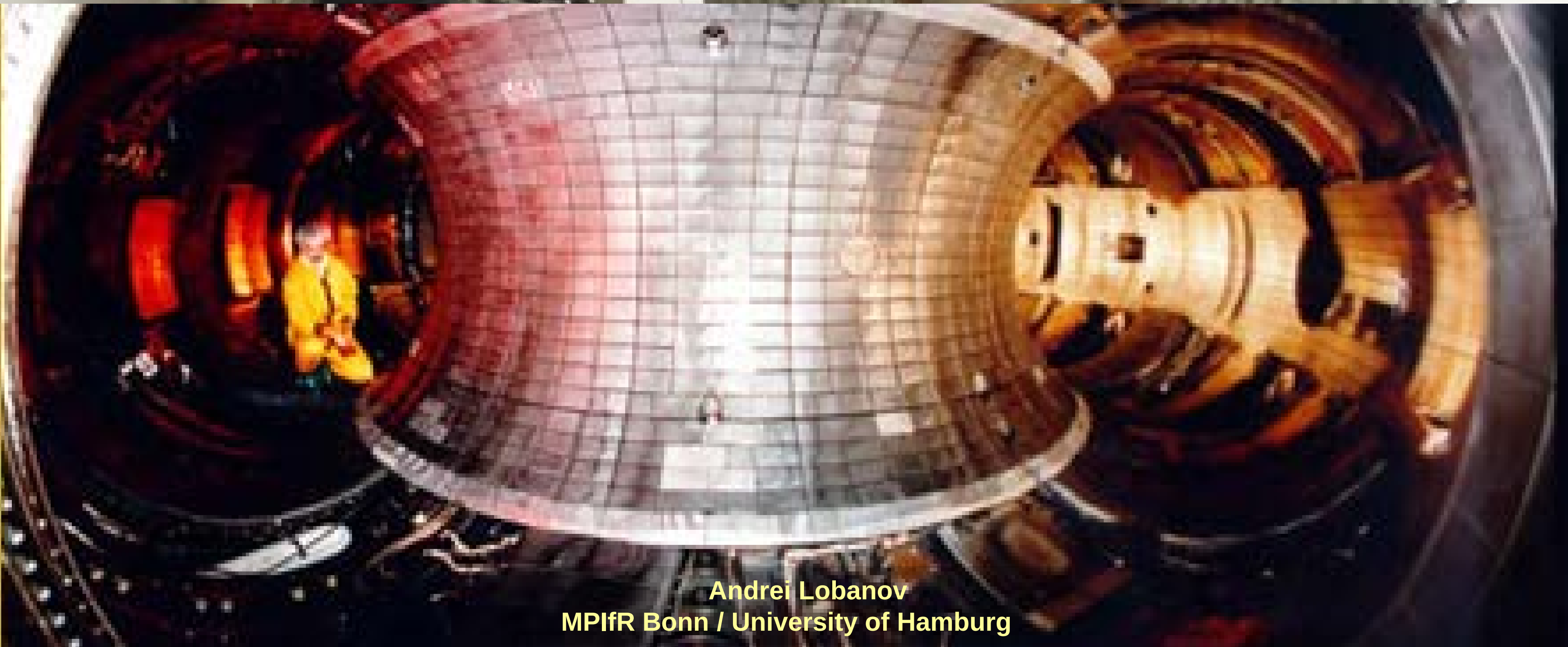
# WISP Dark Matter eXperiment
# &
# Prospects for Broadband DM Searches in the $10^{-2}$ – $10^{-6}$ eV Mass Range



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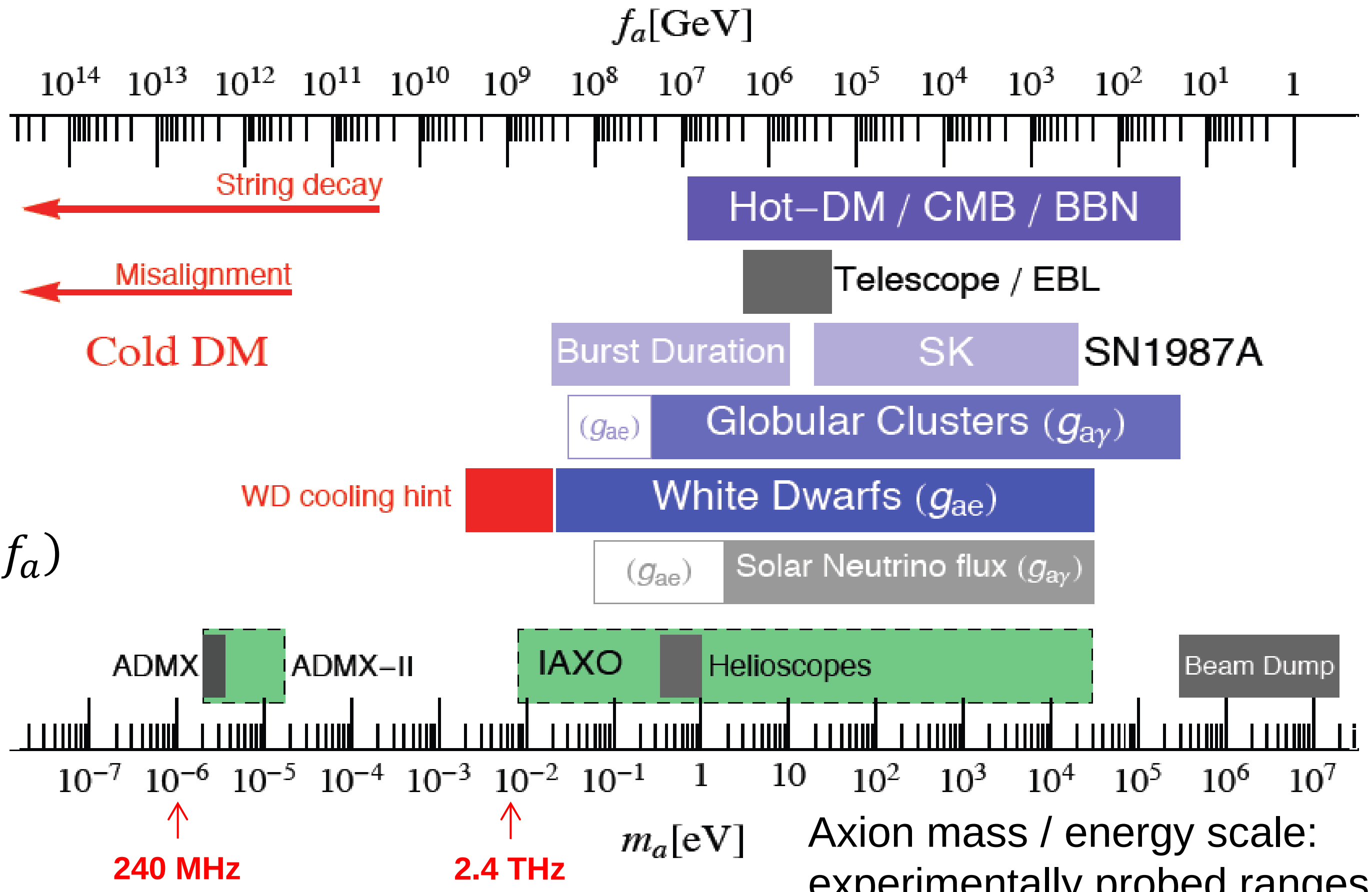
# WISP DM Searches in Radio

- ☐ The strongly motivated mass range for axion DM ($10^{-2} - 10^{-6}$ eV) is probed efficiently by measurements in the 240 MHz – 2.4 THz frequency range.
- ☐ Highly sensitive experiments in this range are needed: narrow band searches with tunable microwave cavities and new, broadband methods.

Axion: pseudo-scalar particle, dynamically removing the CP-violation.

