First results from WISP Dark Matter eXperiment

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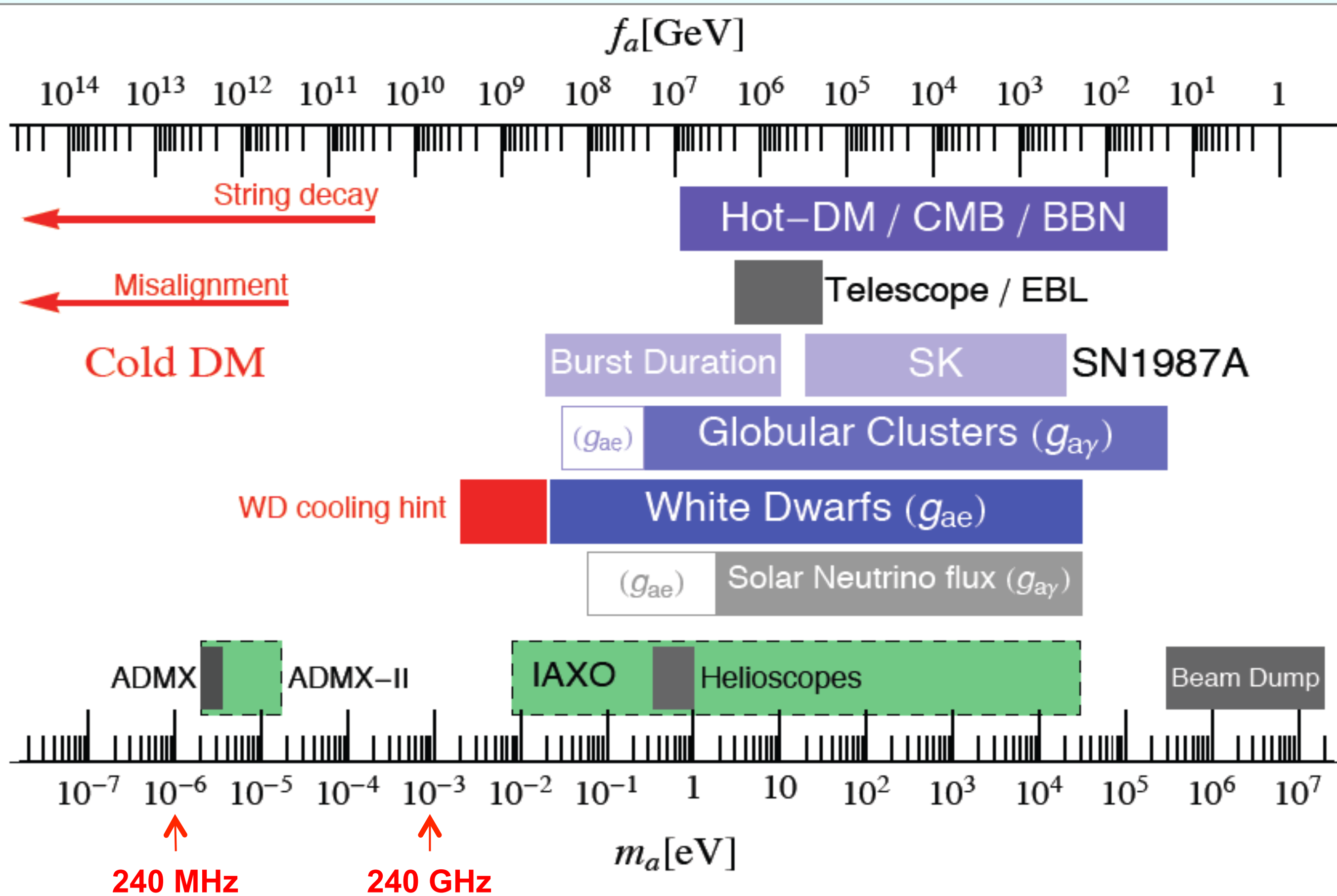
WISP DM Searches in Radio

- The strongly motivated mass range for axion DM ($10^{-2} - 10^{-7}$ eV) is probed efficiently by measurements in the 20 MHz – 2 THz frequency range.
- Highly sensitive experiments in this range are needed: narrow band searches with tunable microwave cavities and new, broadband methods.



Methodology

- Hidden photons (γ'):
  -- 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 (ϕ):
  -- 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 factor; B_0 —— magnetic field strength; $g_{\phi/\gamma}$ —— form factor; ρ_0 —— DM density; $Q_{\phi/\gamma}$ —— quality factor of DM signal; $m_{\phi/\gamma}$ —— par

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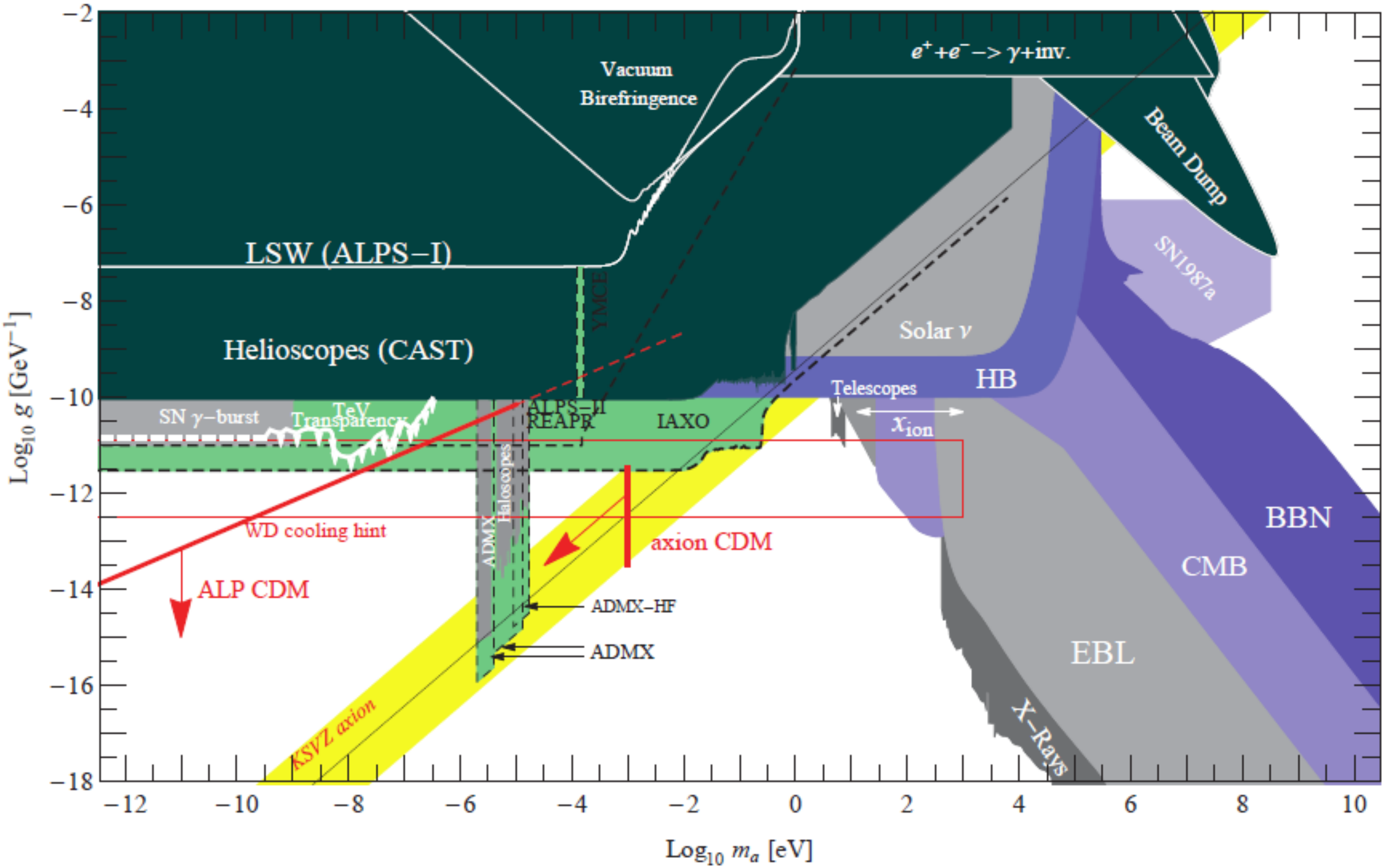
Current Limits: Axions



