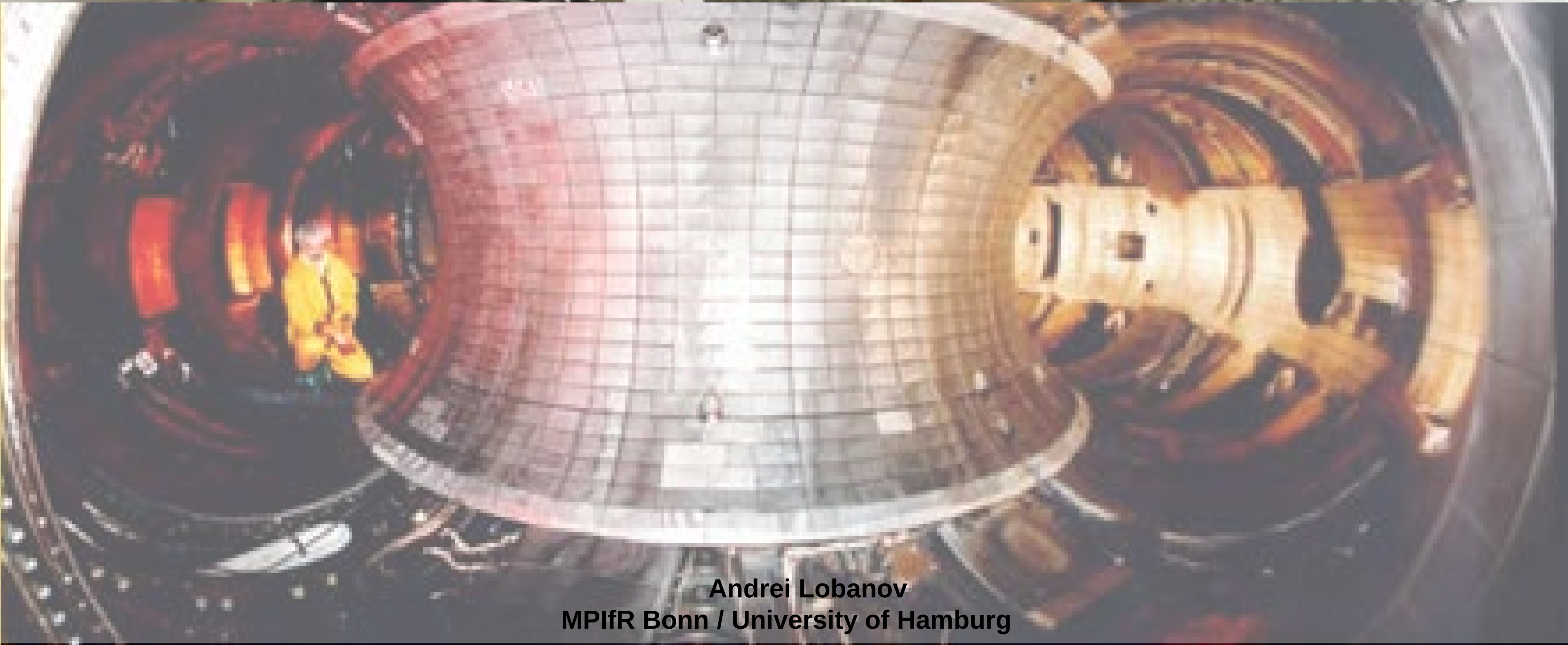
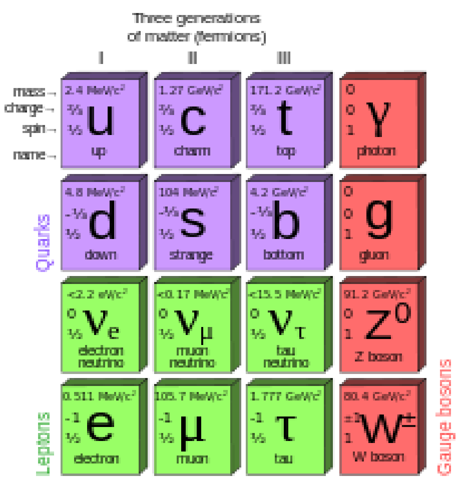
Tuning Your Radio to Axions and Their WISP Cousins

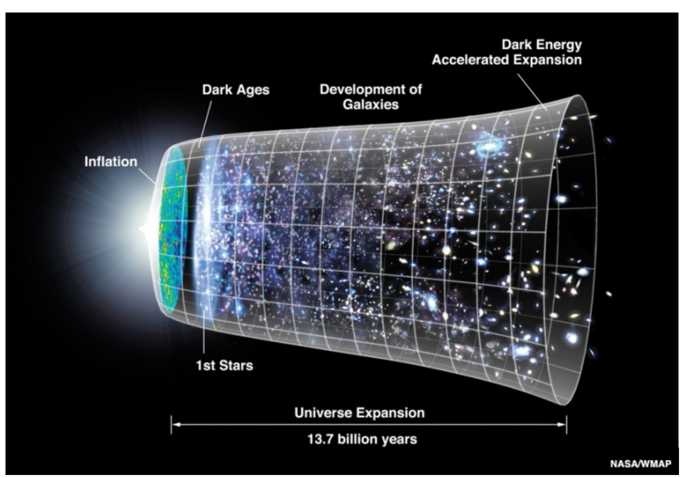


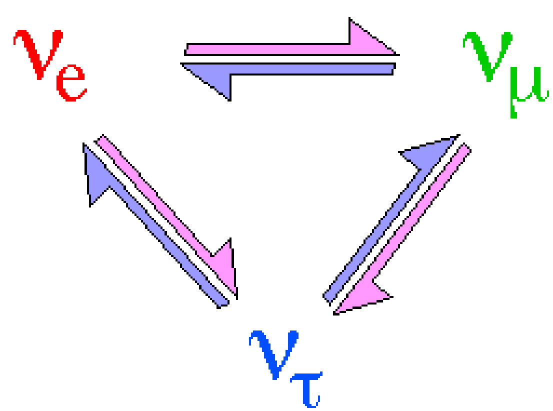
Andrei Lobanov
MPIfR Bonn / University of Hamburg

Two+ Clouds of SM

- Standard Model: $SU(3)\times SU(2)\times U(1)$ gives us (nearly) all things we may need in life.
- *„The beauty and clearness of the dynamical theory, […], is at present obscured by two clouds […]" (Lord Kelvin, 1900) … still true today?*
  – gravitation and dark energy
  ...plus some „lesser evils" such as dark matter, strong CP problem, etc...
- Most of the solutions proposed invoke a „hidden sector" of the global parameter space, weakly coupled to „normal matter" of the SM through weakly interacting massive (WIMP) or slim (WISP) particles.







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Many Faces of WISP

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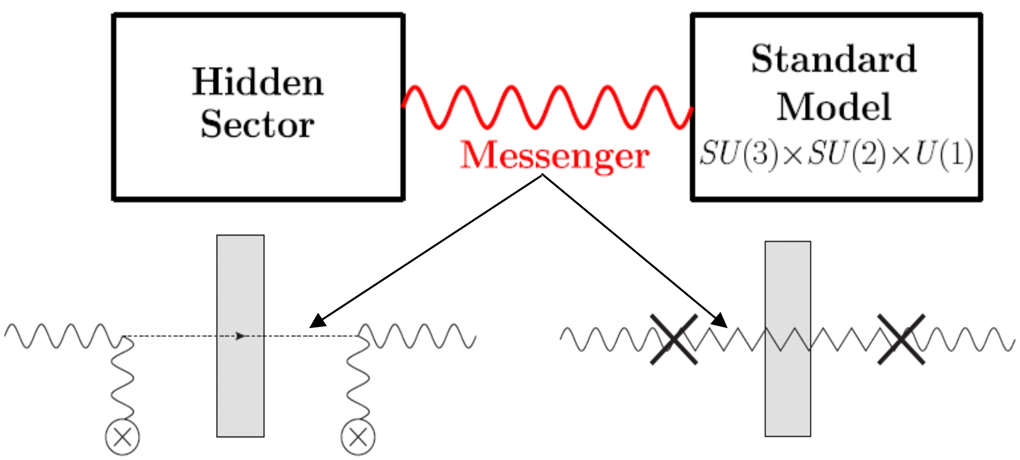
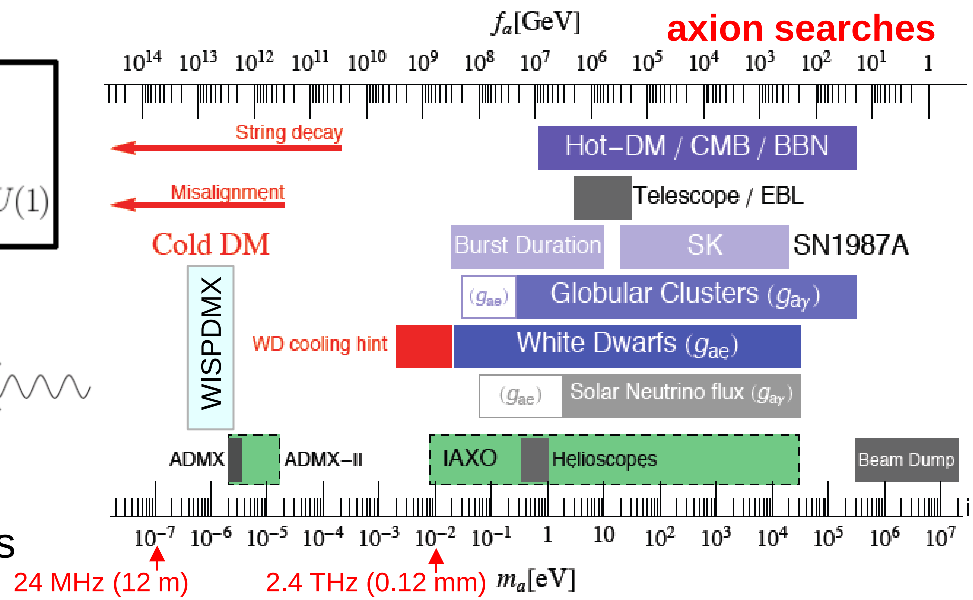
- WISP, and *axions* and *hidden photons* in particular, are strong dark matter candidates. Direct detection of WISP or putting bounds on their properties are important tasks for cosmology and particle physics.
- A number of experimental methods have been employed, both for laboratory and astrophysical searches – all relying on WISP interaction (coupling, kinetic mixing) with ordinary matter (most often: photons).
- Radio (24 MHz—2.4 THz): excellent sensitivity to WISP signal and access to DM/DE relevant particle mass ranges (0.1μev – 10meV)



