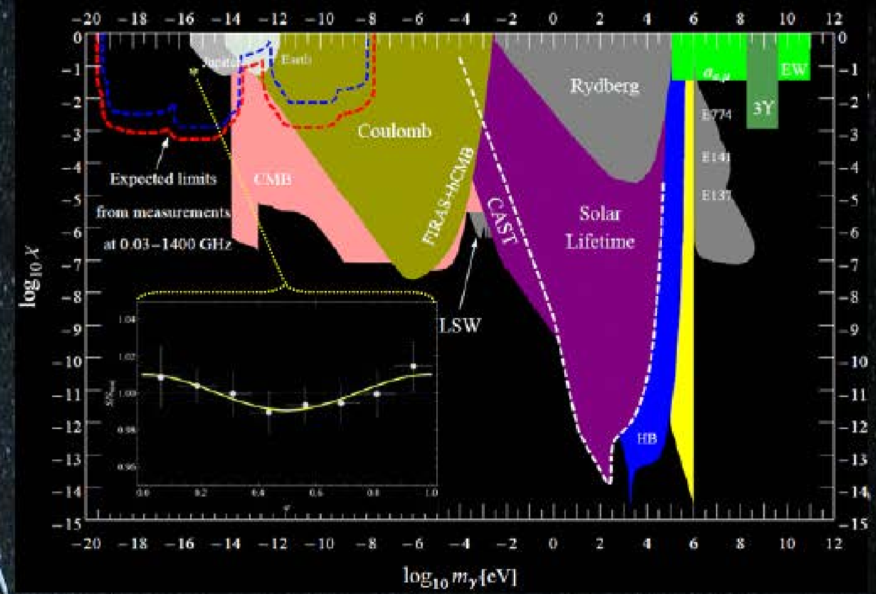

Whispers from the Dark Side:

Radio Probes of WISP Dark Matter

Andrei Lobanov
MPIfR Bonn / University of Hamburg

Max-Planck-Institut für Radioastronomie

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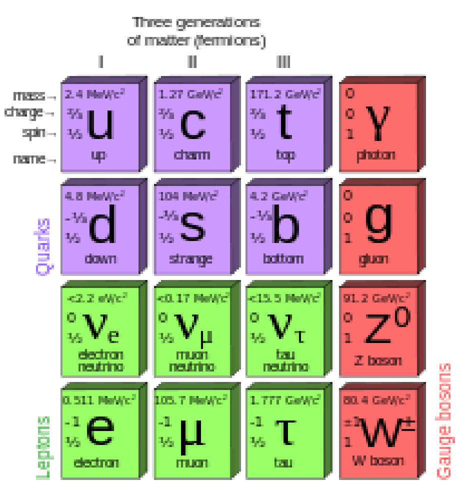
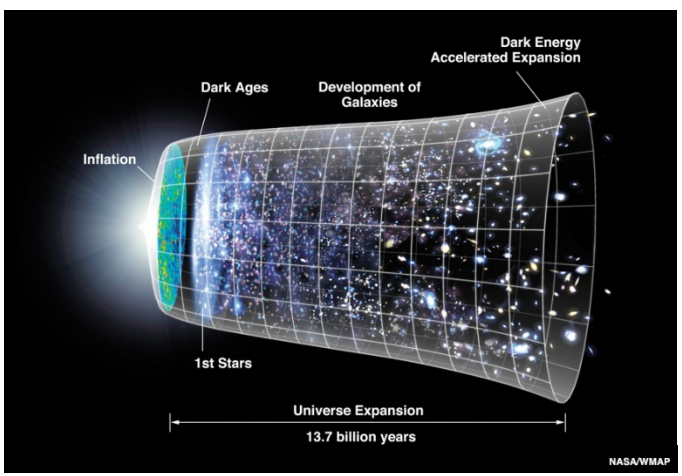
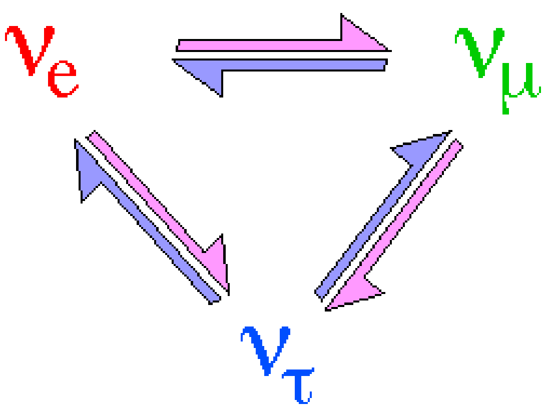
Two+ Clouds of SM

- ❑ 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 […]"*
  - – gravitation and dark energy

  ... plus some „lesser evils“ such as dark matter, neutrino oscillations, strong CP problem, fine tuning, etc...
- ❑ Most of the solutions proposed invoke a „hidden sector“ of the global parameter space, only weakly coupled to „normal matter“ of the SM.

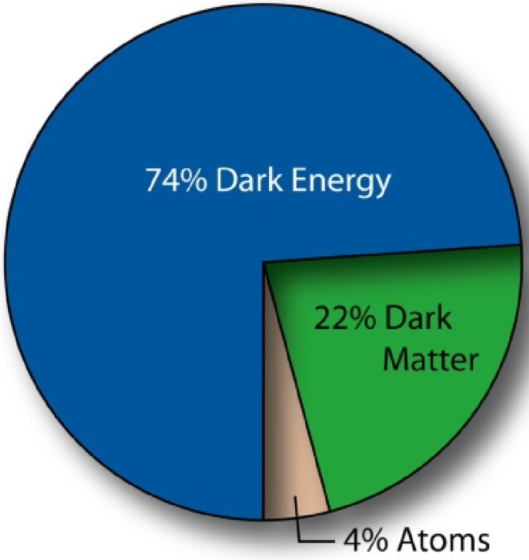


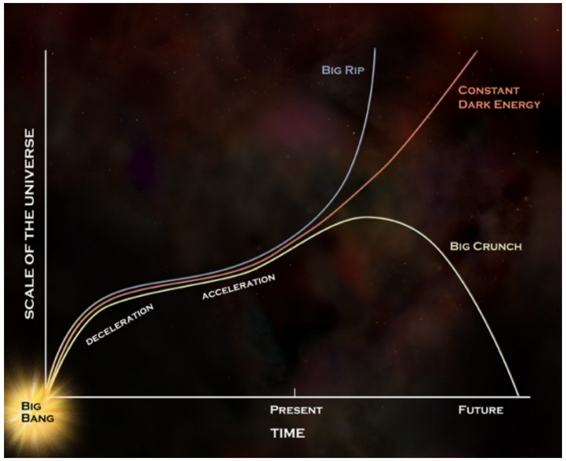




Dark Matter and Dark Energy

- Dark Matter: interacts with SM (mostly) gravitationally.
- Dark Energy: unseen influence (vacuum energy, scalar field, quintescence?) permeating the space and causing acceleration of the Universe
- Evidence for DM and DE:
  – stellar motions in galaxies; galaxy motions in clusters
  – gravitational lensing
  – light curves of distant supernovae
- Possible types of DM:
  – baryonic (MACHOS: BD, Jupiters, etc.)
  – non-baryonic: weakly interacting particles:
  WIMP: neutralinos, gravitinos, $m \gg 1$ eV
  WISP: axions/ALP, MCP, hidden photons, $m \ll 1$ eV
- WISP can also explain DE (*chameleons*) .
- WISP cannot be detected at accelerators.
  Need low energy experiments!





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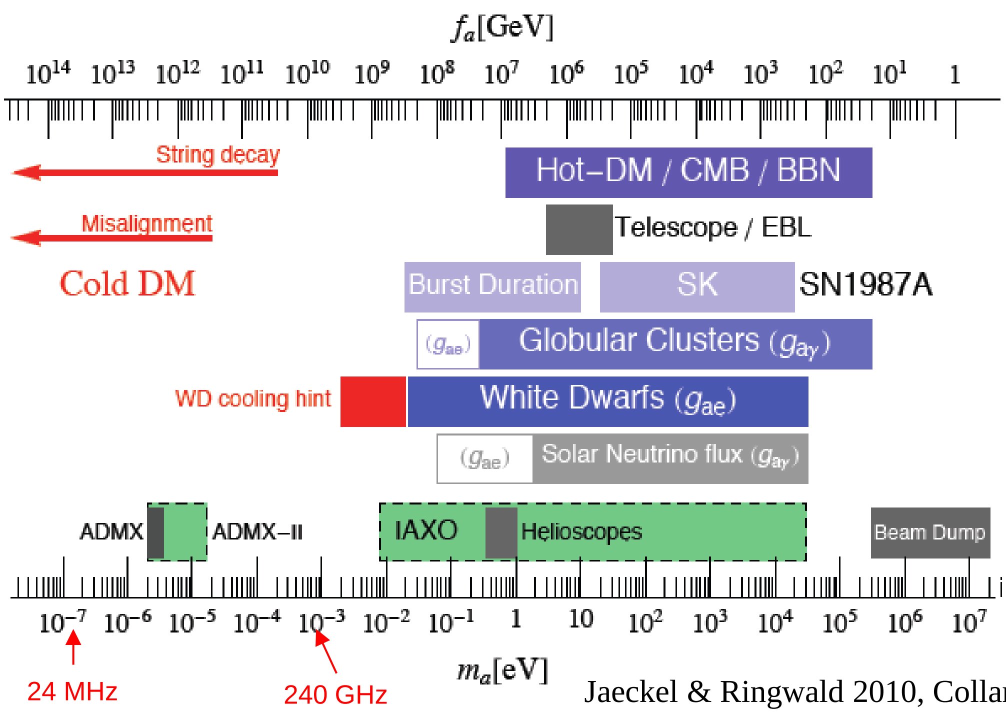
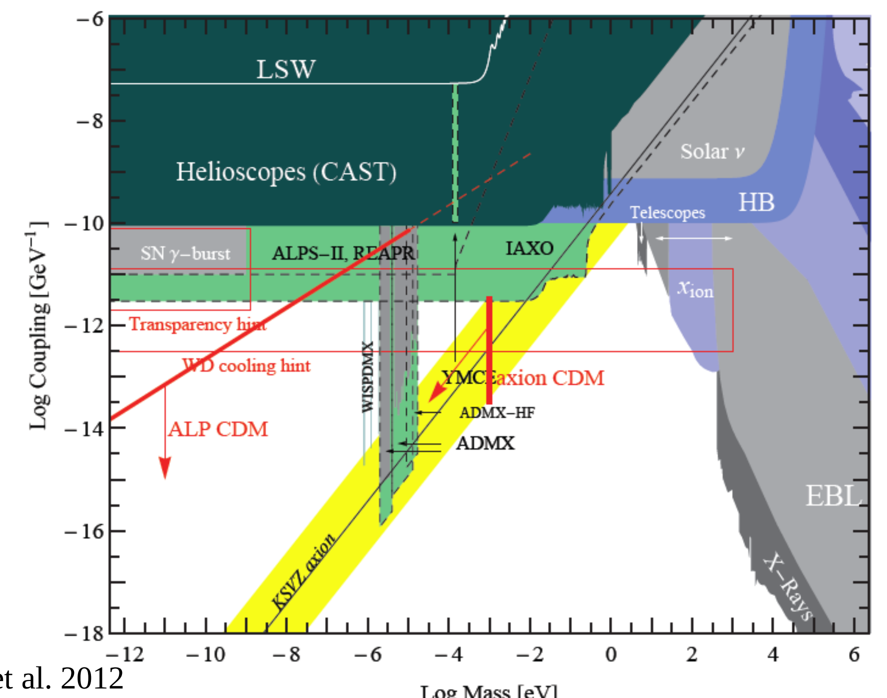
Axions and ALP

- QCD problem: lack of CP-violation in strong nuclear interaction (e.g., no detected neutron dipole moment). Solution: spontaneous $U(1)$ symmetry breaking at a specific energy scale f_a (Peccei & Quinn 1977).
- Axion – a pseudo-scalar particle, dynamically removing the CP-violation; resulting mass $m_a \sim 6\ \mathrm{meV}\ (10^9\ \mathrm{GeV}/f_a)$, strong DM particle candidate
- Axion-like particles (ALP) may arise from other symmetry breakings.