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Current Limits: Hidden Photons

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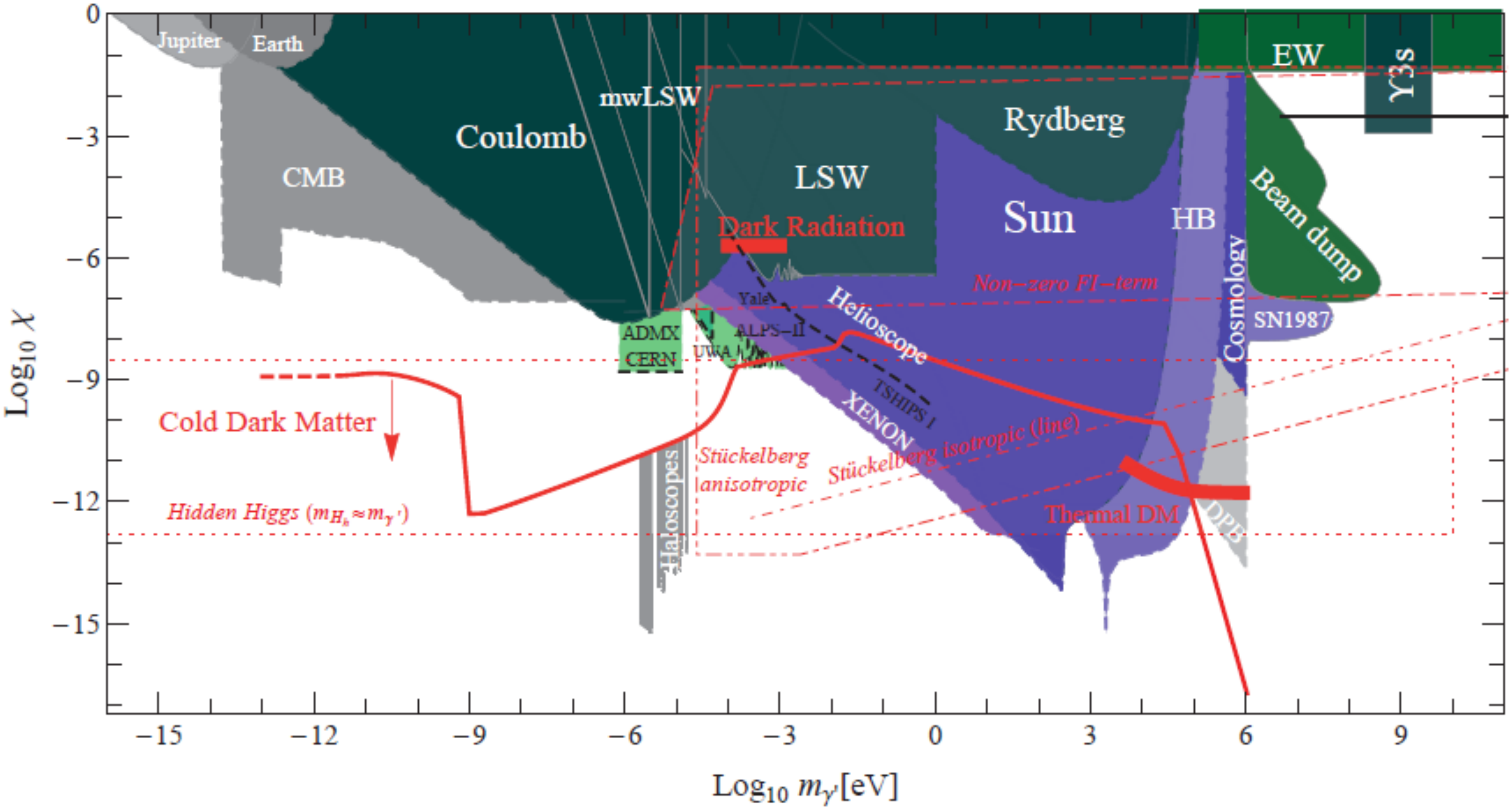

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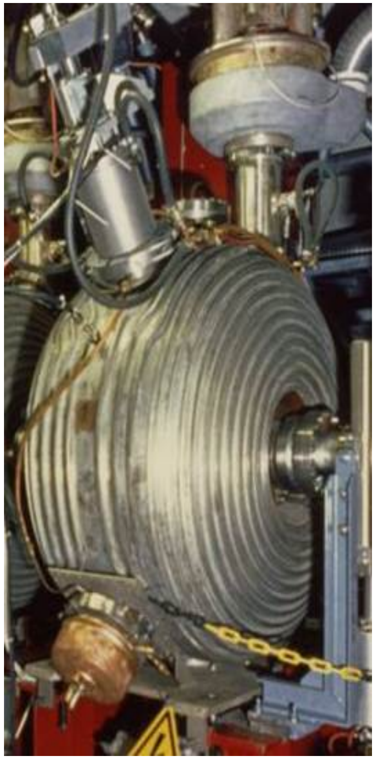
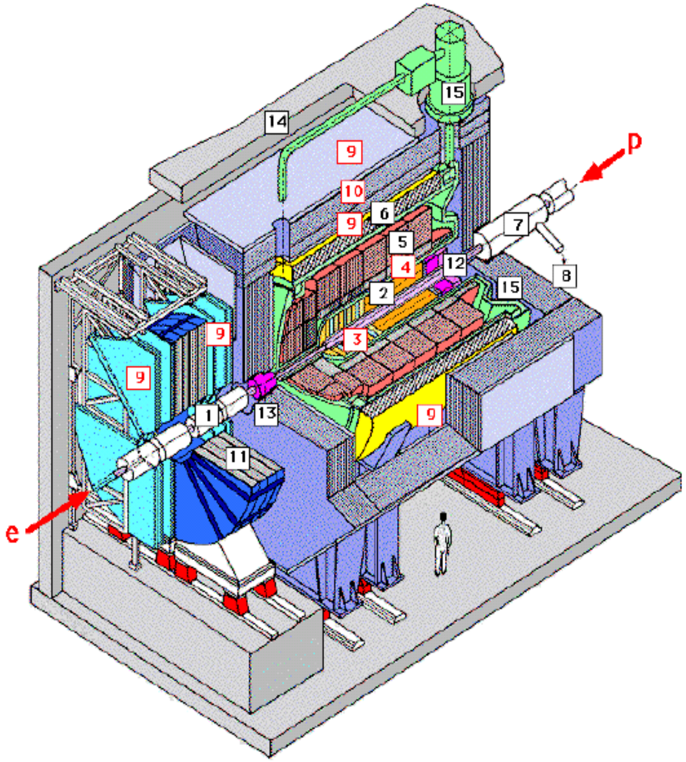
WISPDMX Overvirew

- WISP Dark Matter eXperiment (WISPDMX) is a pioneering search for hidden photon and axion dark matter in the 0.8-2.6 μeV 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 dipole magnet (e.g. 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: Axion searches





Photograph of the HERA 208-MHz cavity (left) and graphical sketch of the H1 magnet to be used for the axion searches with WISPDMX.