axions/ALP/MCP/chameleons hidden photons



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Current Limits: Axions

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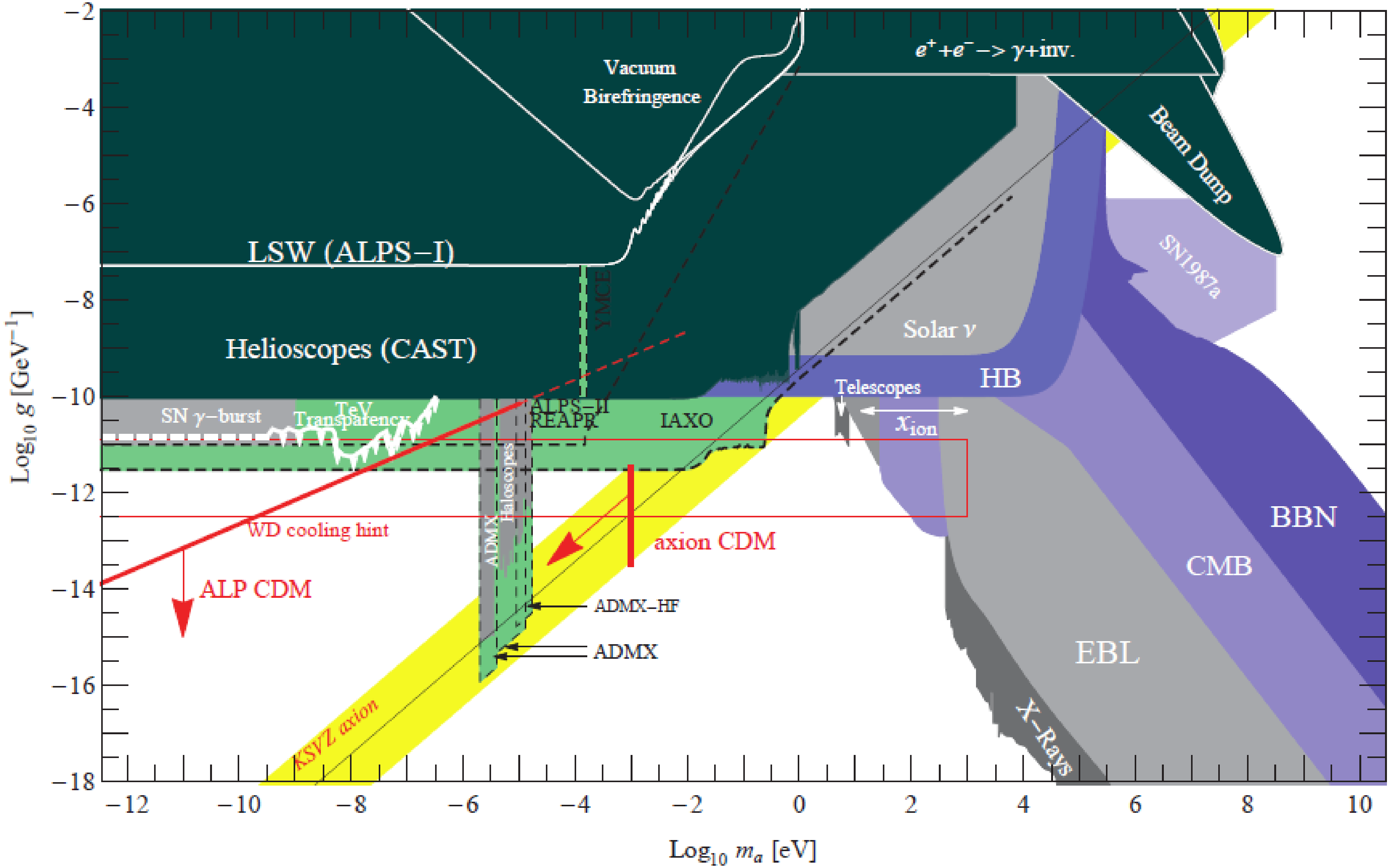

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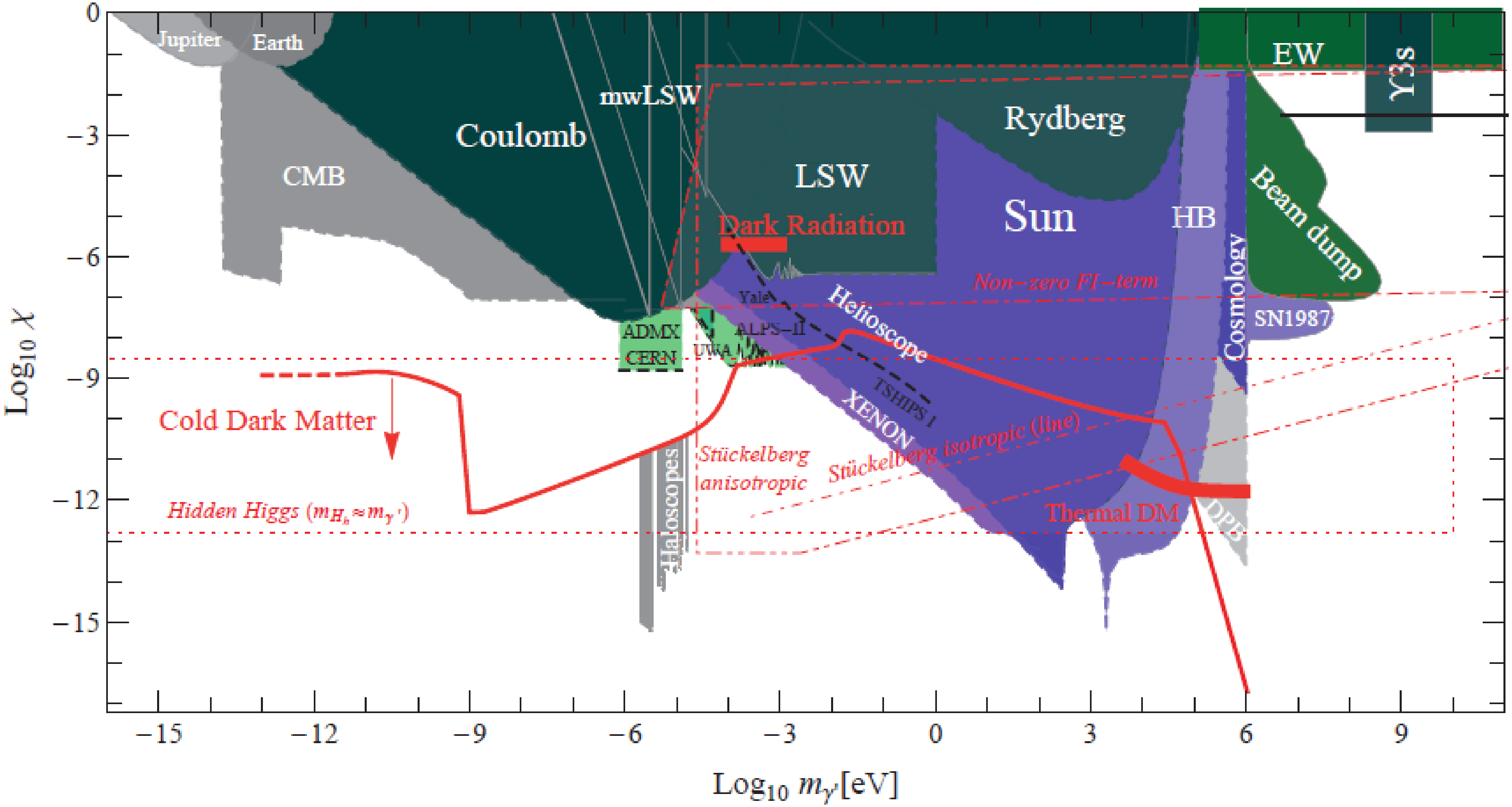
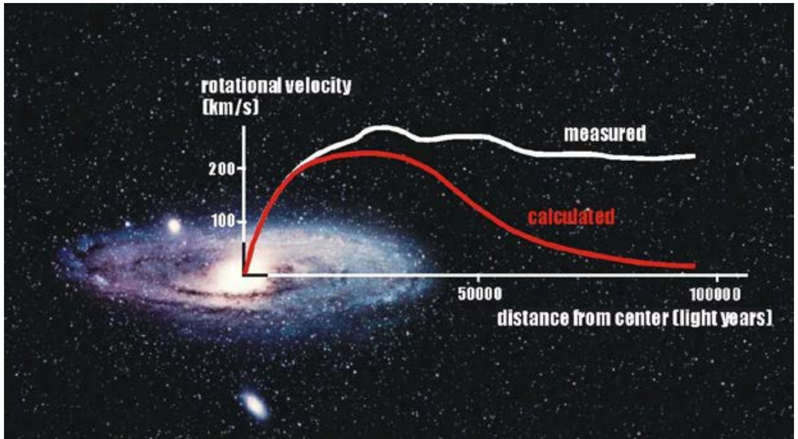
Current Limits: Hidden Photons