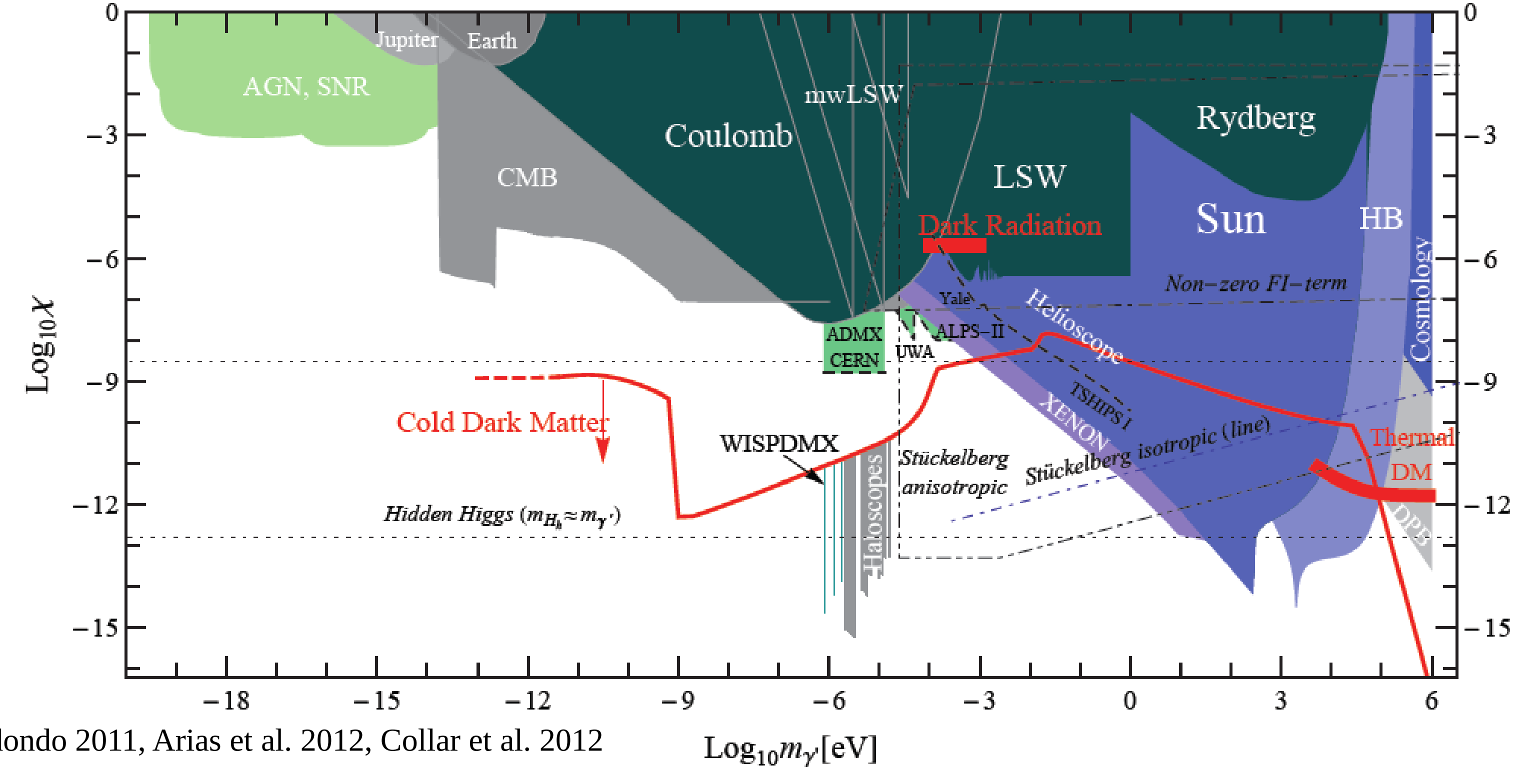




Jaeckel & Ringwald 2010, Collar et al. 2012

Hidden Photons

- Extra $U(1)$ symmetries are featured in many extensions of the SM and they require a gauge boson (hidden photon, γ') 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

Many Faces of WISP

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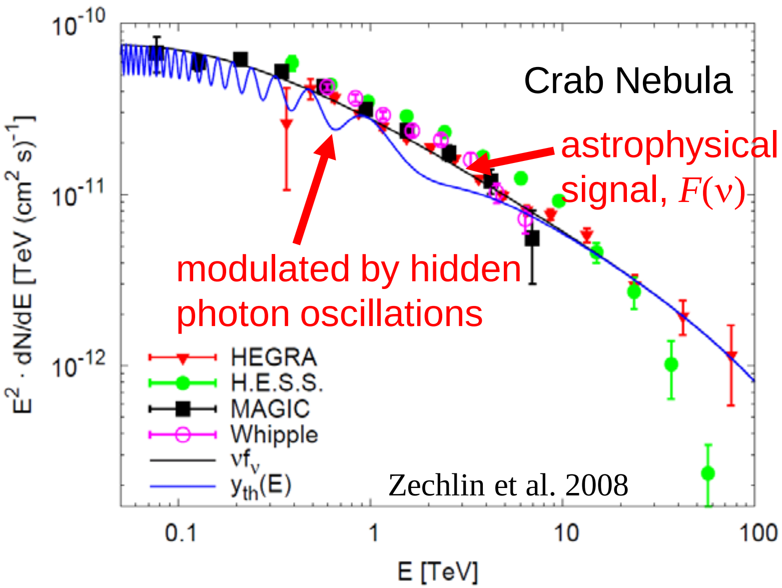
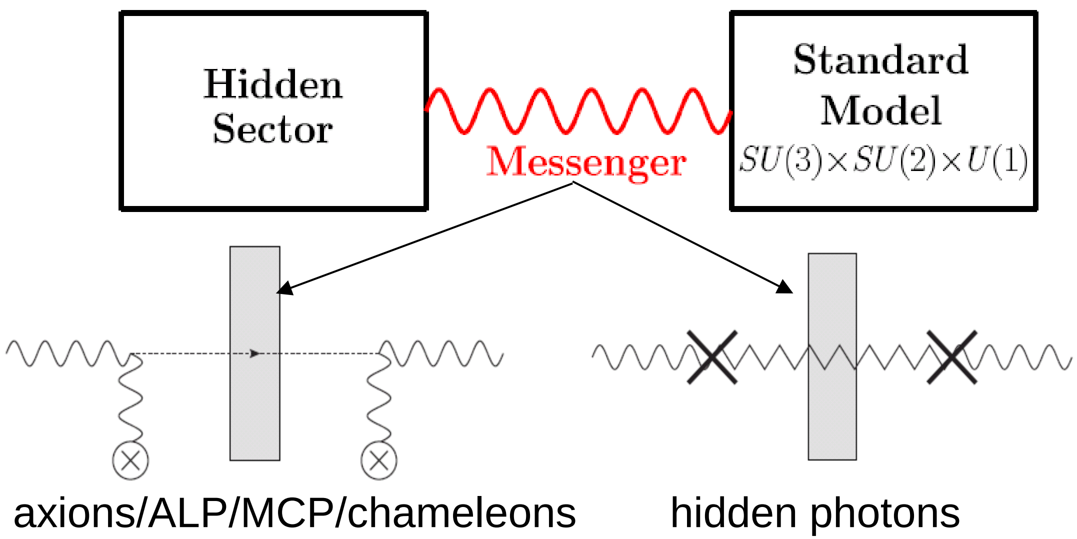
- Direct detection of WISP or putting bounds on their properties are of paramount importance for cosmology and particle physics.
- A number of experimental methods have been employed, both for laboratory and astrophysical searches – all relying on WISP interaction (coupling, kinetic mixing) with ordinary matter (most often: photons).
- Radio regime (0.03—1400 GHz): excellent sensitivity to WISP signal and access to DM/DE – relevant particle mass ranges.





Indirect DM Detection

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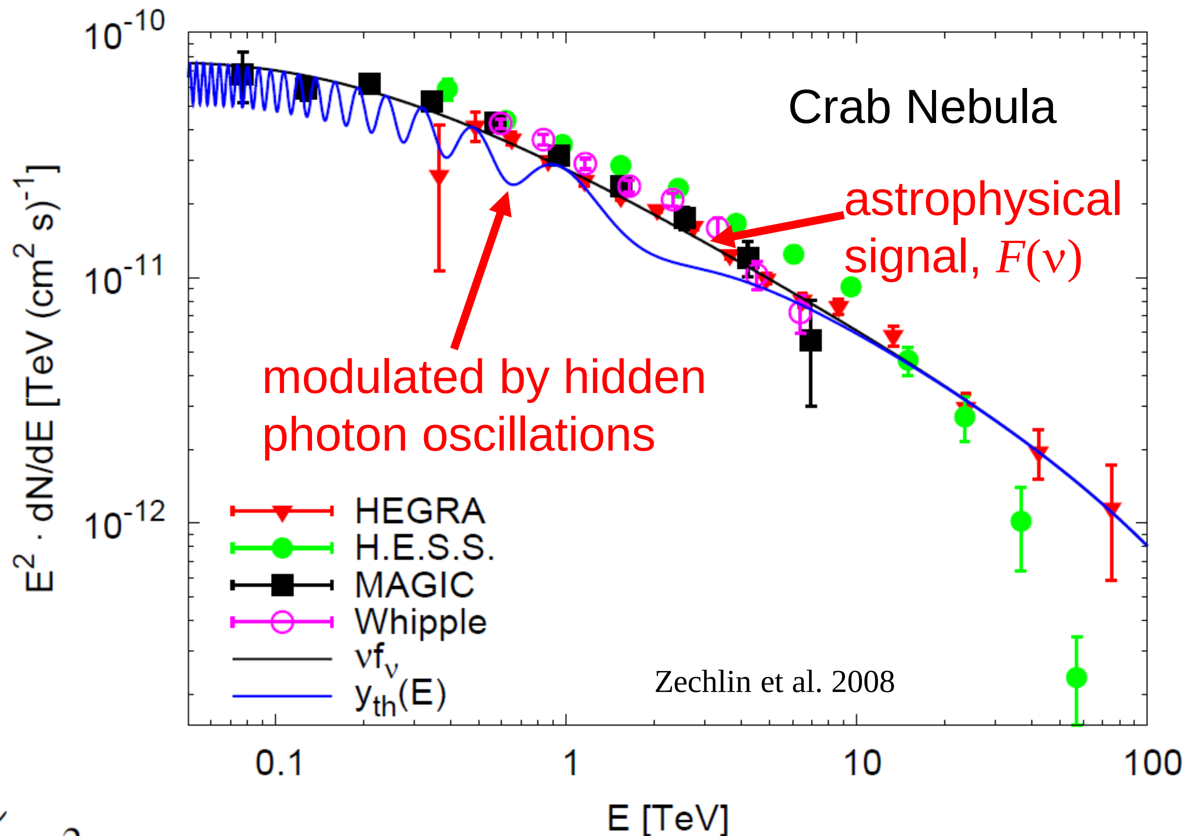
- Probability (and energy spectrum) of the oscillation depends on the mass $m_{\gamma s}$ and (coupling) kinetic mixing parameter χ of the hidden photons.

