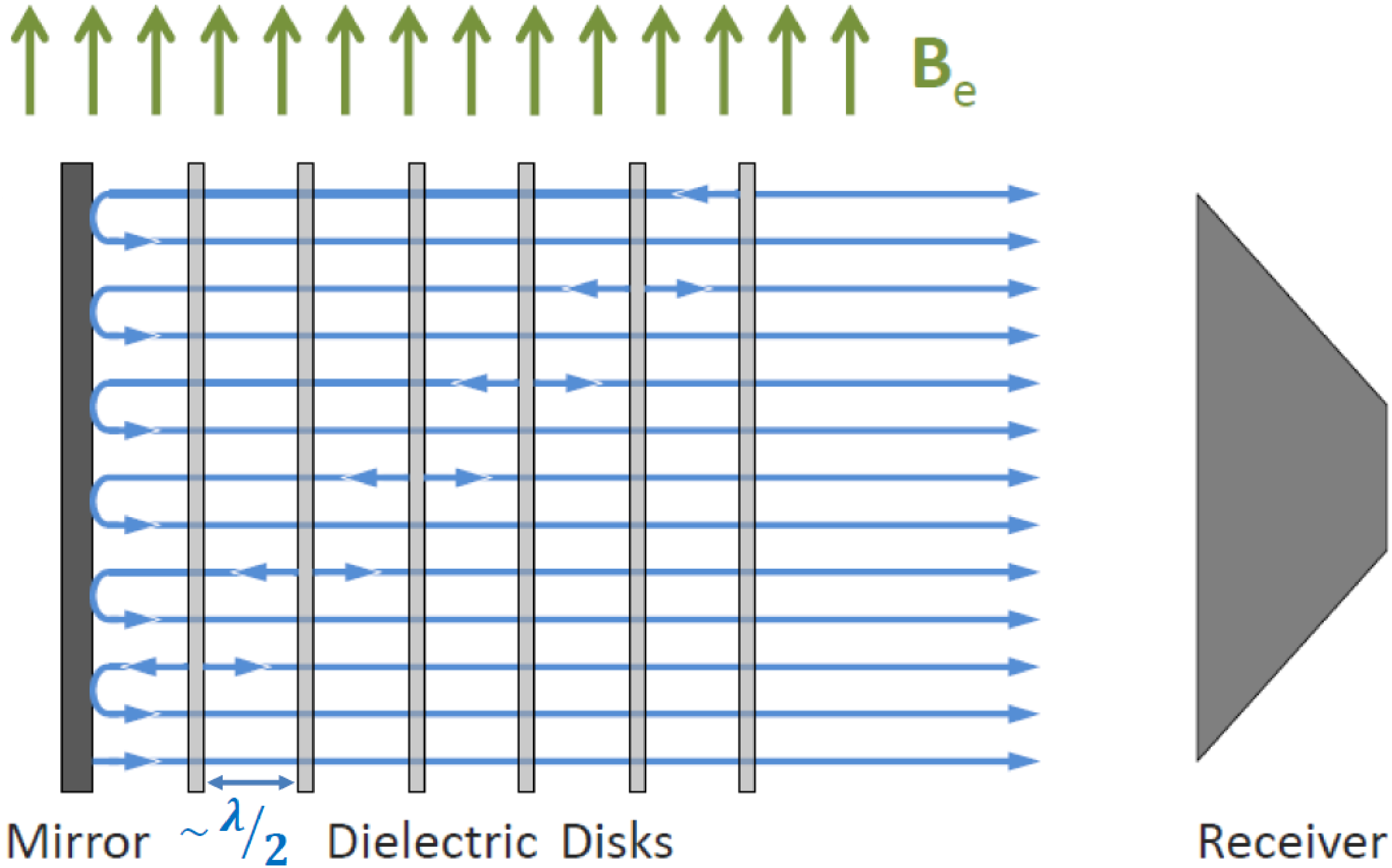
Broadband Reflector Experiment for Axion Detection



Taken from G. Hohshino at PATRAS 2024

Dielectric haloscopes:

"Quasi broadband" approach



Dielectric haloscopes:

"Quasi broadband" approach

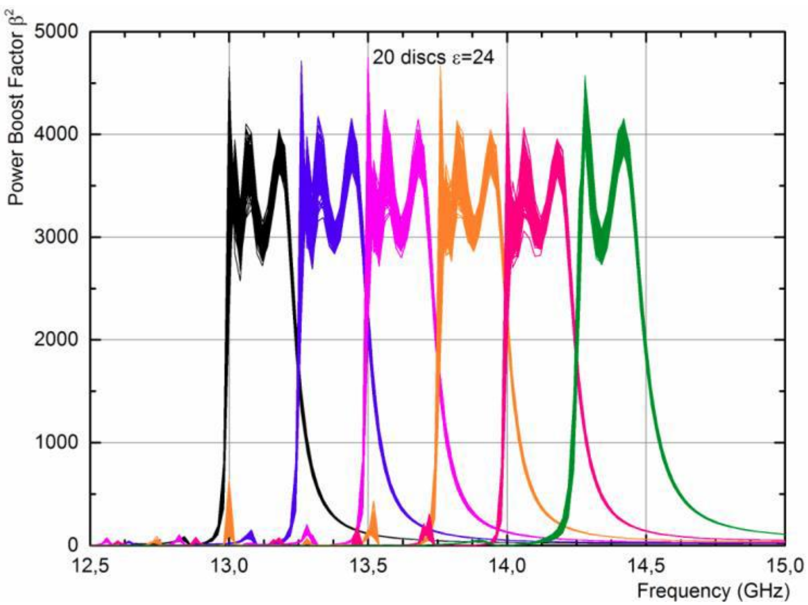
Two effects:

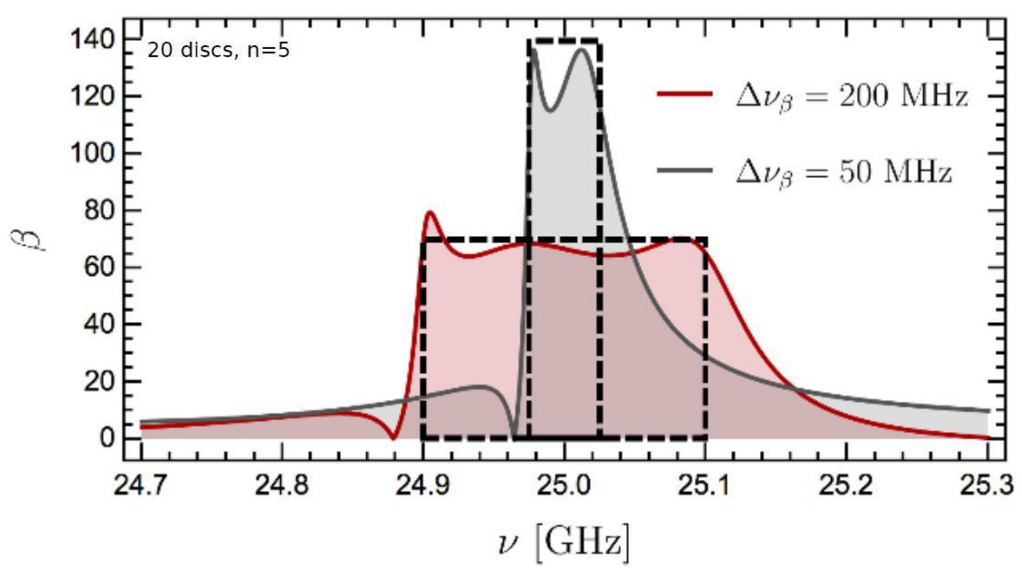
1. Coherent emission from all surfaces

2. Resonant enhancement of emission at surfaces

- Set disk distances to tune resonant effects
- Changing distances changes sensitive frequency range

mean distance ~$\lambda/2$ → frequency   distance variation → width „boost factor"





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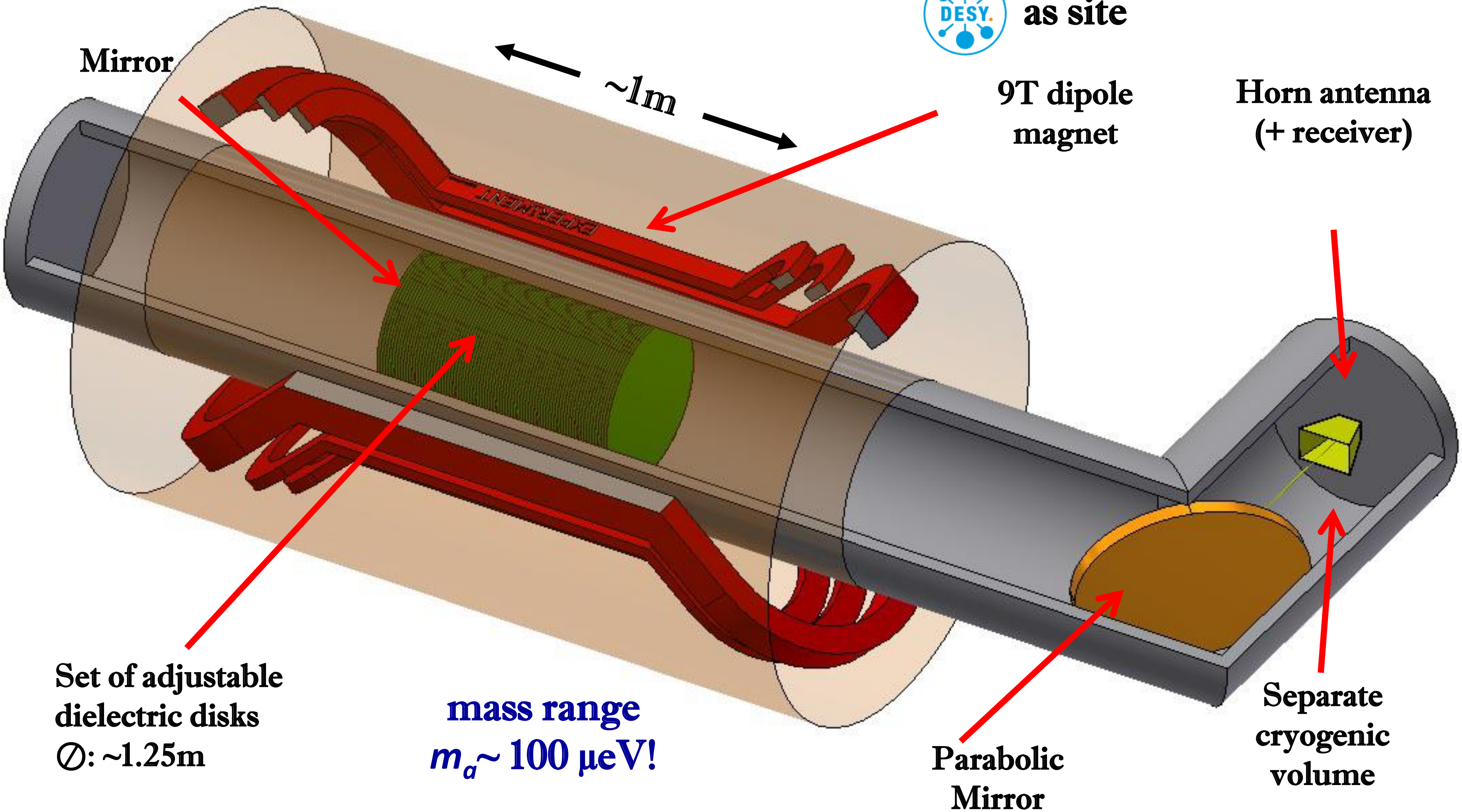
MAgnetized disk and Mirror Axion eXperiment

The European Physical Journal C volume 79, 186 (2019)

DESY as site



mass range

m_a~ 100 μeV!

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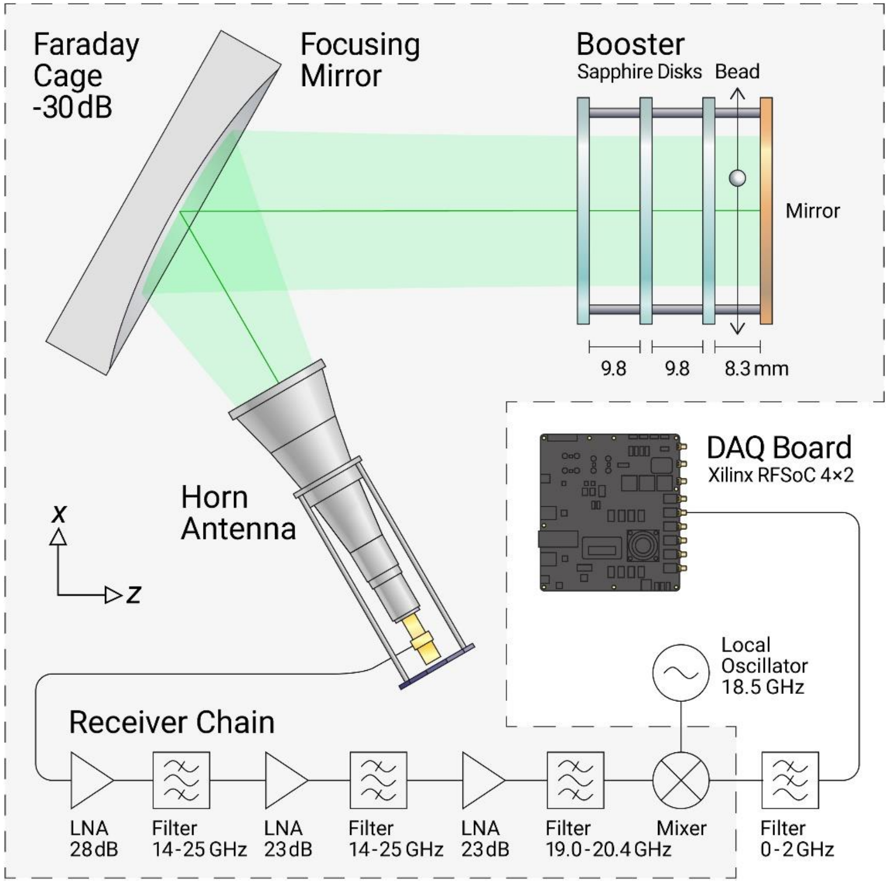
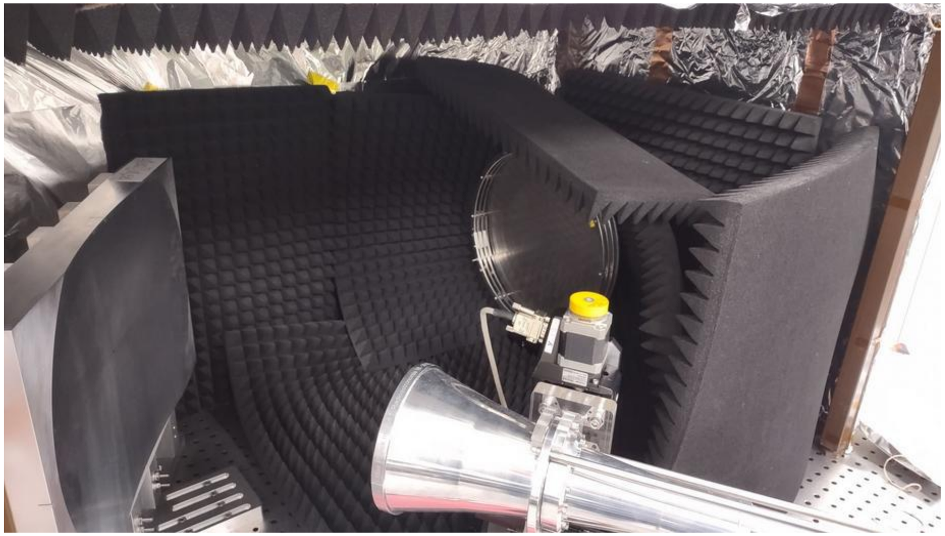
MAgnetized disk and Mirror Axion eXperiment