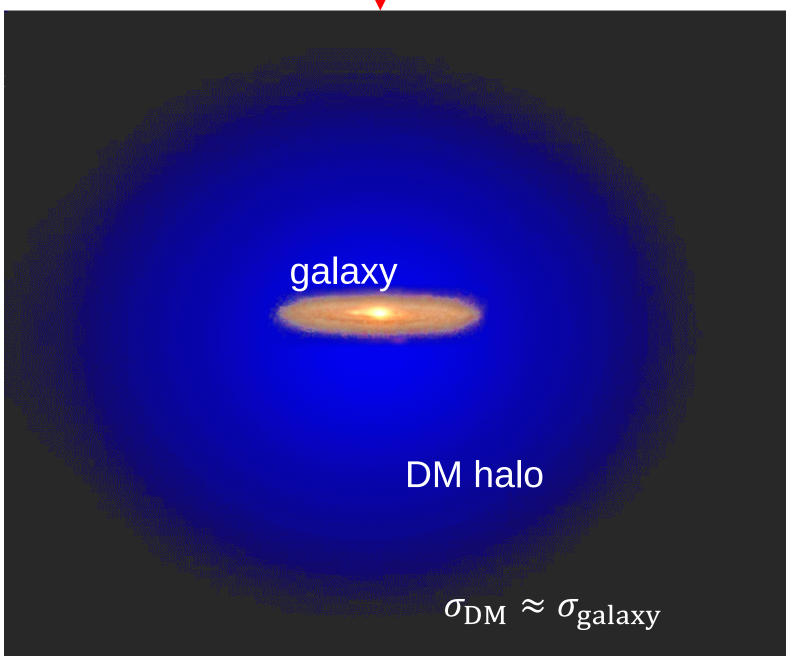


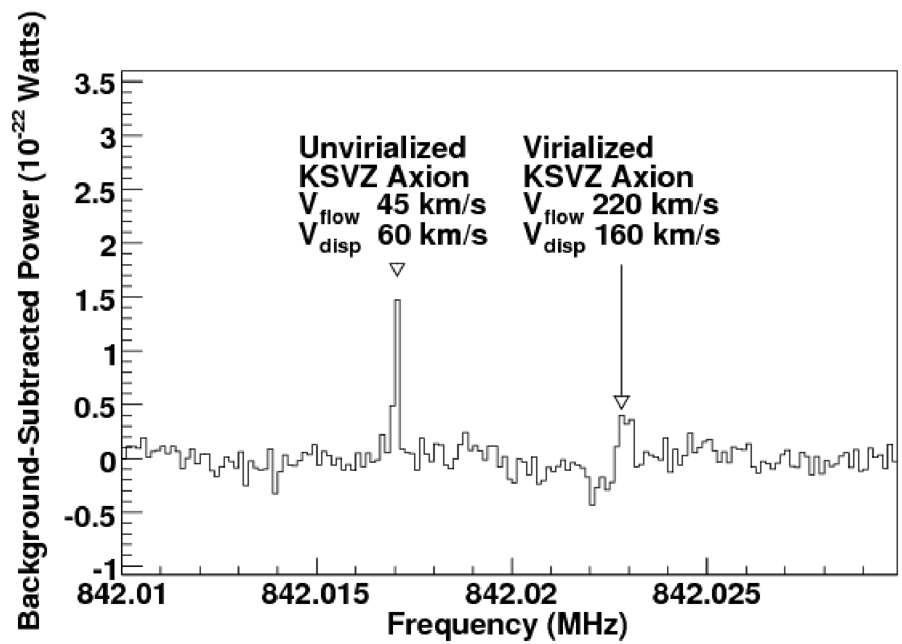
Direct DM Searches



- Dark Matter: sits in a halo, can be virialized with a velocity dispersion similar to the galactic velocity dispersion ($\sigma_g \sim 300$ km/s).
- Axion DM: axion-photon conversion: expect a line with width of

$$\Delta\nu/\nu \sim (\sigma_g/c)^2 \sim 10^{-6}$$





Searching for WISP DM ...

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- 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 and axion-like particles (ϕ):
  -- two-photon coupling (Primakoff process), $\phi \leftrightarrow \gamma + \gamma$, with B-field as a virtual photon
  „Haloscope“ experiments: Coupling strength:

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

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; ρ_0 – DM density; $Q_{\phi/\gamma}$ – quality factor of DM signal; $m_{\phi/\gamma}$ – particle mass

… in A Broad Mass Range

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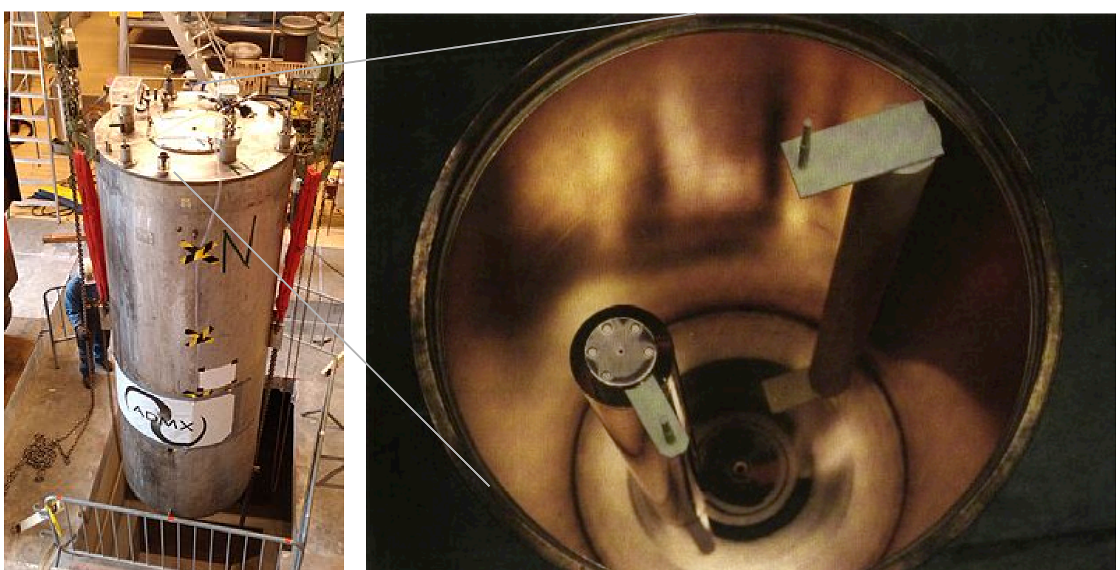
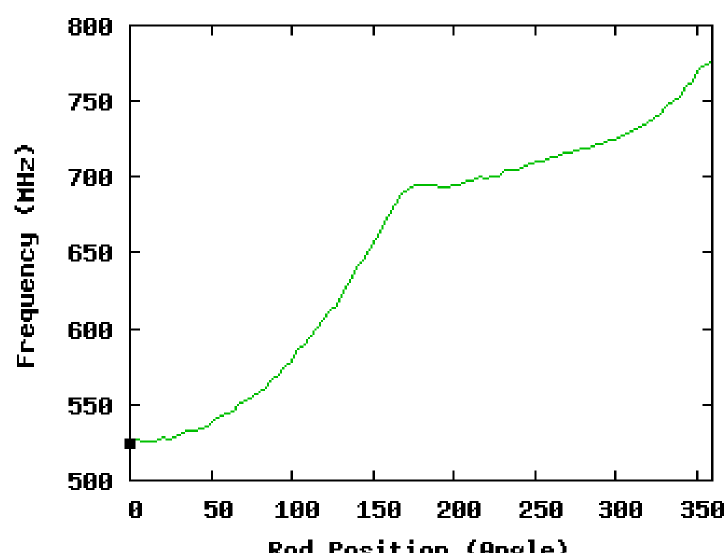
- Resonant measurements have a bandwidth $\Delta\nu/\nu \sim 1/Q \sim 10^{-5}$, hence one needs to tune a cavity and make a large number of measurements in order to scan over a broad range of particle mass.
- Search range: $\Delta\nu/\nu \sim 10^{5}$, which requires $\sim 10^{10}$ measurement steps.
- Alternatives: use multiple resonant modes (requiring fewer tuning steps) or avoid using the resonance at all.

ADMX cavity tuned by an assembly of two tuning rods





Asztalos + 2001, 2010, Bradley+ 2003

Direct WISP dark matter searches in the 0.8–2.0 μeV mass range

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WISPDMX Overview

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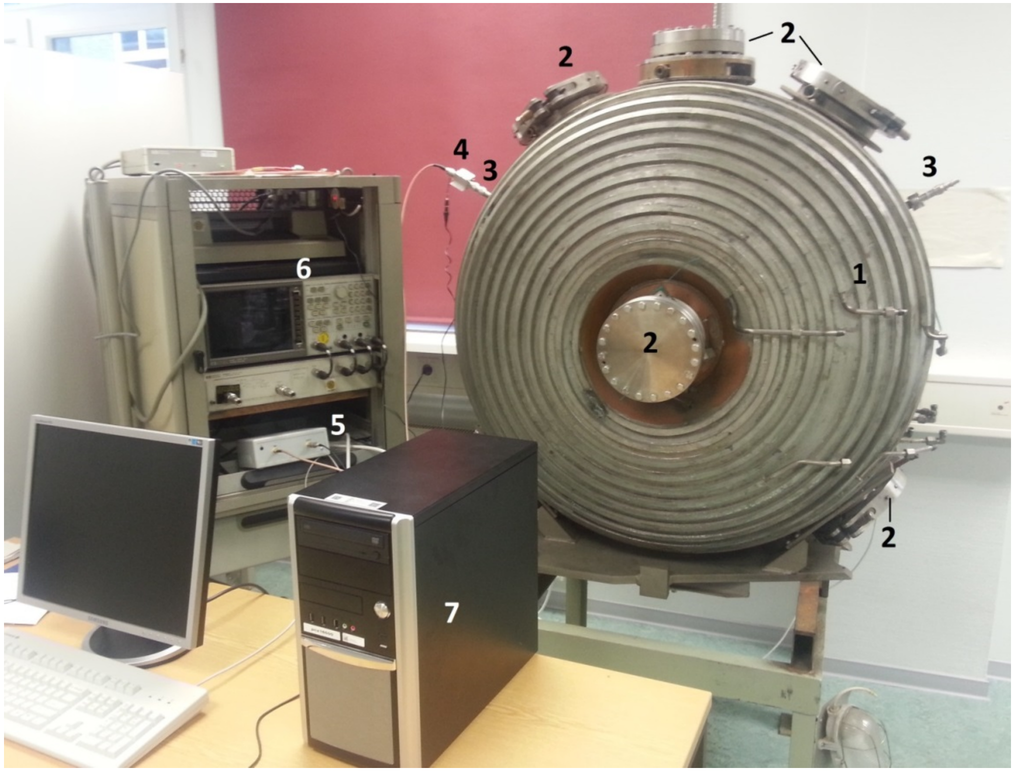
- WISP Dark Matter eXperiment (WISPDMX) is a pioneering search for hidden photon and axion dark matter in the 0.8-2.0 μeV range, exploring the particle masses below the mass range covered by ADMX.