- Maximum distance at which oscillations can be detected depends on the emission process and environment conditions



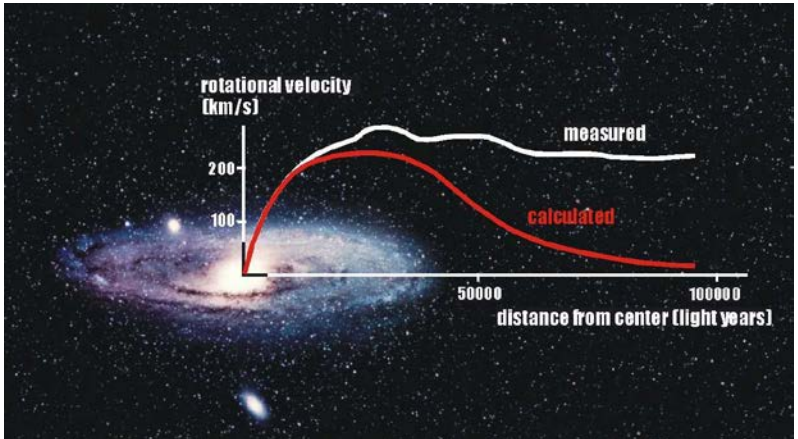
$$\mathcal{L}_\chi = \frac{\sin\chi}{2} A_{\mu\nu} B^{\mu\nu} + \frac{\cos^2\chi}{2} m^2_{\gamma_s} B_\mu B^\mu$$

$$F_{\gamma_s}(\nu) = F(\nu)(1 - P_{\gamma\to\gamma_s})$$

$$P_{\gamma\to\gamma_s}(L) = a_\chi \sin^2\left(\frac{m^2_{\gamma_s}}{4E} L\right) = a_\chi \sin^2\left(\frac{m^2_{\gamma_s}}{8\pi\nu} L\right)$$

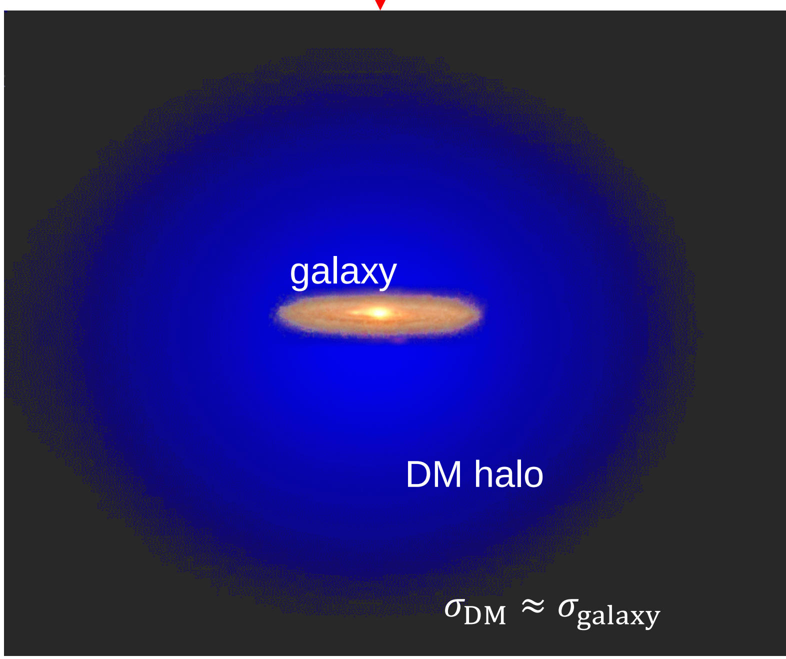
$$L_{\rm osc} \le L \le L_{\rm coh}$$

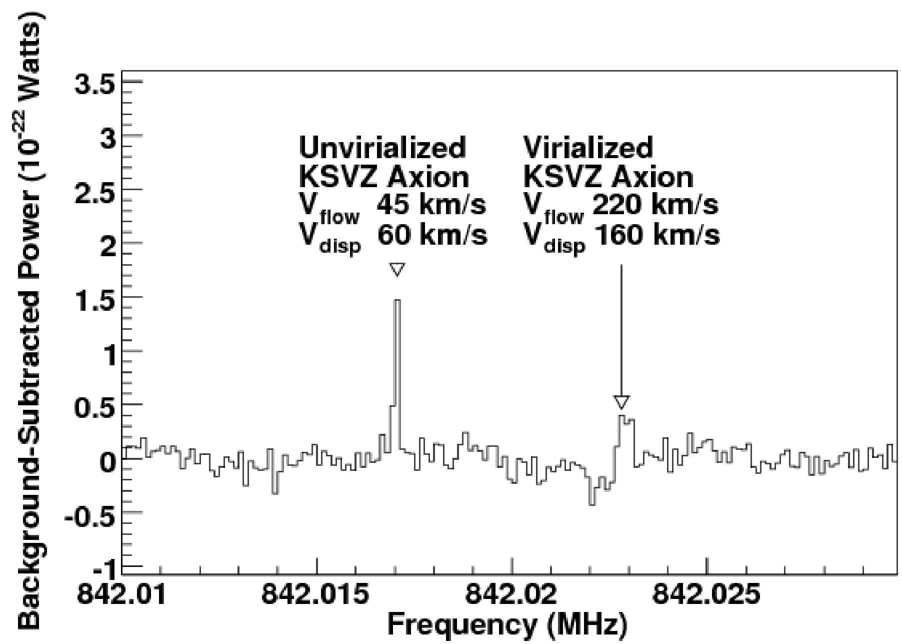
Direct DM Searches



- 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

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





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Quest of Radio Astronomy

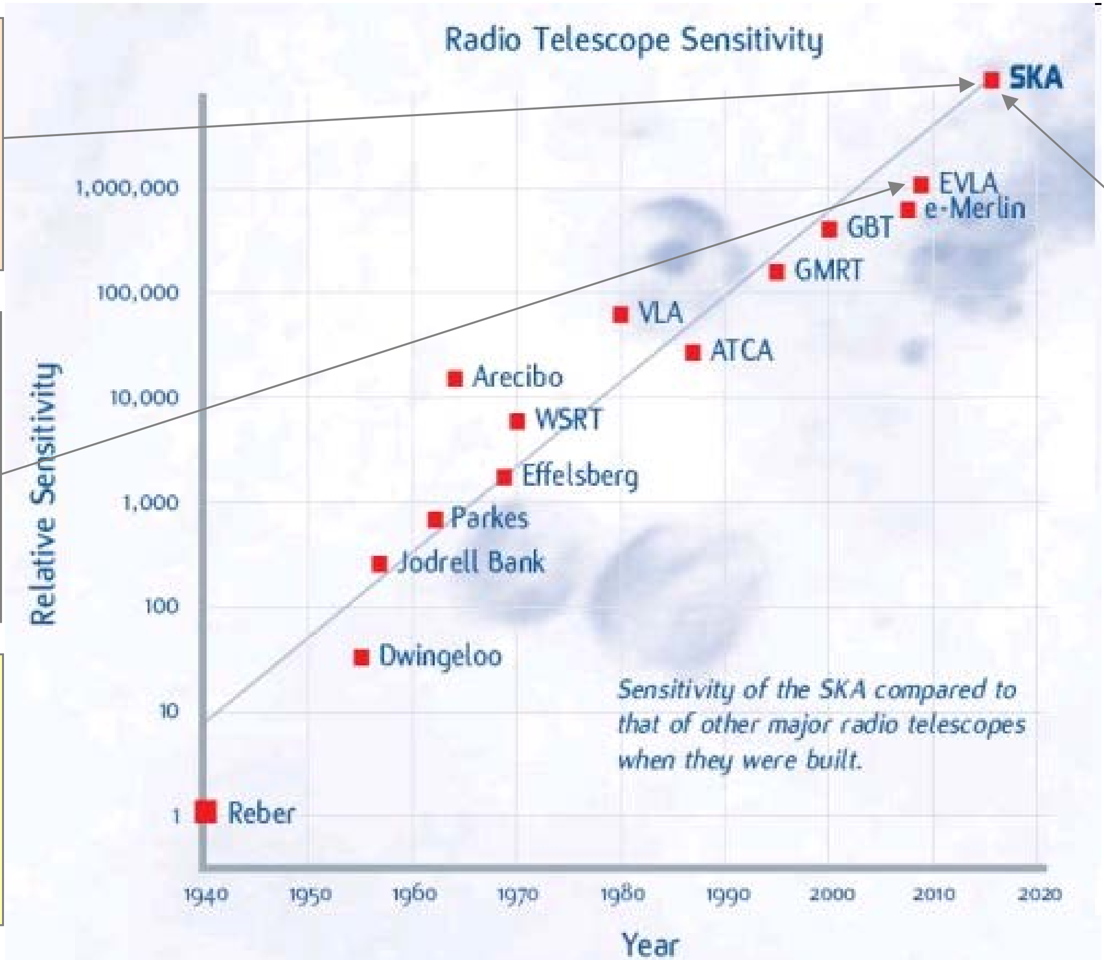
- In the 0.03-1440 GHz range, LOFAR, EVLA, eMERLIN, ALMA,MeerKAT, ASKAP, and SKA push sensitivity,spectral resolution and survey speed by several orders of magnitude

Detecting transient events at a time resolution of 1 nanosecond

Reaching spectral resolution of 0.12 Hz (velocity resolution of ~1 cm/s)

VHE:
1 OMG (10^{20} eV) particle ≈ a tennis ball at 100 km/h

Radio:
70 years of observations < a falling snowflake



Picking up an airport radar on a planet 50 light years away.

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Angular Resolution

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Highest resolution is on highest demand.

Gravitational radius:

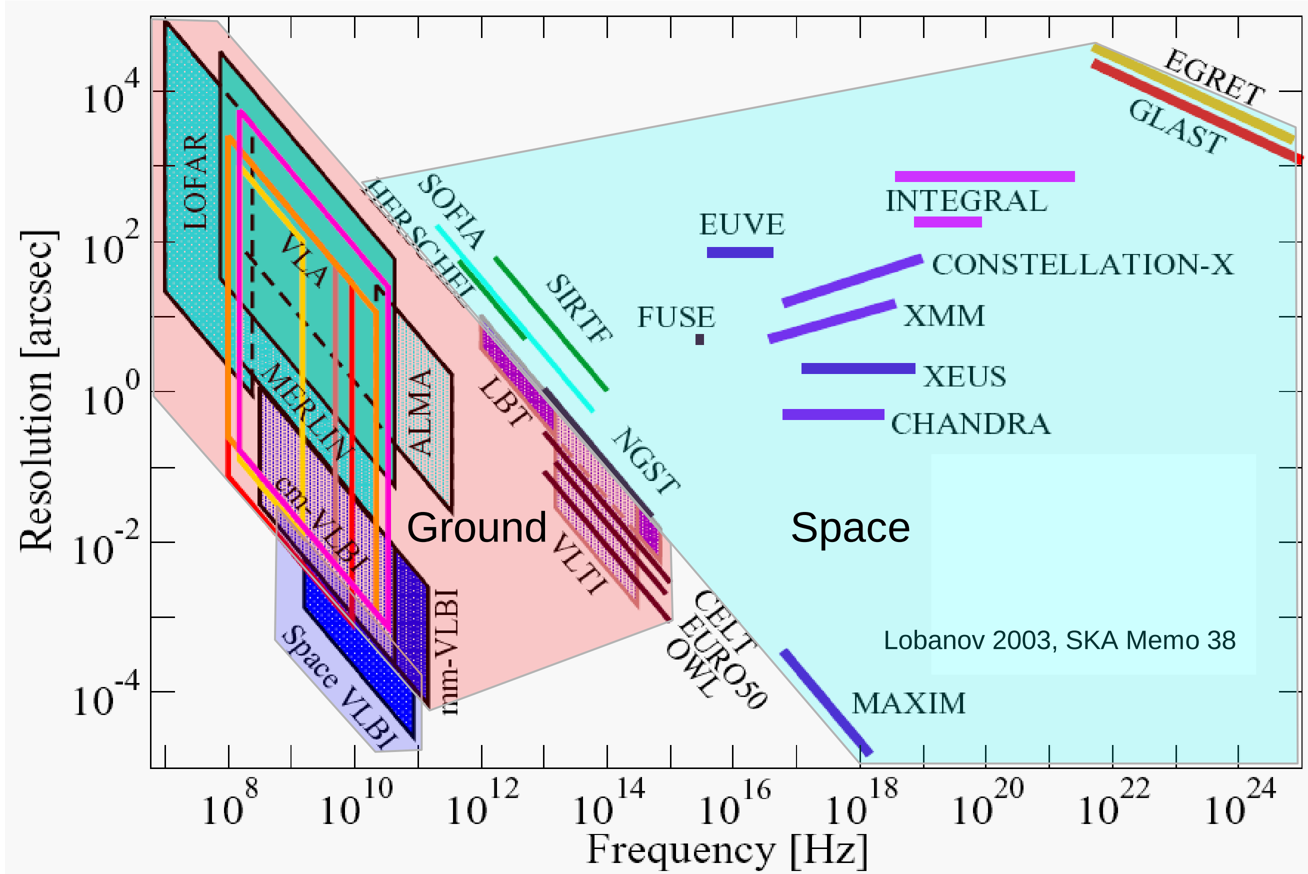
1 nas in AGN:
$M_{bh}=10^8\,M_{sun}$ at 1 Gpc

0.1 nas in XRB:

$M_{bh}=10\,M_{sun}$ at 1kpc

2 µas in M87

5 µas in Sgr A*



Radio interferometry: approaching 10 µas, aiming at 1 µas

1 milliarcsecond – a man on the Moon
1 microarcsecond – a child on the Sun
1 nanoarcsecond – a football field on... Alpha Centauri

WISP DM Searches in Radio

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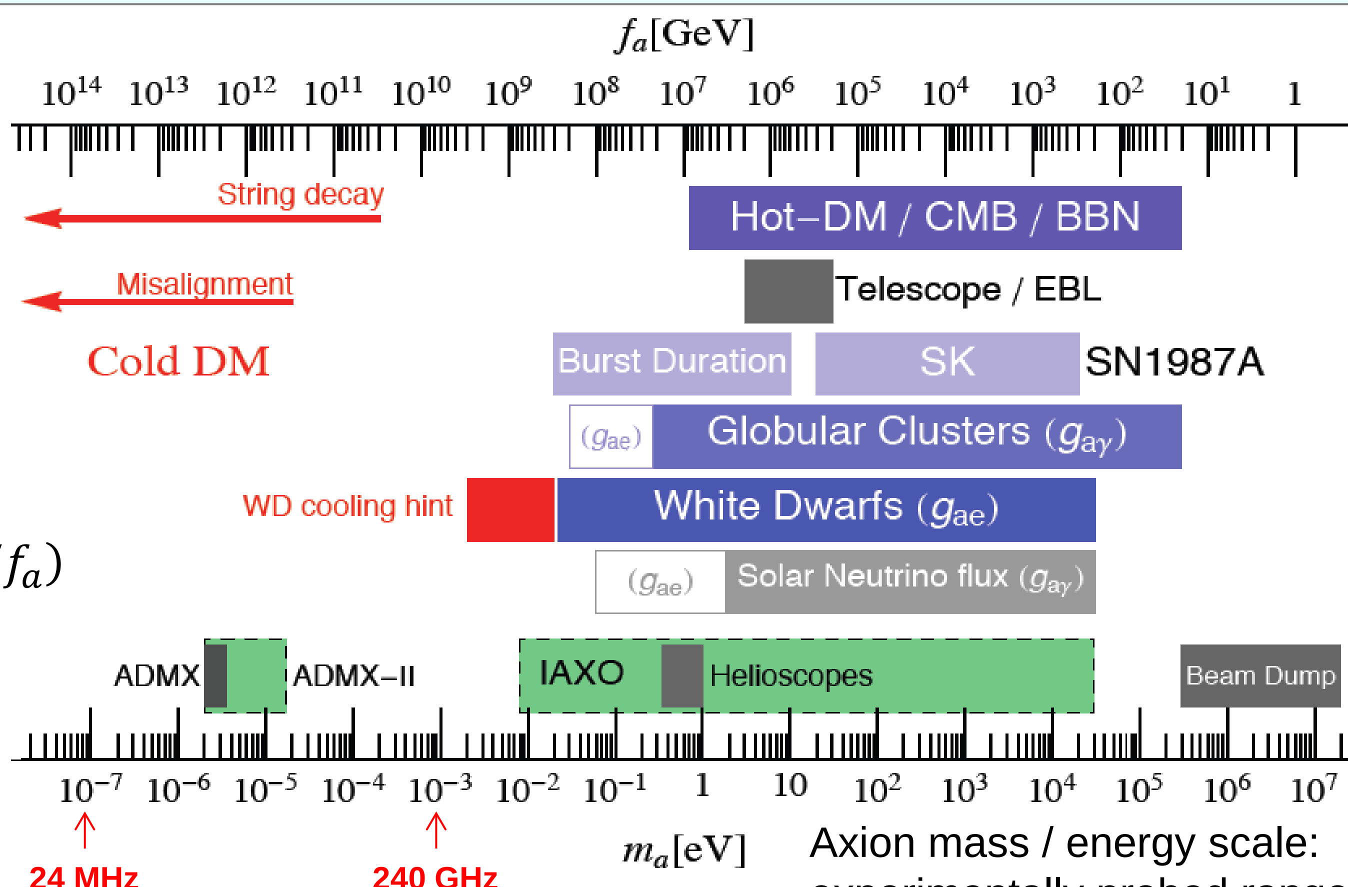
- The strongly motivated mass range for axion DM ($10^{-2} - 10^{-7}$ eV) is probed efficiently by measurements in the 20 MHz – 2 THz frequency range.
- Highly sensitive experiments in this range are needed: narrow band searches with tunable microwave cavities and new, broadband methods.

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

Axion should have a mass

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



Axion mass / energy scale: experimentally probed ranges

Detecting Axions ...

- Axion-photon conversion: $\mathcal{L}_I = \frac{1}{4} g_{a\gamma} \varphi_a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma} \varphi_a \, \mathbf{B} \cdot \mathbf{E}$

- Expected signal from axion-photon conversion:

$$P_{\mathrm{out}} = \kappa \, g_{a\gamma}{}^2 \, V \mathcal{G}_\varphi |\mathbf{B}^2| \, \rho_0 \, \frac{1}{m_a} Q,$$

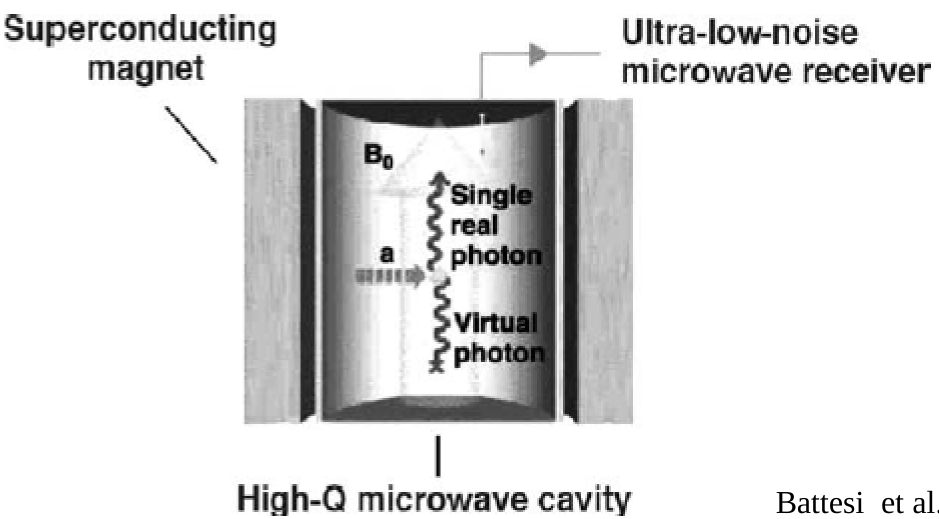
effective volume

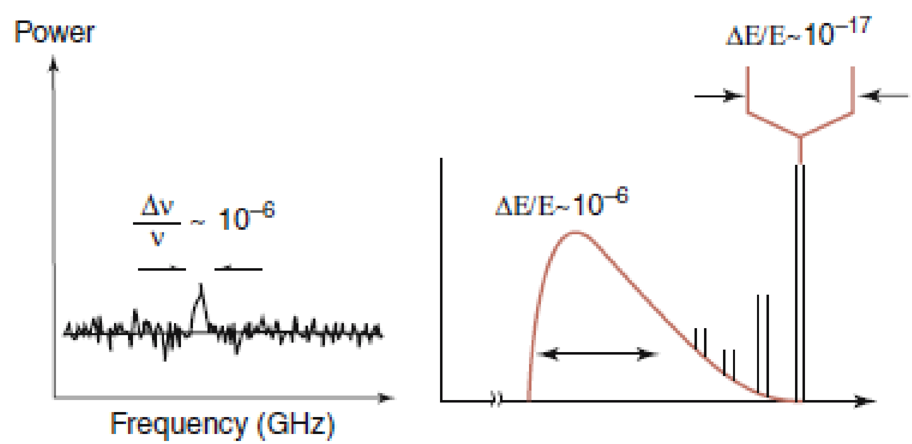
magnetic field

axion (DM) density

resonant enhancement (quality factor)

- Looking for a narrow ($\Delta\nu/\nu \sim 10^{-6}$) signal over a fractional band of 1/Q.