Prototype booster → Obtain boost factor from E-field measurements



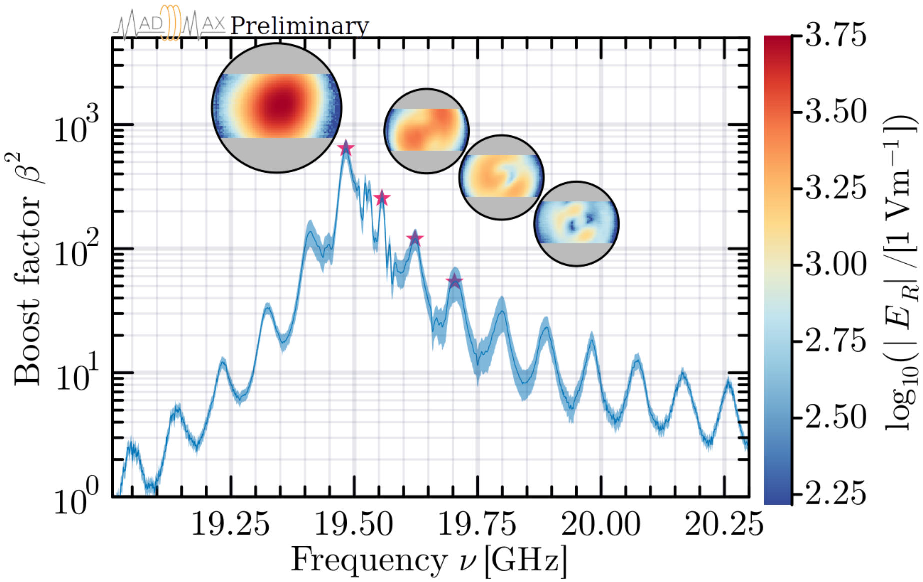


- Set up a simple three disk open booster
- Fixed distances
- Study electromagnetics with „bead-pull“ method

$$\beta^2 = \frac{P_{sig}}{P_0} = \frac{4\pi^2 \epsilon_0 \nu^2 F_{RC}}{8 c P_{in} A} \left| \int dV \, E_R \right|^2$$

arXiv:2408.02368

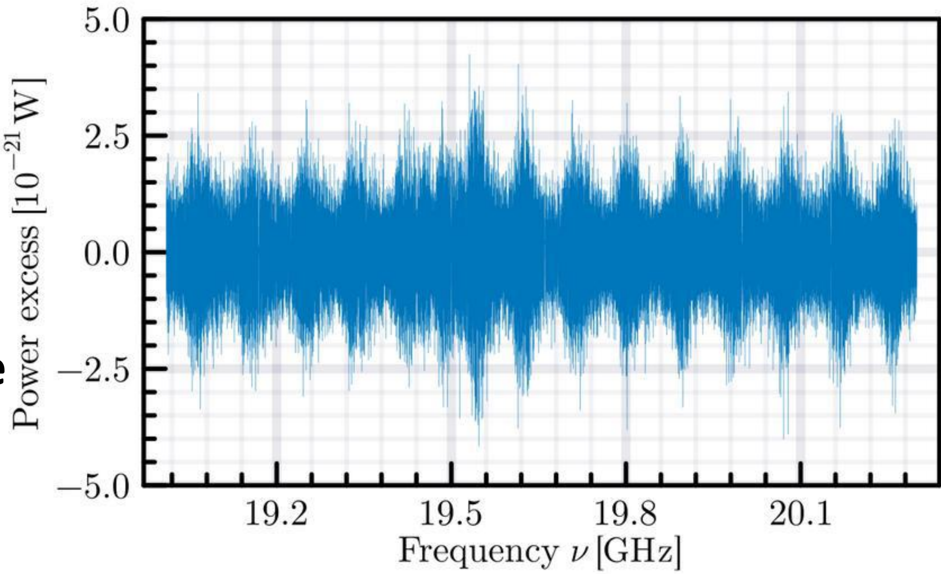
MAgnetized disk and Mirror Axion eXperiment



Measure electric field
Calculate boost factor from measurement

$$\beta^2 = \frac{P_{\mathrm{sig}}}{P_0} = \frac{4\pi^2\epsilon_0\nu^2 F_{\mathrm{RC}}}{8cP_{\mathrm{in}}A}\left|\int \mathrm{d}V\ E_R\right|^2$$

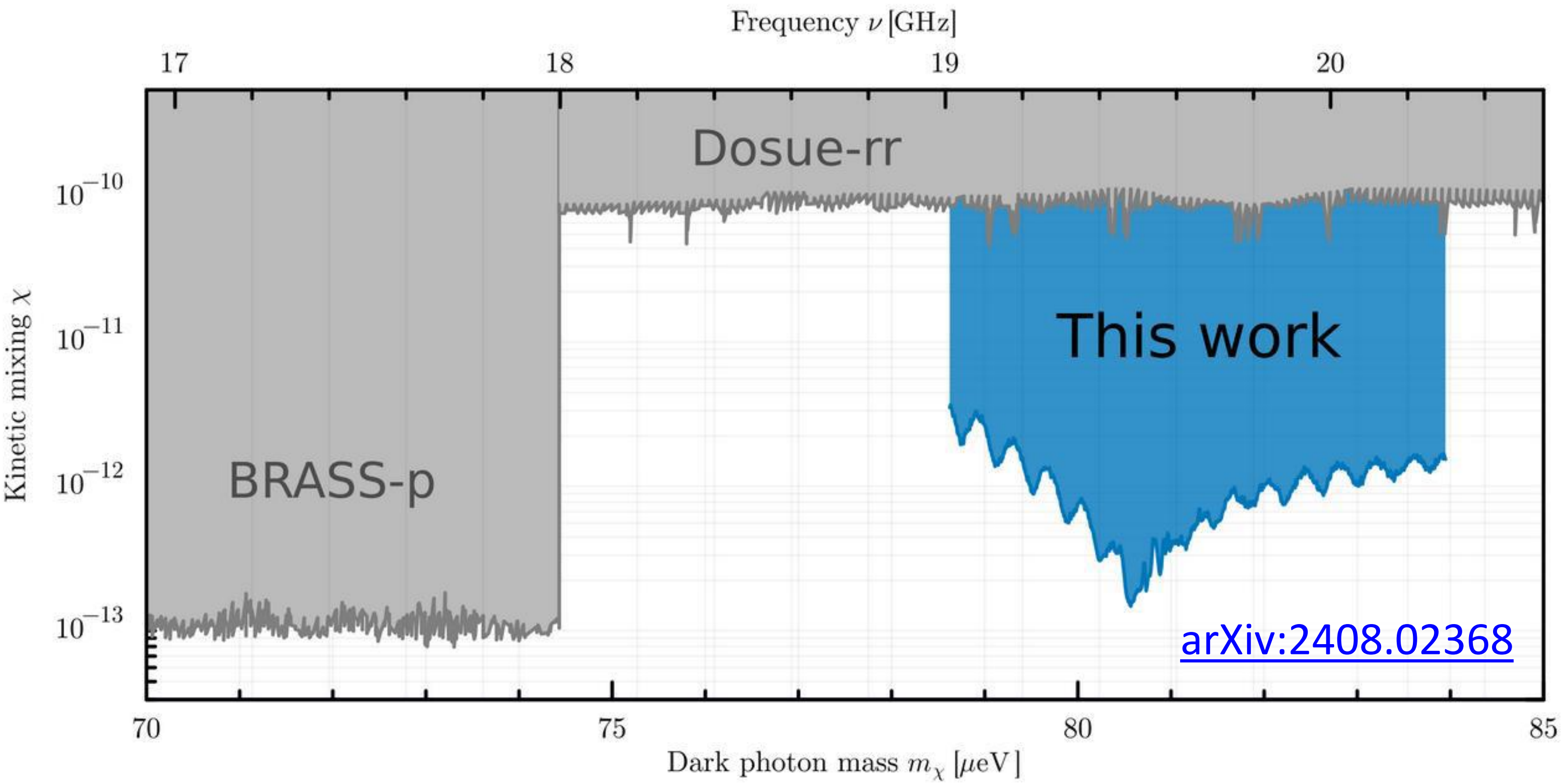
arXiv:2408.02368



- **No signals of unknown origin**
- **Sensitive to dark photon signals ~10^{-21} W**
- **Compute 95%-CI upper limit**
- **Convert to limit on kinematic mixing angle**

MAgnetized disk and Mirror Axion eXperiment

"Simple" 3-disk 300mm prototype booster at room temperature:



Improve existing limits by ~3 orders of magnitude
Resonant and broadband at the same time

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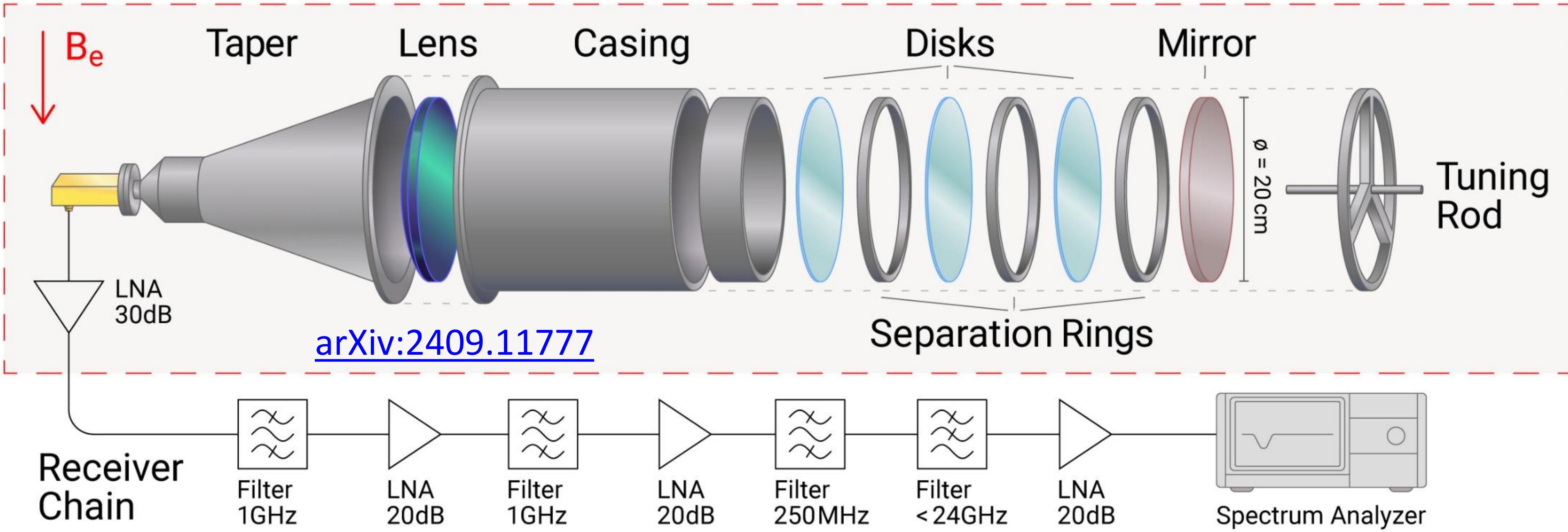
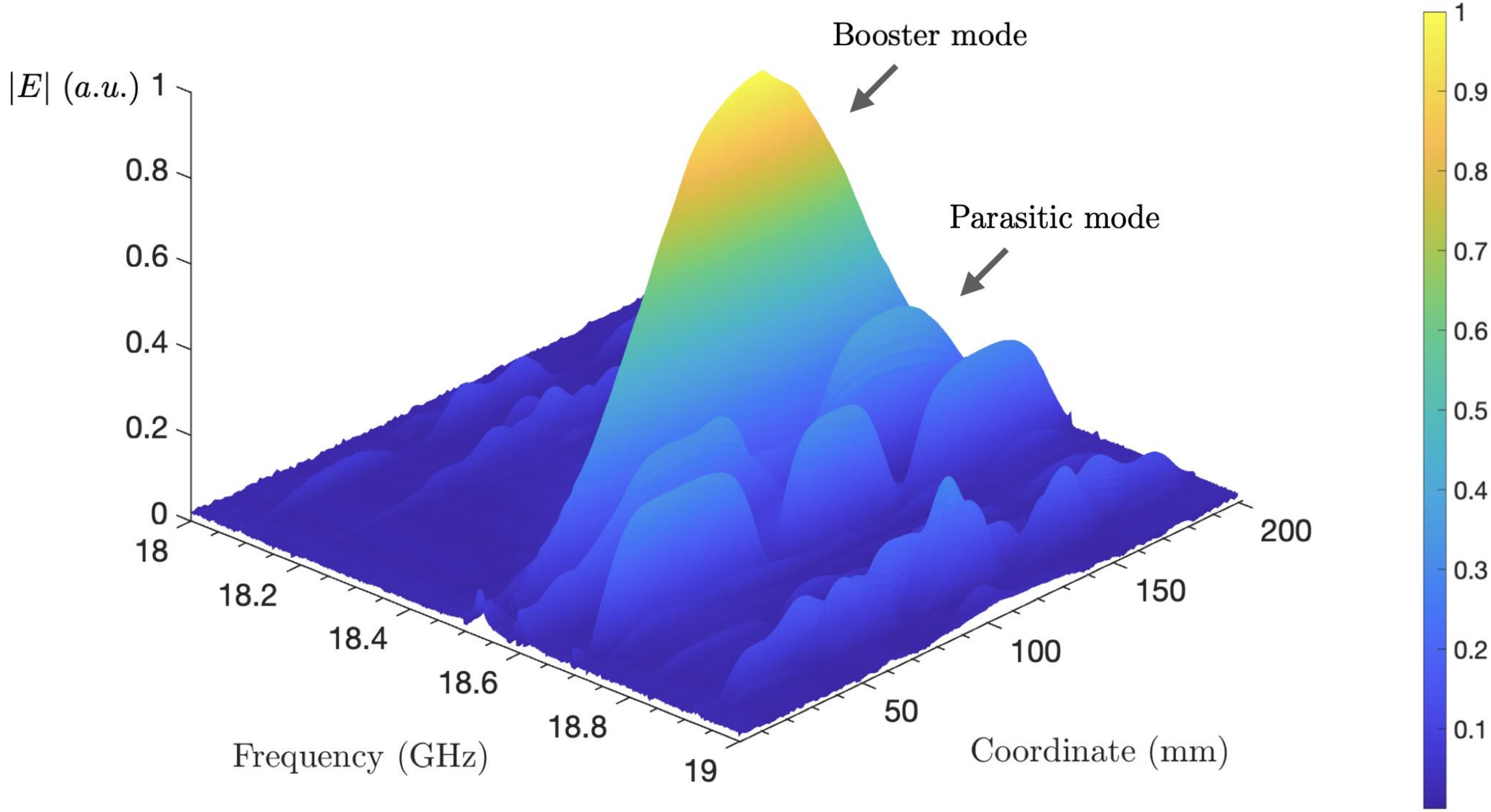
MAgnetized disk and Mirror Axion eXperiment

"Simple" 3-disk 200mm "closed" booster at room temperature:



Closed boundary conditions: finite number of modes
→ Easier to model
→ Boost factor can be determined from 1D model
→ Seperation rings can be exchanged → Tune frequency
→ Use 1.6 T dipole magnet at CERN

MAgnetized disk and Mirror Axion eXperiment



Identification of correct mode vie "bead pull measurements"

arXiv:2409.11777

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MAgnetized disk and Mirror Axion eXperiment