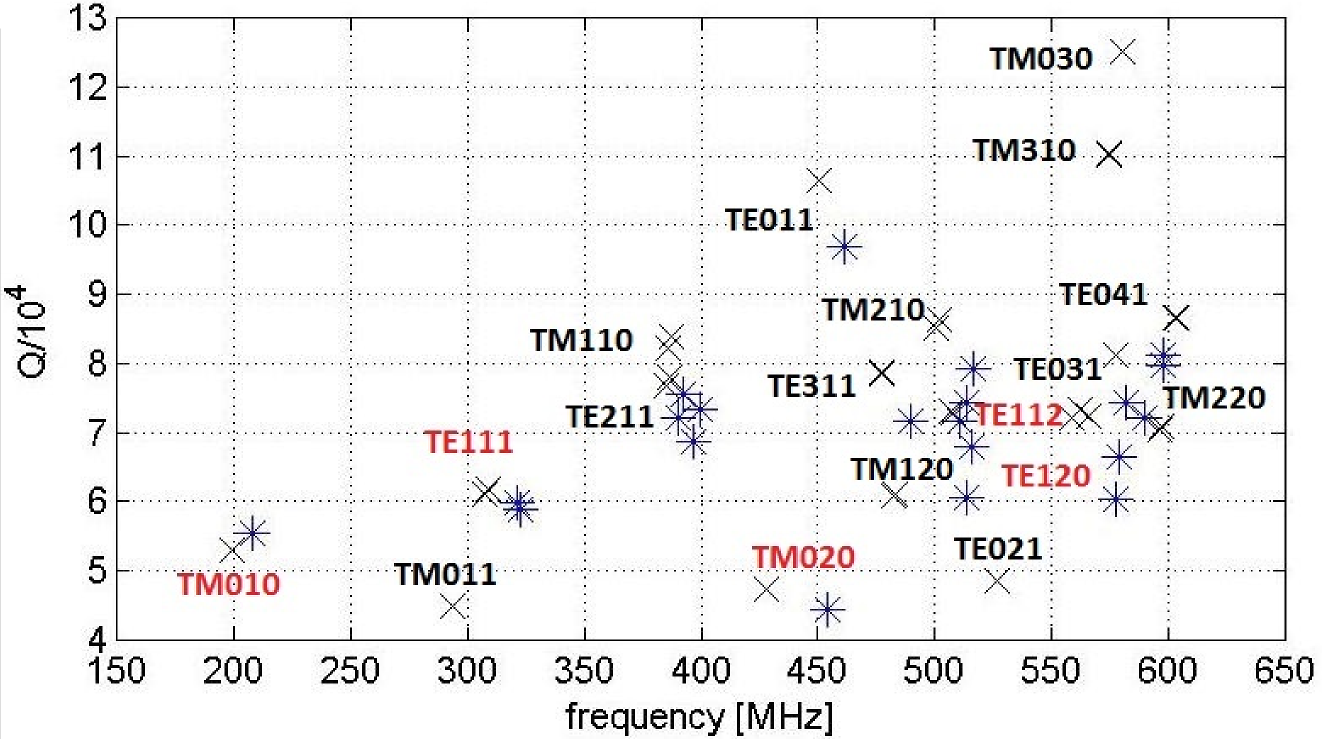
- WISPDMX utilizes a HERA 208-MHz resonant cavity and a 40 dB amplifier chain, and plans to make use of a strong magnet (e.g. 1.15 T H1 magnet).
- Uses multiple resonant modes in the 200-600 MHz range.
- Completed Phase 1: hidden photon searches at nominal resonances of the cavity.
- Currently in Phase 2: HP searches with cavity tuning
- Phase 3: ALP searches



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 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

Results from Phase 1

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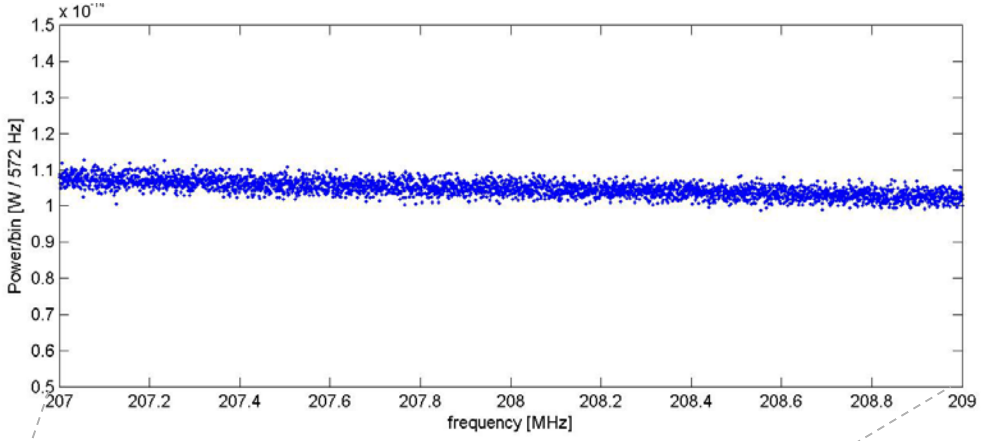
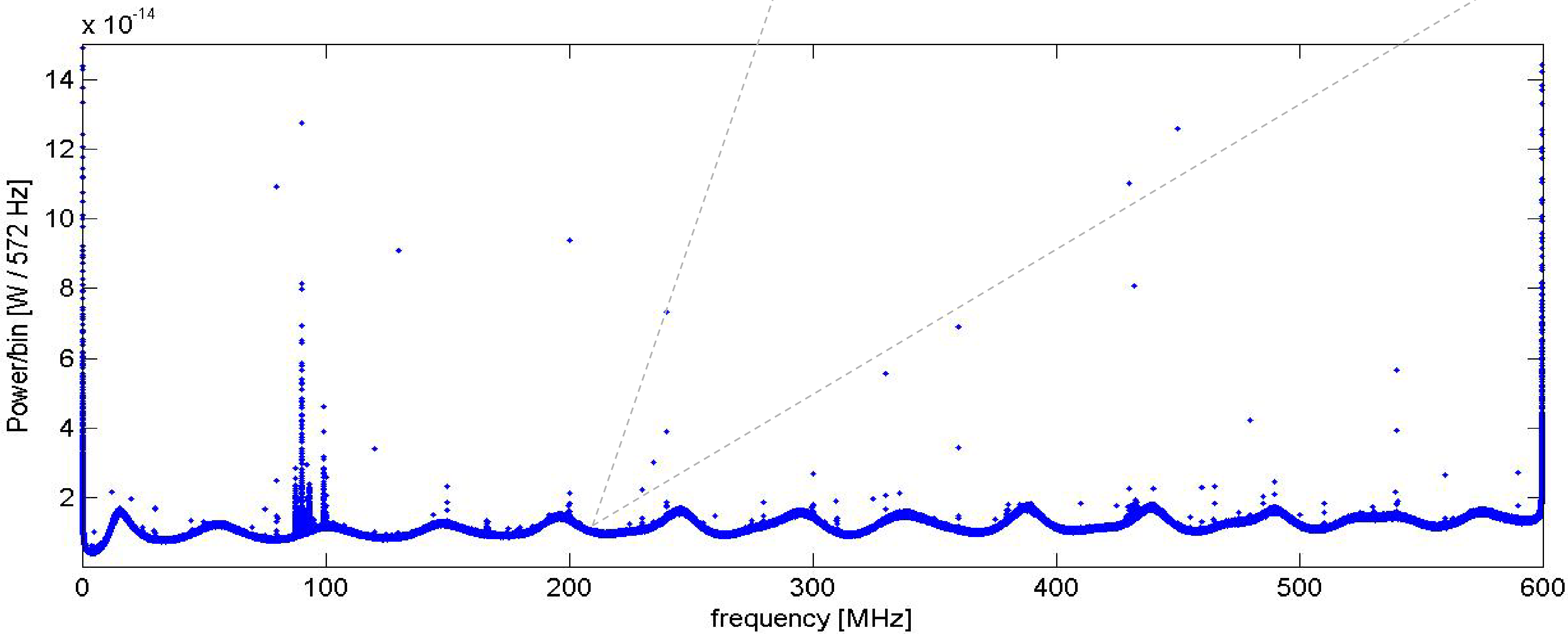
Measured power in the 600 MHz band and narrowband section of the spectrum centered on the fundamental resonant mode (207.9 MHz of the cavity).





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Exclusion Limits at Resonances

- Recording broadband (600 MHz) signal; useful range: 180--600 MHz; frequency resolution $\Delta\nu = 572\ \mathrm{Hz}$.
- 40.3 dB amplification; effective measurement time of 1.7 hours.
- No HP signal detected. Gaussian distribution of measured power around rms; no daily modulation; no significant RFI signals.
- Limits, assuming $\rho_0 = 0.39\ \mathrm{GeV/cm^3}$ 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	$1.08 \cdot 10^{-14}$	0.85972093	$5.4 \cdot 10^{-13}$
TE_{111}	0.01	321.45113	59770	0.674	$1.08 \cdot 10^{-14}$	1.3294150	$8.4 \cdot 10^{-13}$
TE_{111}	0.01	322.74845	58900	0.671	$1.08 \cdot 10^{-14}$	1.3347803	$8.5 \cdot 10^{-13}$
TM_{020}	0.01	454.42411	44340	0.317	$1.08 \cdot 10^{-14}$	1.8793470	$10.1 \cdot 10^{-13}$
TE_{112}	0.01	510.62681	71597	0.020	$1.09 \cdot 10^{-14}$	2.1117827	$28.2 \cdot 10^{-13}$
TE_{112}	0.01	515.97110	67840	0.019	$1.09 \cdot 10^{-14}$	2.1338849	$29.5 \cdot 10^{-13}$
TE_{120}	0.01	577.59175	60350	0.036	$1.10 \cdot 10^{-14}$	2.3887274	$20.4 \cdot 10^{-13}$
TE_{120}	0.01	579.25126	66520	0.037	$1.10 \cdot 10^{-14}$	2.3955906	$19.1 \cdot 10^{-13}$