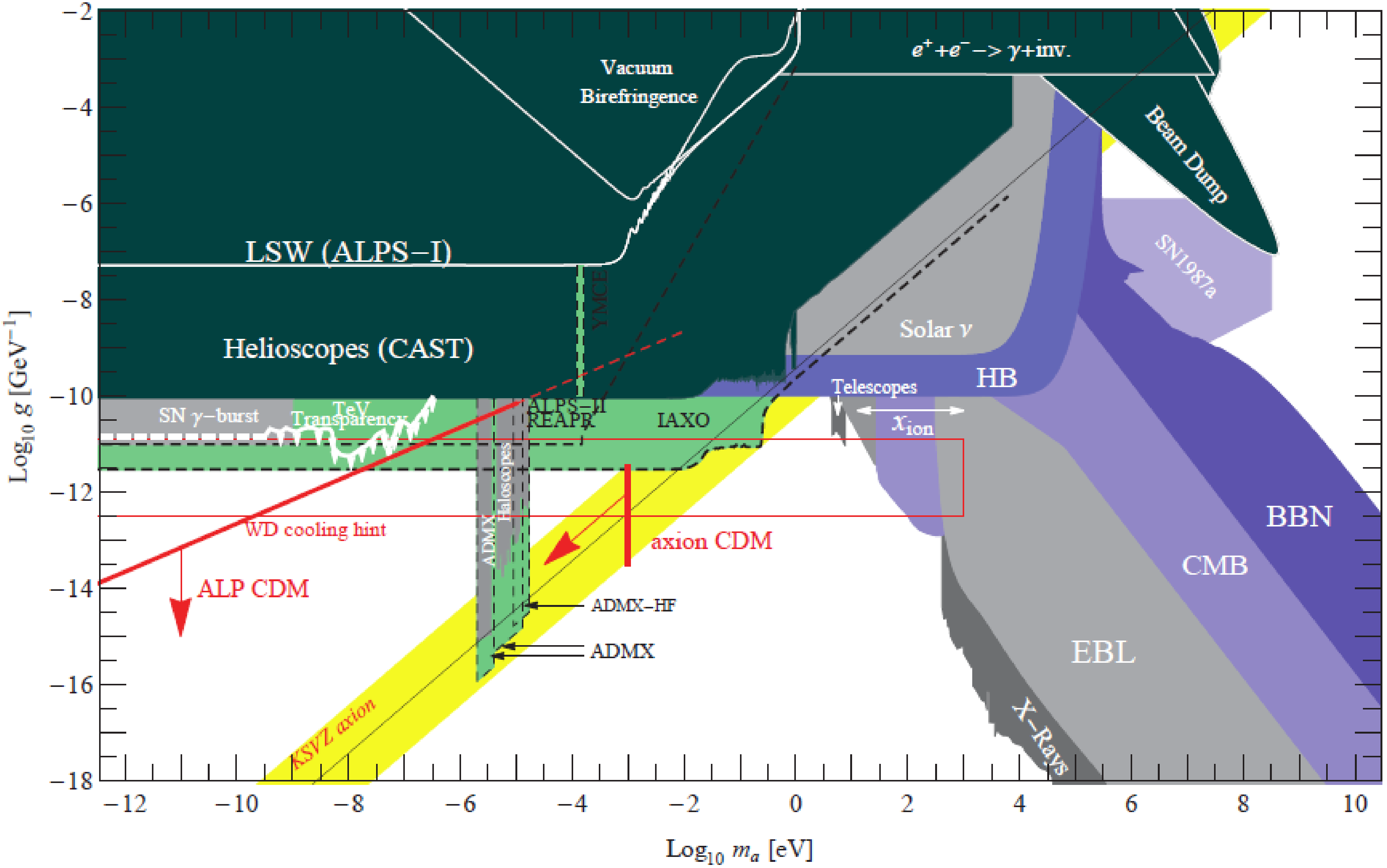
Axion should have a mass

$m_a \sim 6\ \mathrm{meV}\ (10^9\ \mathrm{GeV}/f_a)$



Axion mass / energy scale: experimentally probed ranges

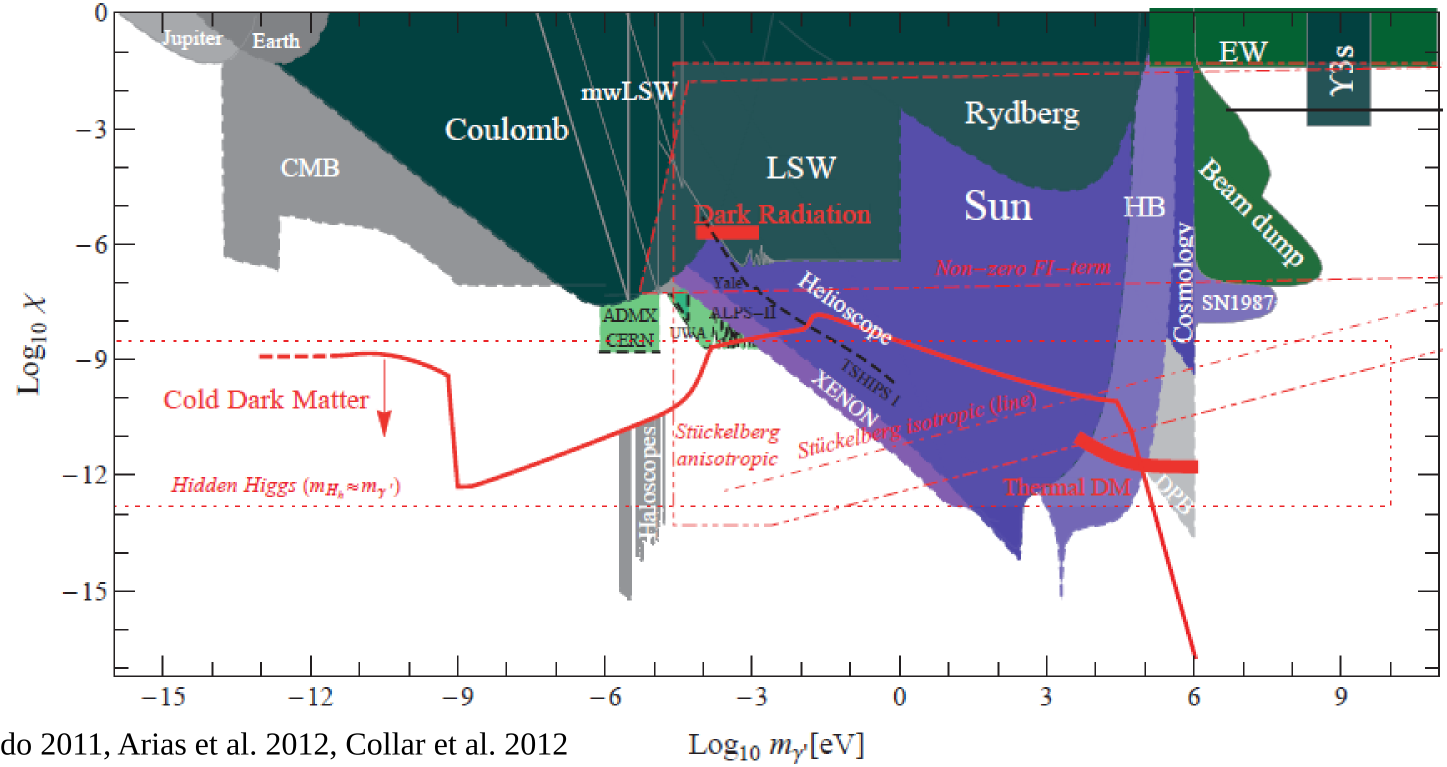
# Current Limits: Axions/ALP



Redondo 2011, Arias et al. 2012, Collar et al. 2012

# Hidden Photons: Current Limits

- ☐ Extra *U*(1) symmetries are featured in many extensions of the SM and they require a gauge boson (hidden photon, $\gamma'$) that interacts with SM particles only via kinetic mixing: $\mathcal{L}_I = 1/2\ \chi\, F_{\mu\nu} B^{\mu\nu}$ .
- ☐ String compactification: $10^{-12} \leq \chi \leq 10^{-3}$; upper bound – „natural“ limit.
- ☐ HP mass, $m_{\gamma'}$, is not well constrained – broad searches are needed.



Redondo 2011, Arias et al. 2012, Collar et al. 2012

# Methodology: Resonant Enhancement

❑ Hidden photons ($\gamma'$):
-- spontaneous photon conversion (kinetic mixing), $\gamma \leftrightarrow \gamma'$

Haloscope experiments: Coupling strength (mixing angle):

$$\chi \propto\ t_{\rm mes}^{-1/4}\,{\rm SNR}^{1/2}\,T_{\rm n}^{1/2}\,V_0^{-1/2}\,Q_0^{-1/2}\,\mathcal{G}_{\gamma'}^{-1/2}\,\rho_0^{-1/2}\,Q_{\gamma'}^{-1/4}\,m_{\gamma'}^{-1/4}$$

❑ Axions and axion-like particles ($\phi$):
-- two-photon coupling (Primakoff process), $\phi \leftrightarrow\ \gamma + \gamma$, with B-field as a virtual photon

Haloscope experiments: Coupling stregnth:

$$g[{\rm GeV}^{-1}] \propto\ t_{\rm mes}^{-1/4}\,{\rm SNR}^{1/2}\,T_{\rm n}^{1/2}\,B_0^{-1/4}\,V_0^{-1/2}\,Q_0^{-1/2}\,\mathcal{G}_{\phi}^{-1/2}\,\rho_0^{-1/2}\,Q_{\phi}^{-1/4}\,m_{\phi}^{3/4}$$

$t_{mes}, SNR$ – measurement time and SNR; $T_n$ – noise temperature; $V_0, Q_0$ – cavity volume and quality factors; $B_0$ – magnetic field strength; $\mathcal{G}_{\phi/\gamma}$ – form factor; $\rho_0$ – DM density; $Q_{\phi/\gamma}$ – quality factor of DM signal; $m_{\phi/\gamma}$ – particle mass

# WISP Dark Matter eXperiment

## Direct WISP dark matter searches in the 0.8–2.0 $\mu$eV mass range

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Andrei Lobanov[4,1], Wolf-Dietrich Möller[2], Javier Redondo[5,6], Andreas Ringwald[2],
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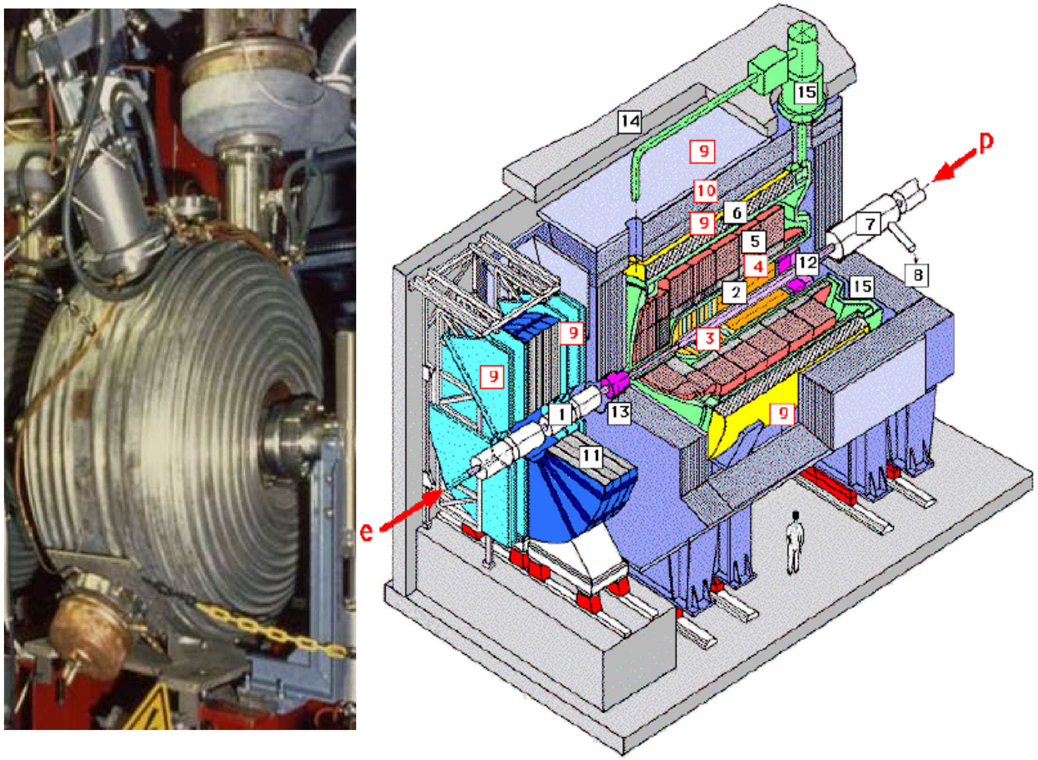
# WISPDMX Overvirew

- WISP Dark Matter eXperiment (WISPDMX) is a pioneering search for hidden photon and axion dark matter in the 0.8-2.0 $\mu$eV range, exploring the particle masses below the mass range covered by ADMX.