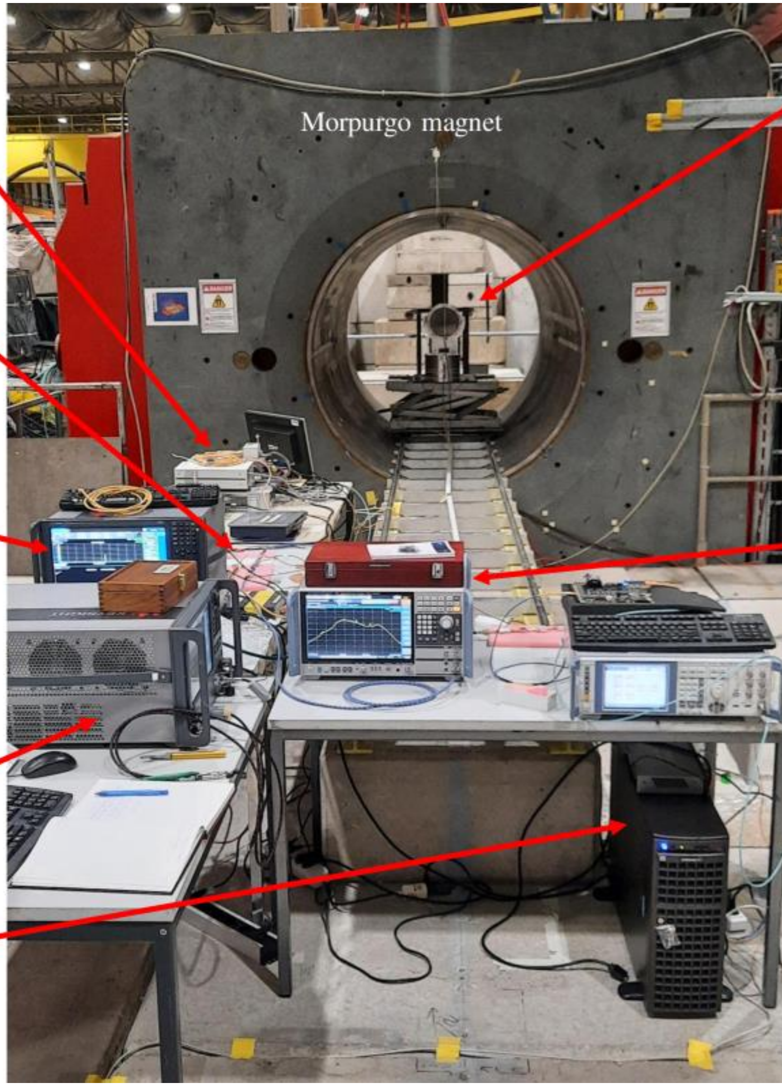
B-field & T - monitors

Receiver chain outside the B-field

Spectrum analyzer for RFI measurement

VNA for S11 calibration measurements

Computer with GPU

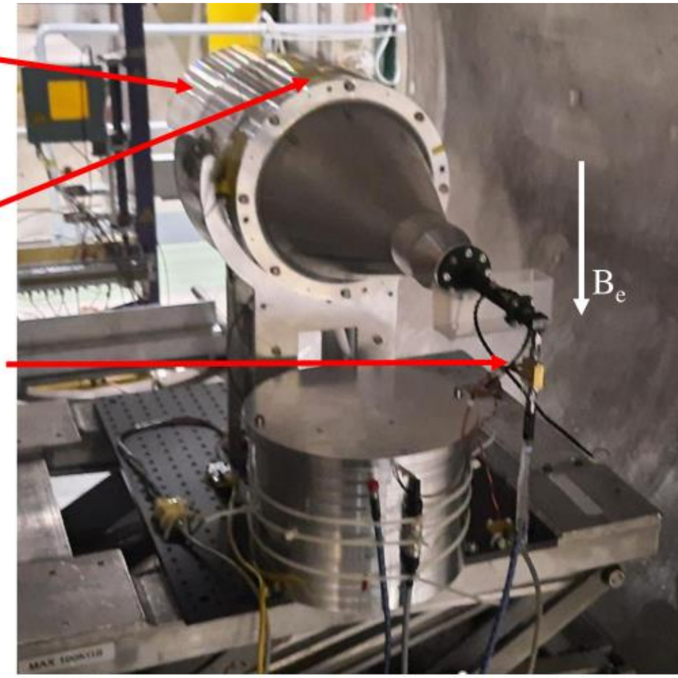


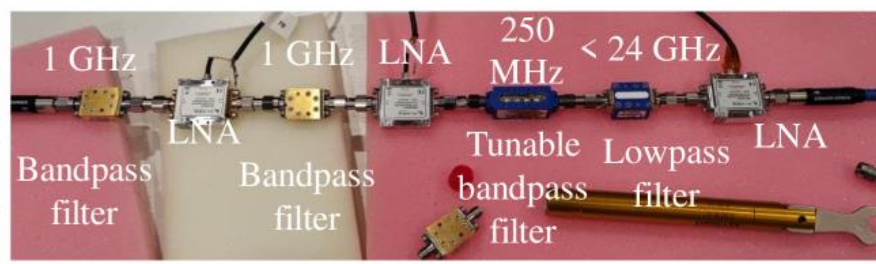
CB200

B-field probe

First LNA with T-sensor attached

R&S spectrum analyzer FSW43

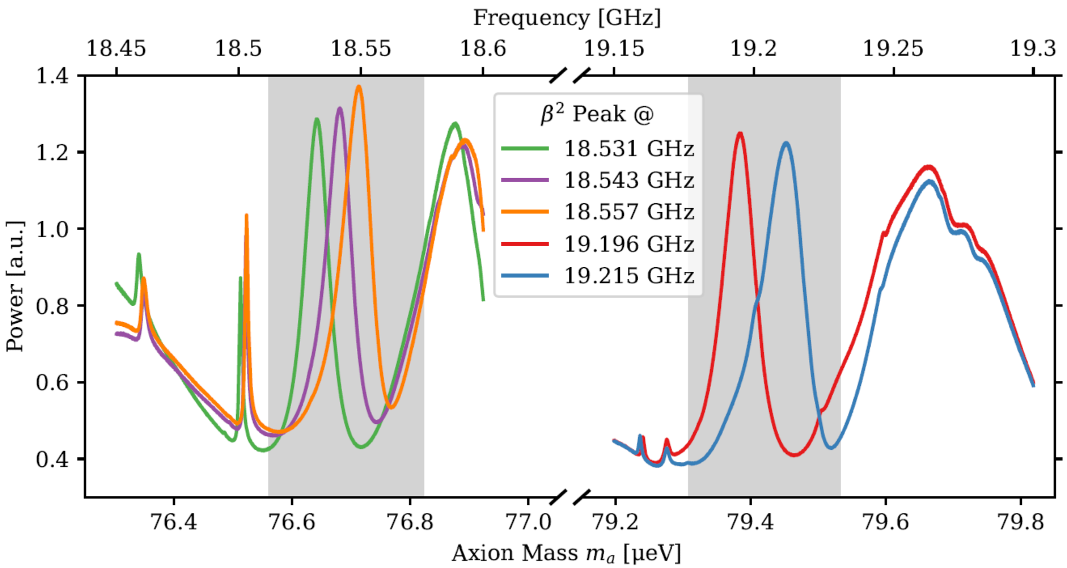




Receiver chain outside the B-field

arXiv: 2409.11777

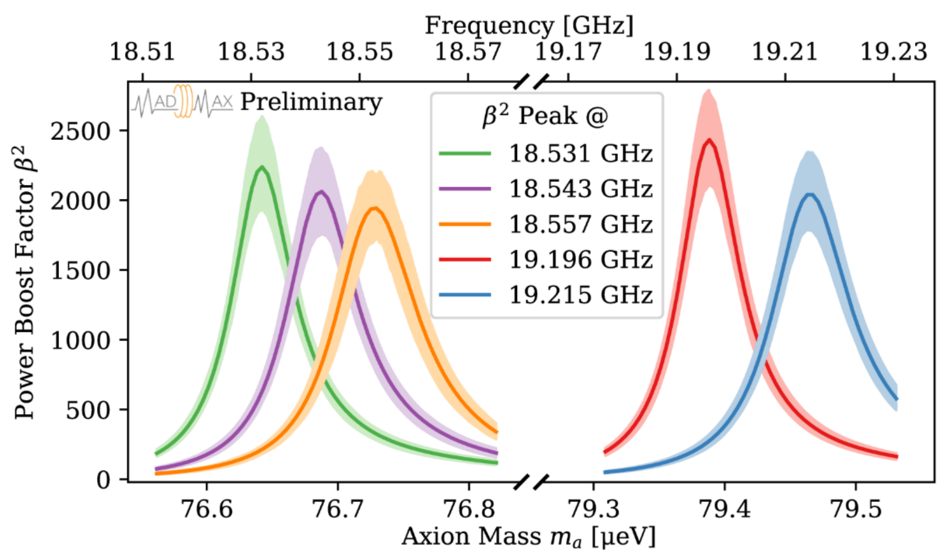
MAgnetized disk and Mirror Axion eXperiment



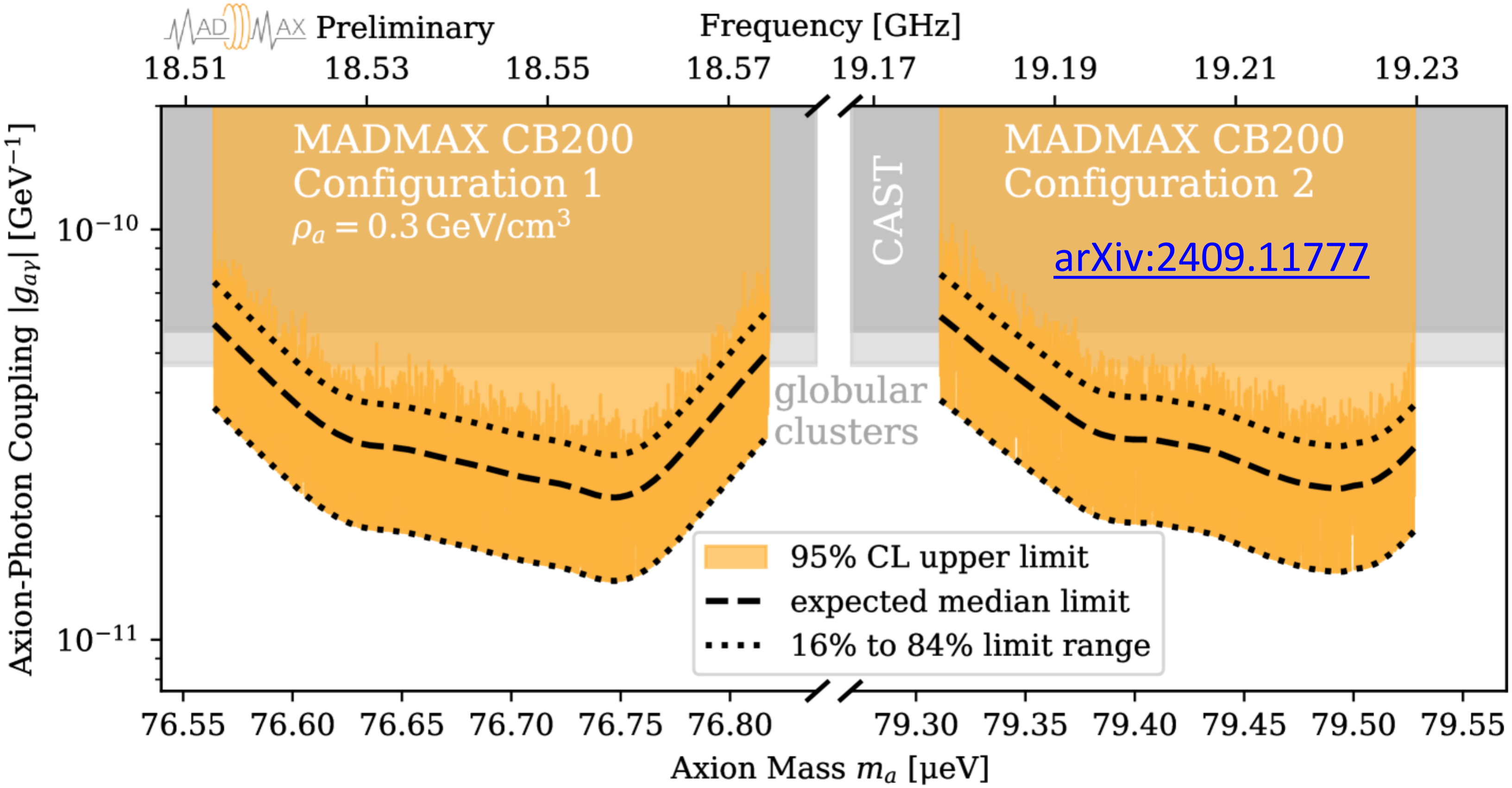
Tuned booster to 5 different frequency bands
RF behavior via reflectivity
Data taking: Measure power spectrum inside magnet

1D modelling of booster RF behavior
→ Calculate boost factors

[arXiv:2409.11777](https://arxiv.org/abs/2409.11777)



MAgnetized disk and Mirror Axion eXperiment

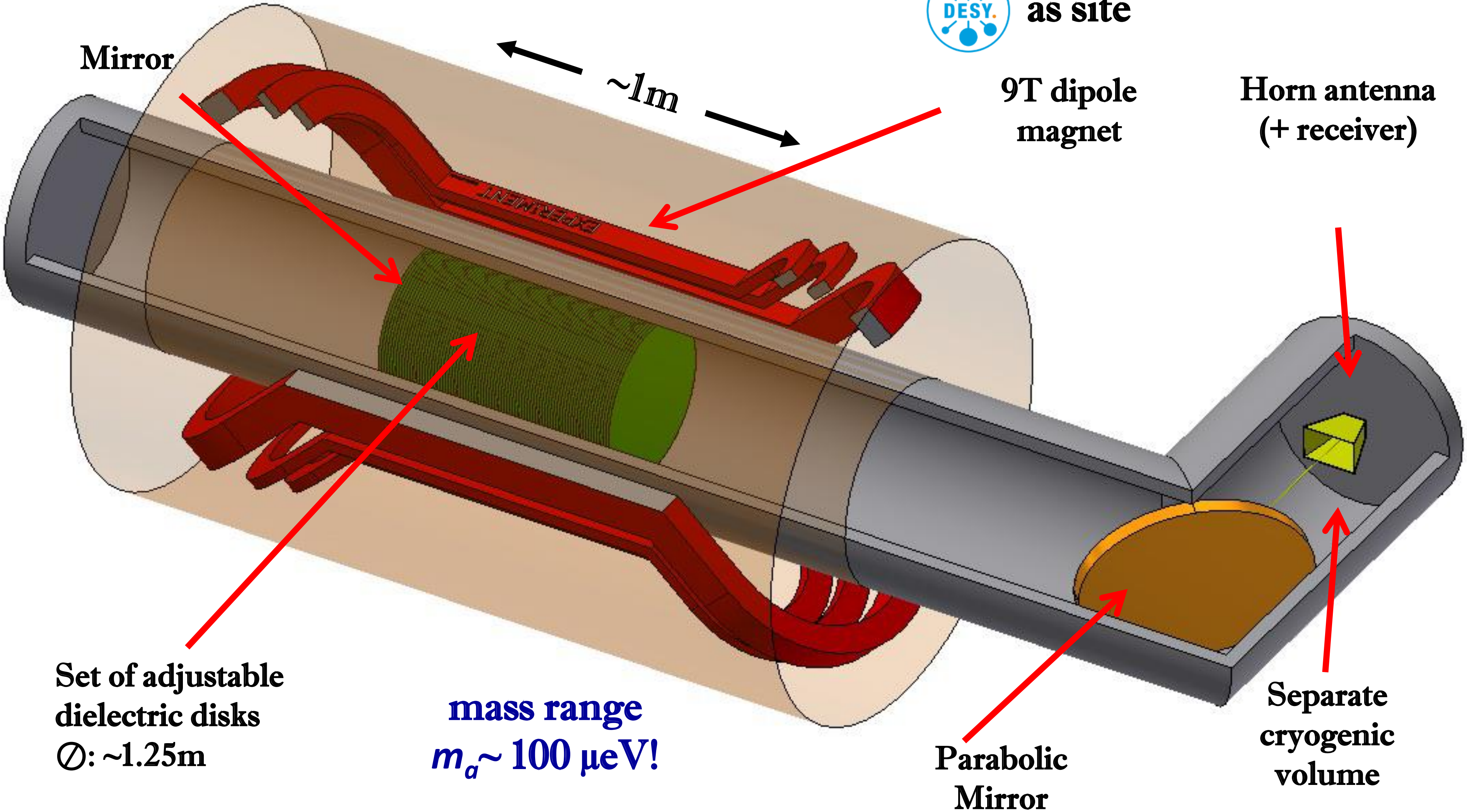


Improve existing limits by factor ~2
Good understanding of boost factor determination: Measuremet + Modelling
→ Proof of concept!