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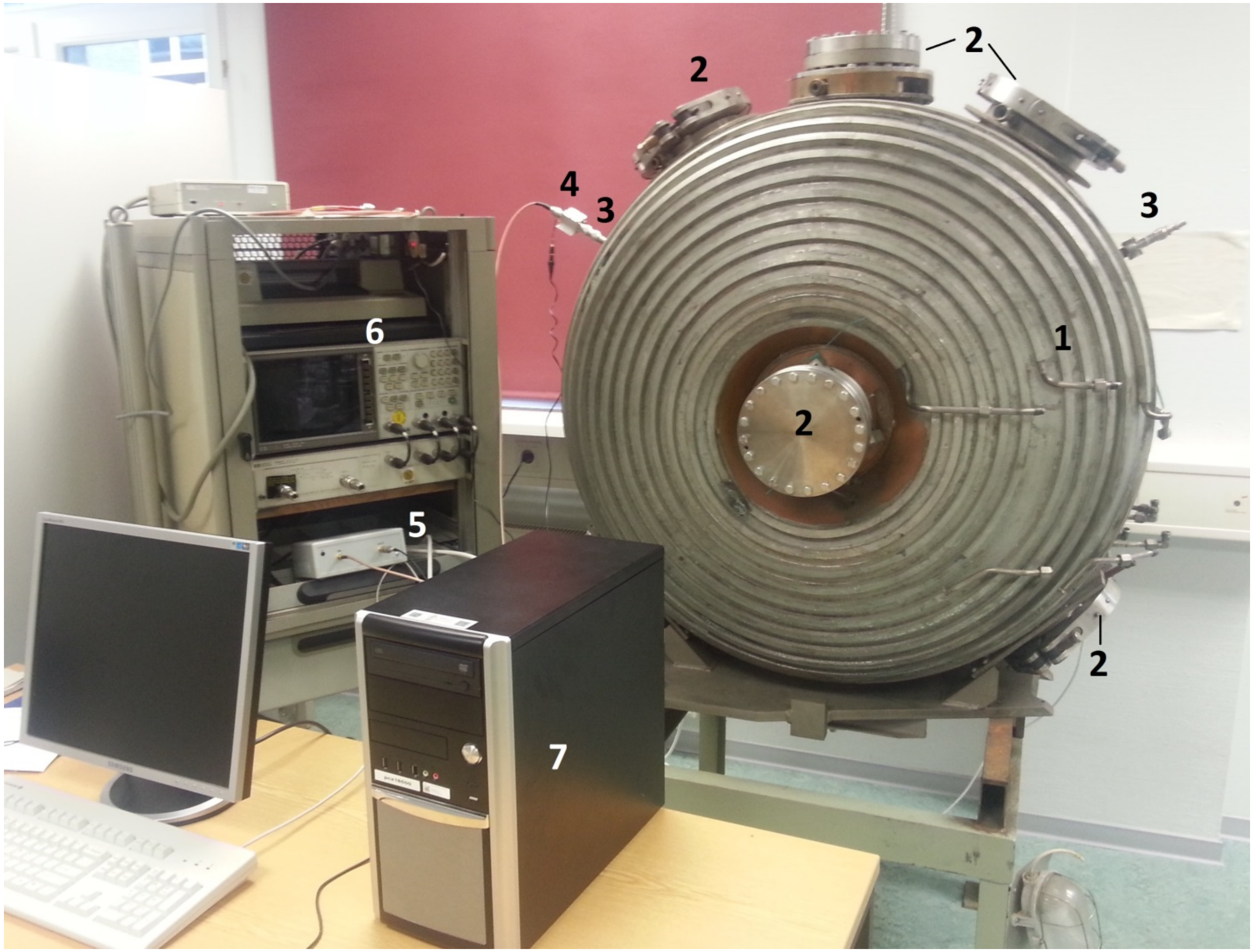
WISPDMX Phase 1



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 on board digitizer (Alazar ATS-9360, 1.8Gs/s)

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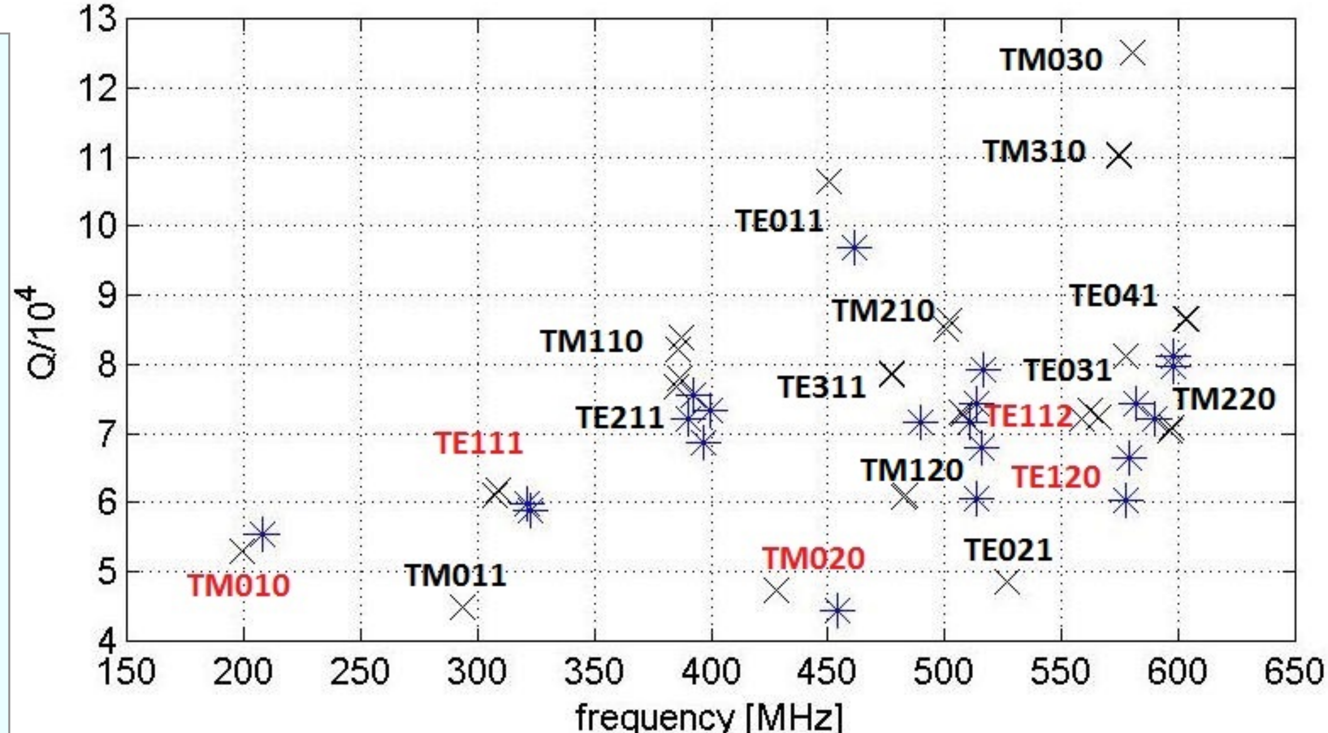
Accessible Resonant Modes