HP Exclusion Limits

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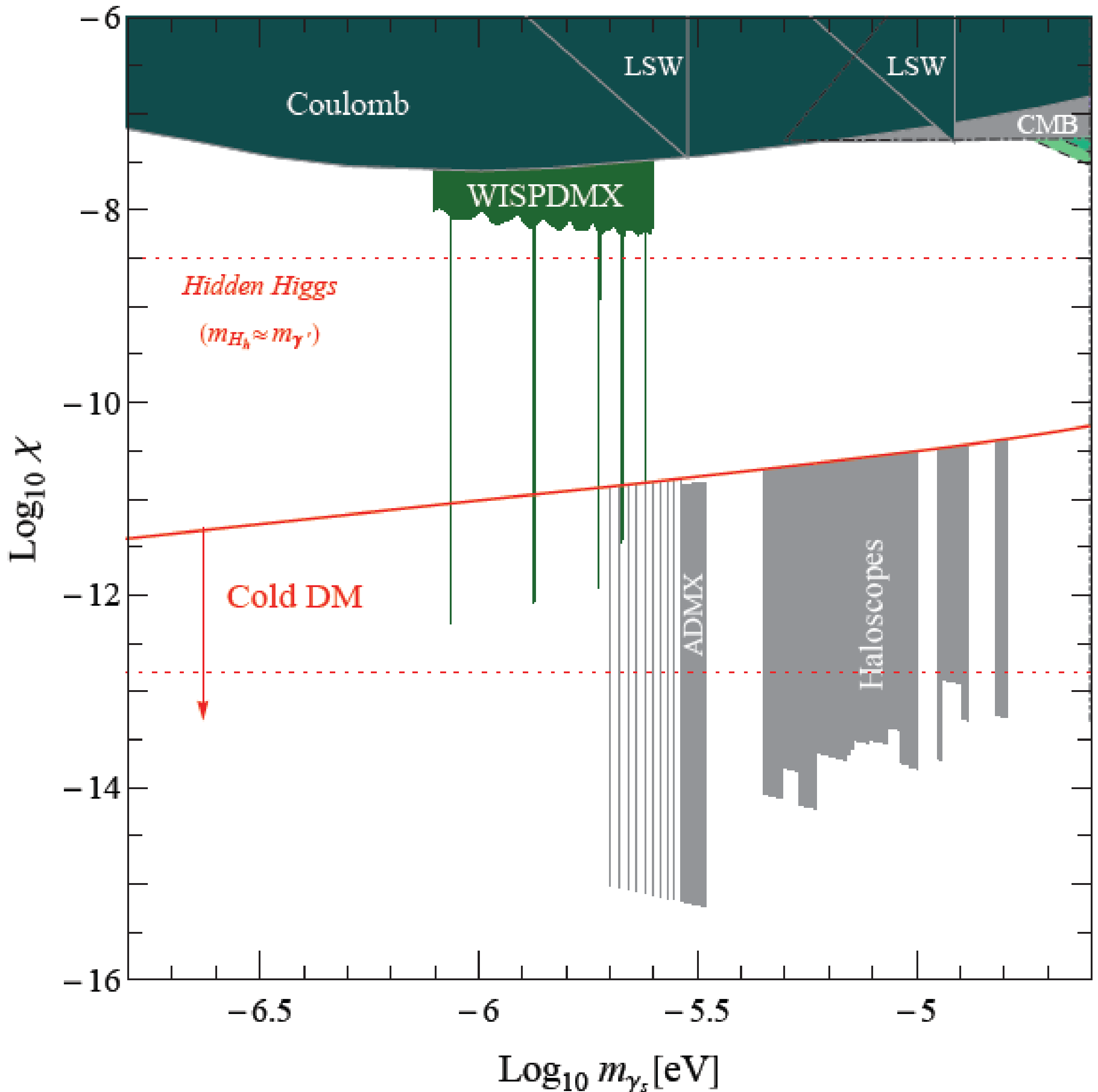
- Exclusion limits from WISPDMX Phase 1 measurements: evaluating the broadband signal.
- Further improvements (factor ~10^2) will come from stronger amplification, improving the frequency resolution, optimizing the antenna probes and cooling the apparatus.



WISPDMX: Phase 2

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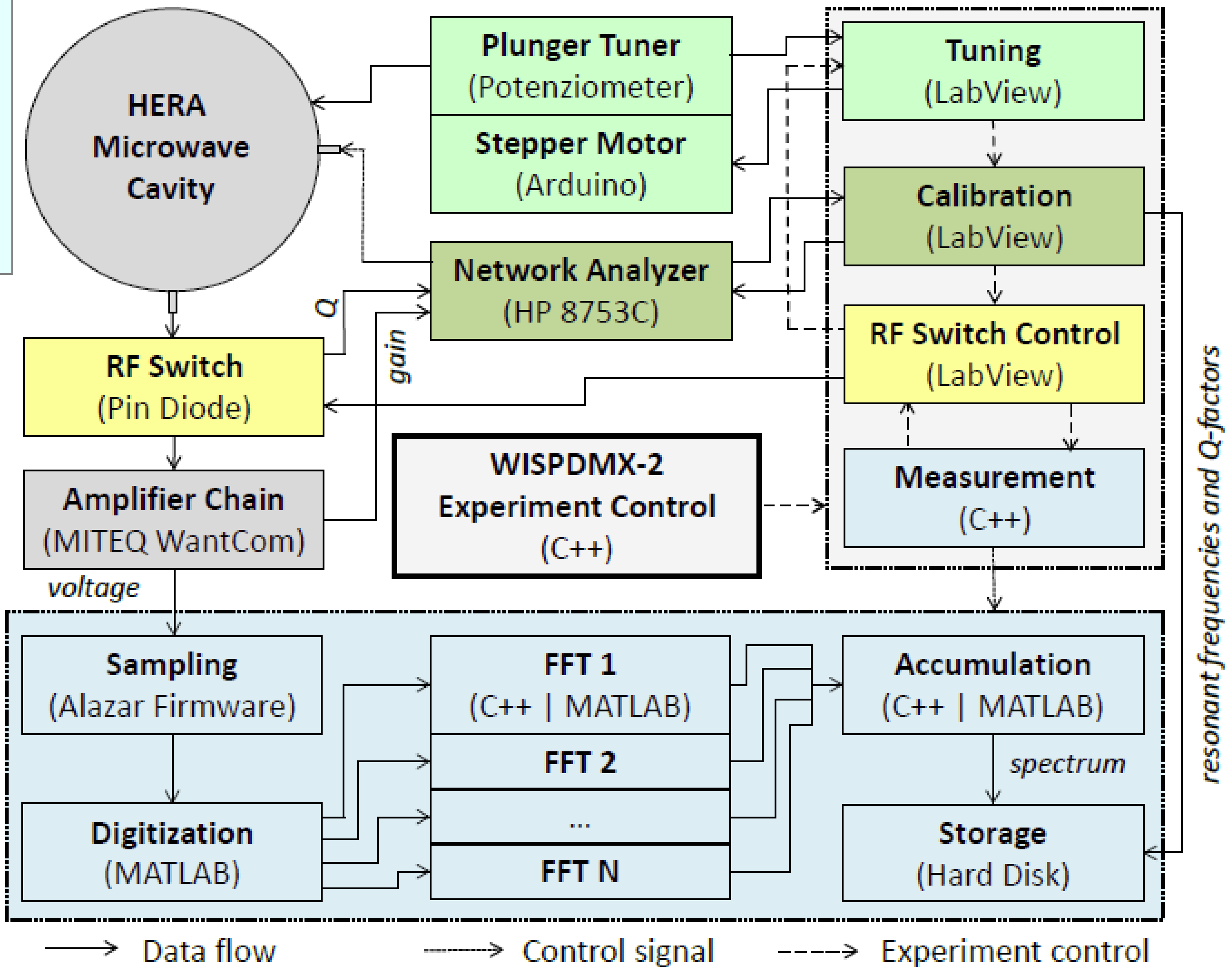
- ❑ Cavity tuning, 500 MHz bandwidth, 100 Hz resolution, automated experim-ent control



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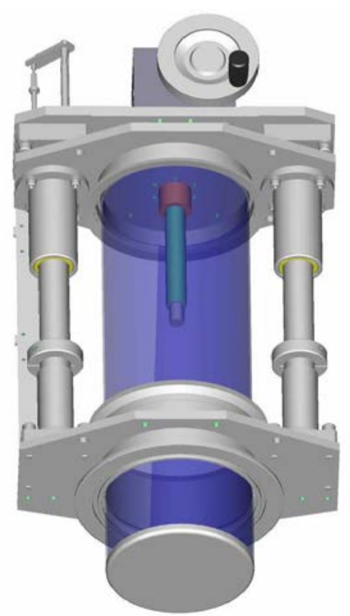
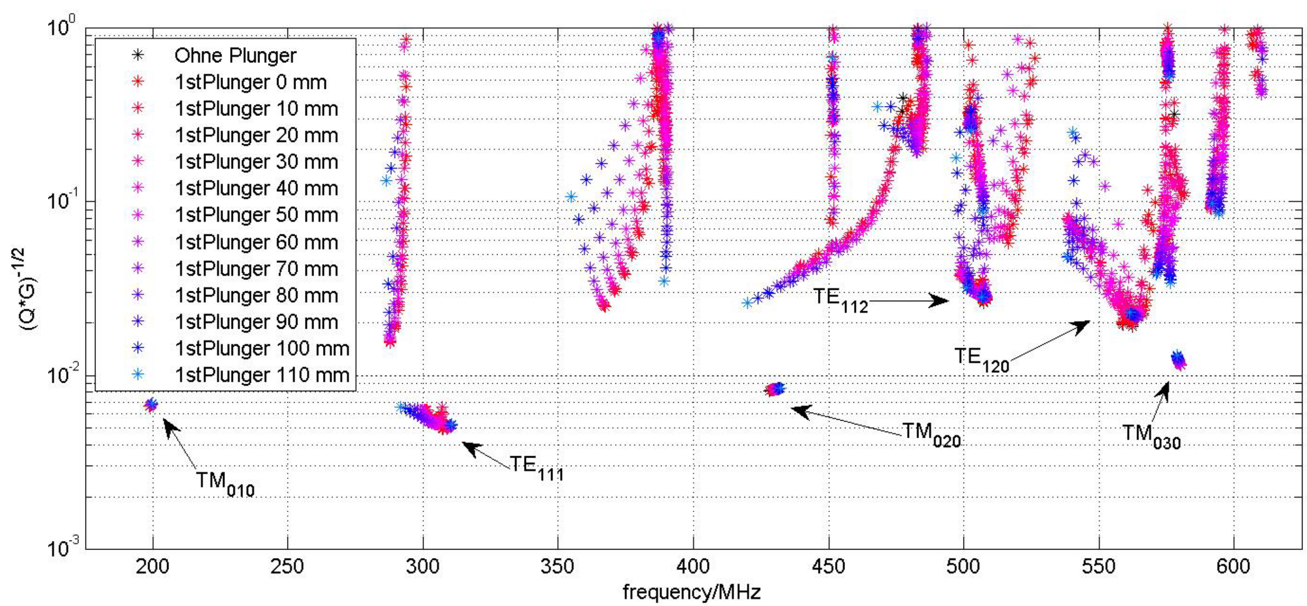
Phase 2: Tuning the Cavity