MAgnetized disk and Mirror Axion eXperiment

The European Physical Journal C volume 79, 186 (2019)

DESY as site



mass range

m_a~ 100 μeV!

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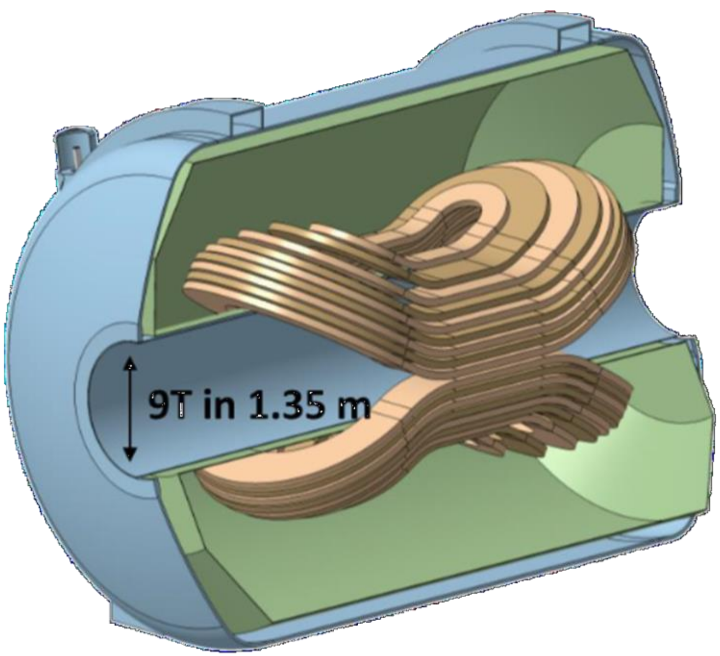
MADMAX MAgnetized disk and Mirror Axion eXperiment

Magnet: large bore (1.35m) high-field (9.1 T) dipole magnet needed
→ Being developed in cooperation with CEA-Itrfu
→ First of its kind!



IEEE TRANSACTIONS ON
APPLIED SUPERCONDUCTIVITY

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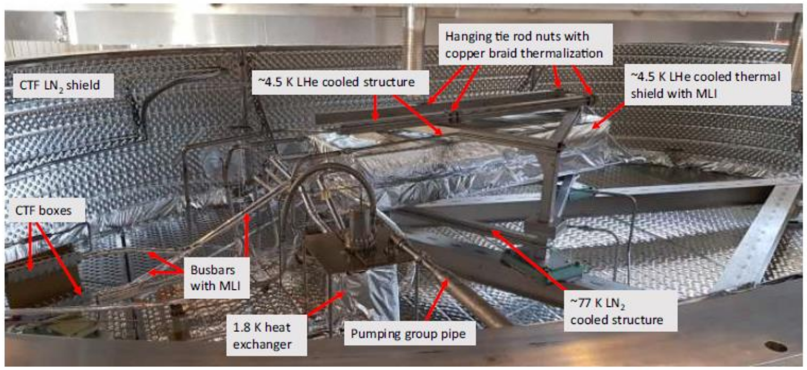
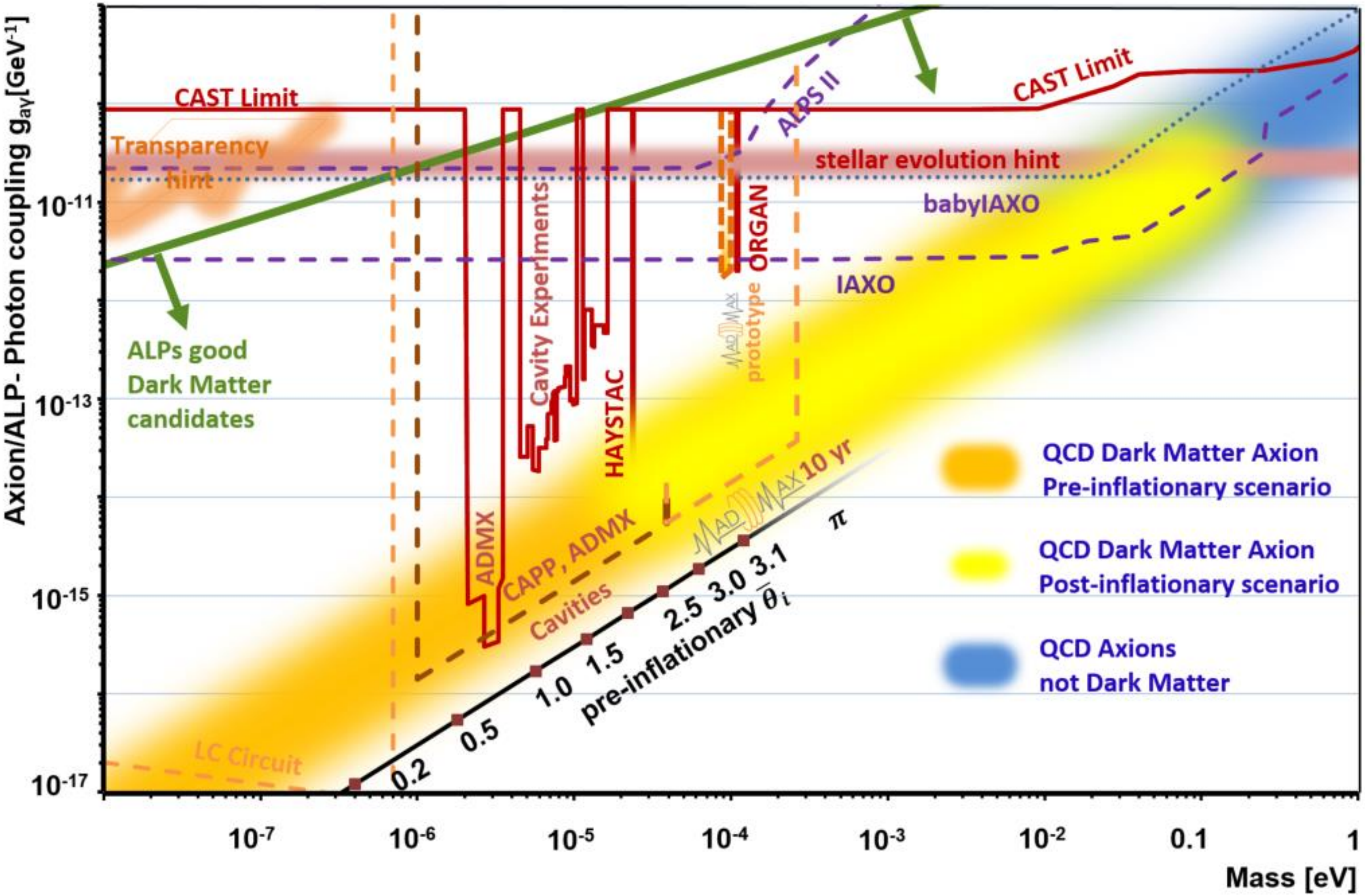
OCTOBER 2023 VOLUME 33 NUMBER 7 ITASE9 (ISSN 1051-8223)



For more, see C. Lorin *et al.*, “Development, Integration, and Test of the MACQU Demo Coil Toward MADMAX Quench Analysis,” Art no. 4500711.

Limits and projections in perspective



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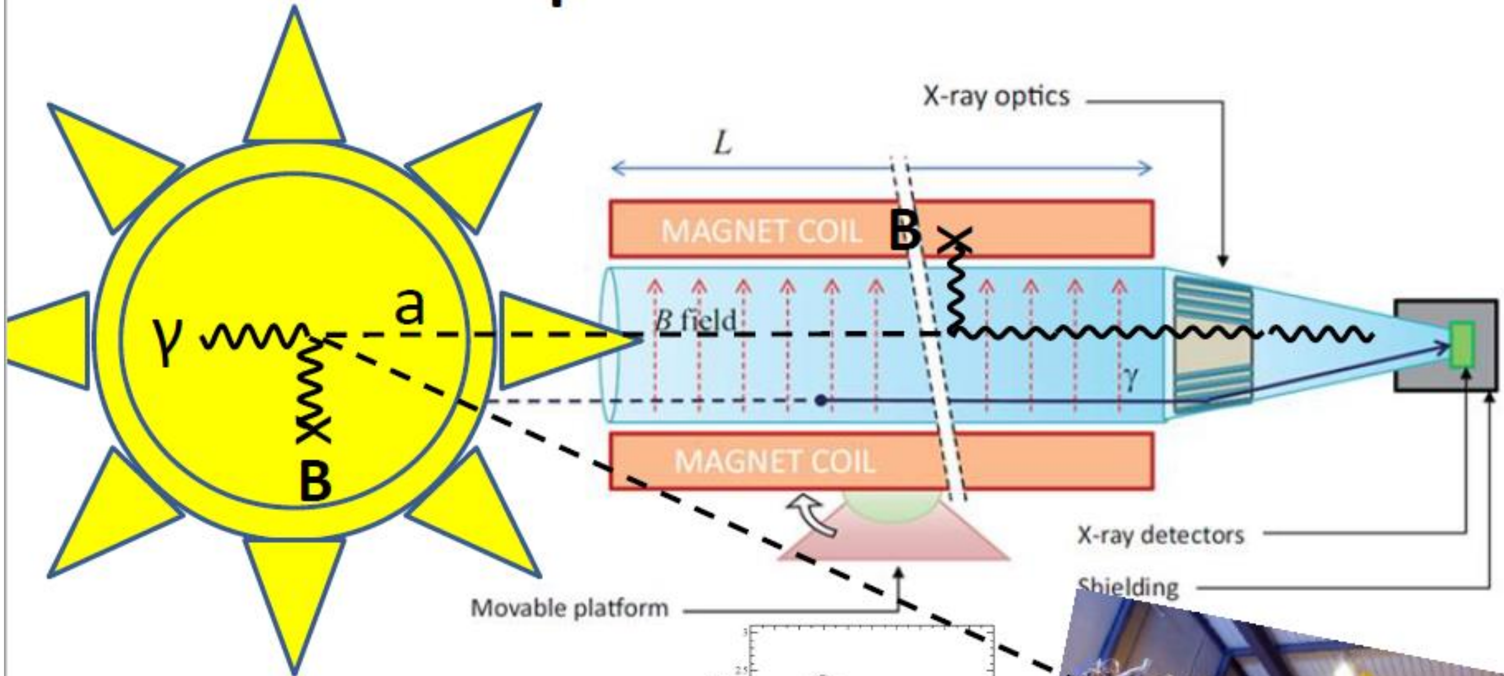
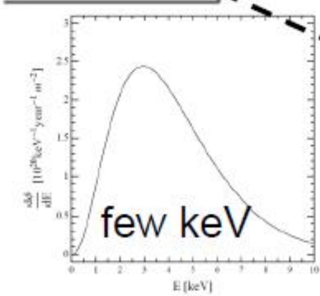
Helioscope: detection of solar axions





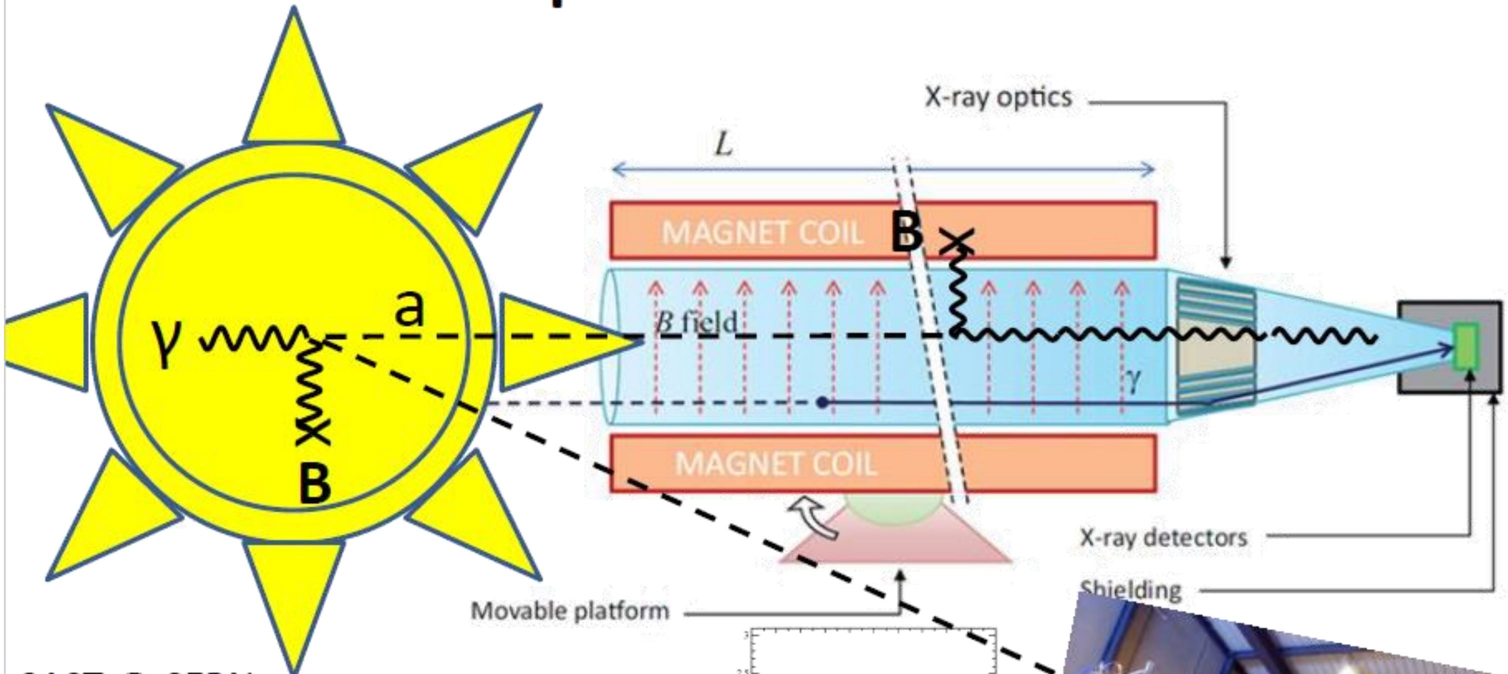
Axion production in sun
Via inverse Primakoff effect
→ Thermal spectrum ~ few keV
→ Detect x-ray photons!

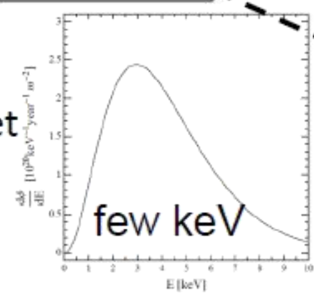
$$\mathcal{P}(a \to \gamma) = 2.6 \times 10^{-17} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 \mathcal{F}(qL),$$

$$\mathcal{F} = \left(\frac{2}{qL}\right)^2 \sin^2\left(\frac{qL}{2}\right) \quad q = k_\gamma - k_a \sim m_a^2/2\omega$$

→ Need to point magnet and detector towards sun!