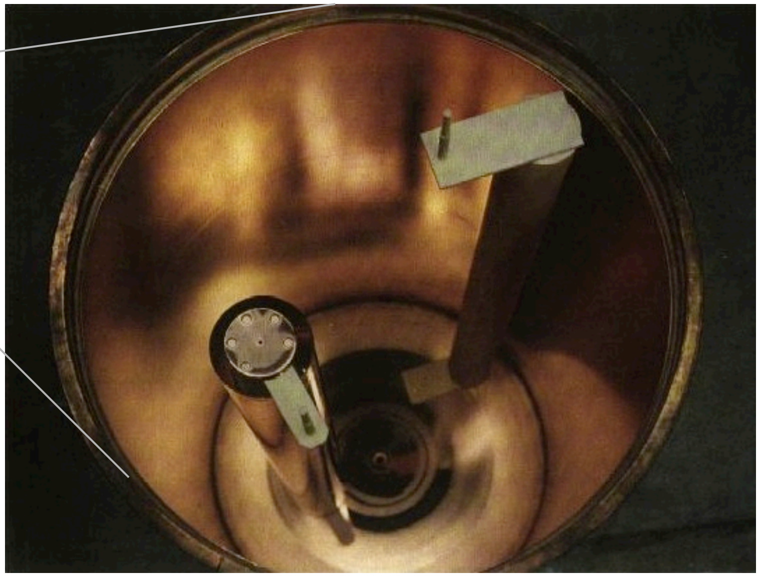


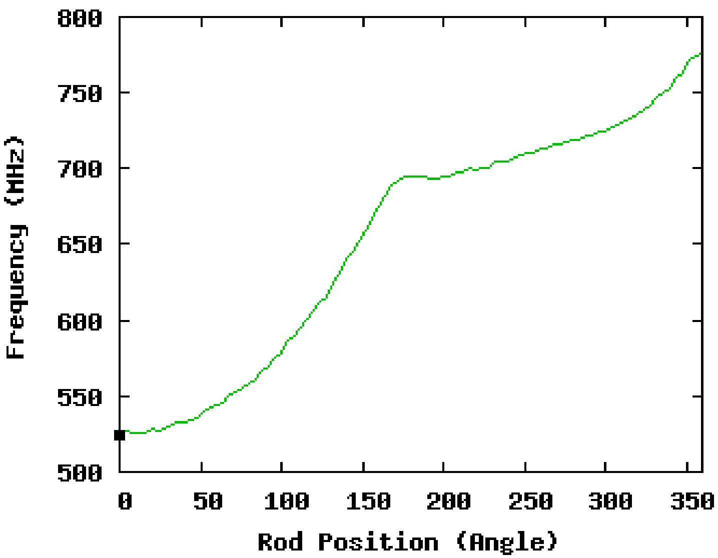
Battesi et al. 2008

… in A Broad Mass Range

- 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.
- 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 rodes





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Resonant Cavity: 'Haloscope'

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

  Haloscope experiments: Coupling strength (mixing angle):

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

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

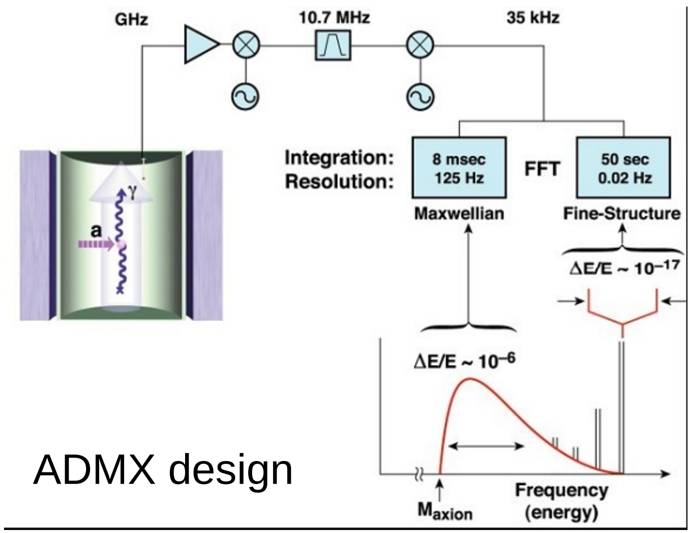
  Haloscope experiments: Coupling stregnth:

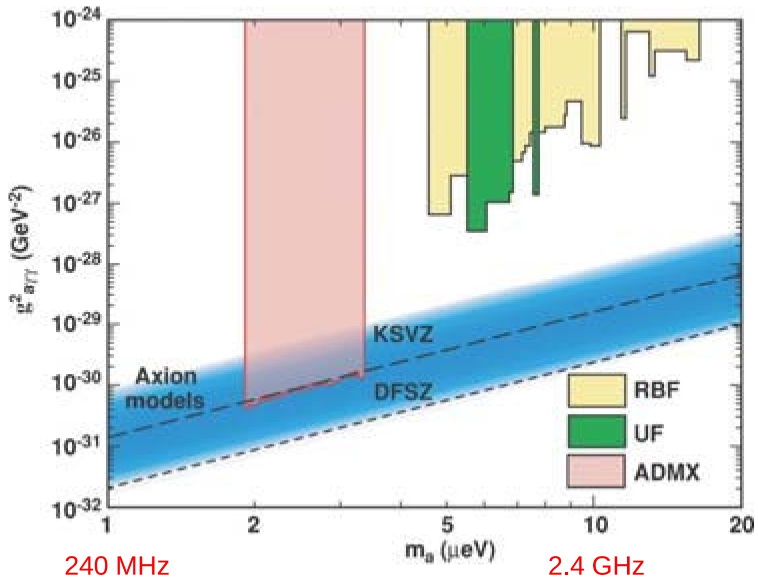
$$g[\mathrm{GeV}^{-1}] \propto t_{\rm mes}^{-1/4}\, \mathrm{SNR}^{1/2}\, T_{\rm n}^{1/2}\, B_0^{-1/4}\, V_0^{-1/2}\, Q_0^{-1/2}\, \mathcal{G}_{\phi}^{-1/2}\, \rho_0^{-1/2}\, Q_{\phi}^{-1/4}\, m_{\phi}^{3/4}$$

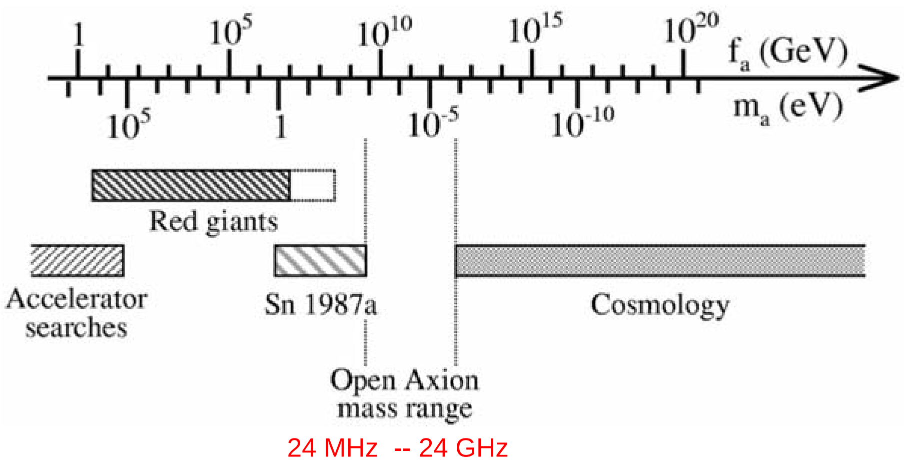
t_{mes}, SNR – measurement time and SNR; T_n – noise temperature; V_0, Q_0 – cavity volume and quality factors; B_0 – magnetic field strength; $\mathcal{G}_{\phi/\gamma}$ – form factor; ρ_0 – DM density; $Q_{\phi/\gamma}$ – quality factor of DM signal; $m_{\phi/\gamma}$ – particle mass

ADMX Experiment

- Miscorwave cavity (haloscope) experiments can probe the axion coupling down to QCD predictions.
- ADMX experiment has probed the 2 – 3.3 μeV (500 – 800 MHz) range.
- Need to cover the entire 1 – 5 μeV range and the 1 – 2 μeV (200 – 500 MHz) in particular.





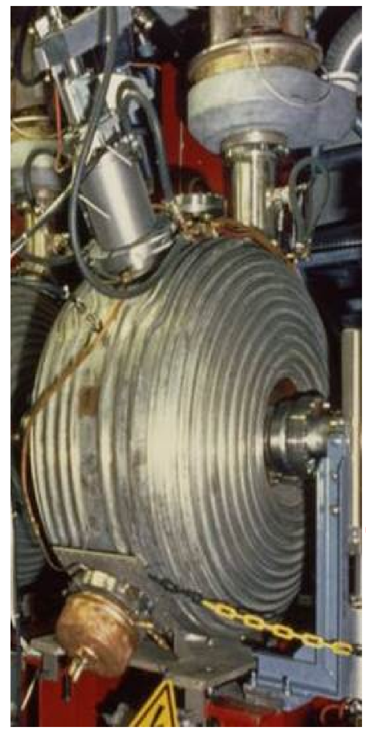


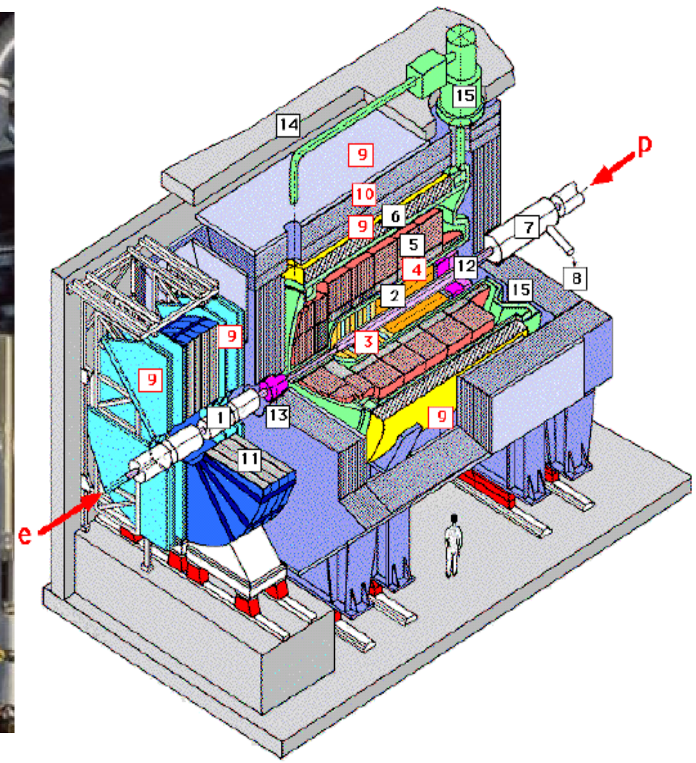
Bradley et al. 2003, Asztalos et al. 2006, 2010

WISPDMX Overvirew

- 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).
- Currently completing Phase 1: hidden photon searches at nominal resonances of the cavity.
- Phase 2: HP searches with cavity tuning
- Phase 3: ALP searches