- Tuning plunger assembly: one plunger ready, second being manufactured
- 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

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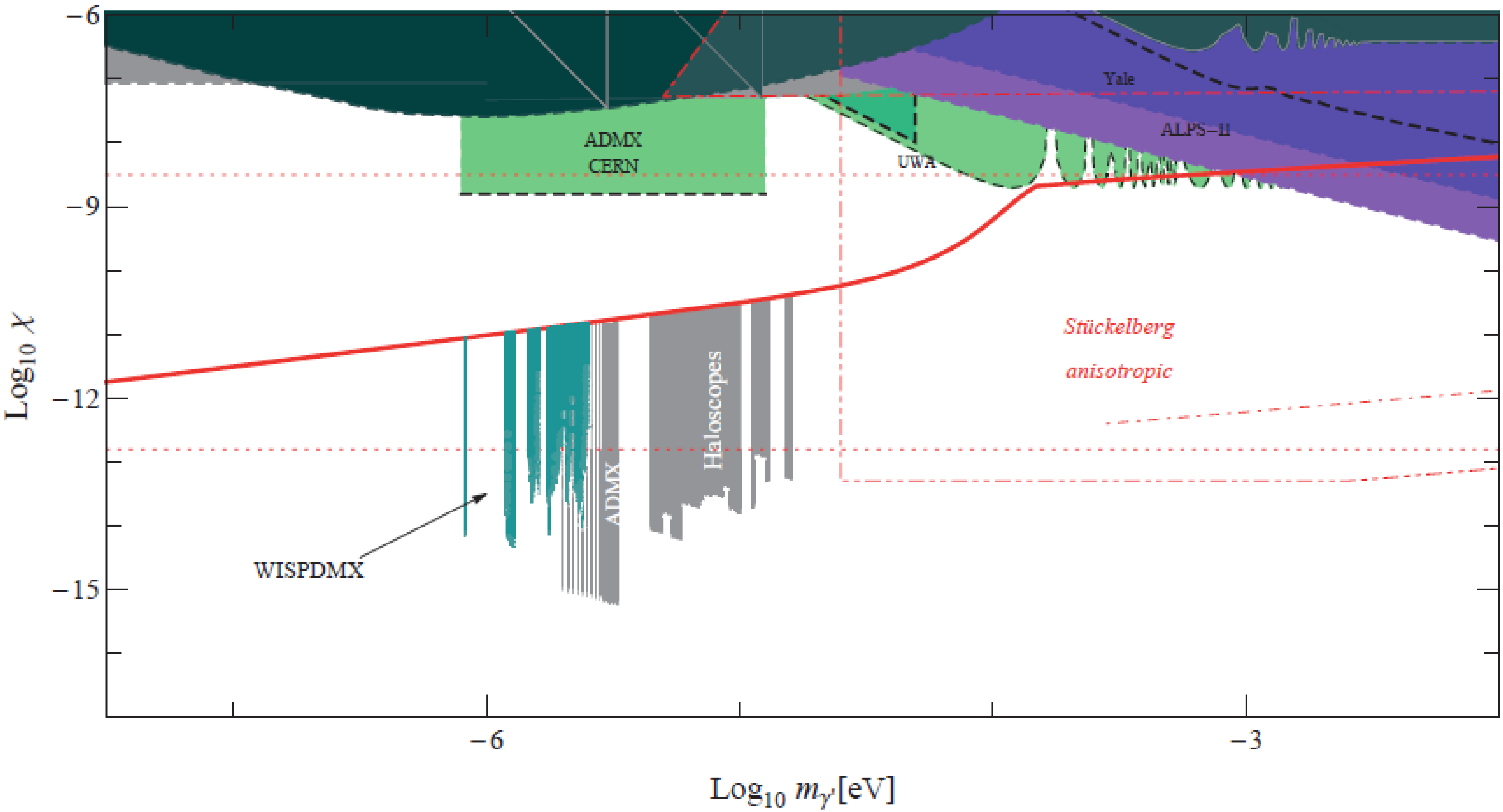
- WISPDMX: expected HP dark matter exclusion limits from tuned cavity measurements.



Phase 3: Expected ALP Limits

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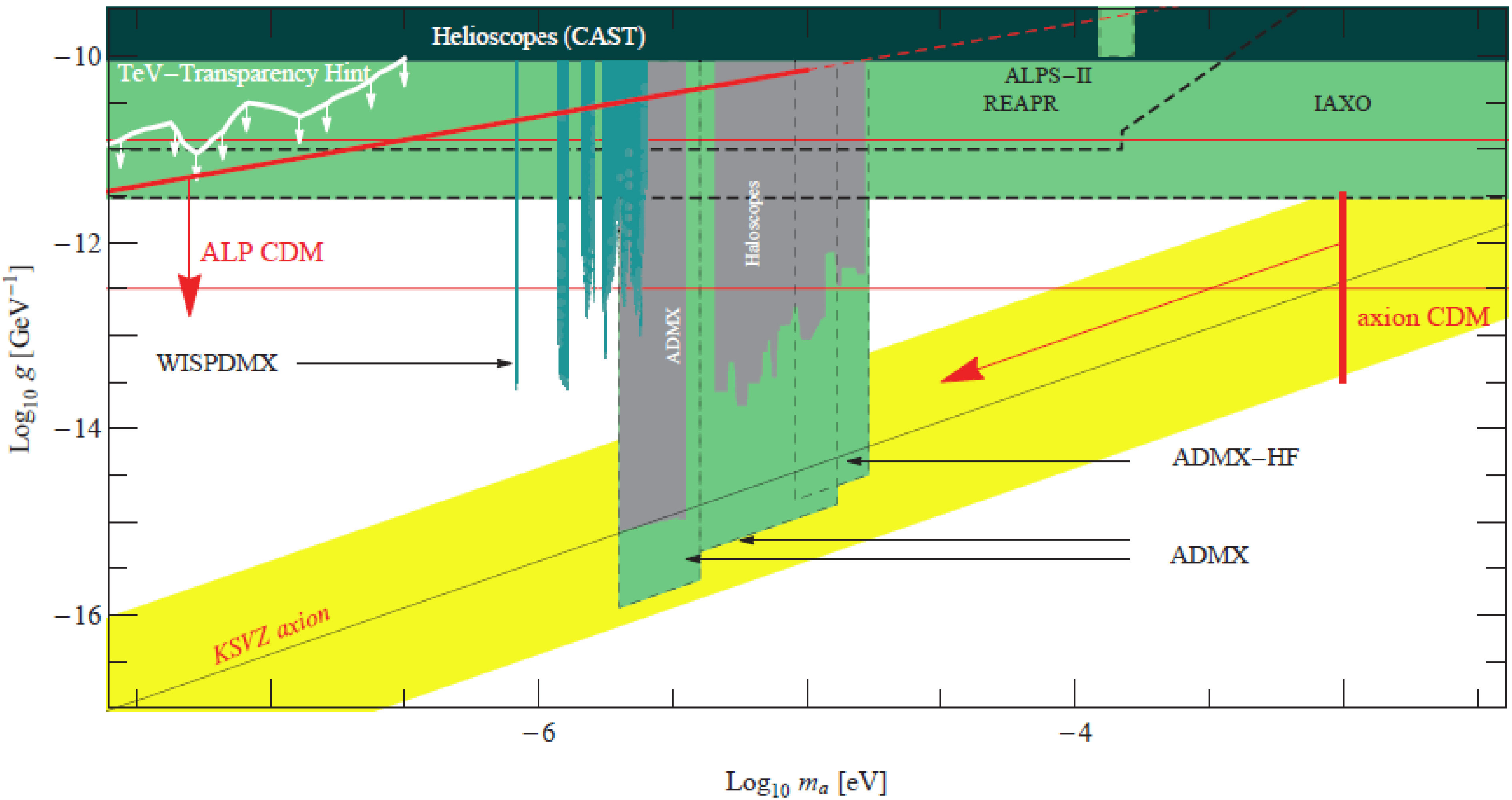
- WISPDMX: expected ALP exclusion limits from measurements with tuned cavity combined with the solenoid magnet from H1 detector (1.15 Tesla)



Narrow or Broad?