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



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

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First Results: Noise Spectra

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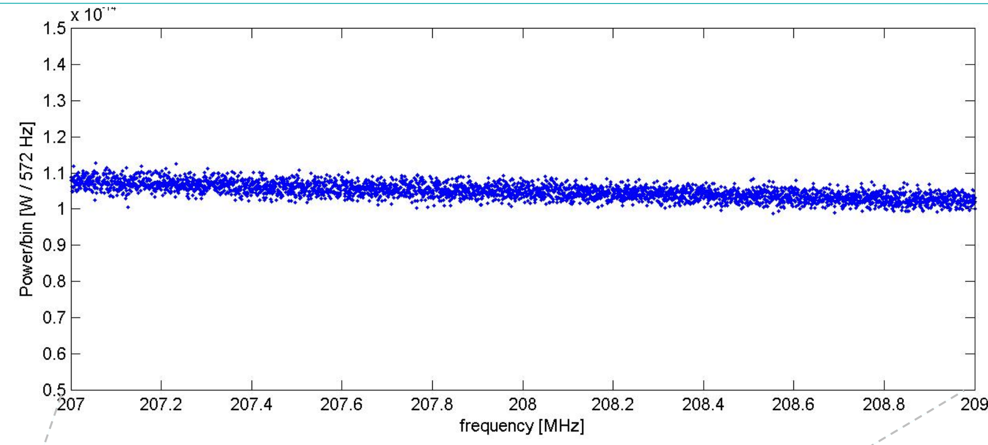
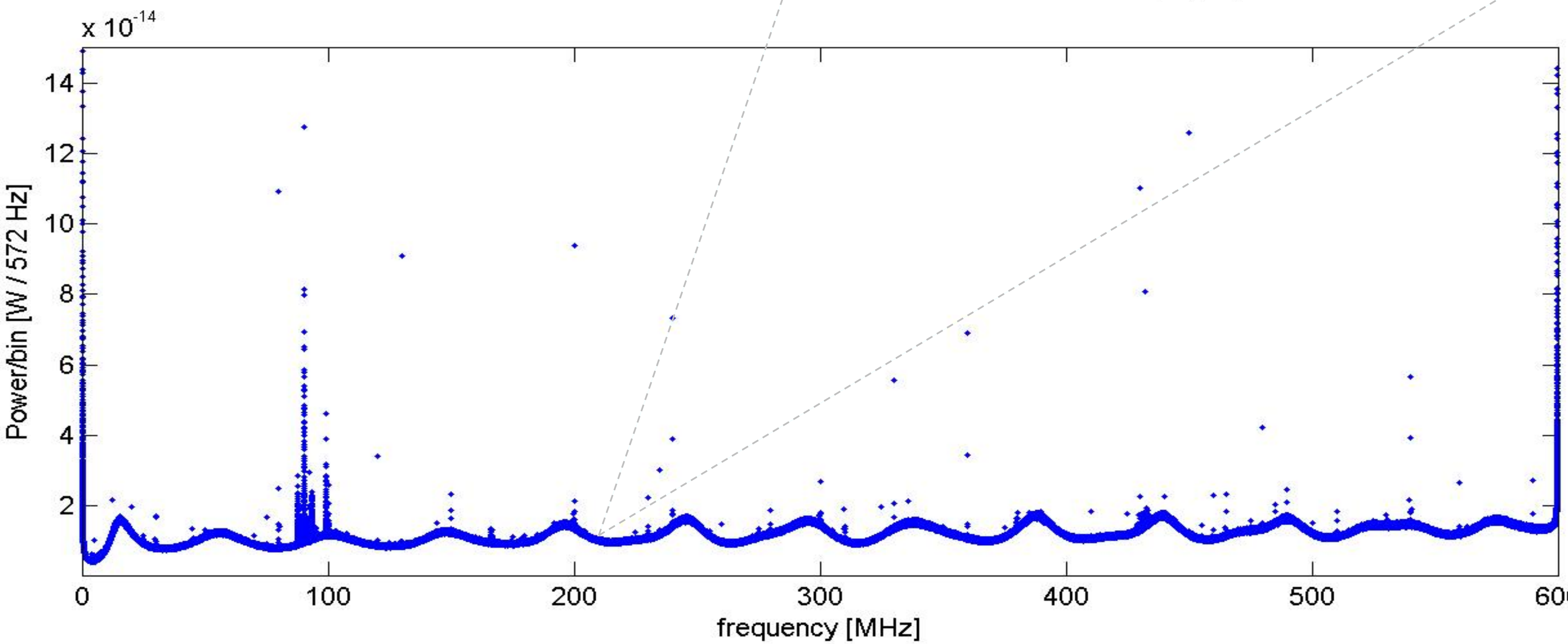
Measured power in the 600 MHz band and narrowband section of the spectrum centered on the fundamental resonant mode (207.9 MHz of the cavity).





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First Results

- Recording broadband (600 MHz) signal; useful range: 180--600 MHz; frequency resolution $\Delta\nu = 574$ Hz.
- 40.3 dB amplification; effective measurement time of1.7 hours.
- No HP signal detected. Gaussian distribution of measured power around rms; no daily modulation; no significant RFI signals.
- Limits, assuming $\rho_0 = 0.39\ GeV/cm^3$ and $Q_{\phi/\gamma} = 2.2\cdot 10^6$:

	κ	f/MHz	Q	$\mathcal{G}$	P/W(95 % CL)	$m_{\gamma'}/\mu$eV	χ(95 % CL)
TM_{010}	0.1	207.87961	55405	0.429	$1.08\cdot10^{-14}$	0.85972093	$5.4\cdot10^{-13}$
TE_{111}	0.01	321.45113	59770	0.674	$1.08\cdot10^{-14}$	1.3294150	$8.4\cdot10^{-13}$
TE_{111}	0.01	322.74845	58900	0.671	$1.08\cdot10^{-14}$	1.3347803	$8.5\cdot10^{-13}$
TM_{020}	0.01	454.42411	44340	0.317	$1.08\cdot10^{-14}$	1.8793470	$10.1\cdot10^{-13}$
TE_{112}	0.01	510.62681	71597	0.020	$1.09\cdot10^{-14}$	2.1117827	$28.2\cdot10^{-13}$
TE_{112}	0.01	515.97110	67840	0.019	$1.09\cdot10^{-14}$	2.1338849	$29.5\cdot10^{-13}$
TE_{120}	0.01	577.59175	60350	0.036	$1.10\cdot10^{-14}$	2.3887274	$20.4\cdot10^{-13}$
TE_{120}	0.01	579.25126	66520	0.037	$1.10\cdot10^{-14}$	2.3955906	$19.1\cdot10^{-13}$