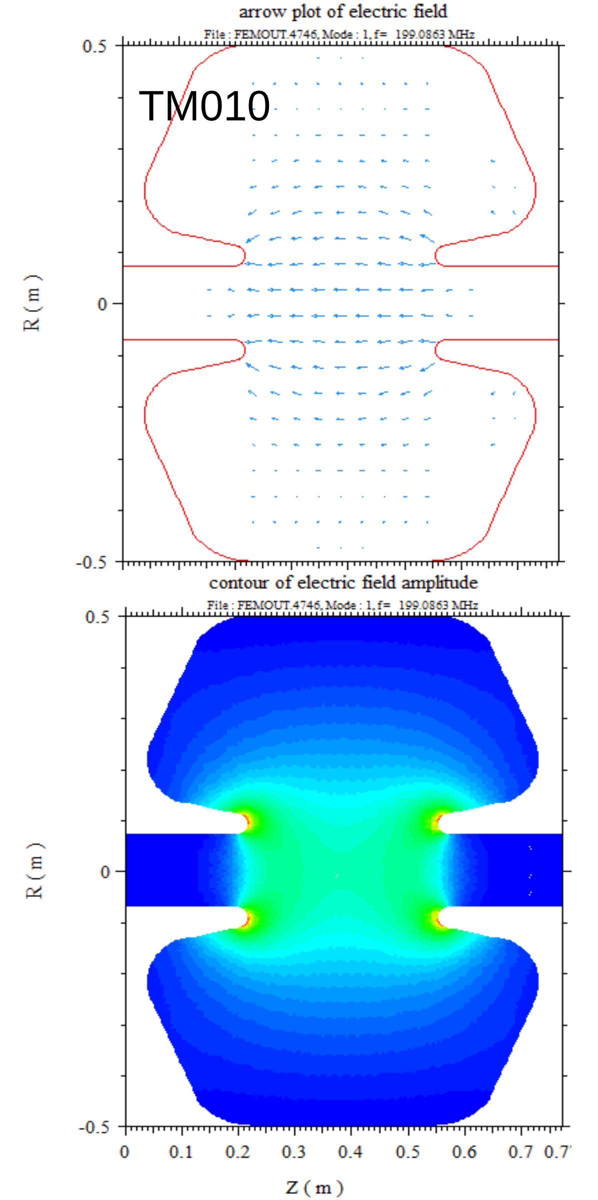




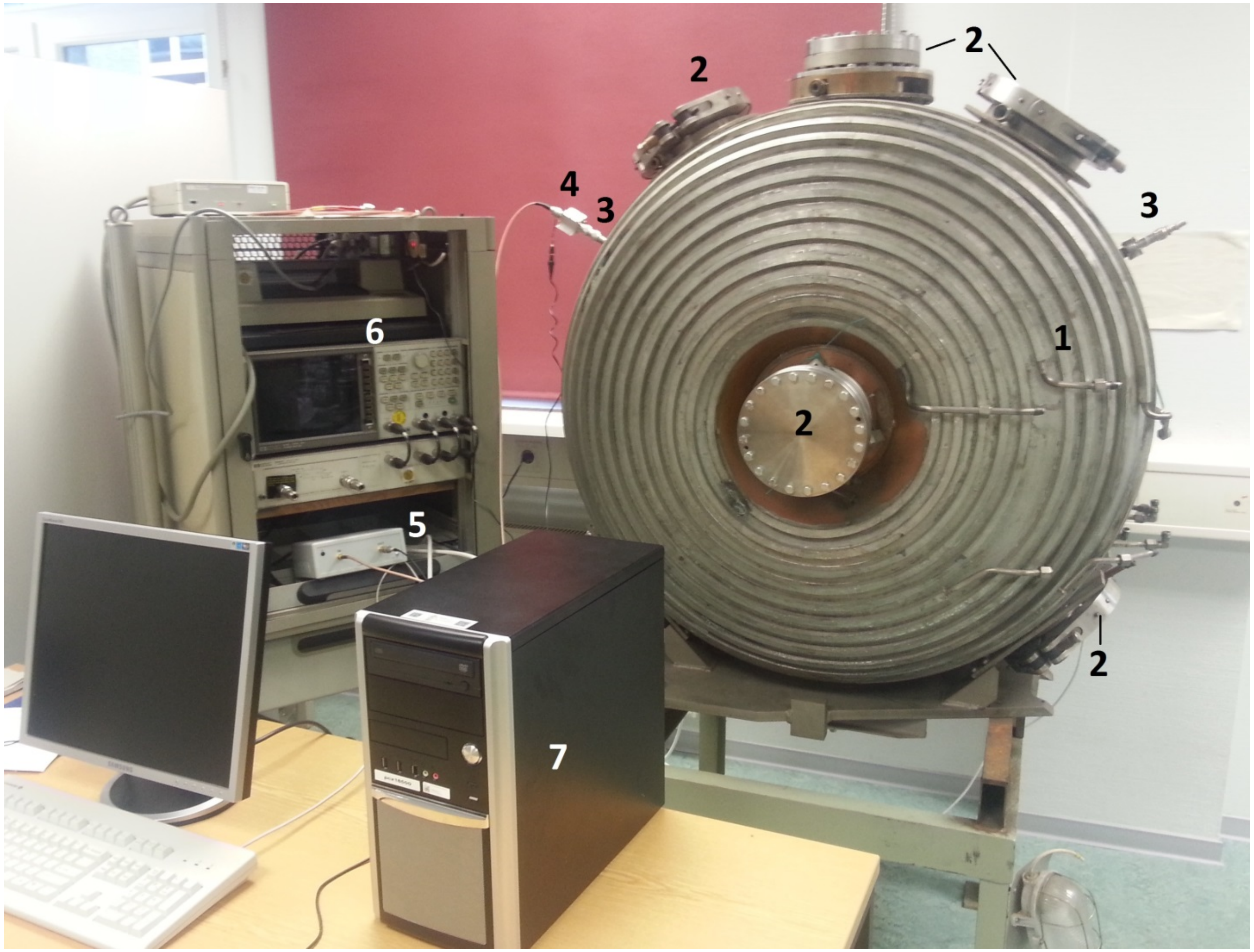
Photograph of the HERA 208-MHz cavity (left) and graphical sketch of the H1 detector with the 1.15 T magnet that can be used for the ALP searches.

Specifics of WISPDMX

- Combining existing elements (cavity, amplifier, magnet).
- 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 μeV 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)

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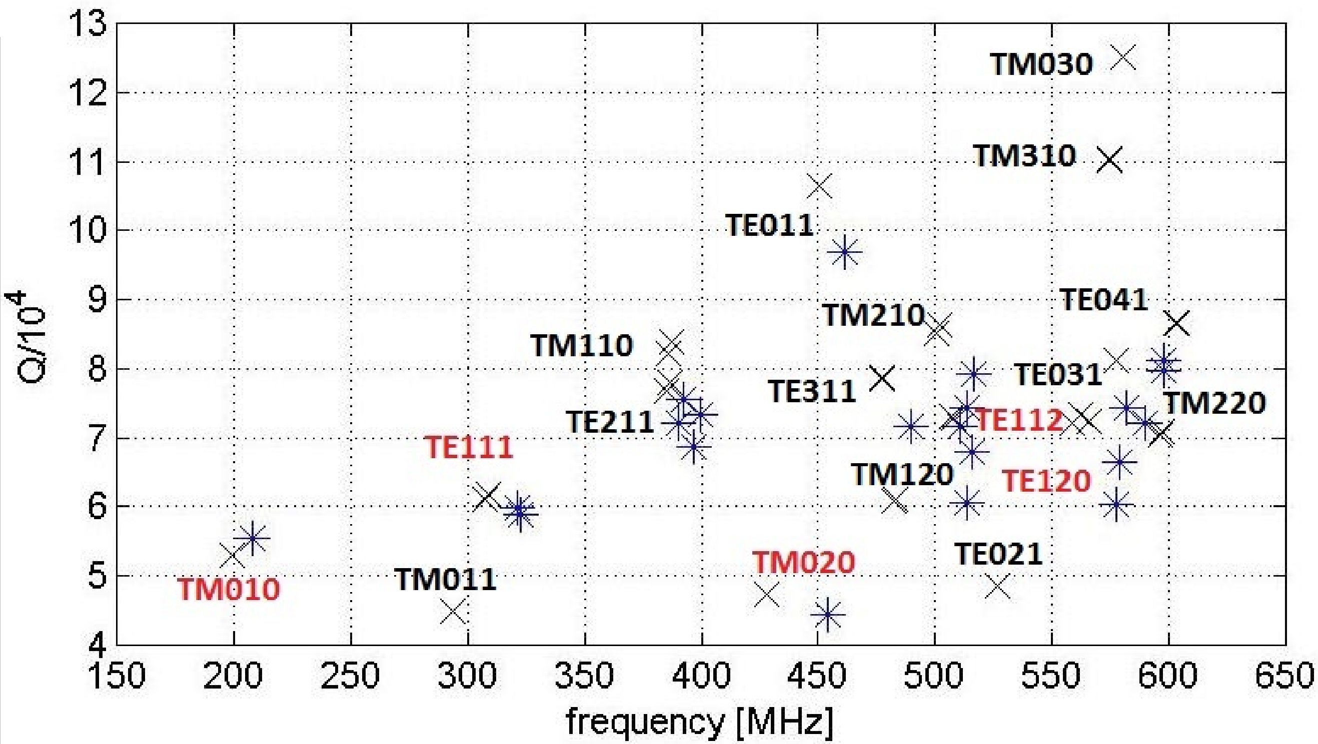
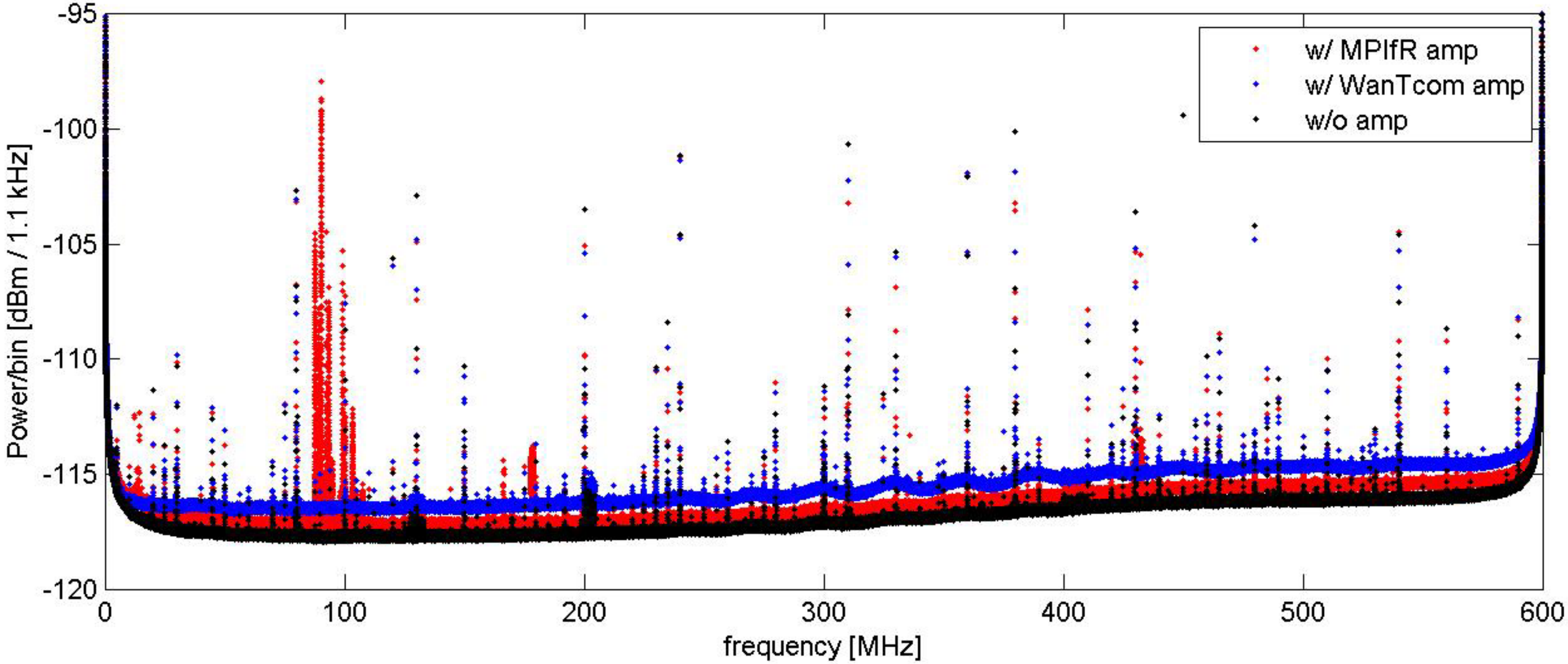
Accessible Resonant Modes

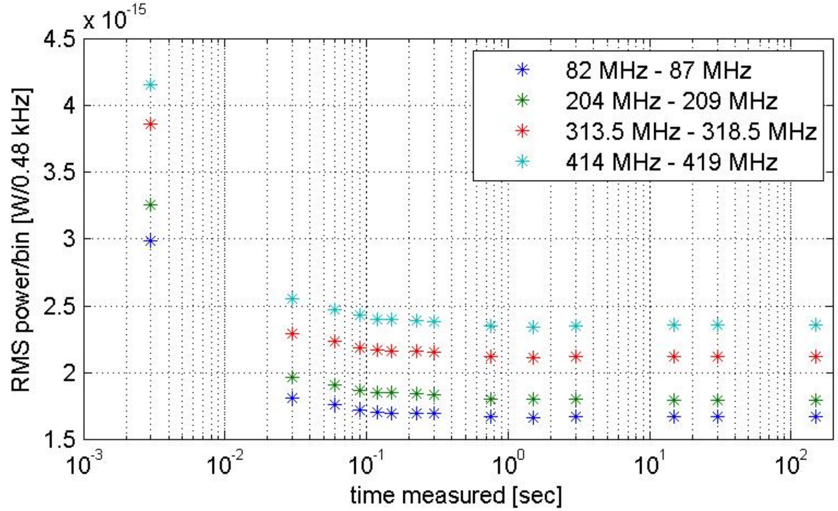
- Five resonant modes identified which have non-zero form factors for hidden photon measurements.
- Outside resonance: $G_f \approx 0.0018$ – hence measurements in the entire spectral range could also be used for constraining χ.