- Scanning over a large mass range?
- Trying to get to lower particle masses? →

Need to decide between going

narrow **or** **~~wide~~ broad**

- Tn~1K, B~5T, V~100 l, G~1.0
- Tn~100K, B~5T, V~10 m^3, G~0.01

Need for Broadband Searches

- Intrinsic measurement band $W_{meas} \sim 10^{-5}\nu$ limits severely the integration time and frequency scanning rate of microwave cavity searches

WISPDMX scanning speed for axions

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \sim \frac{30\text{ MHz}}{\text{year}}\left(\frac{4}{\text{SNR}}\right)^2\left(\frac{3\,\text{K}}{T_n}\right)^2\left(\frac{g}{10^{-15}/\text{GeV}}\right)^4\left(\frac{V}{460\,\ell}\right)^2\left(\frac{B_0}{1.15\,\text{T}}\right)^4\left(\frac{\mathcal{G}_\phi}{0.5}\right)^2 \times\left(\frac{208\,\text{MHz}}{f}\right)^2\left(\frac{Q}{2.7\times10^4}\right)\left(\frac{10^6}{Q_\phi}\right)\left(\frac{\rho_0}{0.3\,\text{GeV}/\text{cm}^3}\right)^2.$$

and hidden photons

$$\frac{df}{dt} = \frac{1}{N_{\text{rep}}}\frac{f}{Q}\frac{1}{t} \sim \frac{135\text{ MHz}}{\text{year}}\left(\frac{3}{N_{\text{rep}}}\right)\left(\frac{4}{\text{SNR}}\right)^2\left(\frac{300\,\text{K}}{T_n}\right)^2\left(\frac{\chi}{10^{-14}}\right)^4\left(\frac{V}{460\,\ell}\right)^2\left(\frac{\mathcal{G}_{\gamma'}}{0.5\times0.25}\right)^2 \times\left(\frac{208\,\text{MHz}}{f}\right)^2\left(\frac{Q}{2.7\times10^4}\right)\left(\frac{10^6}{Q_{\gamma'}}\right)\left(\frac{\rho_0}{0.3\,\text{GeV}/\text{cm}^3}\right)^2, \quad (2.19)$$

- Want to have an experiment without resonant enhancement required.

Detection Limits

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- 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_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_n; *... reaching quantum limit*

  – increasing the magnetic field strength, *B*; *... destructive ;-)*

  – increasing the volume, *V*. *... with TOKAMAKs? spherical reflectors? or dedicated radiometry chambers?*

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Spherical Reflectors

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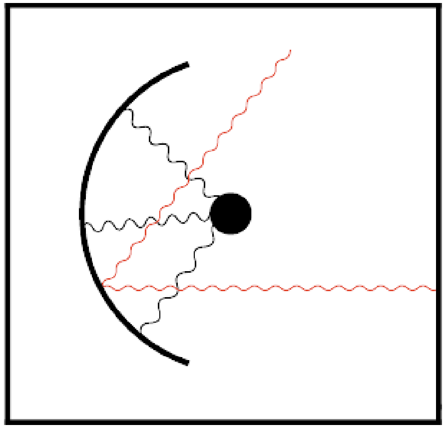
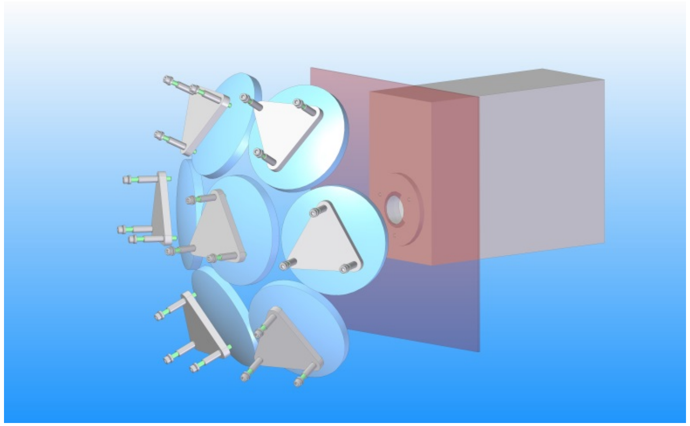
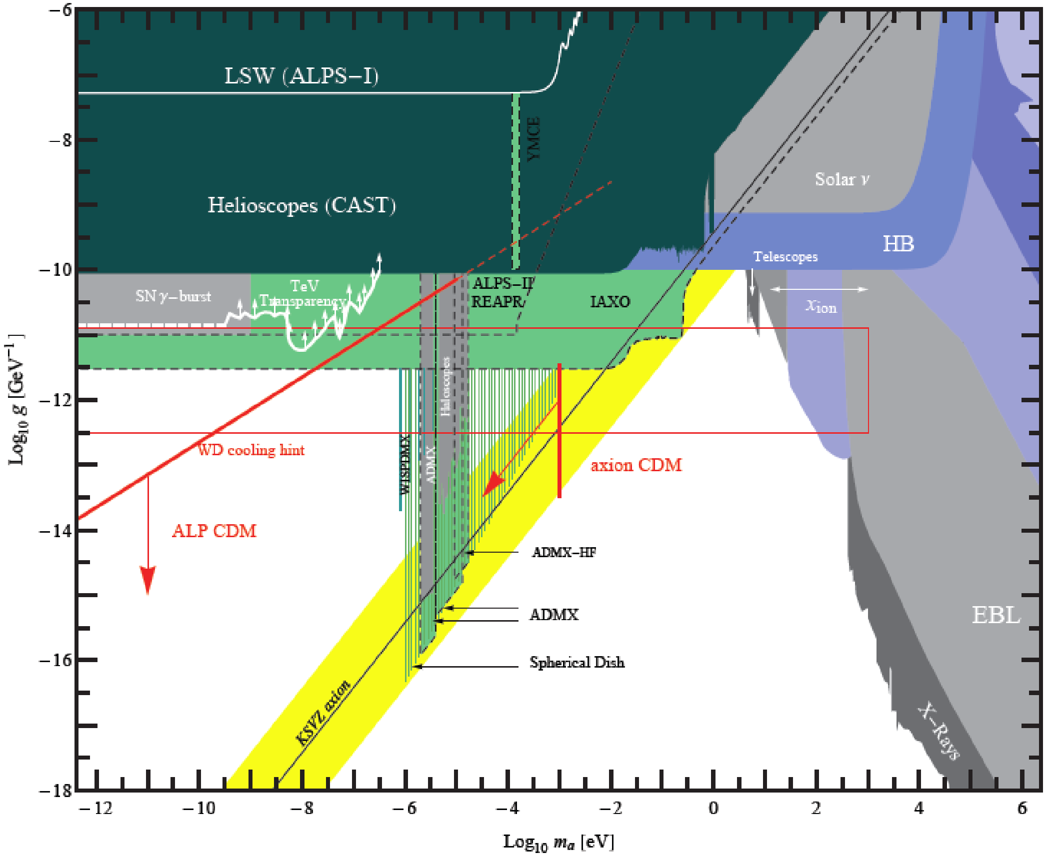
- Employing spherical reflectors enhance (focus) the near field EM signal from the reflector surface which arises due to its interaction with WISP dark matter (Horns et al. 2013). Promising for masses above 10 μeV.
- Suzuki+ 2015, first results. Pilot study at DESY/Karslruhe (Döbrich et al.)







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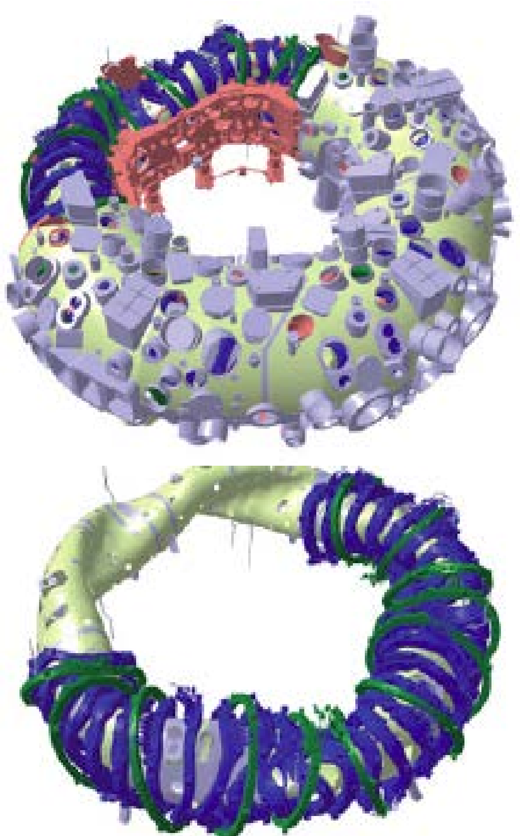
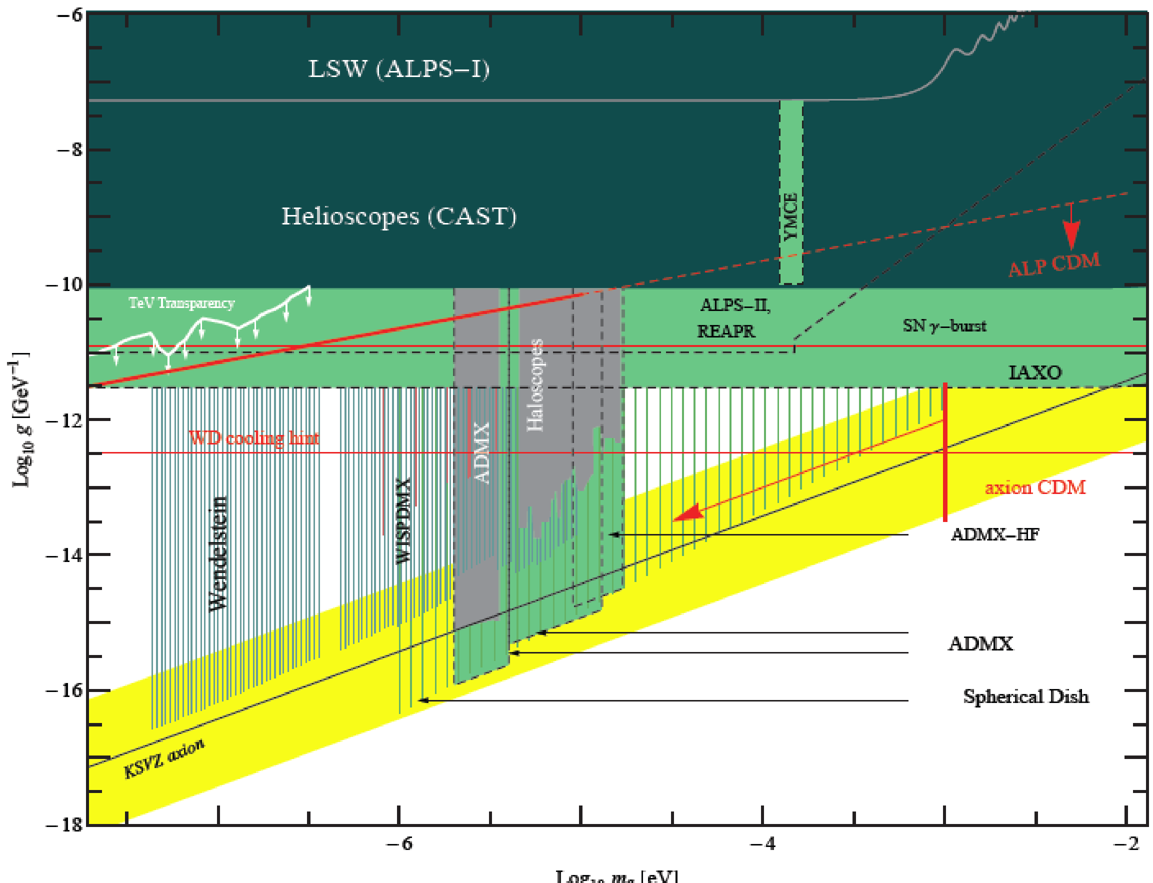
Superconducting Tokamaks

- Large chamber volume (>10 m³), 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 ~ 100 $(\nu/1\mathrm{GHz})^{-1}$ and double shielding of the plasma vessel – but complicated B-field.