Helioscope: detection of solar axions





CAST @ CERN:
Decommissioned LHC 9T Dipole magnet pointed towards sun.
Detector:
Maximize collection ares (x-ray optic)
Minimize detectors size (low-background)
→ IAXO sensitivity to
QCD Axions for m_a~100 meV
→ $g_{a\gamma\gamma} < 7 \cdot 10^{-11}$

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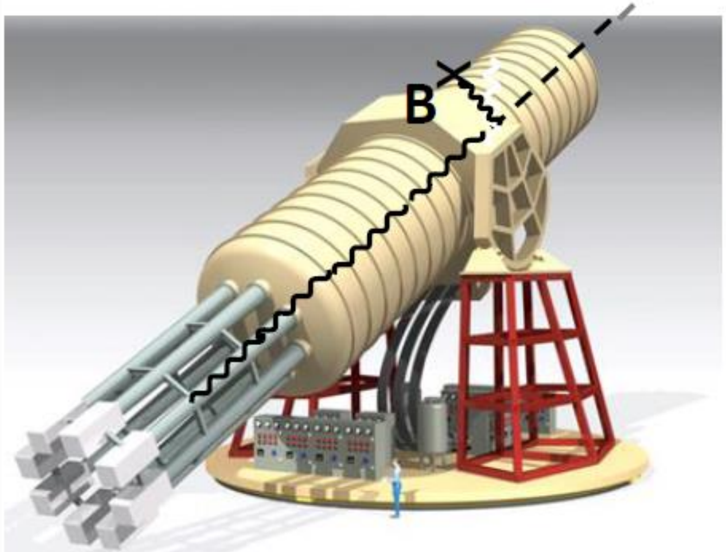
Helioscope: detection of solar axions

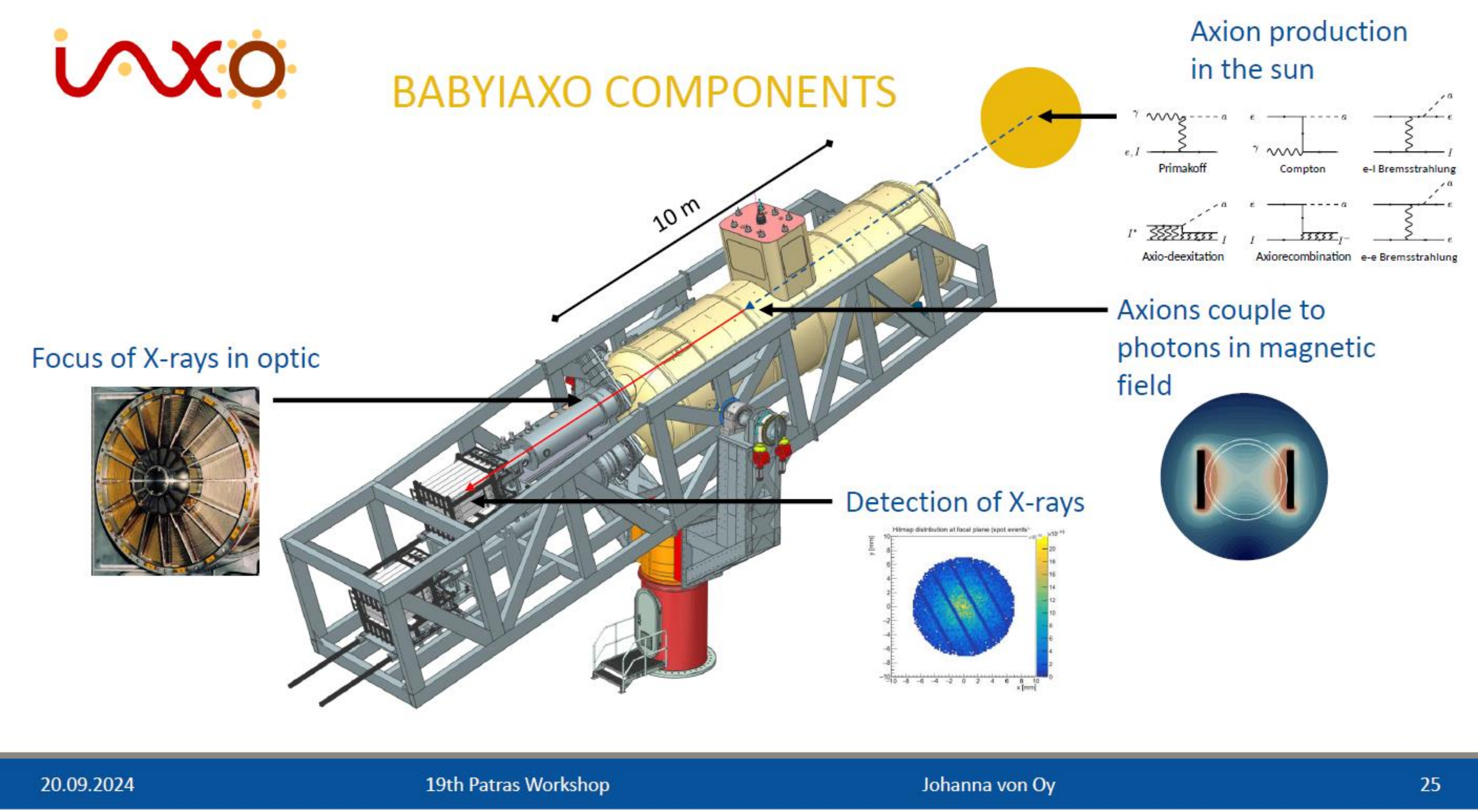
Next generation: IAXO

CAST, Magnets for Colliders,
x-ray optics for satellites,
Low-Background Detectors.

- Toroidal 8-coil magnet ~6T L=~20m, 600mm bore,
- Locations: probably DESY
- sensitivity to axions with m_a ~10meV

$$g_{a\gamma\gamma} \sim 3 \cdot 10^{-13}$$




BABYIAXO COMPONENTS
10 m
Axion production in the sun
Primakoff
Compton
e-I Bremsstrahlung
Axio-deexitation
Axiorecombination
e-e Bremsstrahlung
Axions couple to photons in magnetic field
Focus of X-rays in optic
Detection of X-rays
20.09.2024
19th Patras Workshop
Johanna von Oy
25

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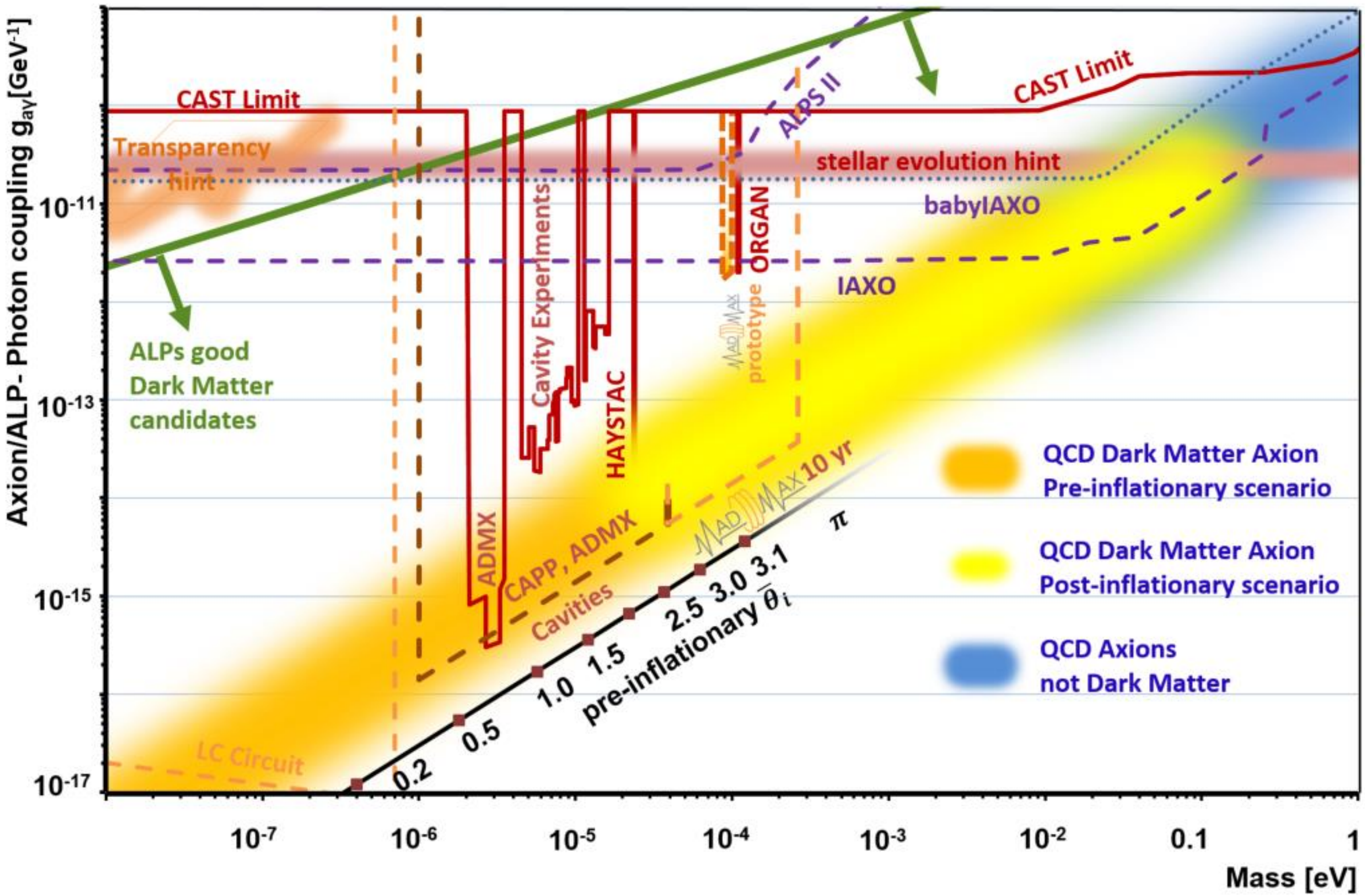

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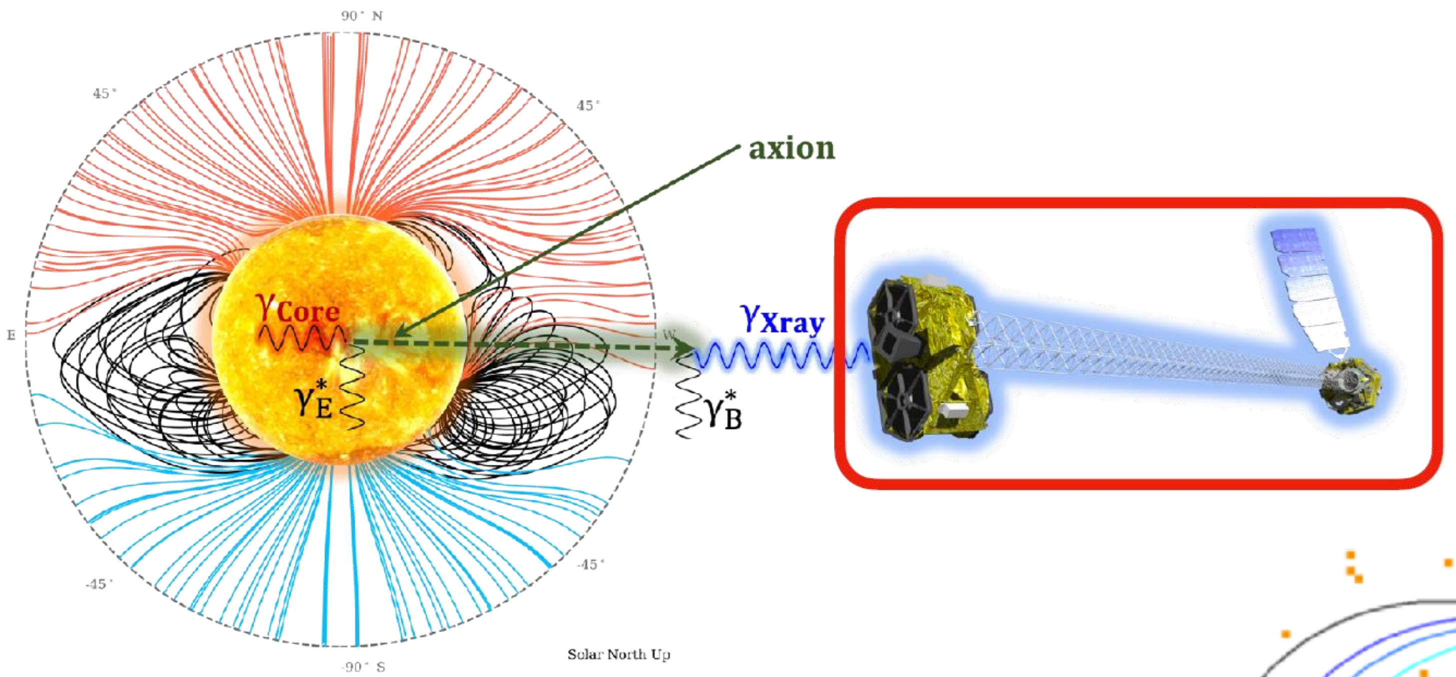
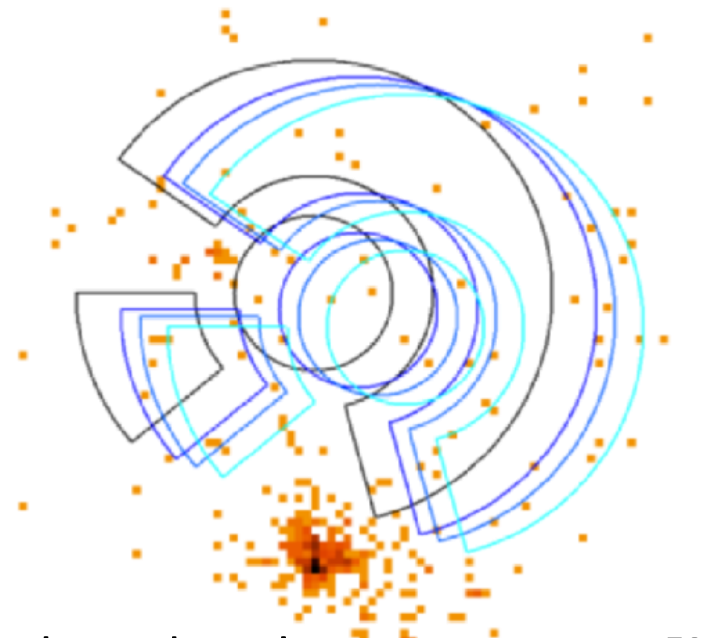
NUSTAR as axion telescope





Observed center of solar disk for 6.4 hours during 2020 solar minimum in 2020
Signal region: $r < 0.1\ R_\odot$
Bkg. Region: $0.15\ R_\odot < r < 0.3\ R_\odot$
Remove wedges containing X-ray bright points