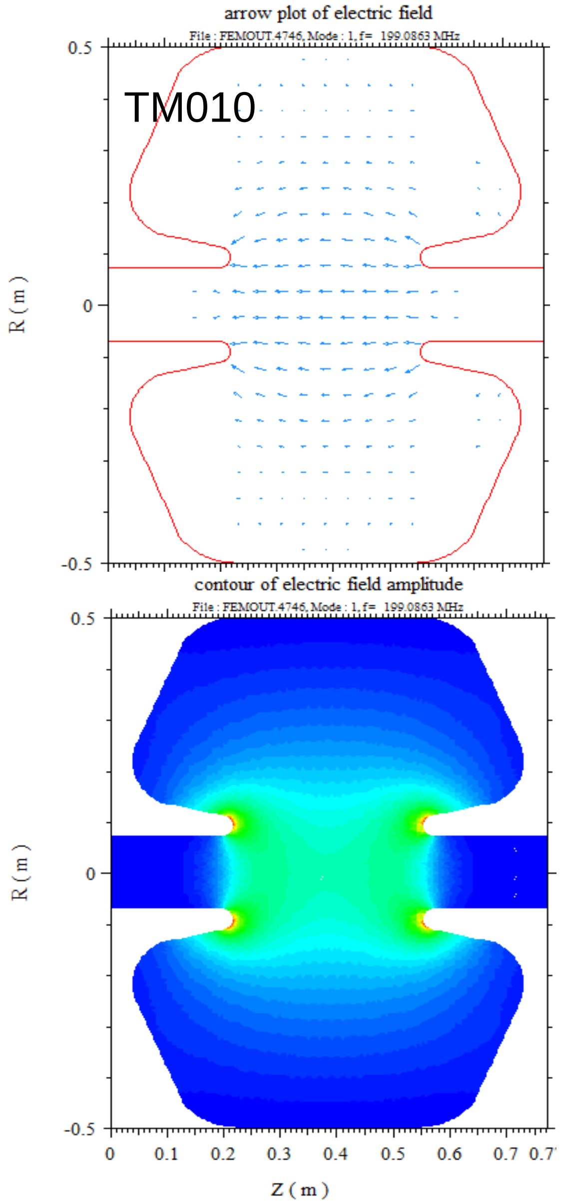
- WISPDMX utilizes a HERA 208-MHz resonant cavity and a 40 dB amplifier chain, and plans to make use of a strong magnet (e.g. 1.15 T H1 magnet).
- Further support from SFB and PIER funding.
- Currently completing Phase 1: hidden photon searches at nominal resonances of the cavity.
- Phase 2: HP searches with cavity tuning
- Phase 3: ALP searches



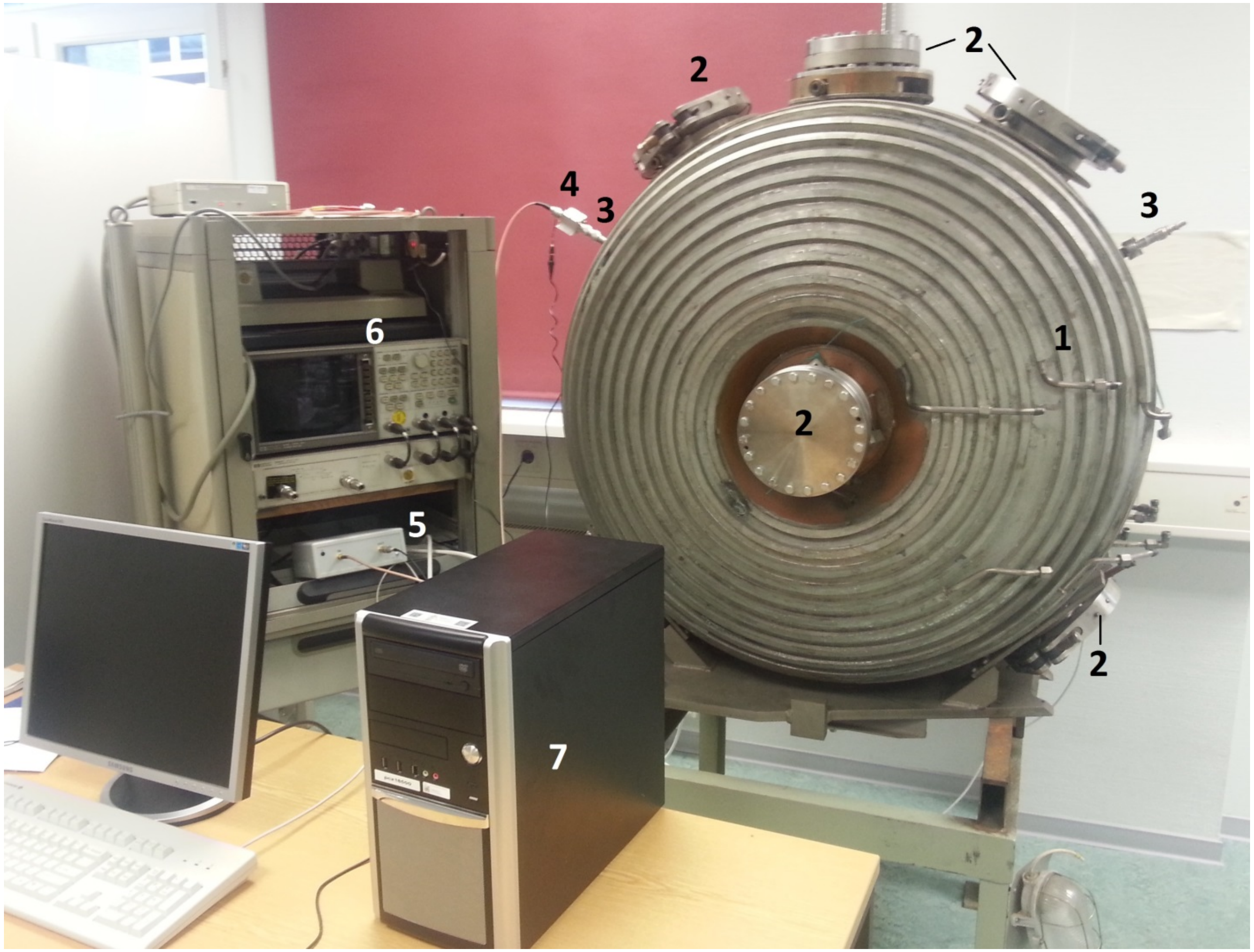
Photograph of the HERA 208-MHz cavity (left) and graphical sketch of the H1 detector with the 1.15 T magnet that can be used for the ALP searches.

# Specifics of WISPDMX

- Combining existing elements (cavity, amplifier, downconverter, magnet, plunger).
- H1 magnet: provides $B$ = 1.15 Tesla in a volume of 7.2 $m^3$ and the total chamber volume of ~100 $m^3$
- HERA 208-MHz proton ring accelerator cavity: $V$ = 460 l., TM010 at 207.9 MHz, with $Q$ = 46000.
- Presently, limited tuning and no cooling.
- Planning to measure at several resonant modes simultaneously: using TM and TE modes with non-zero form factors.
- Broad-band digitization and FFT analysis using a commercial 12-bit digitizer/spectral analyzer .
- Will attempt “long” measurements, with $t_{mes}$ ~ 1 day (frequency stability may be an issue).
- Tuning will be made with a plunger assembly, with the goal of tuning over ~60 % of the 0.8-2 $\mu$eV range.