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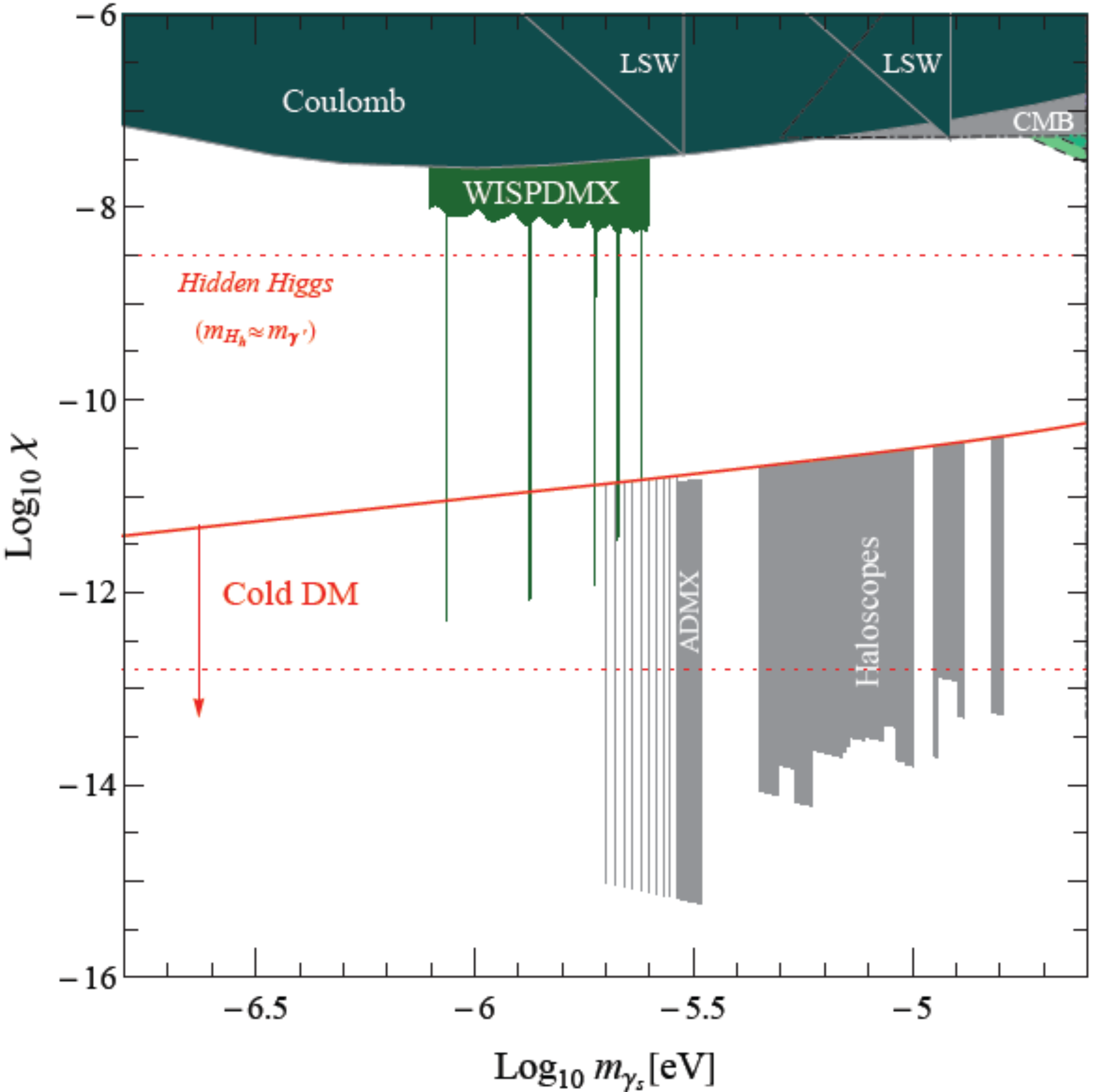
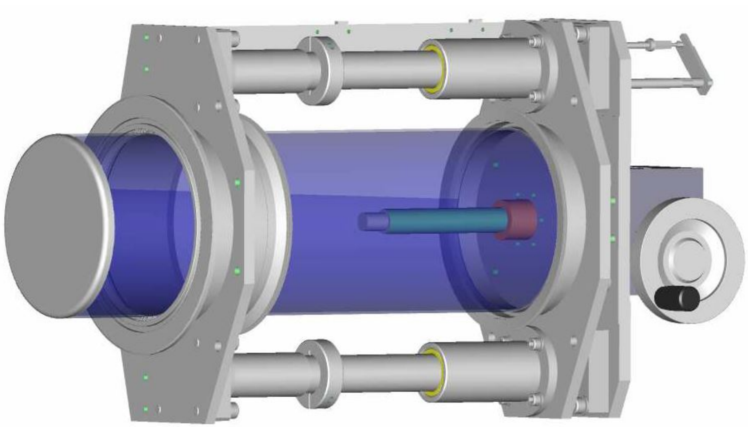
Exclusion Limits

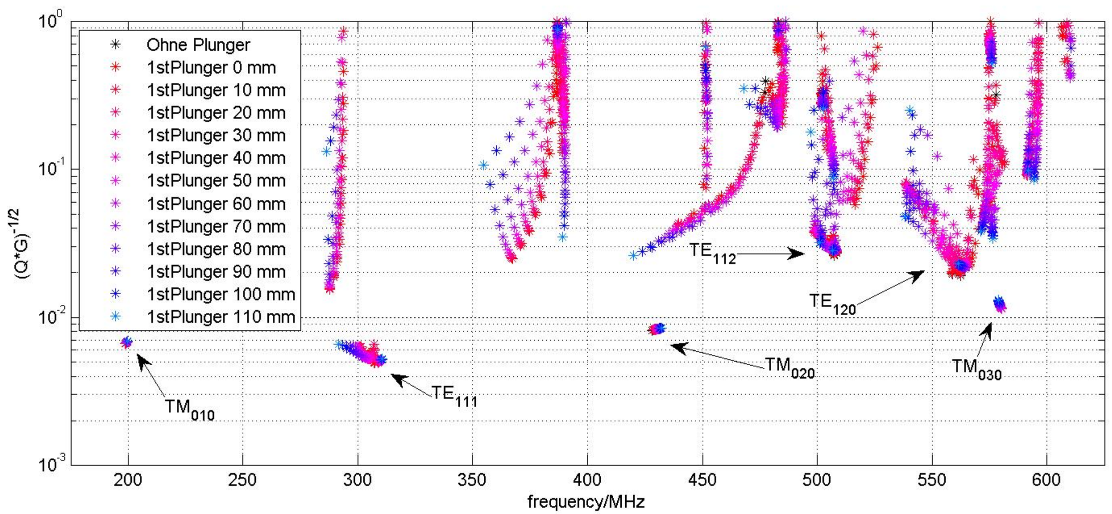
- Exclusion limits from WISPDMX Phase 1 measurements: evaluating the broadband signal.
- Further improvements (factor ~10^2) will come from stronger amplification, improving the frequency resolution (using downconverter), and cooling the apparatus.