E. Todarelli at Partas workshop 2024

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NUSTAR as axion telescope

E. Todarelli at Partas workshop 2024

Quiet Sun’s Magnetic Field

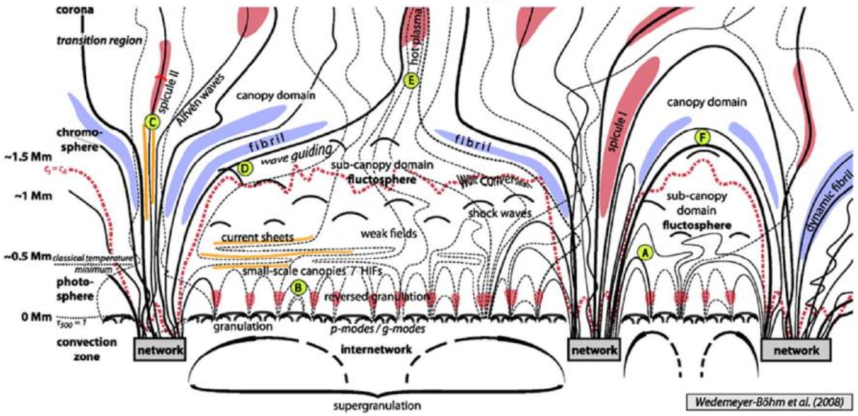
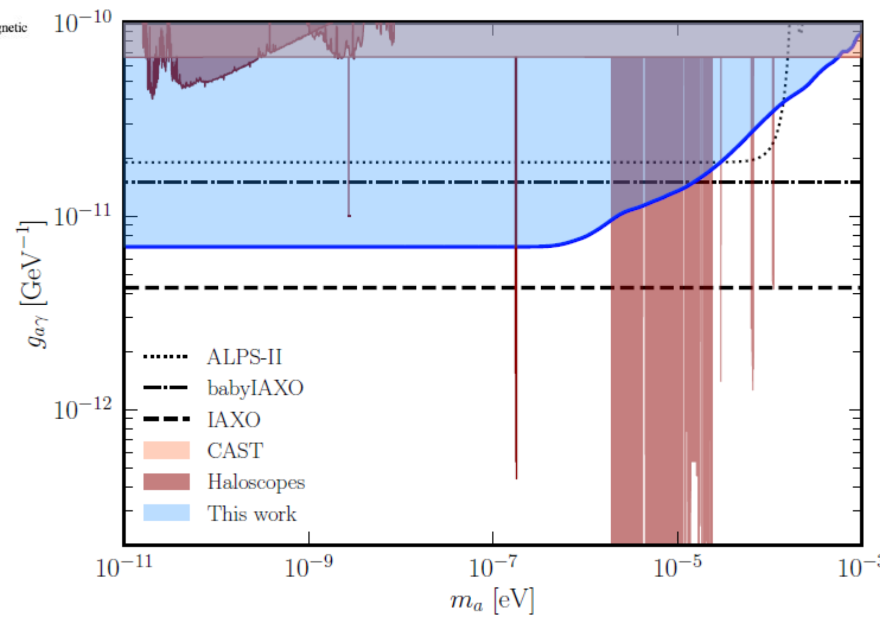


Fig. 16 Schematic, simplified structure of the lower quiet Sun atmosphere (dimensions not to scale): The *solid lines* represent magnetic field lines that form the magnetic

Axions produced in sun
Convert axions to photons
in solar B-field

Very competitive limits
Limit depends on solar B-model

arXiv:2407.03828



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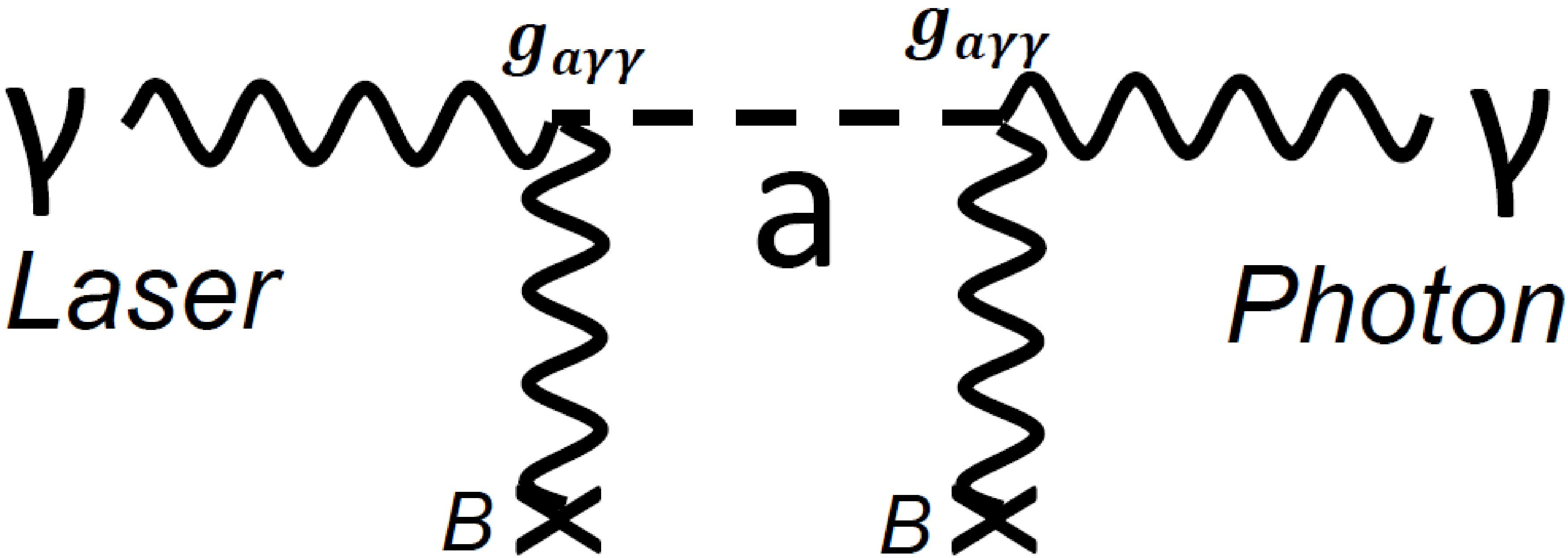
Lab experiments:

photon → axion → photon → Detector

→ No model uncertainty by astrophysics or cosmology!

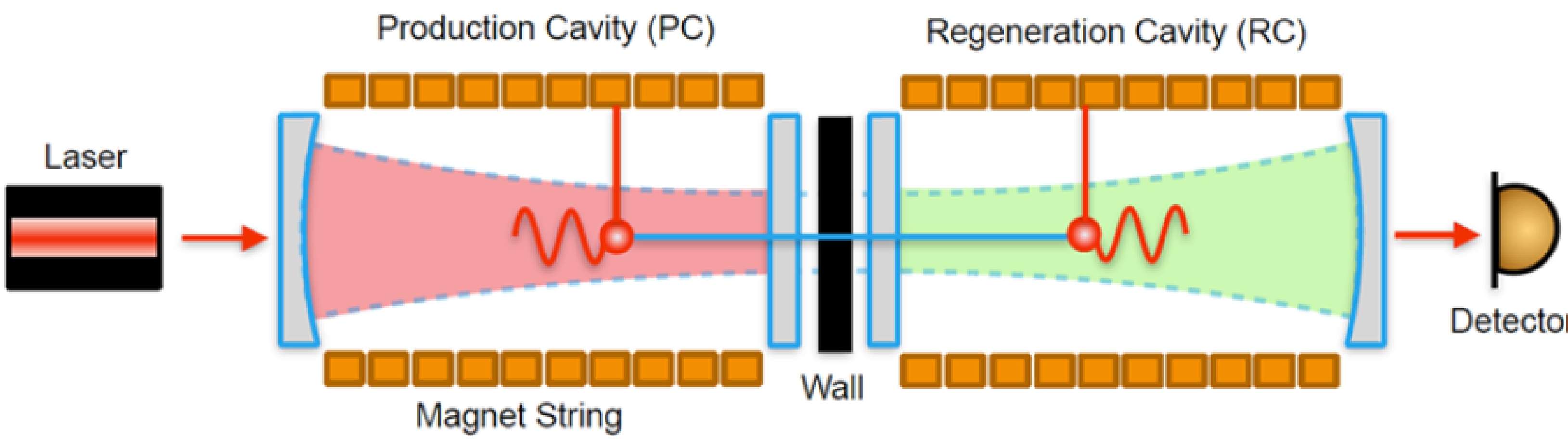
→ Axions with momentum



$$P_{\gamma \to ALP \to \gamma} = 6 \cdot 10^{-38}\, \mathcal{F}_{PC}\mathcal{F}_{RC} \cdot \left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\right)^{4} \left(\frac{B}{1T}\right)^{4} \left(\frac{l}{10m}\right)^{4}$$

Lab experiments:

Light shining through the Wall



$$P_{\gamma\rightarrow ALP\rightarrow\gamma} = 6\cdot 10^{-38}\,\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\right)^4\left(\frac{B}{1T}\right)^4\left(\frac{l}{10m}\right)^4$$

- Maximize magnet length
- Optical generation and regenaration cavities with high Finesse: „recycle light"
- Optical cavity technology from gravitational wave detectors!

ALPS II at DESY

- **2x strings of 12 HERA dipole magnets: 5.3 T, 106 m**
- **Cryogenic infrastructure**
- **High power laser (HPL) system (30 W)**
- **World record storage time: 7.17 +- 0.01 ms**
- **Heterodyne detection system (Δf ~ 1 μHz)**
- **3 clean rooms at the different stations of the experiment**

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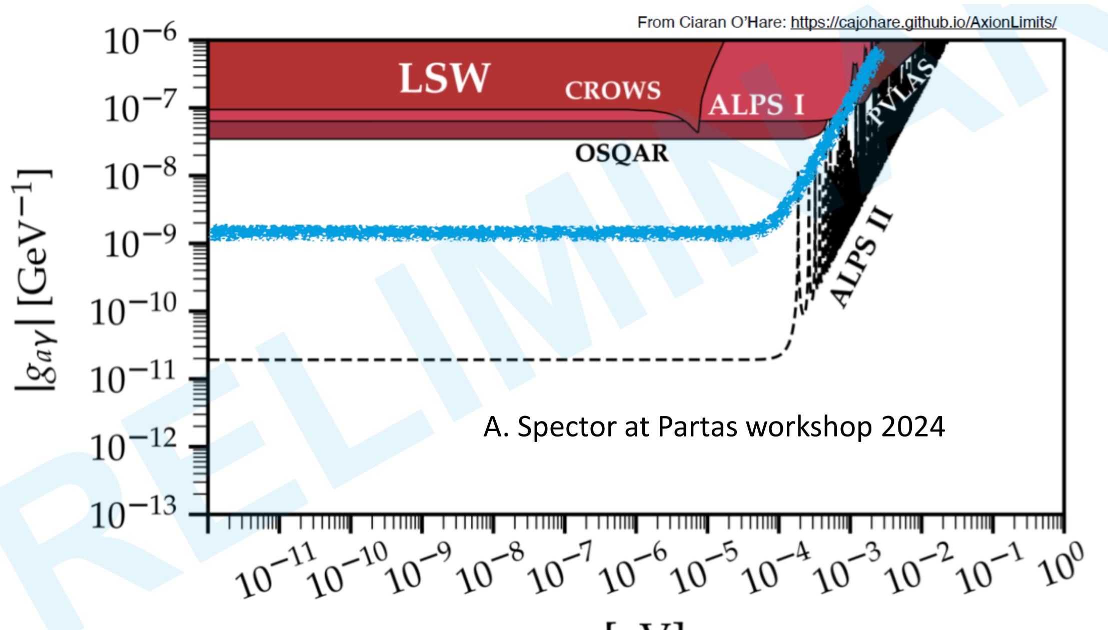
ALPS II at DESY

First data since Feb. 2024
Improve previous limits by > order of mag.



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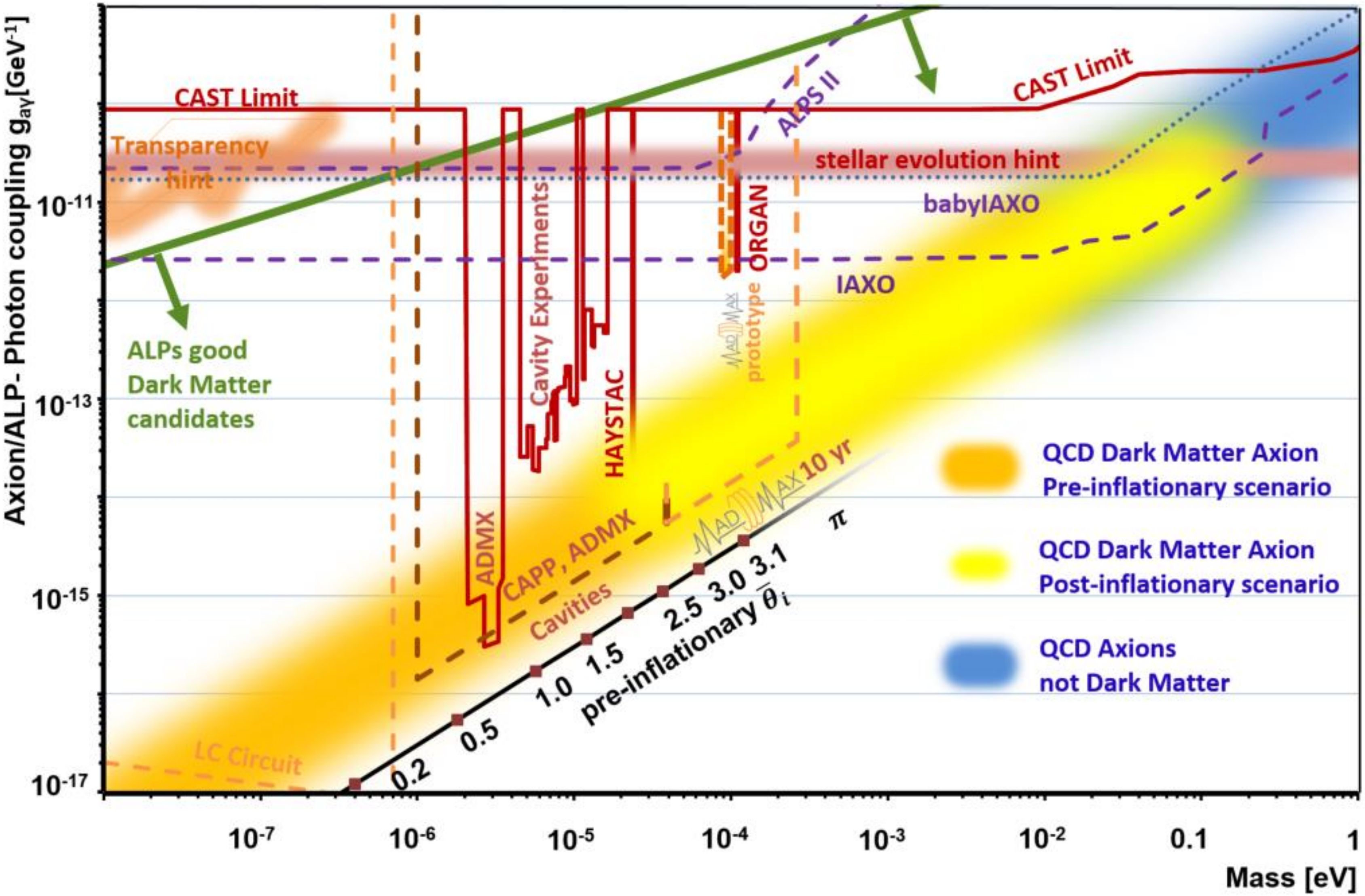
Limits and projections in perspective