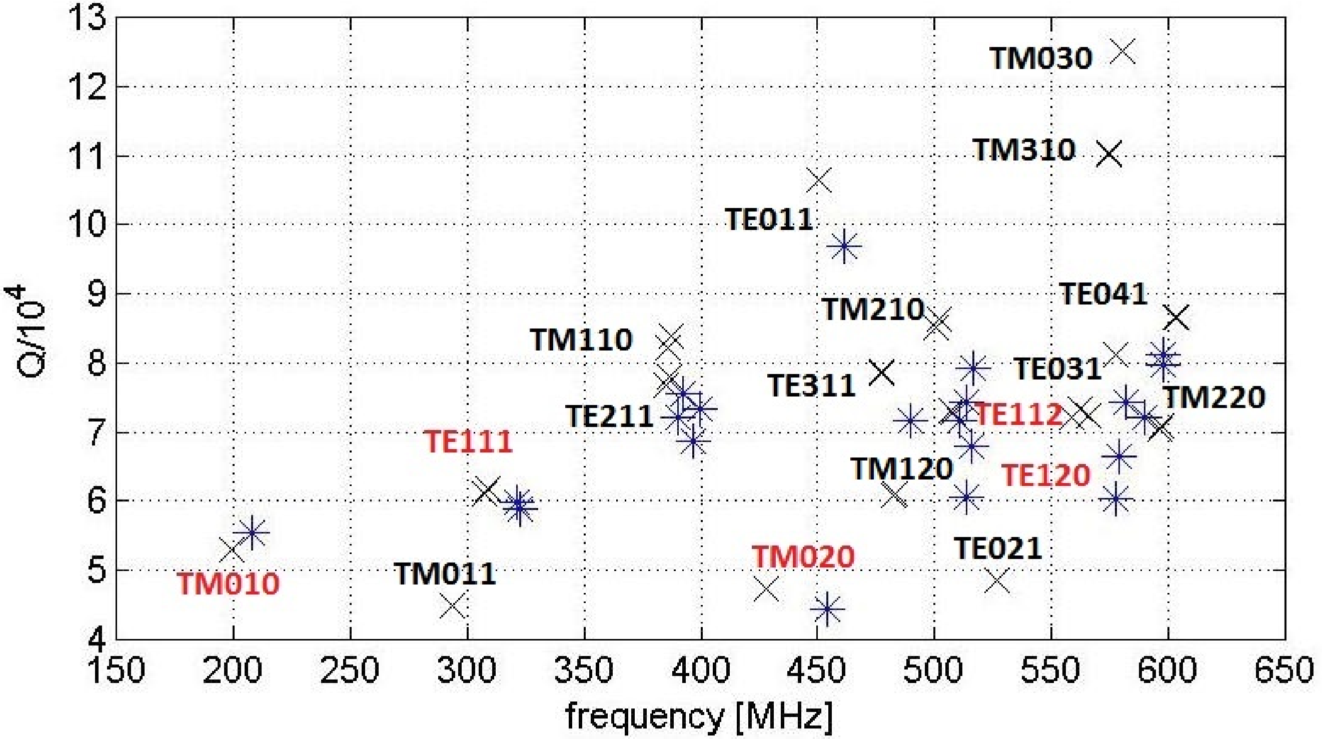
# WISPDMX Phase 1



1 – 208 MHz HERA cavity; 2 – cavity ports; 3 – antenna probes; 4 – WantCom 22 dB amplifier;  5 – MITEQ 18 dB amplifier; 6 – network analyzer (HP 85047A); 7 -- control computer, with onboard digitizer (Alazar  ATS-9360, 1.8Gs/s)

# Accessible Resonant Modes

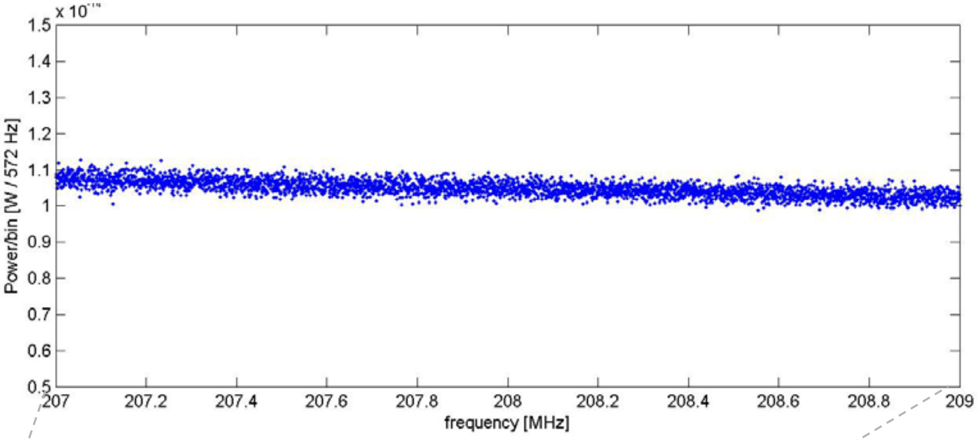
- Five resonant modes identified which have non-zero form factors for hidden photon measurements.
- Outside resonance: $G_f \approx 0.0018$ – hence measurements in the entire spectral range could also be used for constraining $\chi$.

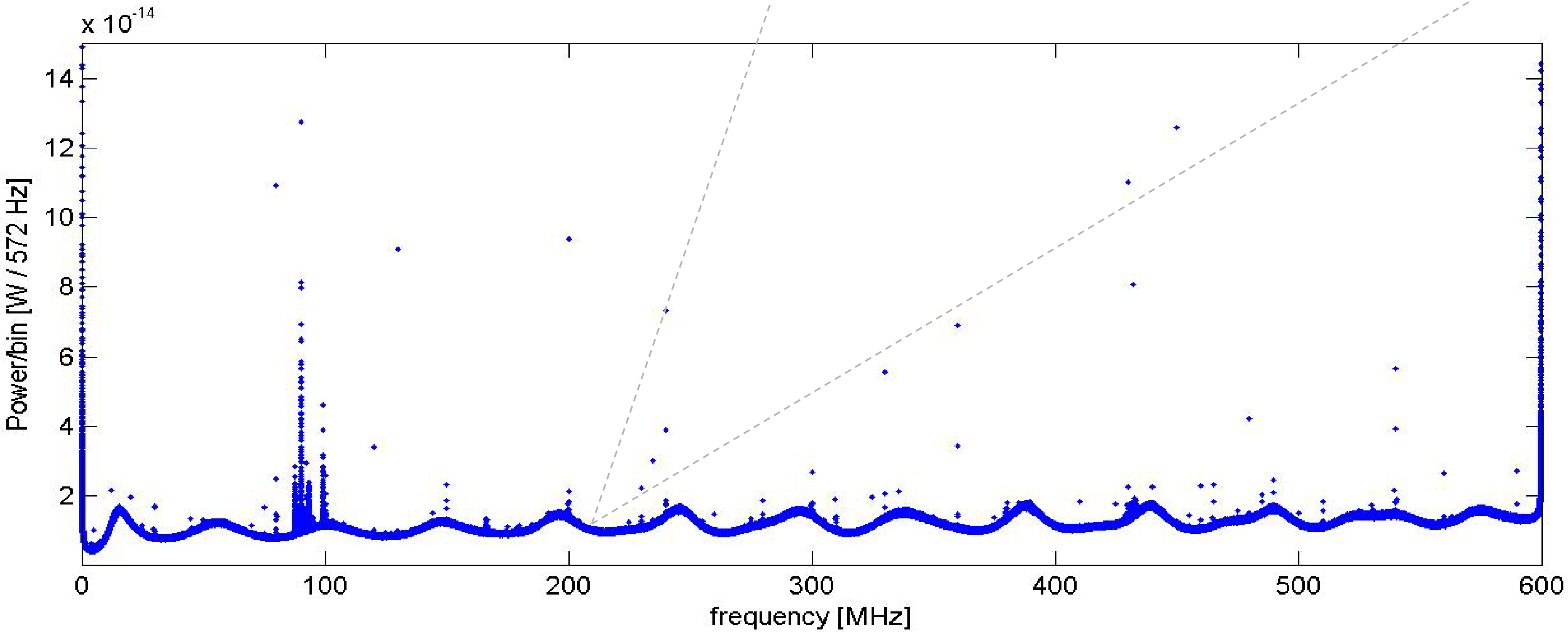


| Mode | TM$_{010}$ | TE$_{111}$ | TM$_{020}$ | TE$_{112}$ | TE$_{120}$ | TM$_{030}$ |
|---|---|---|---|---|---|---|
| $f$/MHz | 199 | 308 | 428 | 508 | 560 | 580 |
| $Q$ | 53000 | 61000 | 47000 | 73000 | 72000 | 125000 |
| $\mathcal{G}$ | 0.43 | 0.67 | 0.32 | 0.019 | 0.036 | 0.061 |

# First Results: Broadband Recording

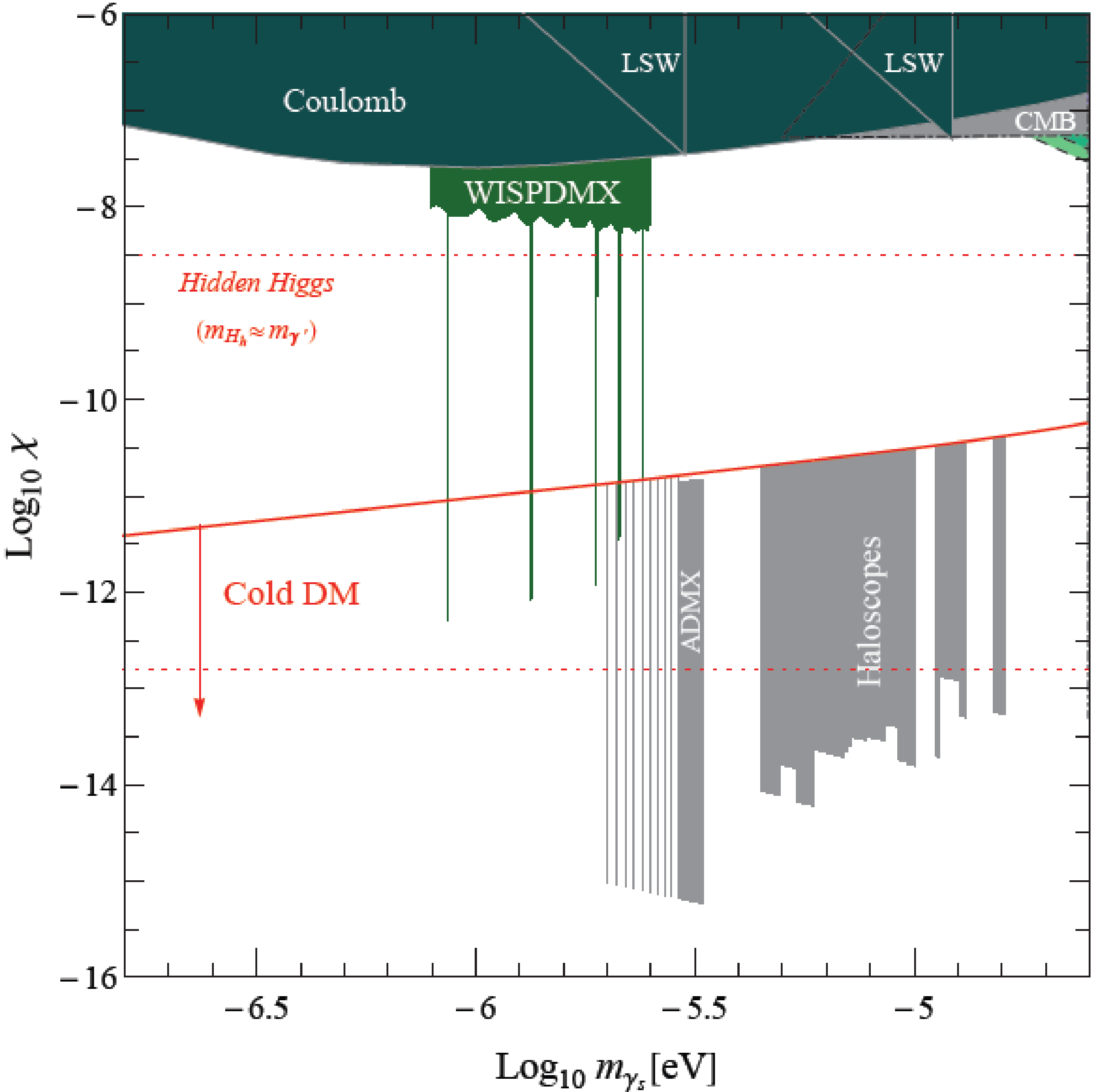
Measured power in the 600 MHz band and narrowband section of the spectrum centered on the fundamental resonant mode (207.9 MHz of the cavity).