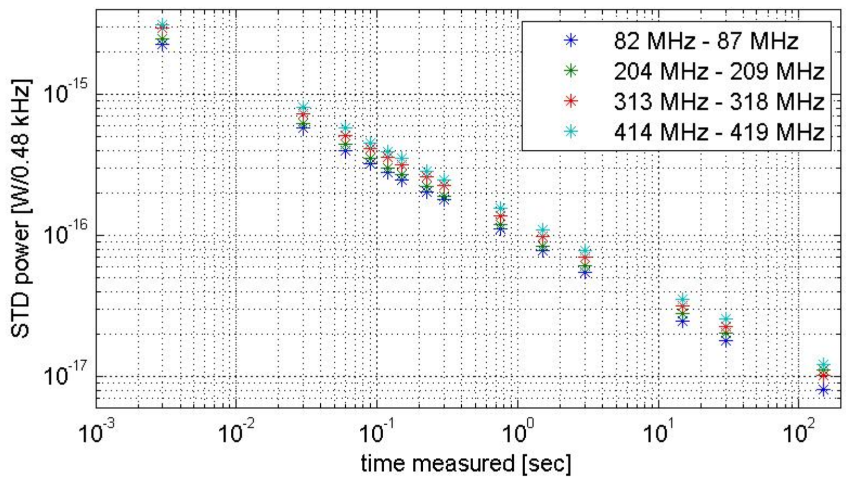


Mode	TM_{010}	TE_{111}	TM_{020}	TE_{112}	TE_{120}	TM_{030}
f/MHz	199	308	428	508	560	580
Q	53000	61000	47000	73000	72000	125000
$\mathcal{G}$	0.43	0.67	0.32	0.019	0.036	0.061

Detector noise







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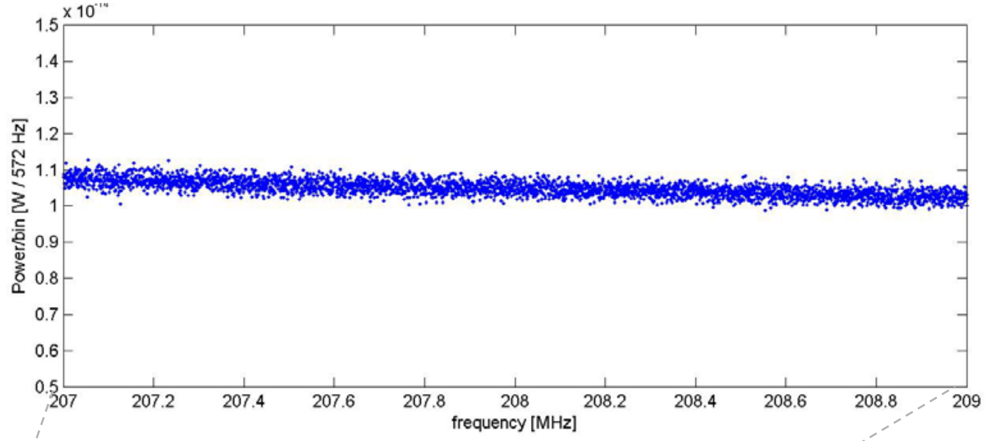
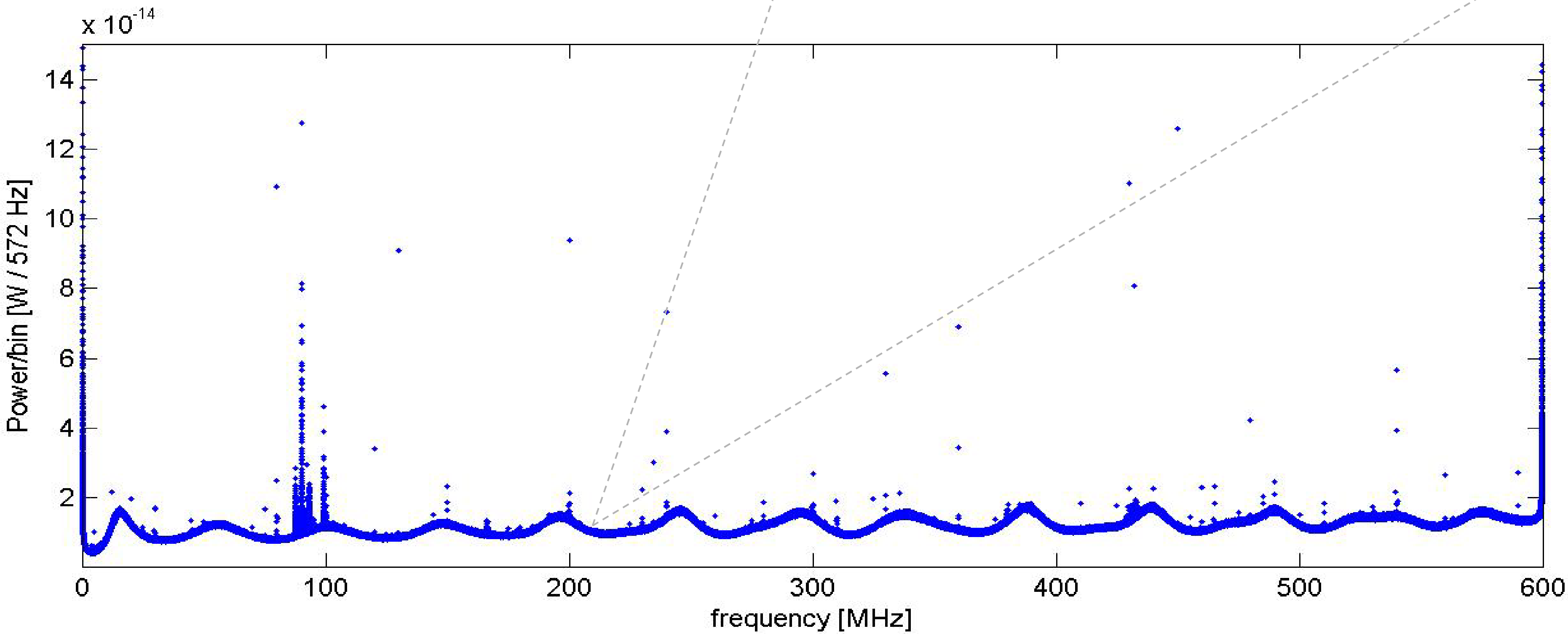
First Results: Noise Spectra

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).





First Results

- 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	$\mathcal{G}$	$P/\mathrm{W}(95\,\%\ \mathrm{CL})$	$m_{\gamma'}/\mu\mathrm{eV}$	$\chi(95\,\%\ \mathrm{CL})$
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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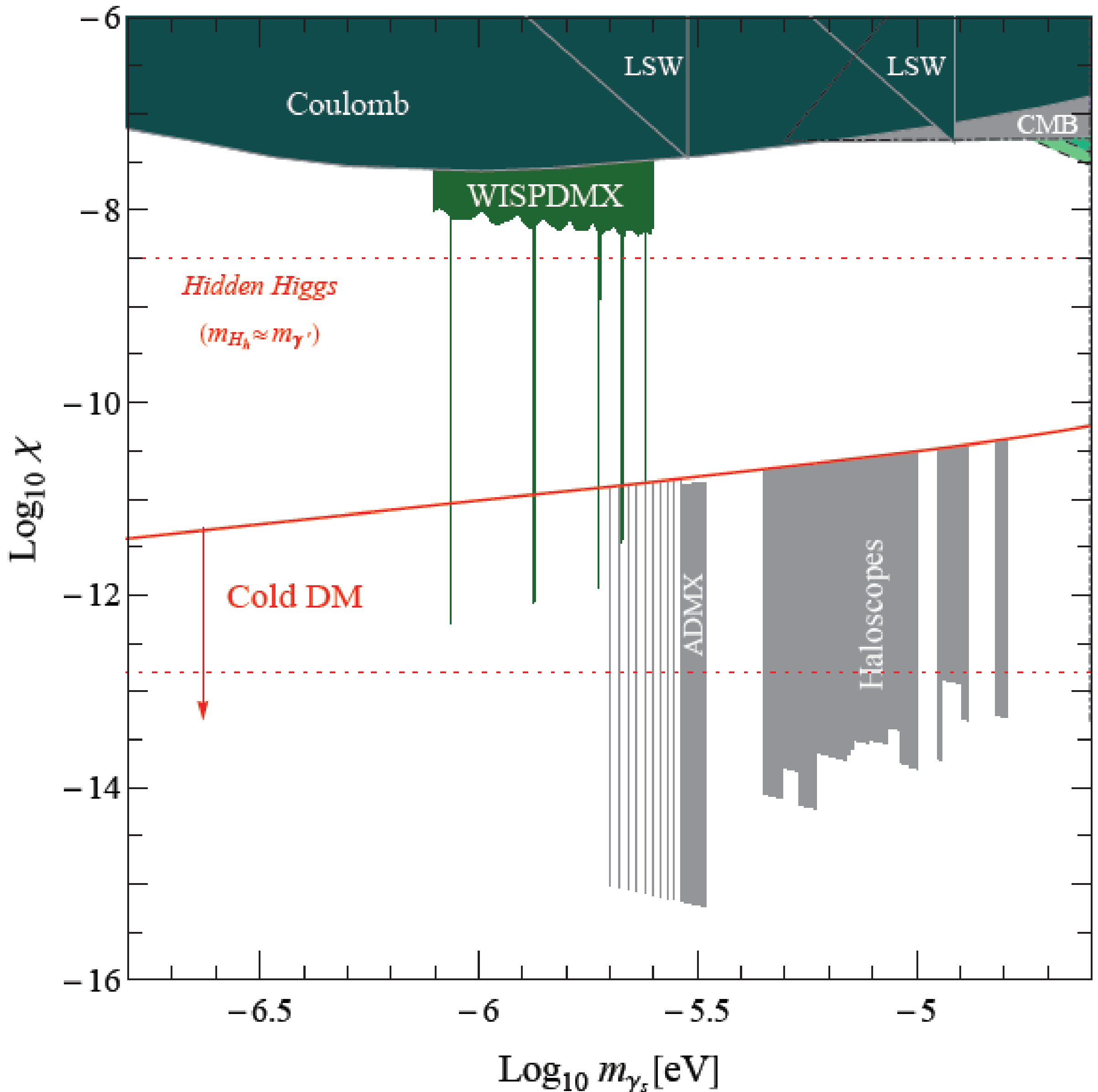
- Exclusion limits from WISPDMX Phase 1 measurements: evaluating the broadband signal.
- Further improvements (factor ~10^2) will come from stronger amplification, improving the frequency resolution (using downconverter), optimizing the antenna probes and cooling the apparatus.