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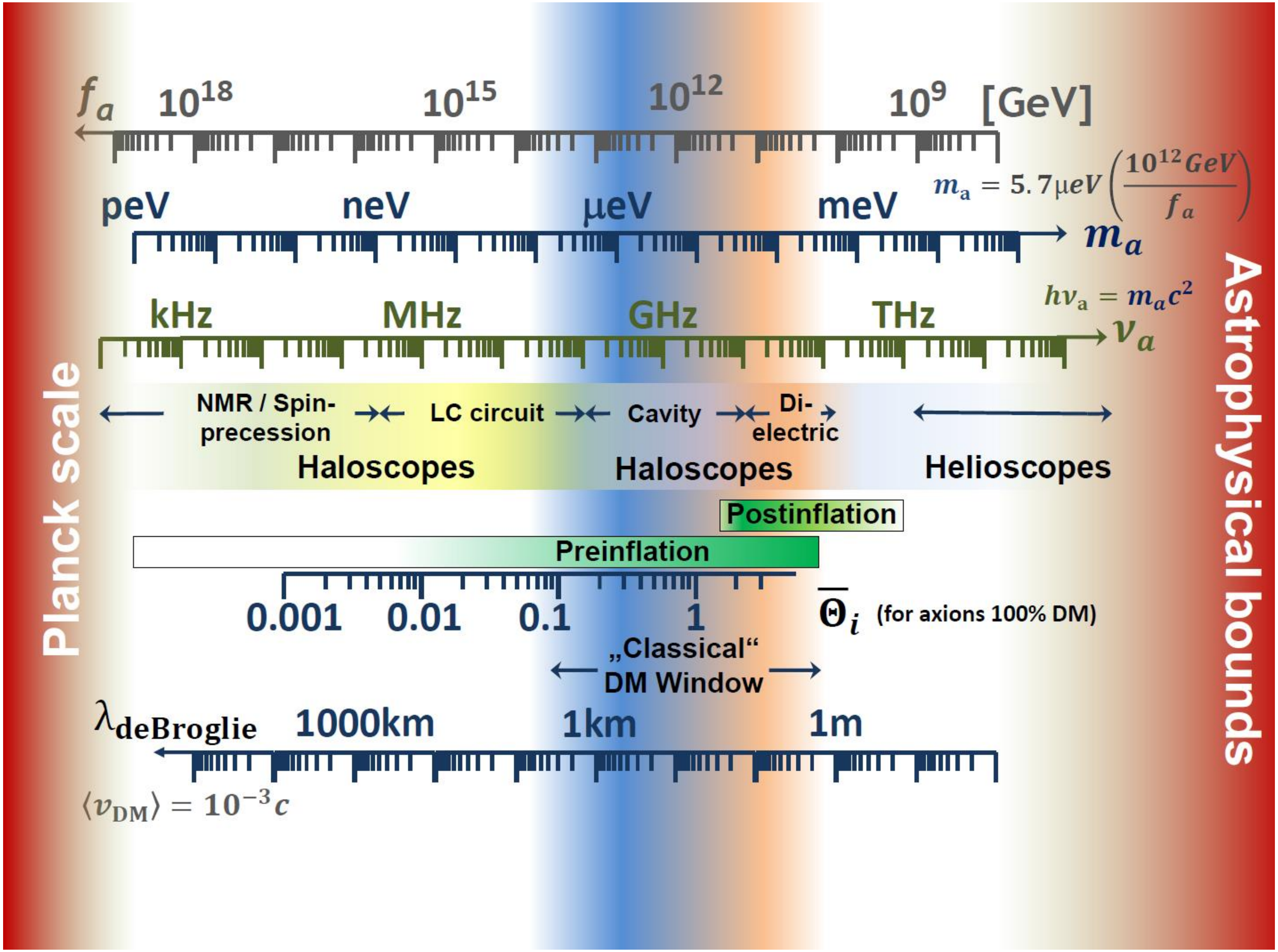

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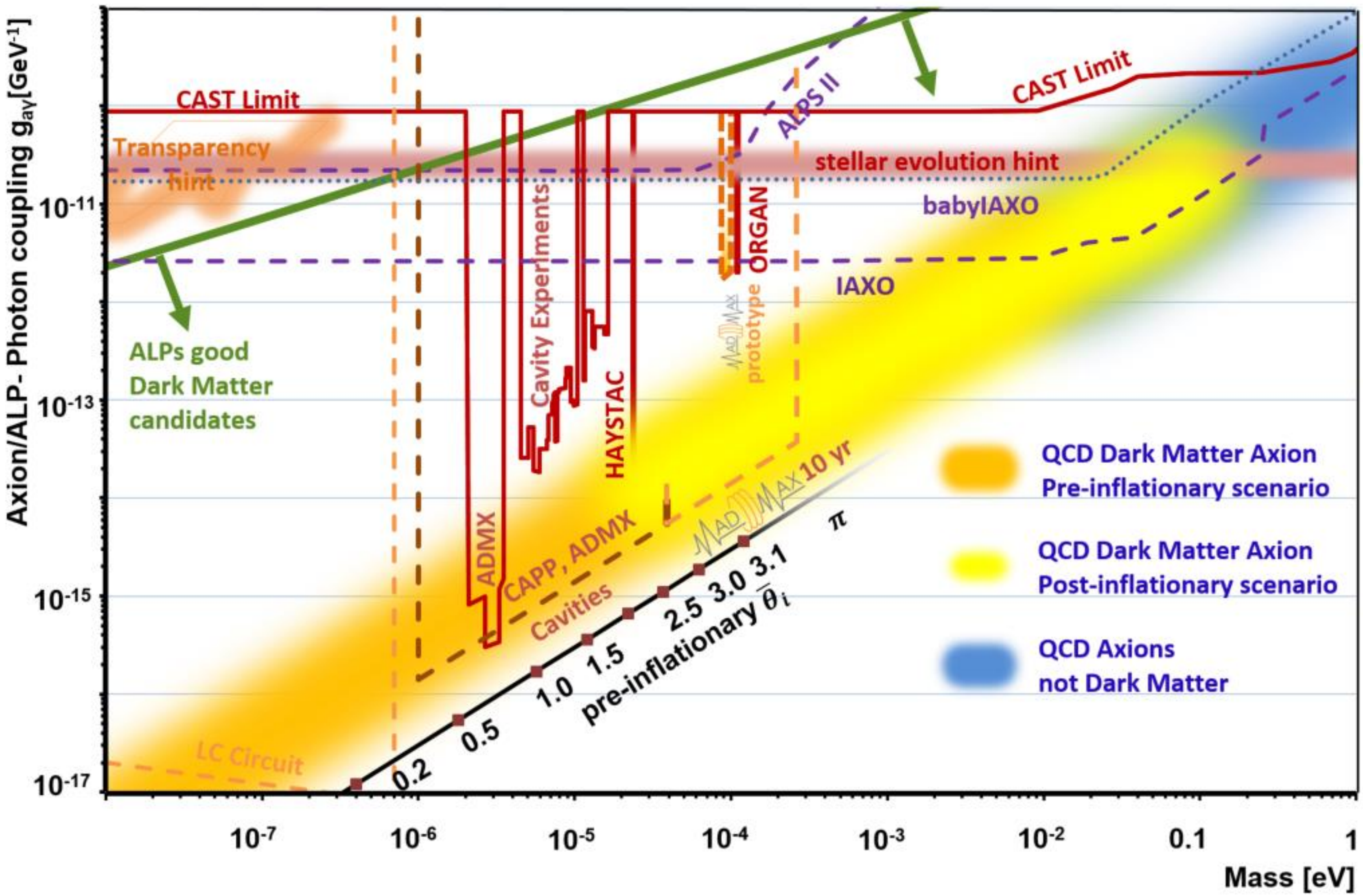
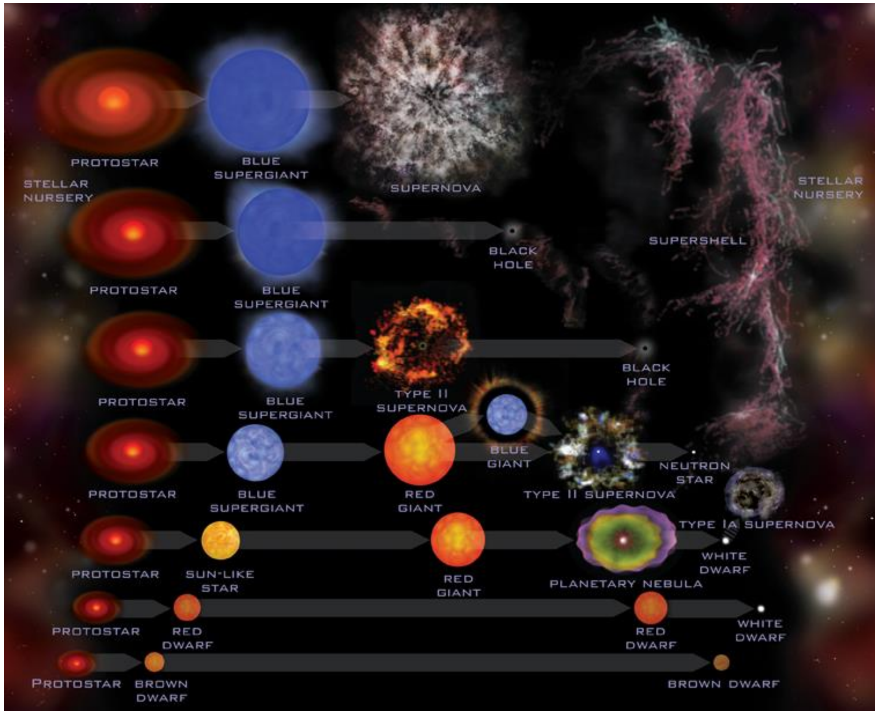


Limits on axion coupling from stellar evolution:



axion couplings with nuclei/electrons/gammas In “hot media/plasmas”:

→ emission of axions

→ Additional cooling of stellar cores, supernovae (progenitors), pulsars, … due to axion emission

→ Stellar evolution influenced depending on coupling strengths

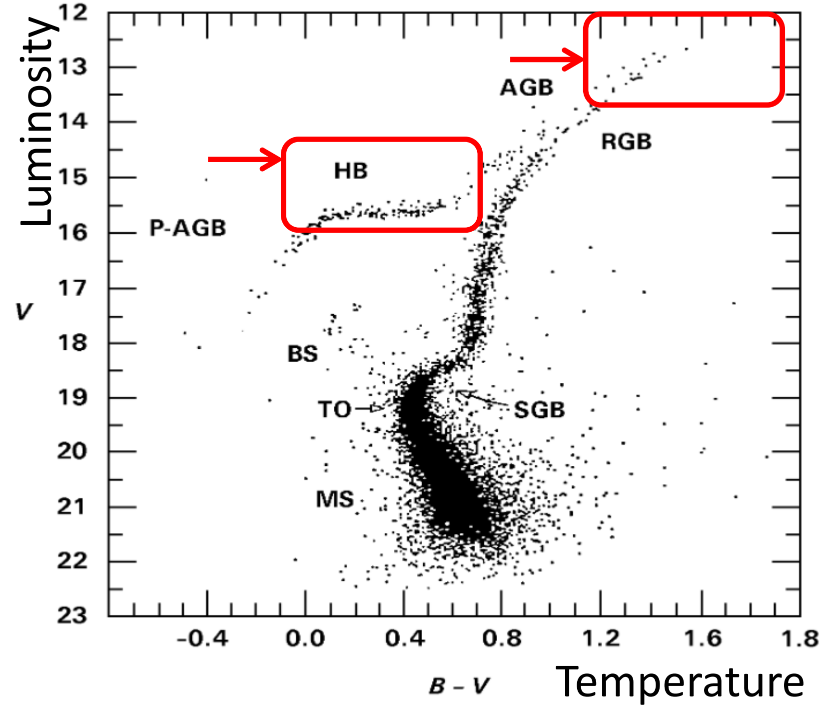
→ Set limits on coupling strength → f_a

Limits from stellar evolution:

Hertzsprung Russel diagram

Count population
→ Information on duration of given stage of evolution
→ Density depends on cooling rate

→ For example tip of red giant branch

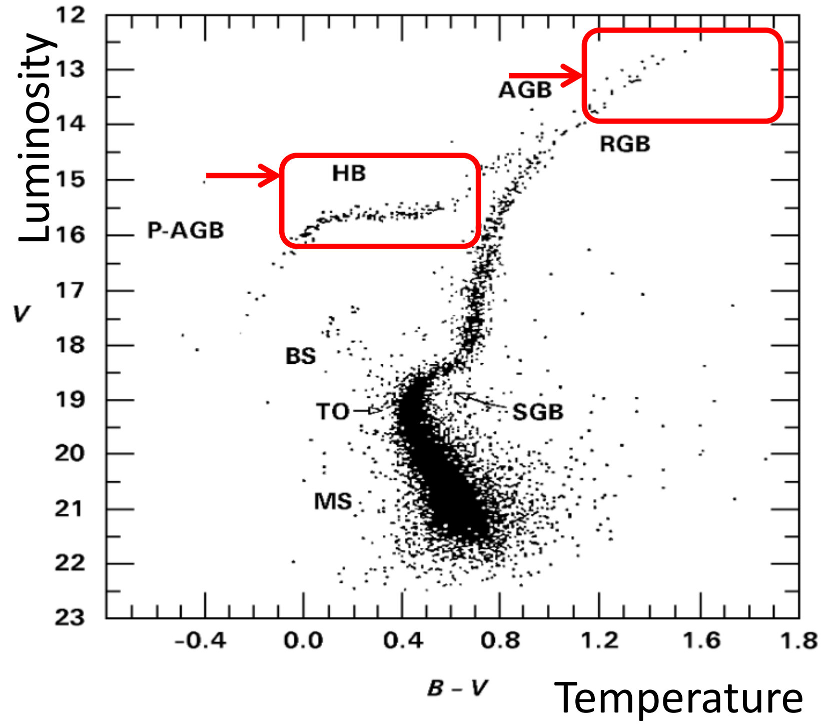


Primakoff energy loss rate proportional to $\frac{T^7}{\rho}$
→ axion emission rate depends on sequence in stellar evolution
Globular cluster: Gravitationally bound system of stars that formed at the same time:

Limits from stellar evolution:

Horizontal branch stars (HB): Helium burning stars after **Red Giant Branch** (RGB) stage: **very hot**
→ Axion couplings could significantly shorten lifetime

Count number of stars in HB and compare to RGB expectations based on standard cooling.



Limits from stellar evolution:

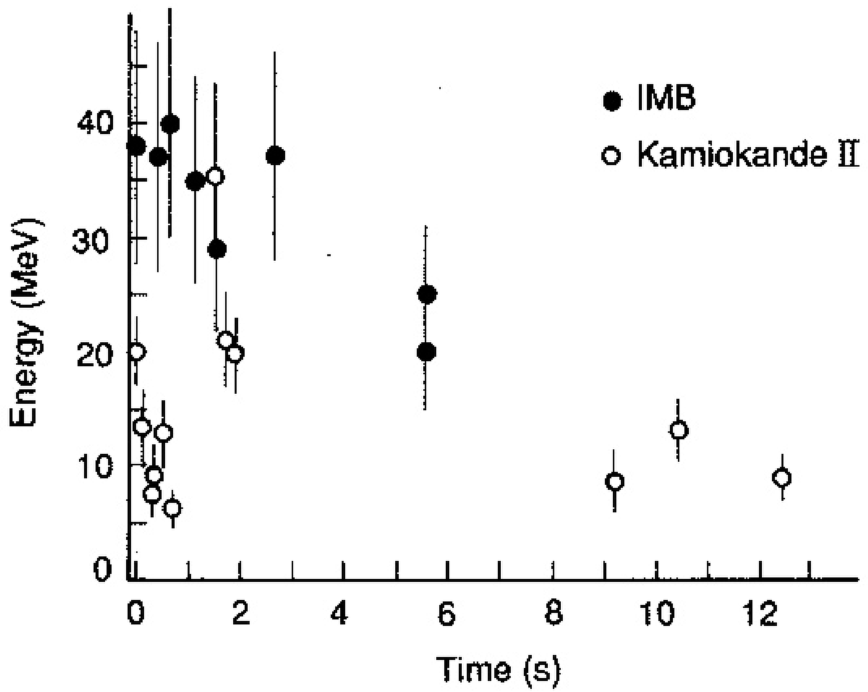
Most sensitive analysis (Raffelt, MPP): **Length of neutrino signal from SN87a:**

Core collapse SN: creation of a proto-neutron start with short life time.