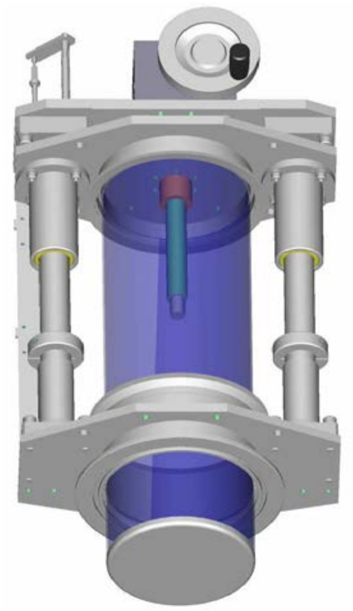
# WISPDMX Exclusion Limits for HP

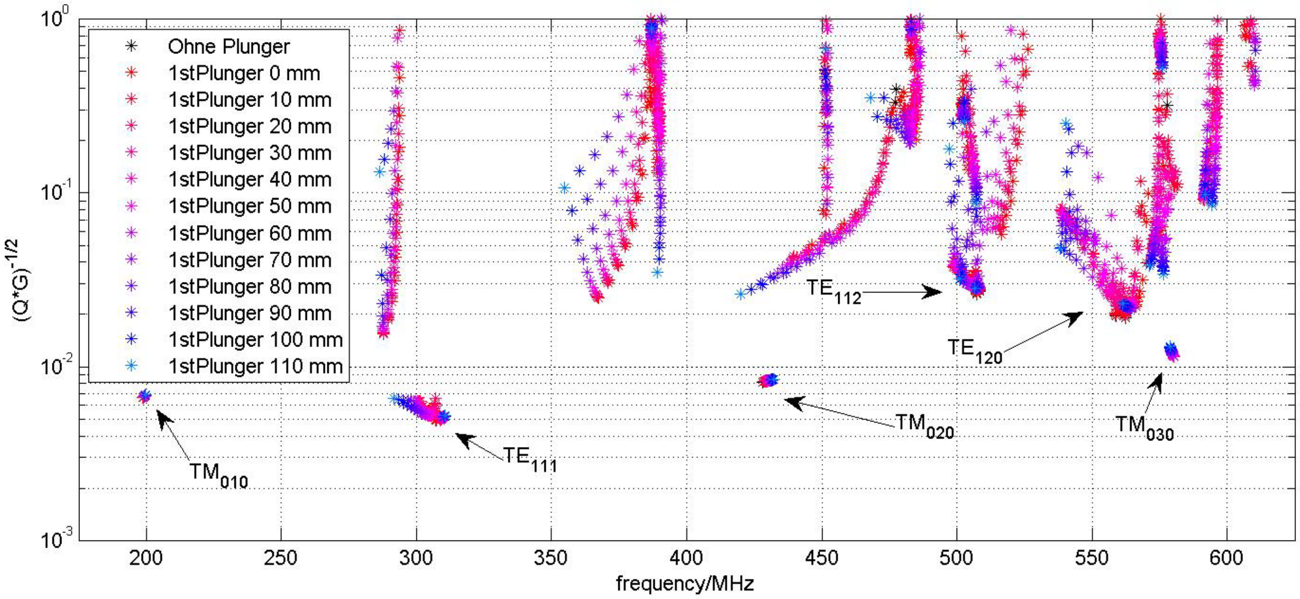
- Exclusion limits from WISPDMX Phase 1 measurements: evaluating the broadband signal.
- Further improvements (factor ~$10^2$) will come from stronger amplification, improving the frequency resolution (using downconverter), optimizing the antenna probes and cooling the apparatus.



# Phase 2: Tuning the Cavity

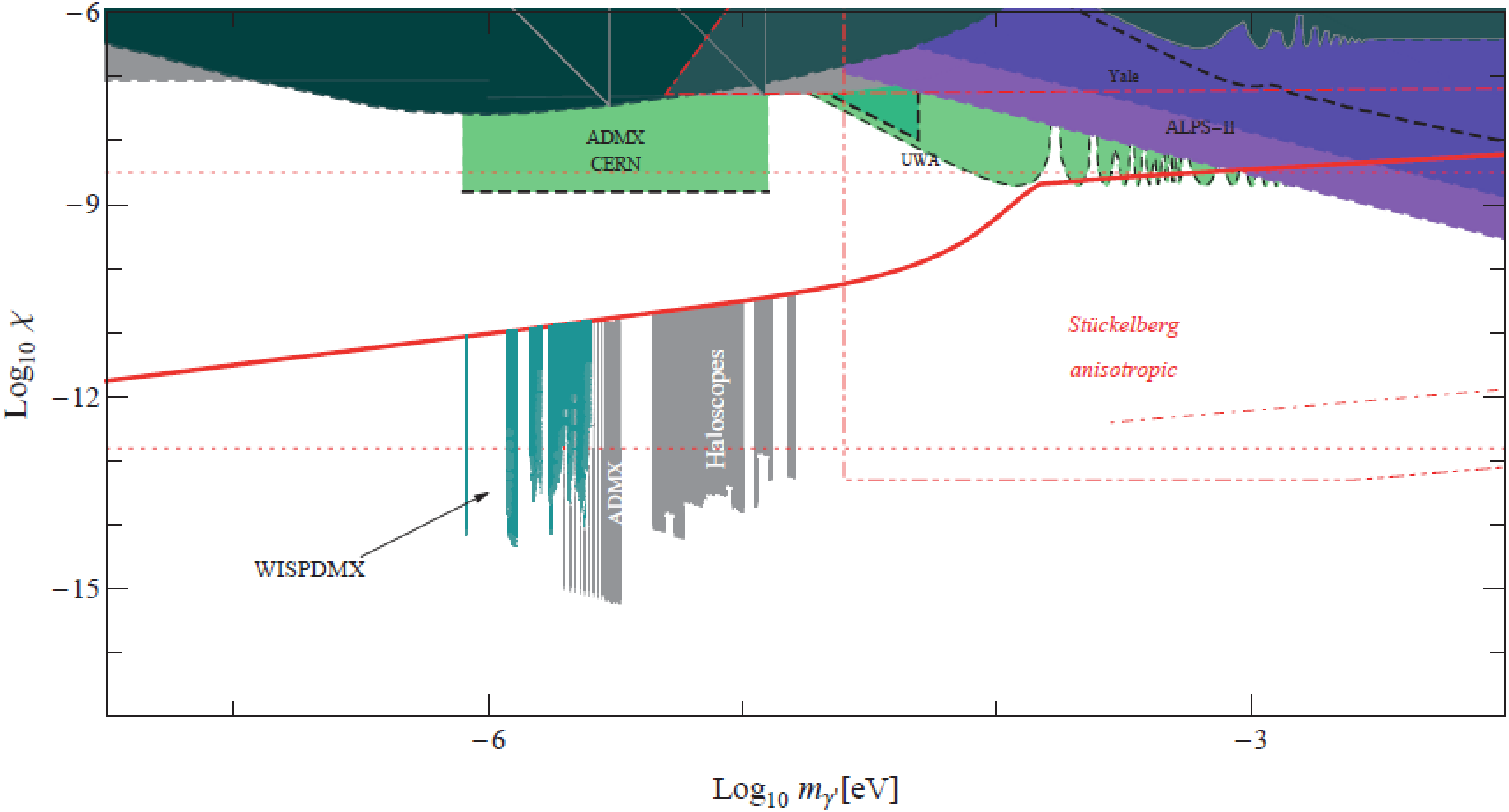
- Tuning pluner assembly is under construction.
- CST simulations of plunger assembly consisting of two plungers.
- The assembly should provide effective coverage of up to 56% of the 200-500 MHz range (up 70% with additional vacuum-pump tuning)
- It will also improve form factors of several modes
- Optimal antenna location is on the plunger frame