W7-X: magnetic coils and plasma vessel



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Critical Issues

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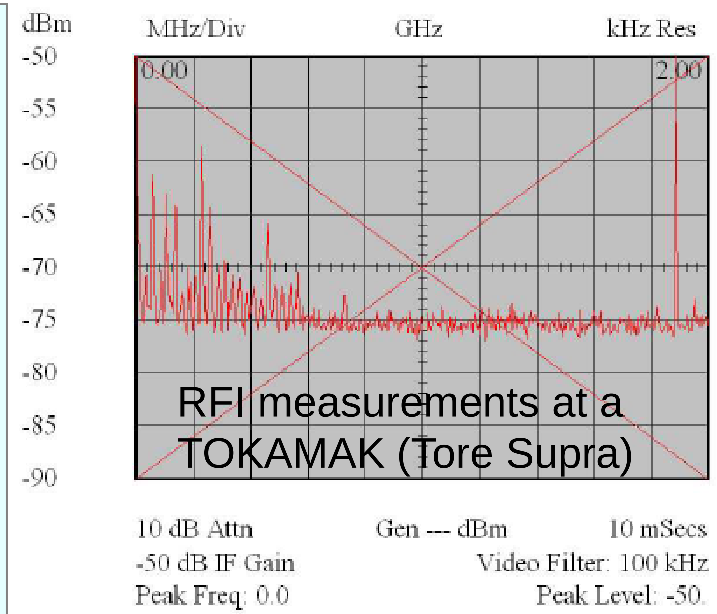
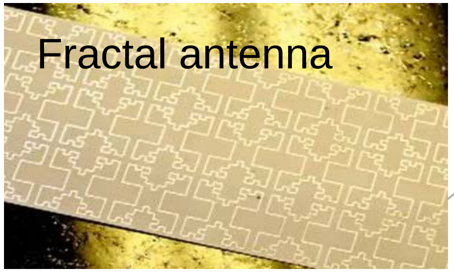
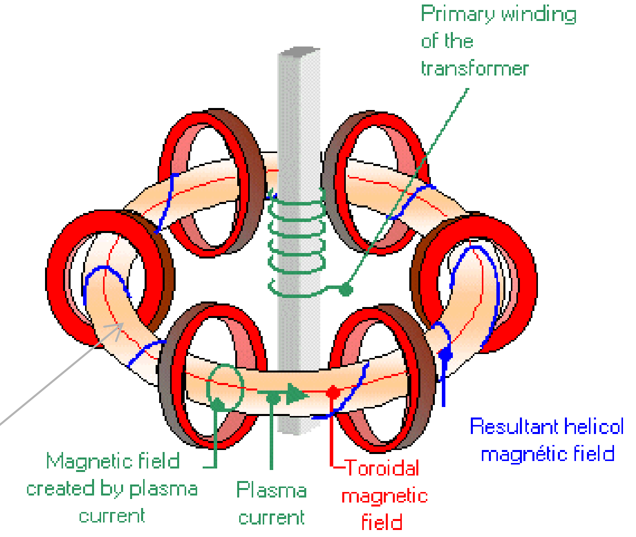
- Background and RFI noise: need to understand the background and reduce it as far as possible. Measurements made at Tore Supra have shown that RFI may be a serious impeding factor and shielding my be required
- Maximizing the effective volume: the receiving element may need to be specially designed 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



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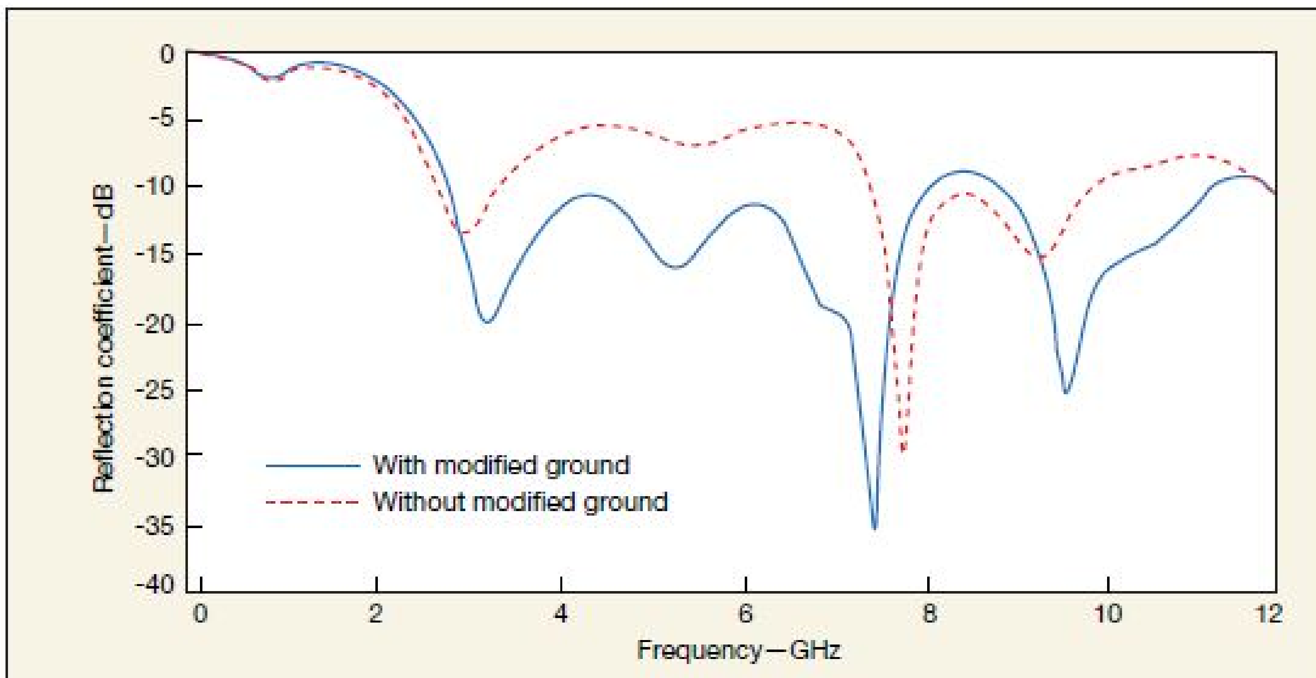
Radiometry Chambers?

- „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

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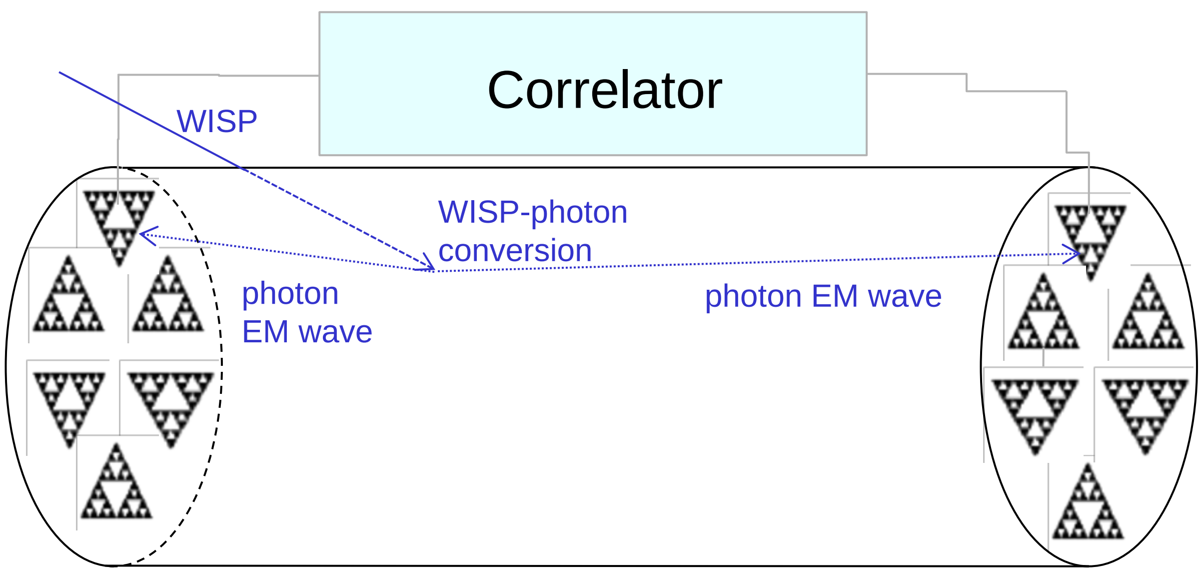
- Time resolution of ~3 ns (L_{xyz}/m).
- Both time and spectral resolution (~10 Hz) are achieveable with exitsing radioastronomy detector backends
- Coherent addition of signal – effective Q ~ number of detector elements.
- Coherent addition of signal – full directional sensitivity
- Possible prototype: 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^{-7} eV mass range.
- This is an emerging field of study that has a great scientific potential.