During life time of neutron star with T~10MeV:
Neutrino emission (almost 20 neutrinos observed during several seconds)
Life time of neutron star would be shortened by emission of axions due to "**axion nuclear Bremsstrahlung**":

→ Length of neutrino burst:
limit on axion Bremsstrahlung

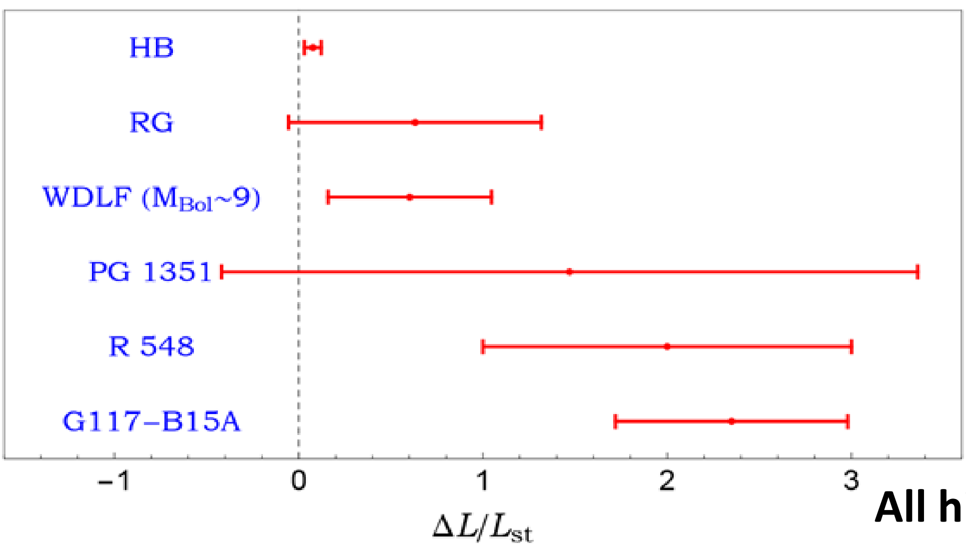
→ $f_a > 10^8$ GeV → $m_a < 1\ eV$



Hints from stellar evolution:

Some systems show cooling anomalies, i.e. more energy loss than expected:

Pulsating white dwarf G117-B15A with P=215s:
Frequency is decreasing due to cooling:
Expected: $\dot{P}_{th} = (2 - 6) \cdot 10^{-15} s s^{-1}$
Measured: $\dot{P}_{obs} = (12.0 \pm 3.5) \cdot 10^{-15} s s^{-1}$
(two more variable white dwarfs with slightly too efficient cooling found: R548, PG1351)
Possible loss mechanism in white dwarfs: "axion electron Bremsstrahlung"



← Horizontâl branch
← Red Giant cooling
← White Dwarf Luminosity Function
number of white dwarfs per luminosity bin

White Dwarf pulsating frequency

All hints together: If interpreted as ALPs cooling:

$$g_{a\gamma\gamma} \sim 5 \cdot 10^{-11} GeV^{-1}$$

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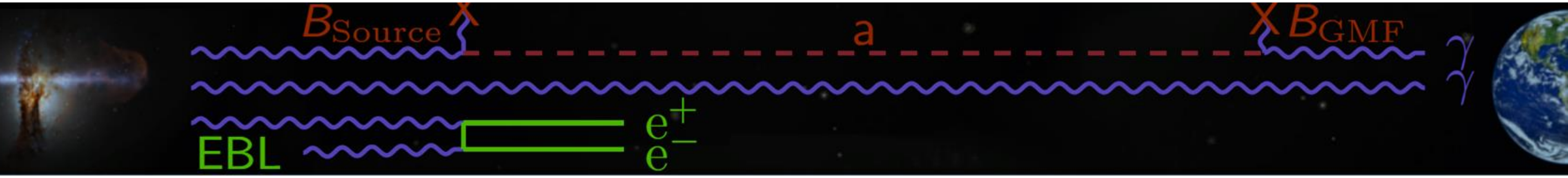
Hints from transparency of the universe:



Some astrophysical sources can emit very high energy gamma rays $\gg 1\,TeV$.
Especially for blazars (AGN with jet pointing towards earth):
can be detected on earth using Cherenkov telescopes → MAGIC, HESS, CTA

Photons can interact with infrared band of Extra Galactic Background Light (EBL) resulting from stars, interstellar dust emission, etc.

→ High energy gamma rays are absorbed (pair creation)
→ Optical depth τ not zero
→ Flux is attenuated

$$\Phi_{obs}(E_\gamma) = \Phi_s(E_\gamma) \cdot e^{-\tau(E_\gamma, z_s)}$$

Φ_s and Φ_{obs}: fluxes emitted by source and observed at earth, z_s is the red shift of the source .

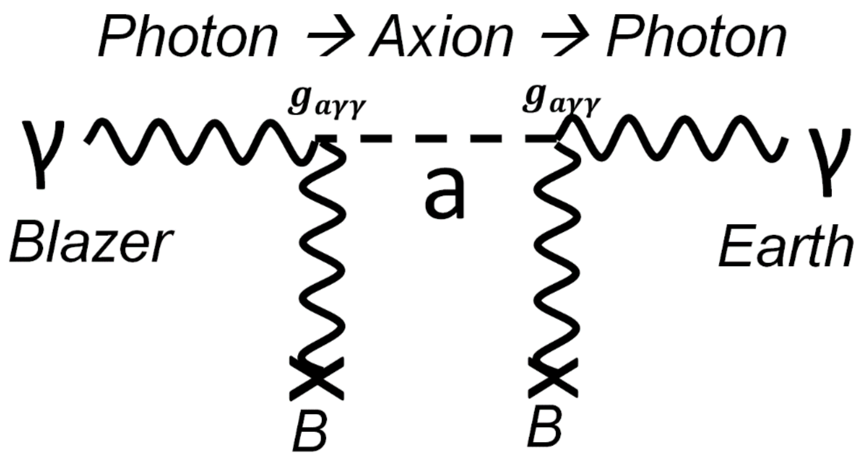
Hints from transparency of the universe:

Transparency is given by:

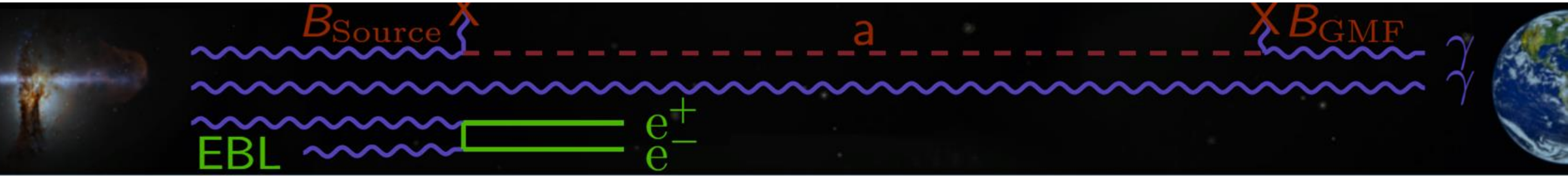
$$\tau(E_\gamma, z_s) = \int_0^{z_s} \int_{E_{th}}^{\infty} \sigma_{\gamma\gamma}(E_\gamma, E) \cdot n_{EBL}(z, E)\; dE\; dl(z)$$

with $l(z)$ the path of the photons, taking into consideration cosmological evolution (expansion), $n_{EBL}(z, E)$ the EBL density at redshift z and energy E and $\sigma_{\gamma\gamma}(E_\gamma, E)$ the angle averaged pair creation cross section.

Photons can evade EBL scattering by: $\gamma \rightarrow ALP \rightarrow \gamma$
Photon to ALPs conversion in magnetic field of source or intergalactic medium



Hints from transparency of the universe:



Source: **blazers**: few mG on 10pc scale,
intergalactic medium: µG on hundred kpc scale,
back conversion in (inter)galactic magnetic field: µG over more than 10kpc,

Depending on line of sight:
Calculate oscillation probabilities as function of direction.

→Investigation of energy dependent flux from blazars, compare to expectations taking into account $\tau\left(E_\gamma, z_s\right)$

→ For ALP scenario: expected flux as function of energy will be different, depending on line of sight (different back-oscillation probabilities).

Analysis of high energy spectra from 12 high z_s sources consistent with ALPs with $g_{a\gamma\gamma} \sim 2 \cdot 10^{-11}\ GeV^{-1}$ for few hundred neV ALP mass.

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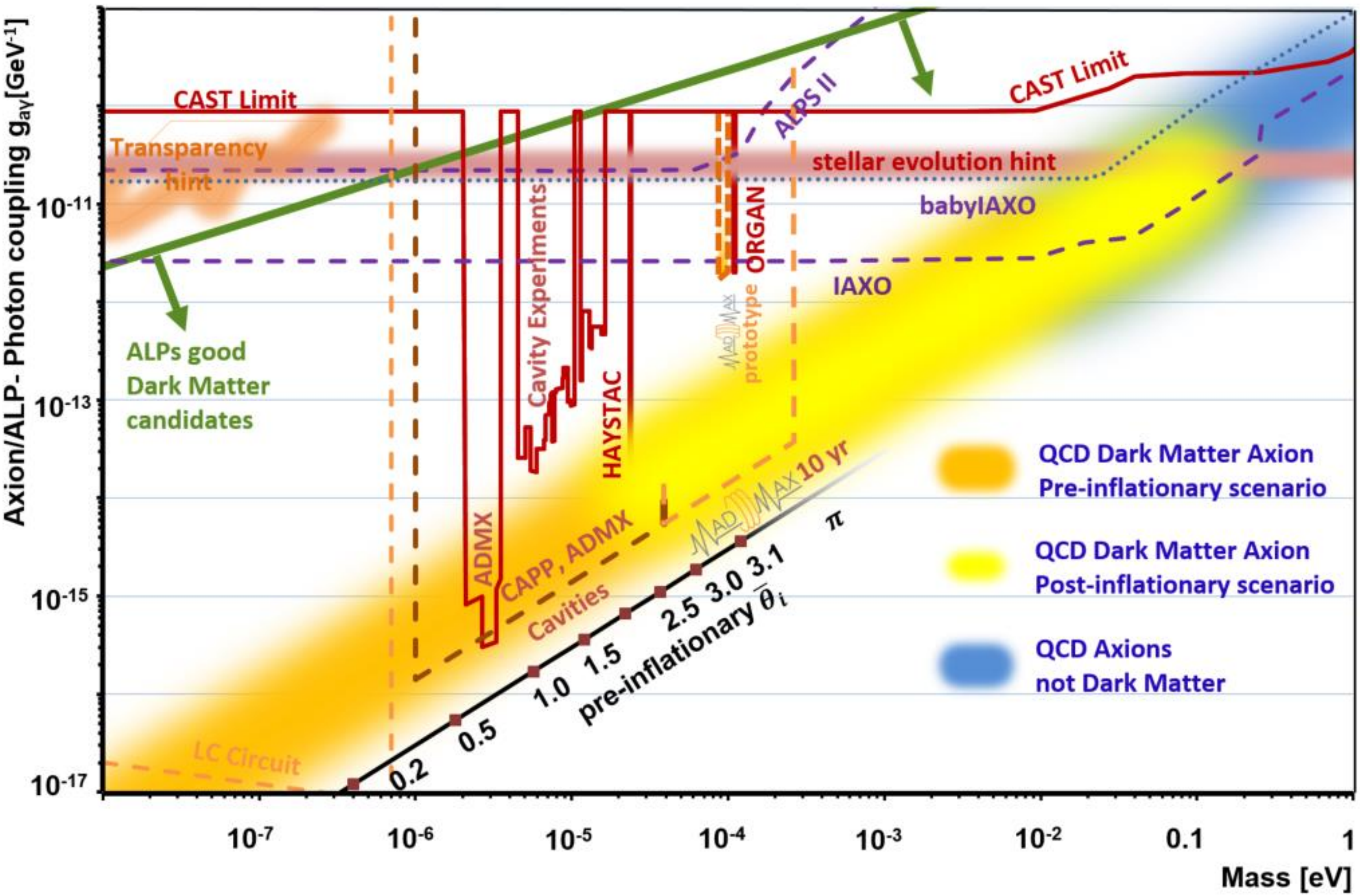

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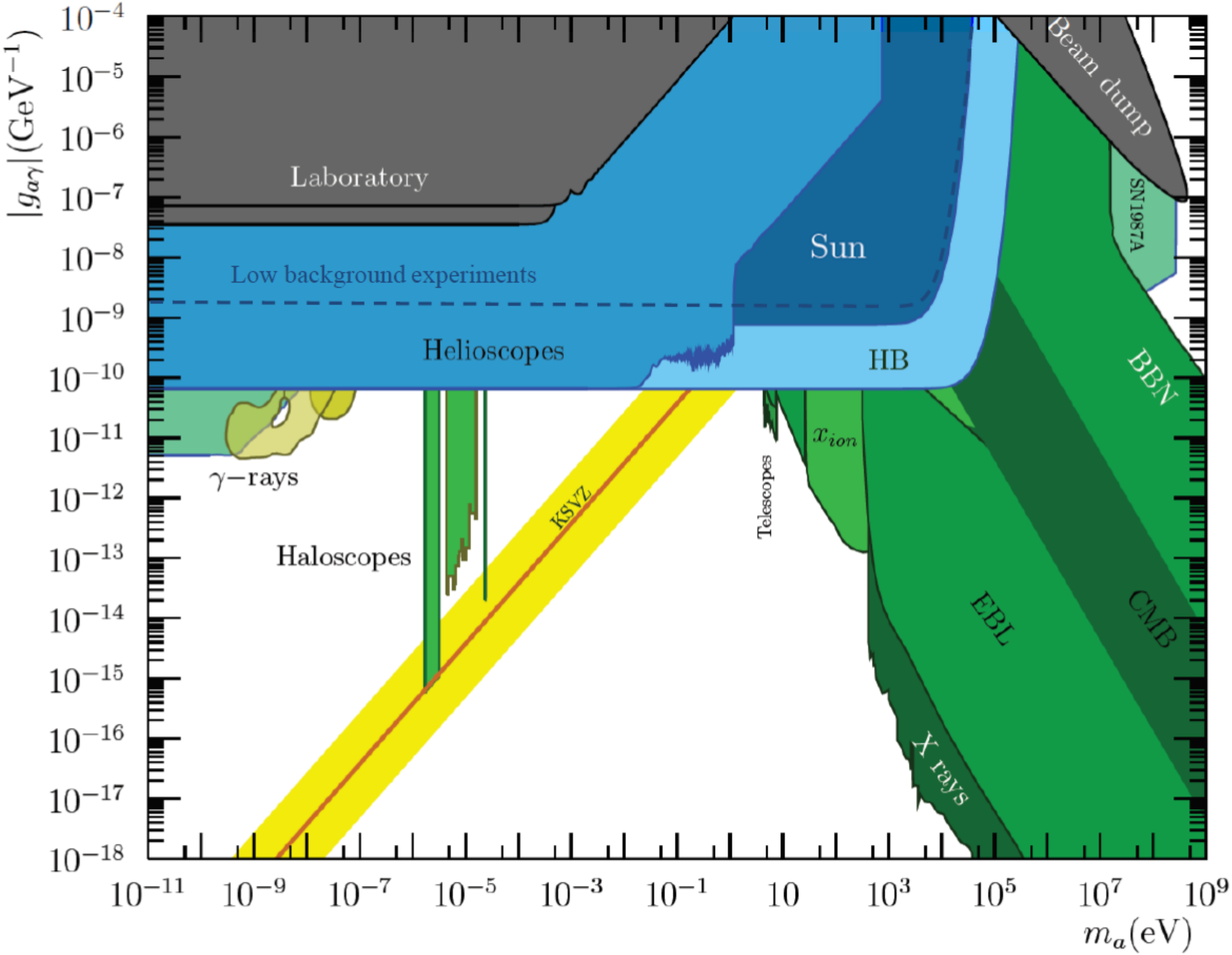

Nuclear Magnetic Resonance:

Axion coupling with nucleus

→ Oscillating electric dipole moment

→ Precession of nuclear spin in material sample in presence of an electric field

→ Resonant transverse magnetization

→ Measure via precision magnetometry

→ Modify B_{ext} to scan different masses (defines sensitivity)