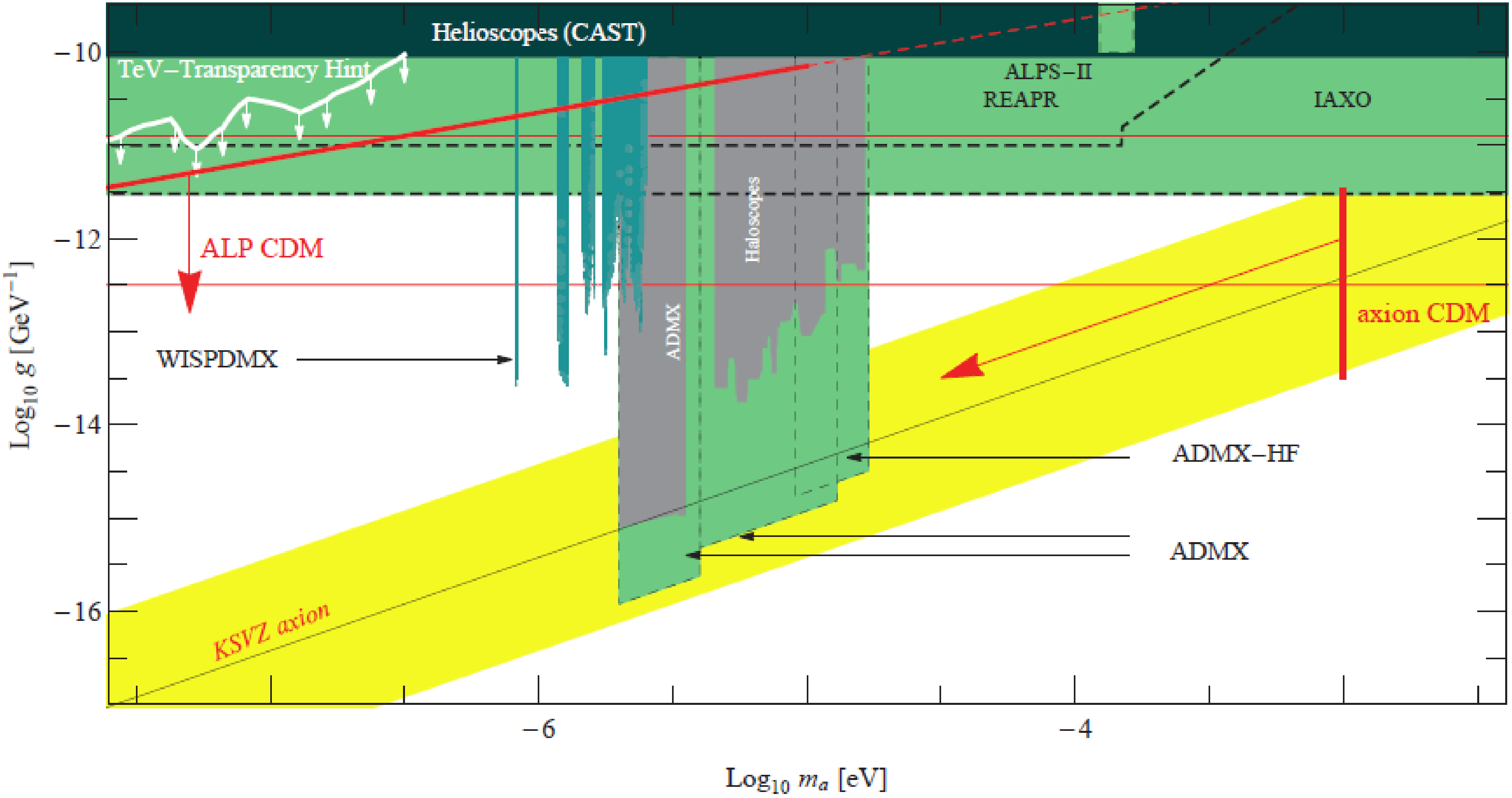
# Phase 2: Expected HP Limits

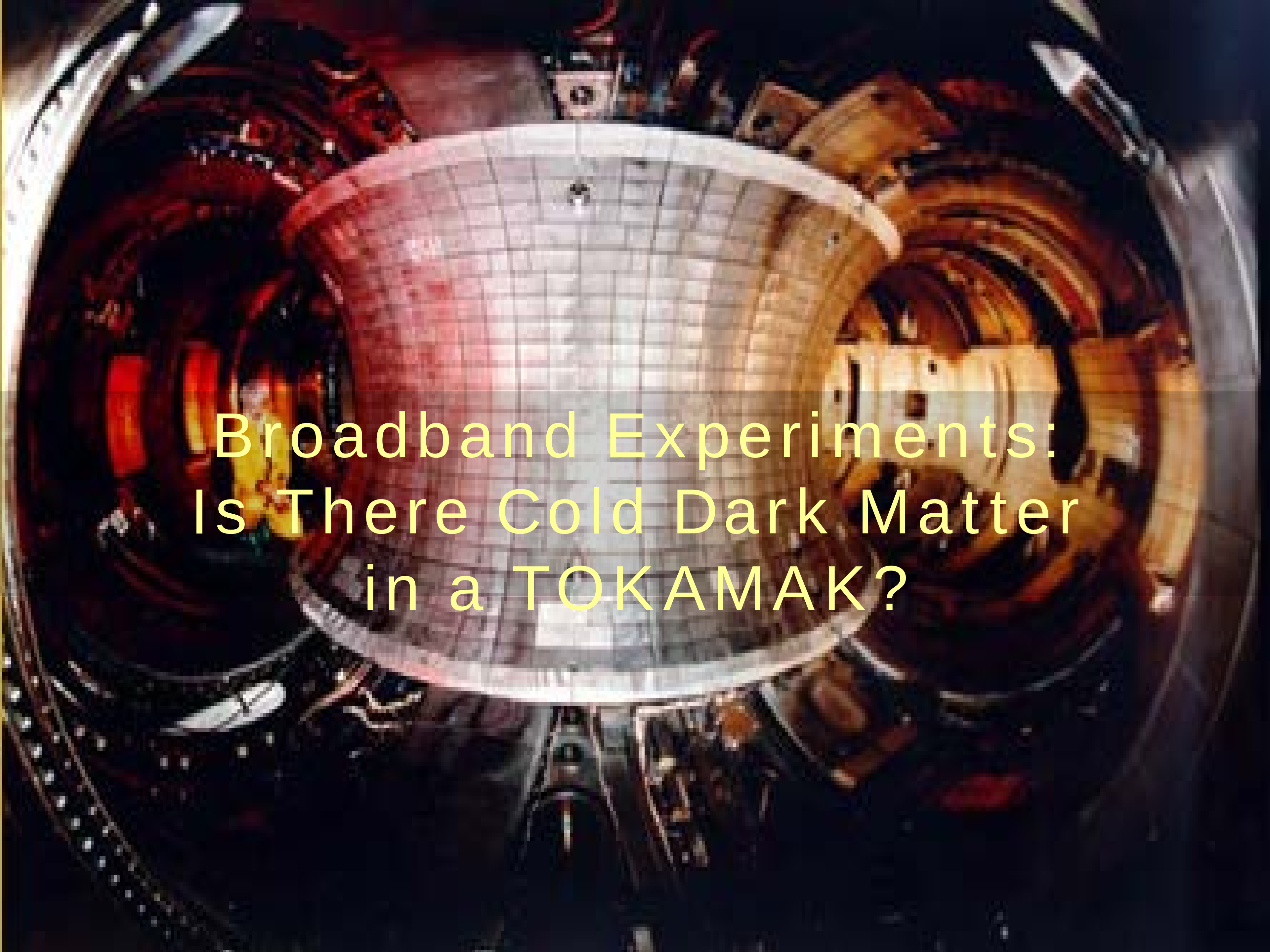
- ❑ WISPDMX: expected HP dark matter exclusion limits from tuned cavity measurements.



# Phase 3: Expected ALP Limits

❑ WISPDMX: expected ALP exclusion limits from measurements with tuned cavity combined with the solenoid magnet from H1 detector (1.15 Tesla)





# Broadband Experiments: Is There Cold Dark Matter in a TOKAMAK?

# Need for Broadband Searches

- Intrinsic measurement band $W_{meas} \approx 10^{-6}\omega$ limits severely the integration time and frequency scanning rate of microwave cavity searches

WISPDMX scanning speed for axions

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \sim \frac{30\ \mathrm{MHz}}{\mathrm{year}} \left(\frac{4}{\mathrm{SNR}}\right)^2 \left(\frac{3\,\mathrm{K}}{T_n}\right)^2 \left(\frac{g}{10^{-15}/\mathrm{GeV}}\right)^4 \left(\frac{V}{460\,\ell}\right)^2 \left(\frac{B_0}{1.15\,\mathrm{T}}\right)^4 \left(\frac{\mathcal{G}_\phi}{0.5}\right)^2 \times \left(\frac{208\,\mathrm{MHz}}{f}\right)^2 \left(\frac{Q}{2.7\times 10^4}\right) \left(\frac{10^6}{Q_\phi}\right) \left(\frac{\rho_0}{0.3\,\mathrm{GeV/cm^3}}\right)^2 .$$

and hidden photons

$$\frac{df}{dt} = \frac{1}{N_{\mathrm{rep}}}\frac{f}{Q}\frac{1}{t} \sim \frac{135\ \mathrm{MHz}}{\mathrm{year}} \left(\frac{3}{N_{\mathrm{rep}}}\right) \left(\frac{4}{\mathrm{SNR}}\right)^2 \left(\frac{300\,\mathrm{K}}{T_n}\right)^2 \left(\frac{\chi}{10^{-14}}\right)^4 \left(\frac{V}{460\,\ell}\right)^2 \left(\frac{\mathcal{G}_{\gamma'}}{0.5\times 0.25}\right)^2 \times \left(\frac{208\,\mathrm{MHz}}{f}\right)^2 \left(\frac{Q}{2.7\times 10^4}\right) \left(\frac{10^6}{Q_{\gamma'}}\right) \left(\frac{\rho_0}{0.3\,\mathrm{GeV/cm^3}}\right)^2 , \tag{2.19}$$

- Want to have an experiment without resonant enhancement required.

# Detection Limits

☐ SNR of detection: $\mathrm{SNR} = \frac{P_{\mathrm{out}}}{P_{\mathrm{noise}}}\sqrt{W\,t} = \frac{P_{\mathrm{out}}}{k_B\,T_n}\sqrt{\frac{t}{W}},$

*W* – signal bandwidth,
$T_{\mathrm{n}}$ – system noise temperature.