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 limits

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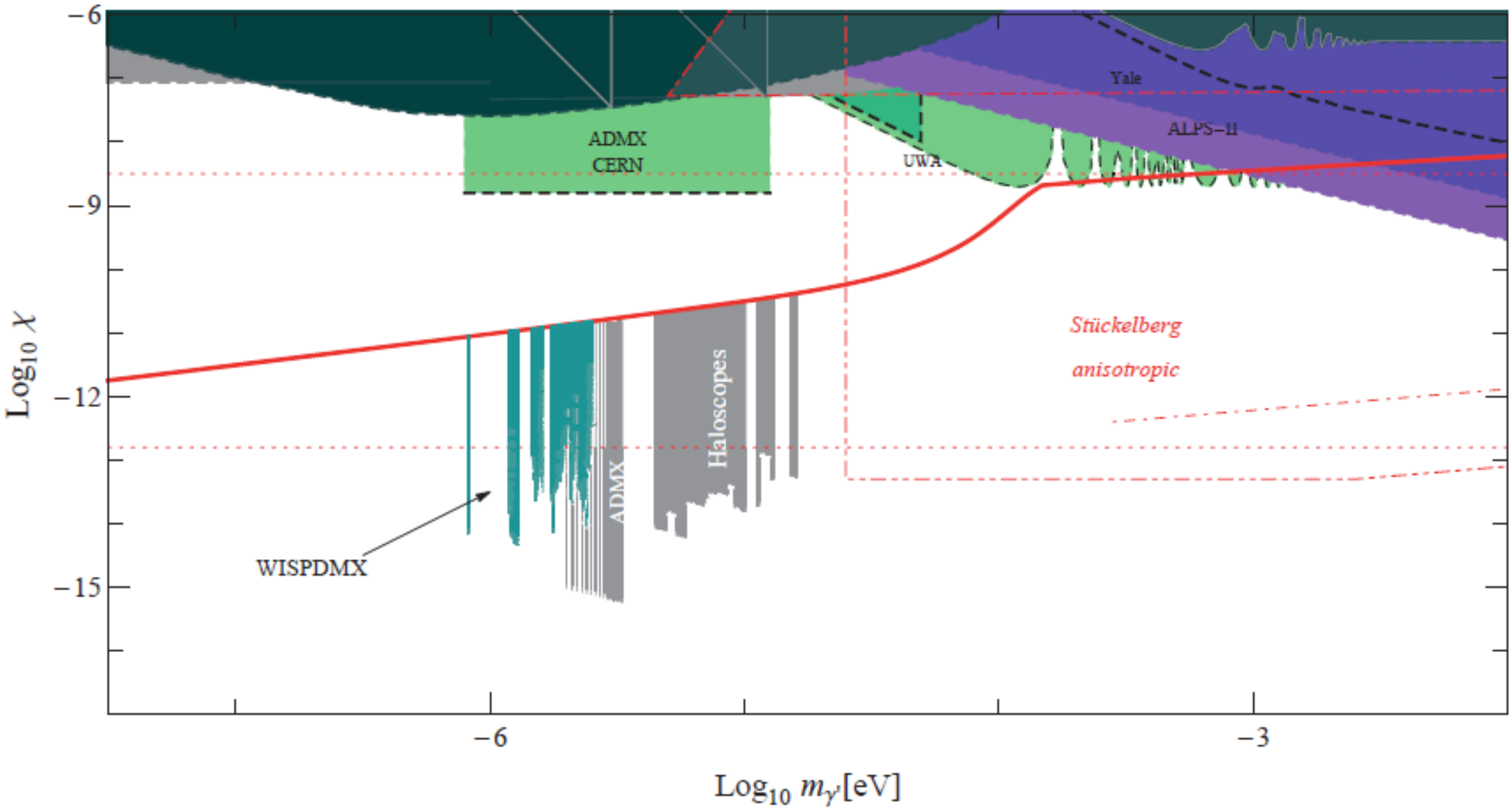

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Phase 3: Expected limits

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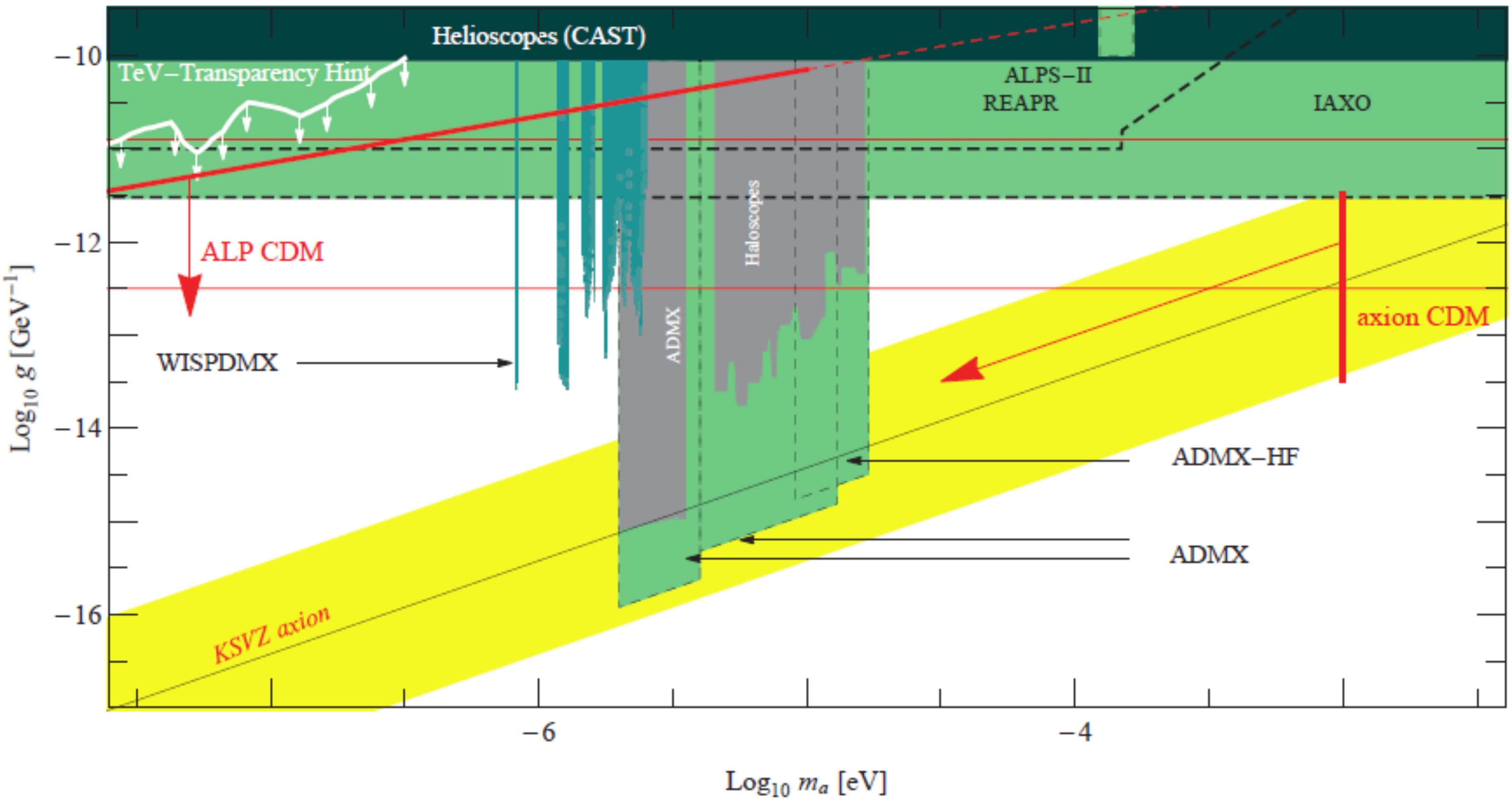