☐ Since $P_{\mathrm{out}} \propto V\,B^2$ and *W* is set by velocity dispersion of the dark matter, improving the detection SNR can be achieved by:

- increasing measurement time, *t*; *... expensive*
- reducing the system noise, $T_{\mathrm{n}}$; *... reaching quantum limit*
- increasing the magnetic field strength, *B*; *... expensive*
- optimising the geometry (form factor), $\mathcal{G}_V$; *... difficult for high Q setups*
- increasing the volume, *V*. *... with TOKAMAKs? or dedicated radiometry chambers?*

# Broadband Experiments

- Suppose we have a mass range ($m_1$,$m_2$=$\alpha m_1$; $\alpha$>1) of interest for WISP searches.
- Number of individual measurements needed to cover this range is:

$$N_{mes} = 1 + \frac{\log\alpha}{\log(\frac{Q}{Q-1})}$$

- $Q$=1 defines the "broad band" case, assuming that a detector technology is available that covers the entire ($m_1$,$m_2$) range with sufficient spectral resolution.
- Reaching a desired sensitivity implies a measurement time

$$t \propto T^2\, B^{-4}\, V^{-2}\, G^{-2}\, Q^{-2}$$

- Then a broad band measurement is more efficient than a narrow band one if

$$t_{broad} < \ t_{narrow}\, N_{mes}$$

- If a narrow band measurement has large $Q$, this implies

$$1 + Q\ \log\alpha > \left(\frac{T_b}{T_n}\right)^2 \left(\frac{B_b}{B_n}\right)^{-4} \left(\frac{V_b}{V_n}\right)^{-2} \left(\frac{G_b}{G_n}\right)^{-2}$$

- Suppose that typically $T_b = 100T_n$, $B_b = 1.0\ B_n$, $V_b = 100V_n$, and $G_b = 0.01G_n$.
- Then, to scan as efficiently over a decade in mass, a narrow band experiment must have Q<10000. Shouldn't we buy into the broad band instead?

# Going Away From Resonance

- ☐ **Several ways to get away:**

  -- focusing the signal (*e.g.*, with a spherical reflector;
  cf., Horns et al. 2013, JCAP, 04, 016; Jaeckel & Redondo 2013, 11, 016)

  -- working in the „mode overlap“ regime (at $\lambda \ll V^{1/3}$)
  (cf., Jaeckel & Redondo 2013, PRD, 88, 5002)

  -- really measuring at $Q = 1$ (radiometry)

- ☐ **Several ways to pay for that:**

  -- taking difraction aboard

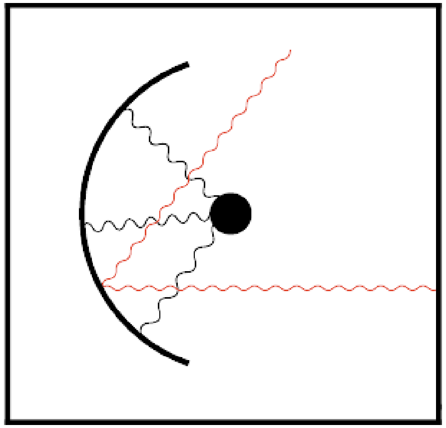
  -- complicating the signal through multiple mode constributions

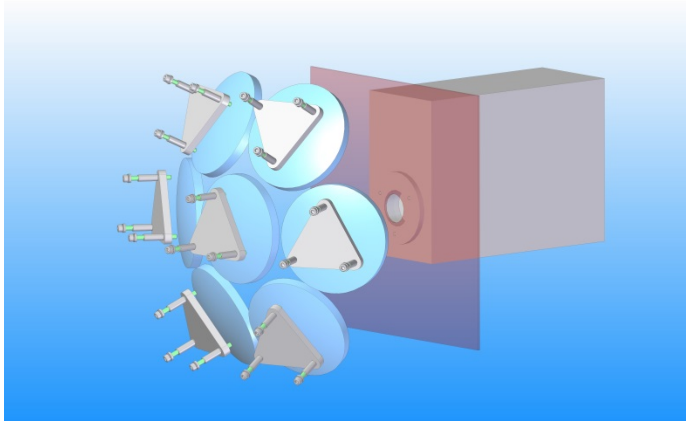
  -- spreading detectors all over

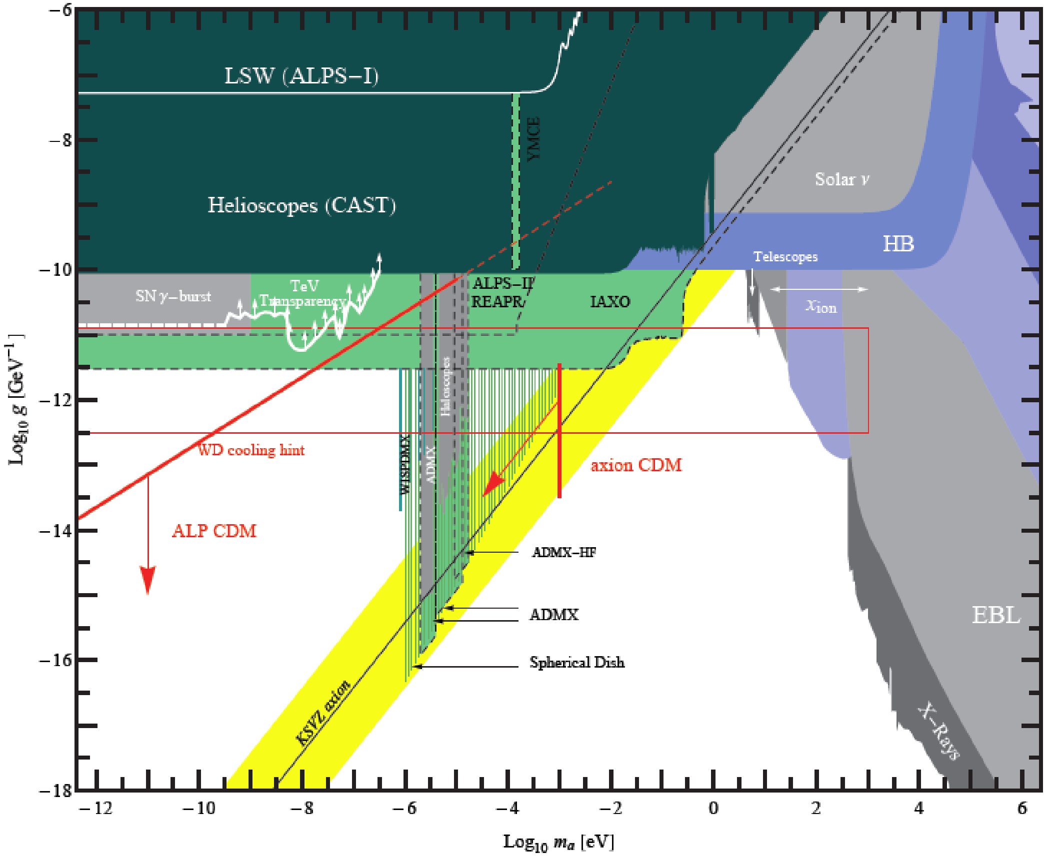
... plus dealing with the environment on much larger scales

# Spherical Reflectors

- ☐ Employing spherical reflectors enhance (focus) the near field EM signal from the reflector surface which arises due to its interaction with WISP dark matter (Horns et al. 2013, Jaeckel & Redondo 2013). Promising for masses above 10 μeV.
- ☐ Pilot study is underway at DESY (see talk on Thursday by Babette Döbrich)