Broadband Experiments

- Suppose we have a mass range (m_1,m_2=αm_1; α>1) of interest for WISP searches.
- Number of individual measurements needed to cover this range is:

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

- 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

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

- Suppose that typically $T_b = 100 T_n$, $B_b = 1.0 B_n$, $V_b = 100 V_n$, and $G_b = 0.01 G_n$.
- 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)

  -- working in the „mode overlap“ regime (at $\lambda \ll V \uparrow 1/3$)

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

- **Several ways to pay for that:**

  -- taking difraction aboard

  -- „dirtying“ the particle coupling (especially to axions)

  -- spreading detectors all over

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

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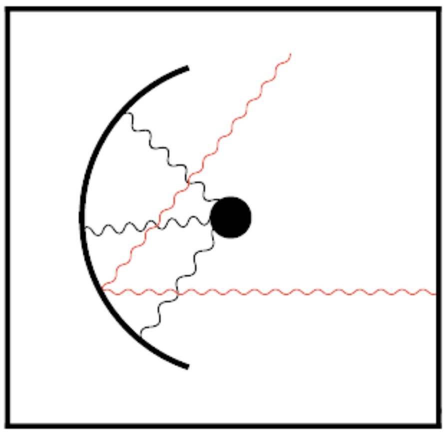
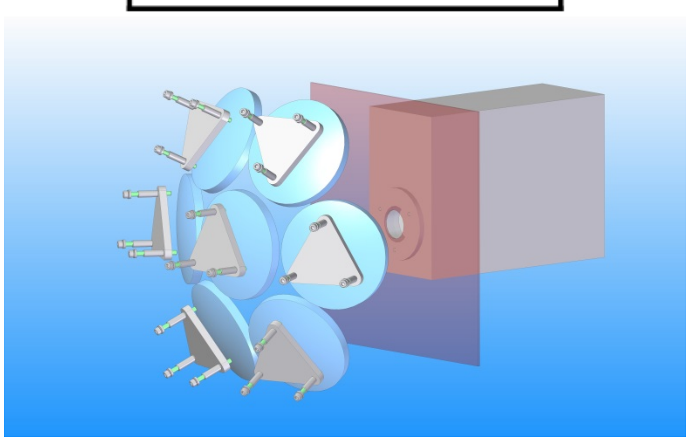
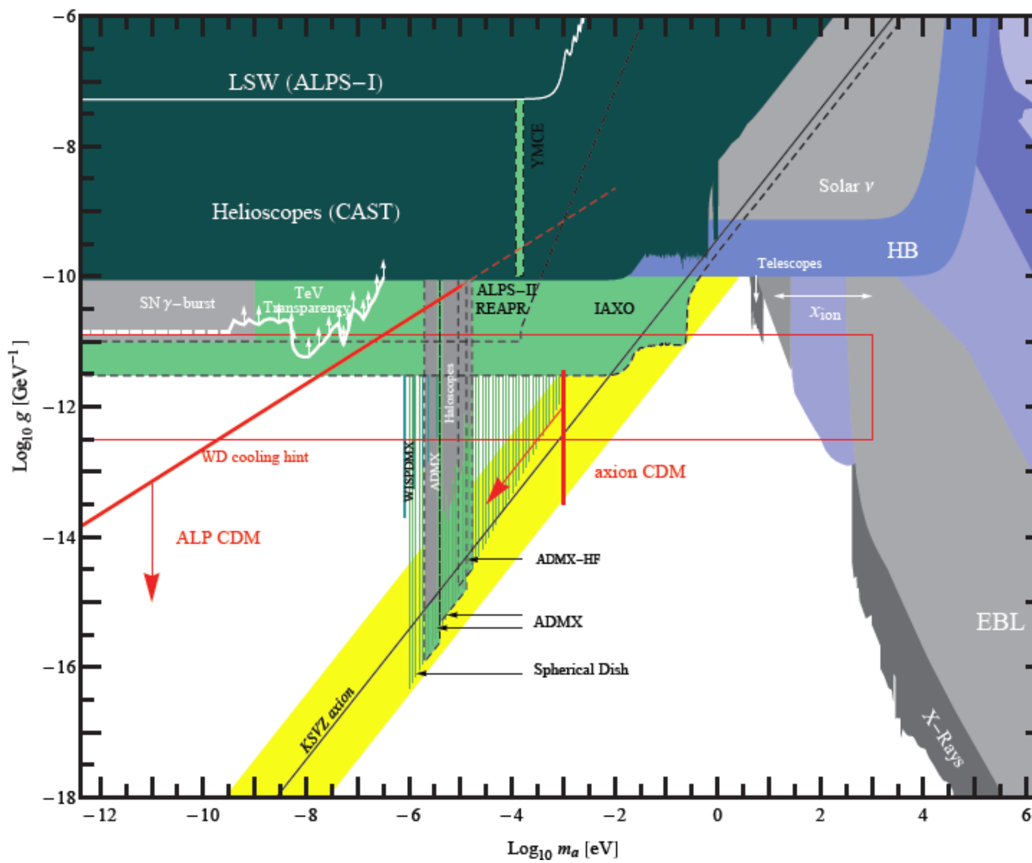
Using Spherical Reflectors

- 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). Promising for masses above 10 μeV.
- Pilot study is underway at DESY (Döbrich et al.)

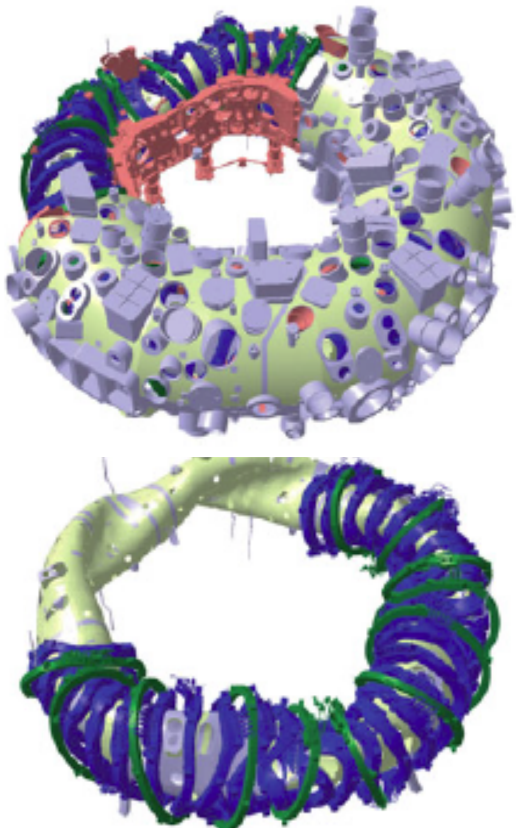




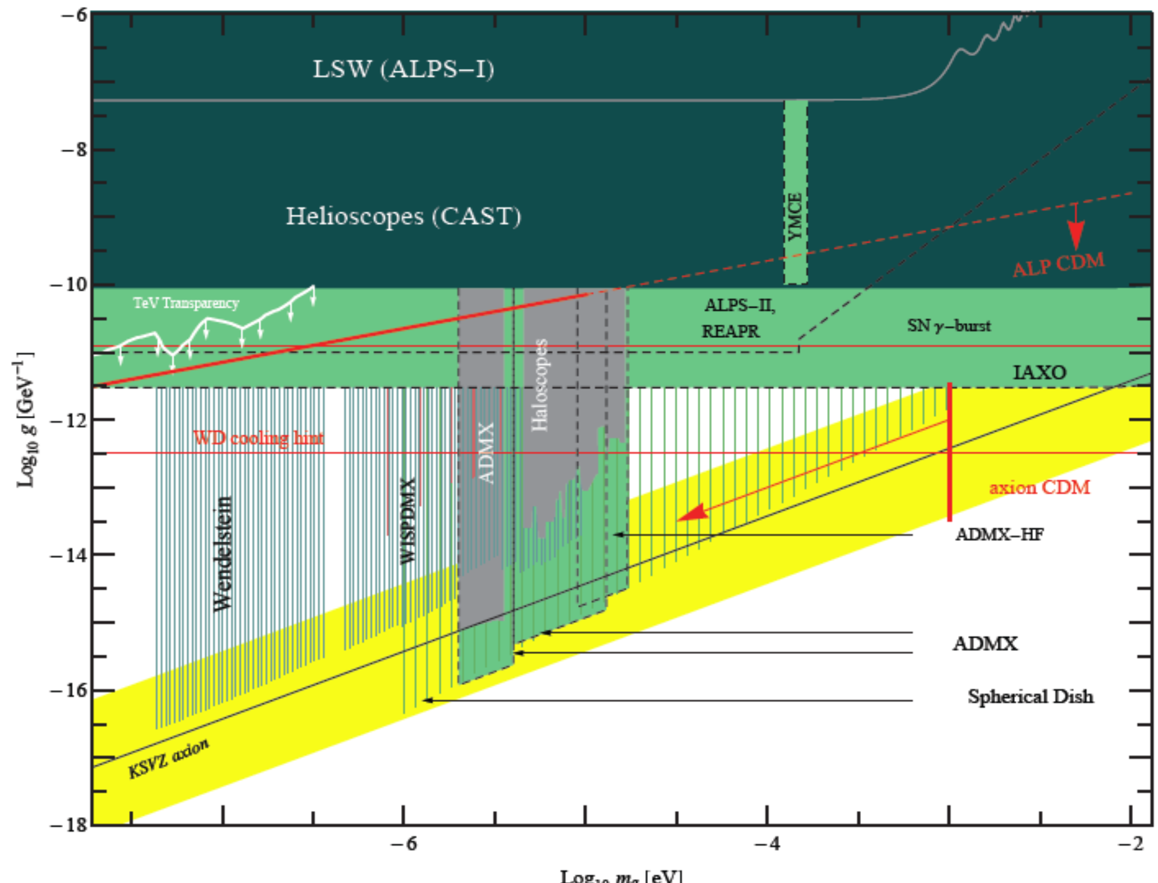


Superconducting Tokamaks

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

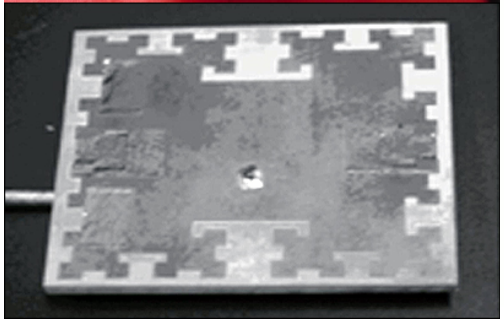


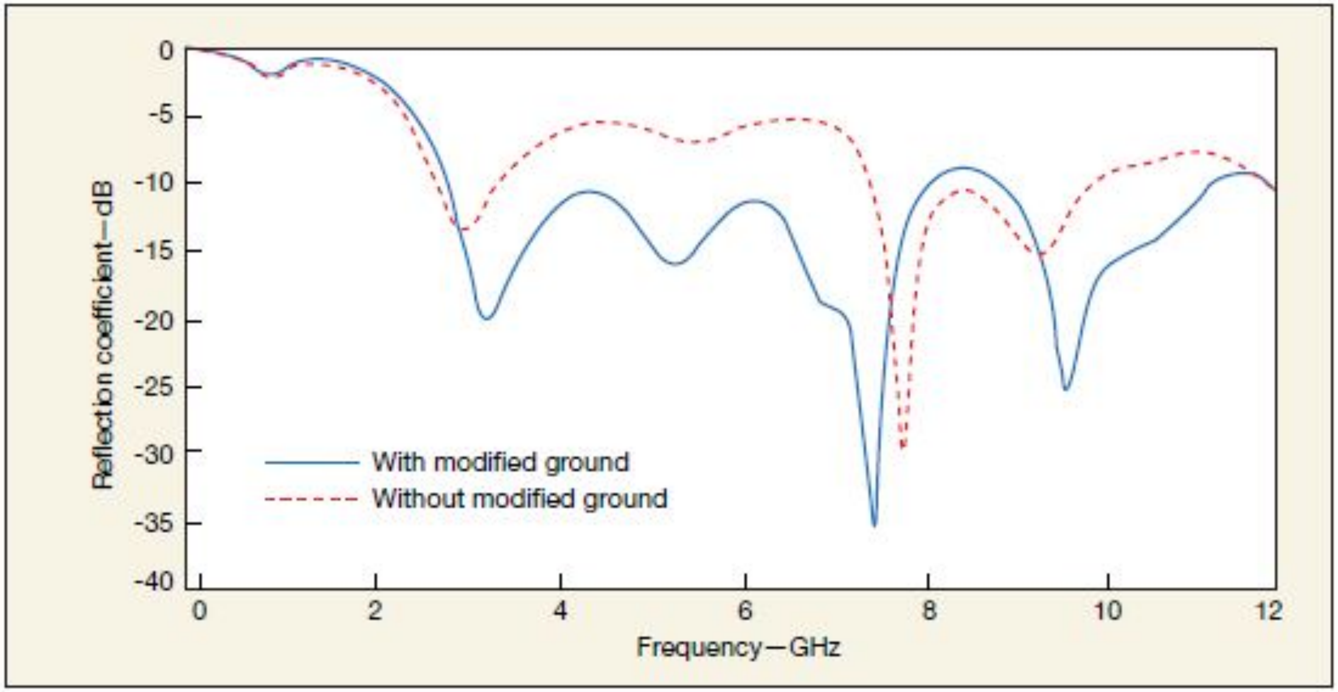
W7-X: magnetic coils and plasma vessel



Thinking (back) inside the Box?

- „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.





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Summary

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

- The radio regime is uniquely suited for closing the last gaps in the strongly favoured 1 – 5 μeV range for the axion mass and extending down to ~10^{-19} eV the range of the hidden photon mass probed.

- Next steps:.
  - Definitive microwave cavity experiments for axion and hidden photon searches at 0.2 – 1.0 GHz (1 – 5 μeV).
  - Pilot broadband measurements with a spherical reflector
  - Further design and implementation of broad-band approaches to WISP searches over the 10^{-2}–10^{-7} eV mass range.

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

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