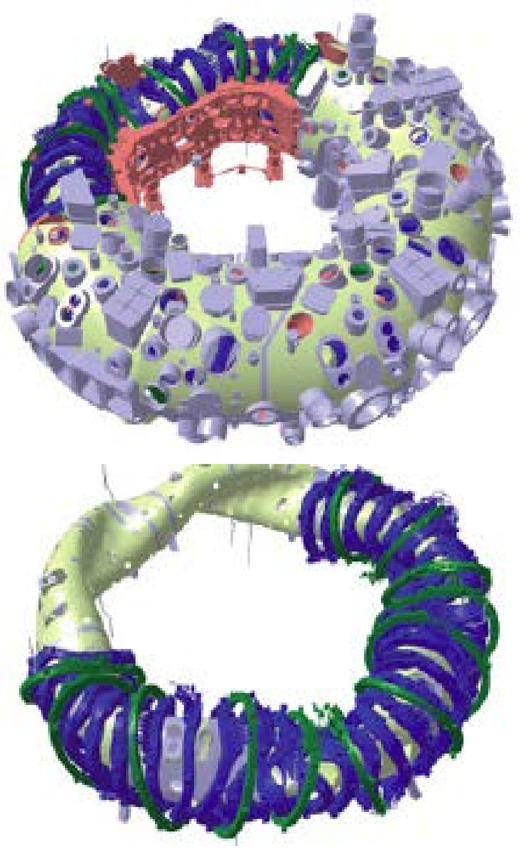




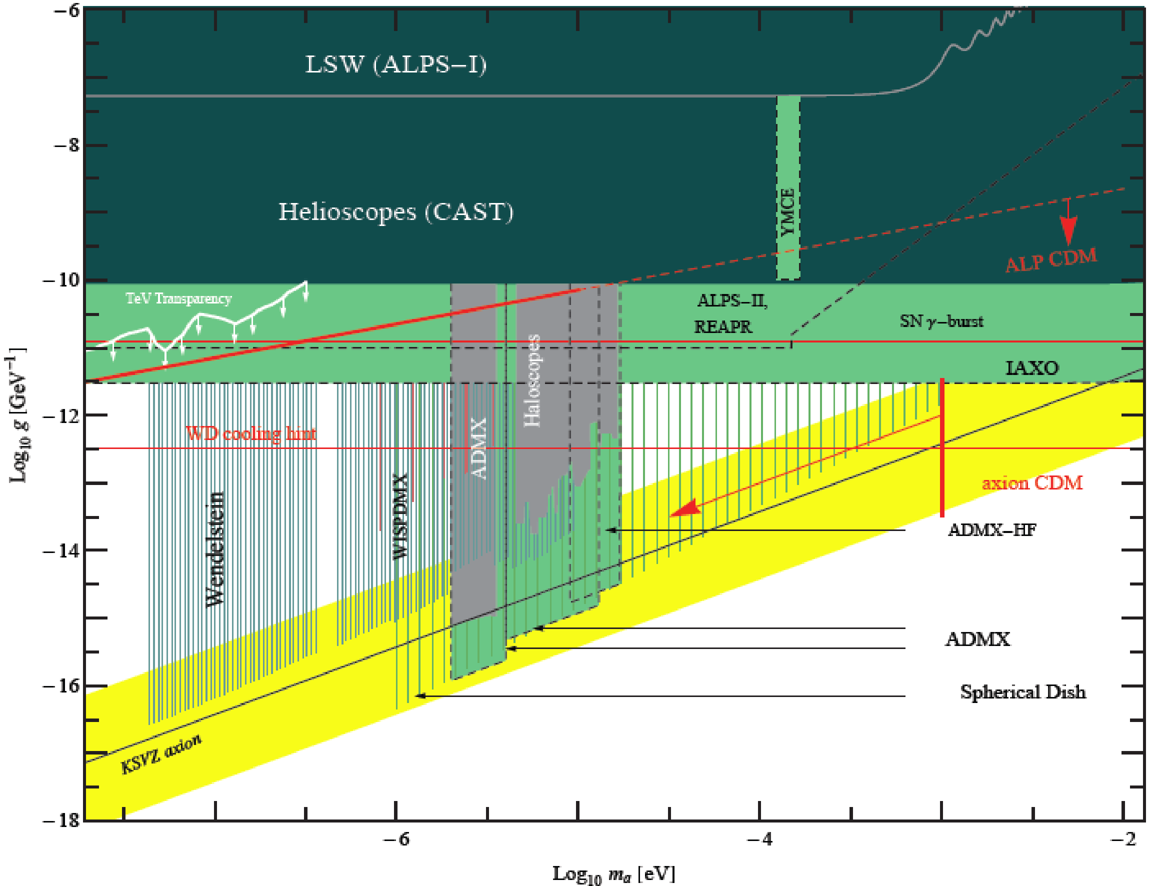


# Superconducting Tokamaks

- Large chamber volume (>10 m$^3$), strong and stable magnetic field
- Tore Supra: initial measurements shown Q~100 and strong RFI at $\nu$<1 GHz.
- Wendelstein (W7-X): stellarator may fare better, with Q ~ 500 $(\nu/1\mathrm{GHz})^{-1}$ and double shielding of the plasma vessel – but complicated B-field.

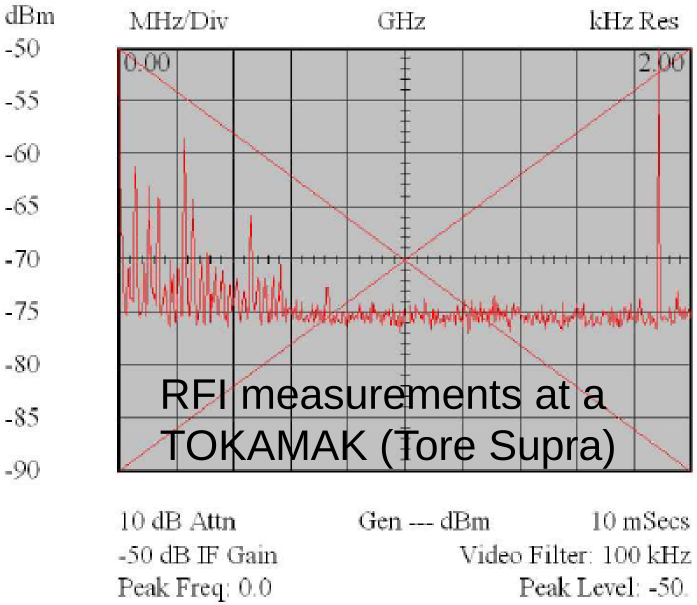


W7-X: magnetic coils and plasma vessel

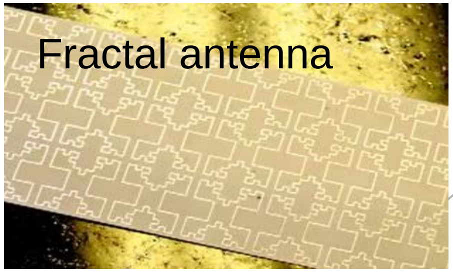


# Critical Issues

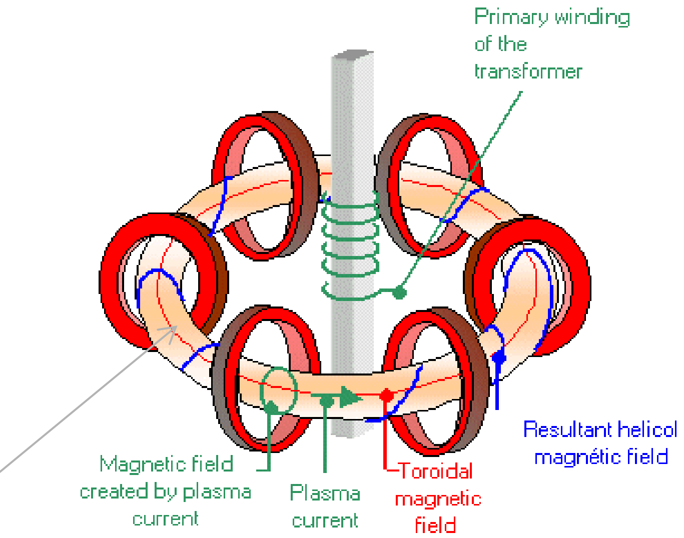
- Background and RFI noise: need to understand the background and reduce it as far as possible. Measurements made at Tore Supra have shown that RFI may be a serious impeding factor and shielding my be required
- Maximizing the effective volume: the receiving element may need to be specially designed so as to maximize the volume coverage. Use of a fractal antenna printed on a dielectric plate and located on the perimeter of the main radius of the torus may provide a viable solution



RFI measurements at a TOKAMAK (Tore Supra)

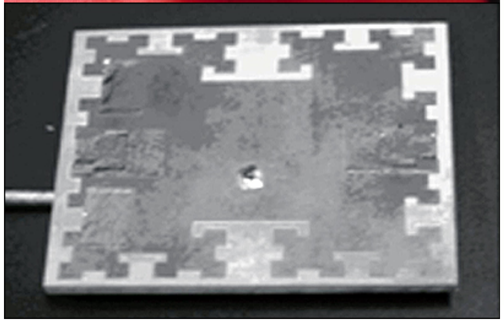


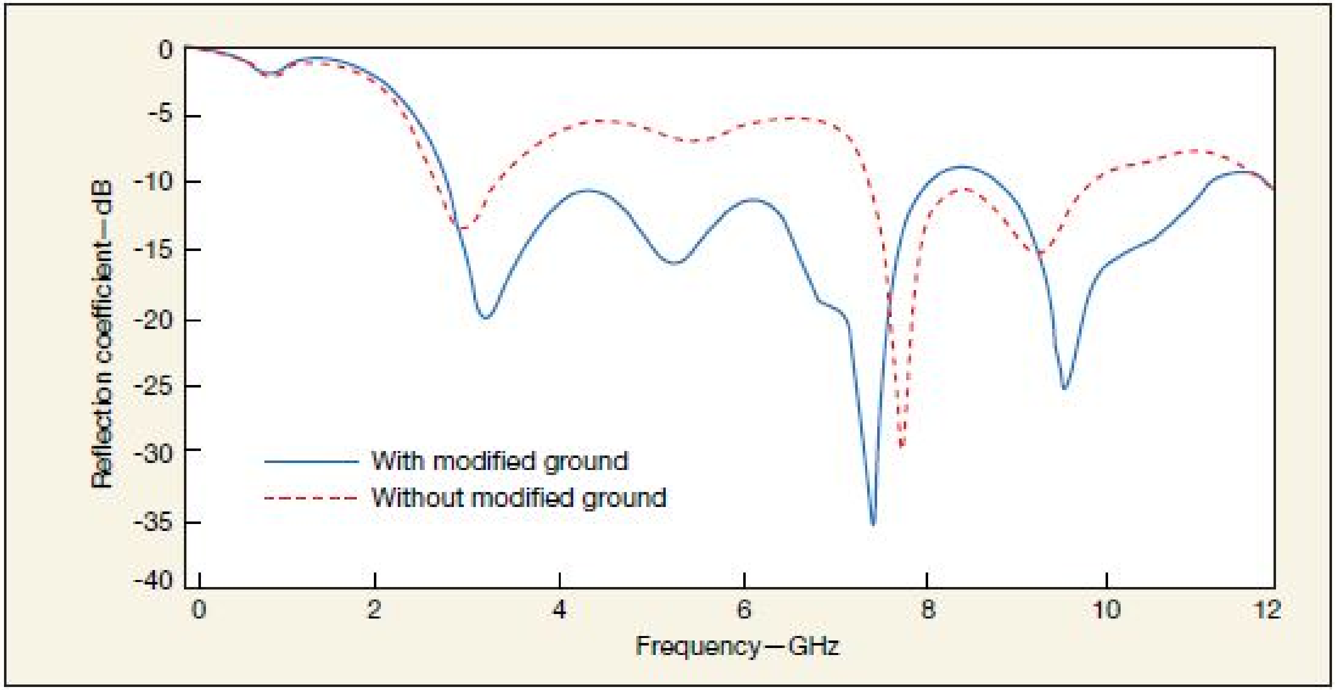
Fractal antenna



# Radiometry Chambers?

- „Squashing the cauliflower“ and going to Q=1 with a detection chamber „coated“ on the inside with fractal antennas.
- Should get a decent bandpass over a broad range of frequencies.
- Should get the sensitivity of the total inner surface area by adding (correlating) signals from individual fractal antenna elements.
- The correlation should also provide full 4π directional sensitivity of measurement.





# Radiometry Chambers

- ❑ Time resolution of ~3 ns ($L_{xyz}$/m).
- ❑ Both time and spectral resolution (~10 Hz) are achieveable with exitsing radioastronomy detector backends
- ❑ Coherent addition of signal – effective Q ~ number of detector elements.
- ❑ Coherent addition of signal – full directional sensitivity
- ❑ Possible prototype: cylindrical chamber, with fractal antenna elements at both ends of the cylinder.

# Summary

- WISP detection relies on low energy experiments; experiments in the radio regime are particularly promising

- WISPDMX: First direct WISP dark matter searches in the 0.8-2.0 μeV range: completing measurements at nominal resonances (Phase 1).

- Next steps:.
  - WISPDMX: Definitive searches for hidden photon (Phase 2) and ALP (Phase 3) dark matter in the 0.8-2.0 μeV range.
  - Further design and implementation of broad-band approaches to WISP searches over the $10^{-2}$–$10^{-6}$ eV mass range.

- This is an emerging field of study that has a great scientific potential.