Phase 2: Tuning the Cavity

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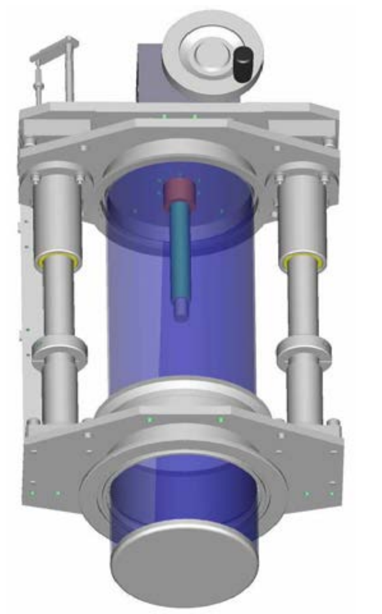
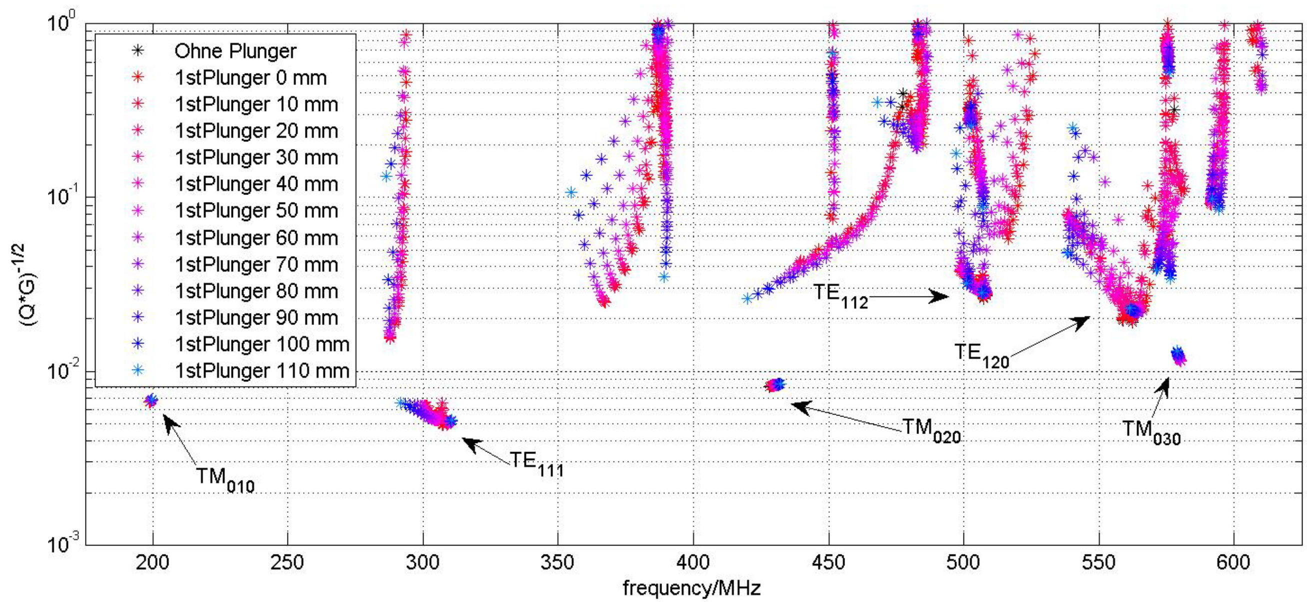
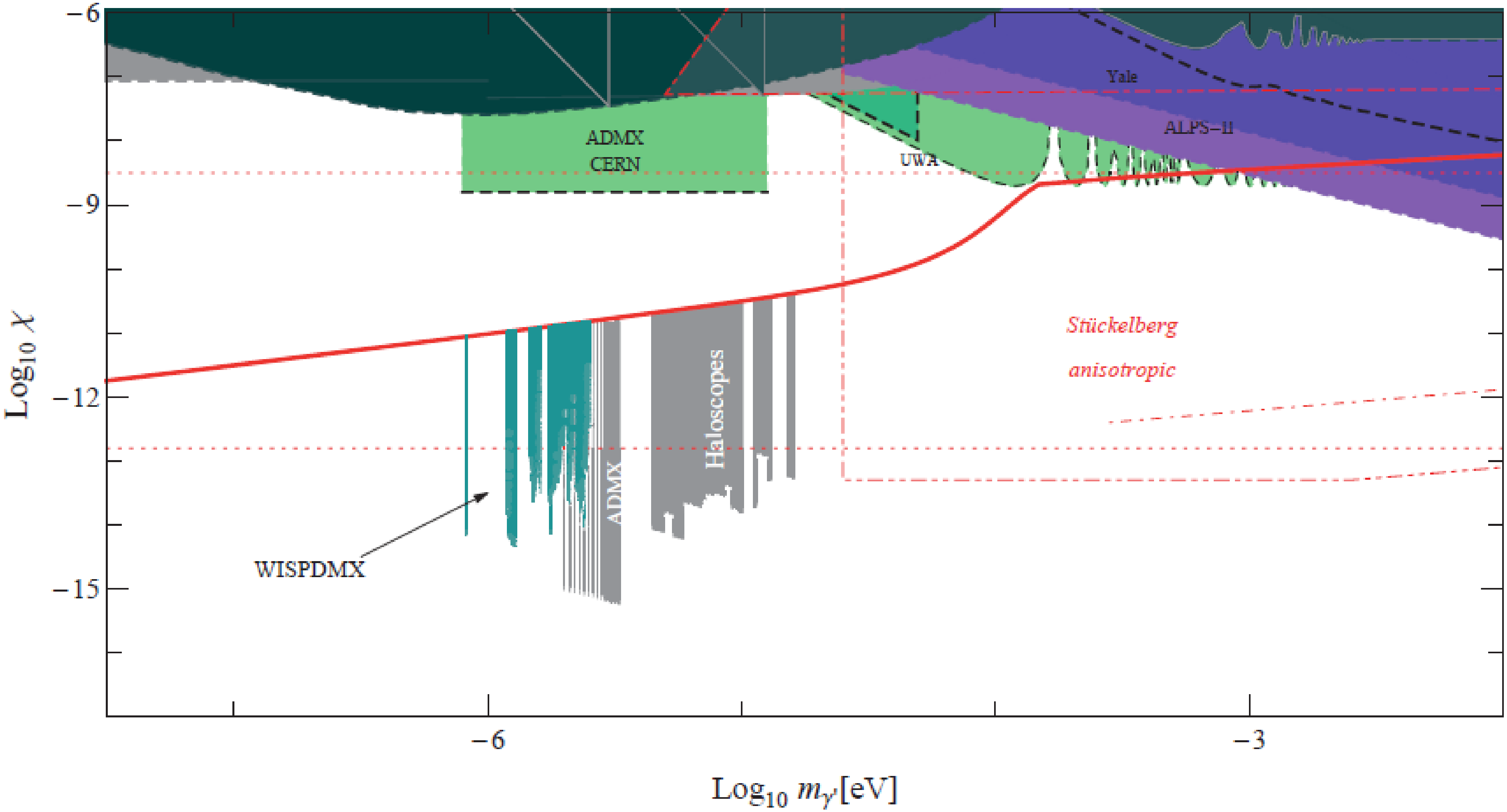
- Tuning pluner assembly is under construction.
- CST simulations of plunger assembly consisting of two plungers.
- The assembly should provide effective coverage of up to 56% of the 200-500 MHz range (up 70% with additional vacuum-pump tuning)
- It will also improve form factors of several modes
- Optimal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

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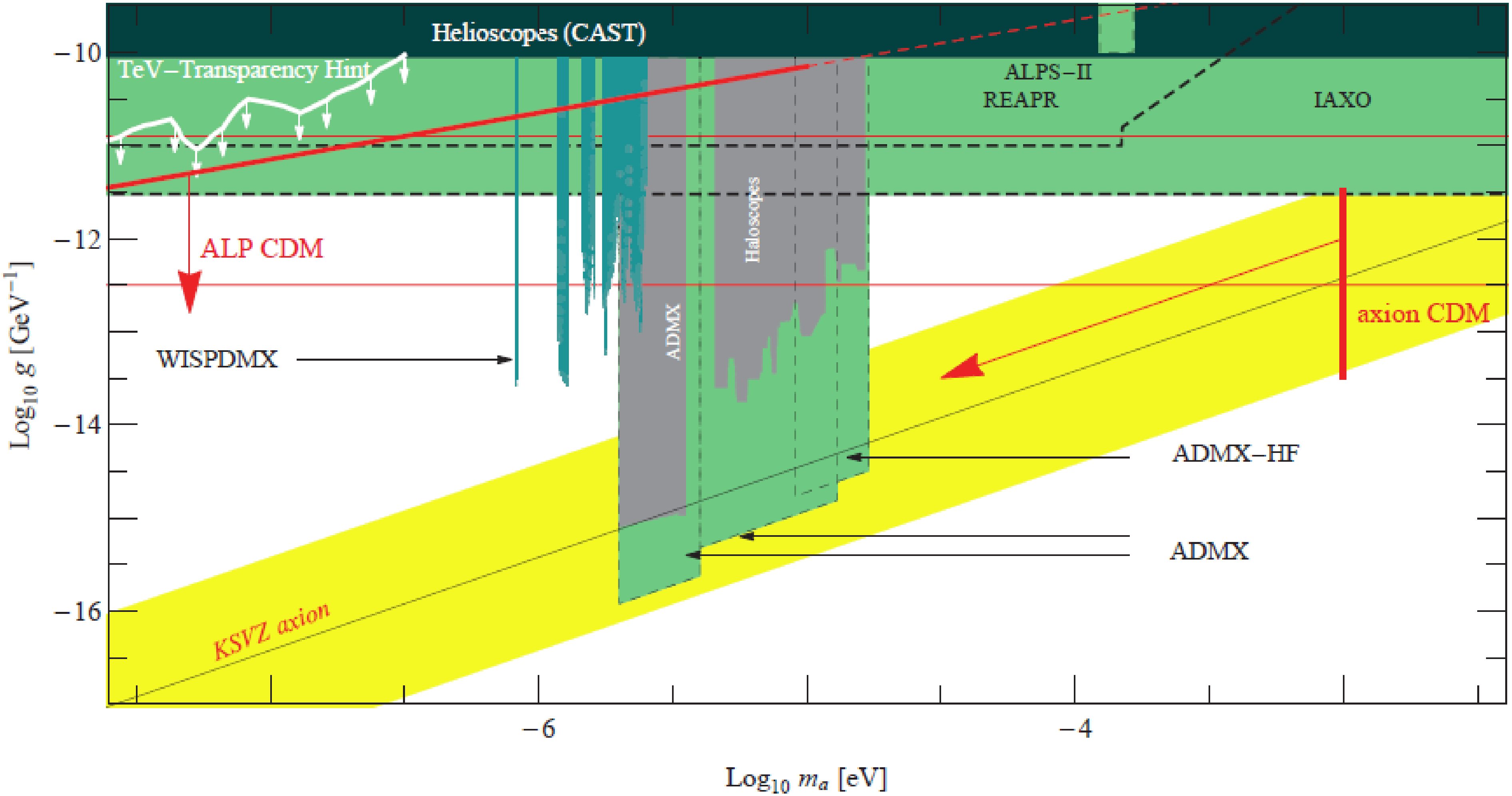
- WISPDMX: expected ALP exclusion limits from measurements with tuned cavity combined with the solenoid magnet from H1 detector (1.15 Tesla)



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

WISPDMX scanning speed for axions

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

and hidden photons

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

- 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_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:

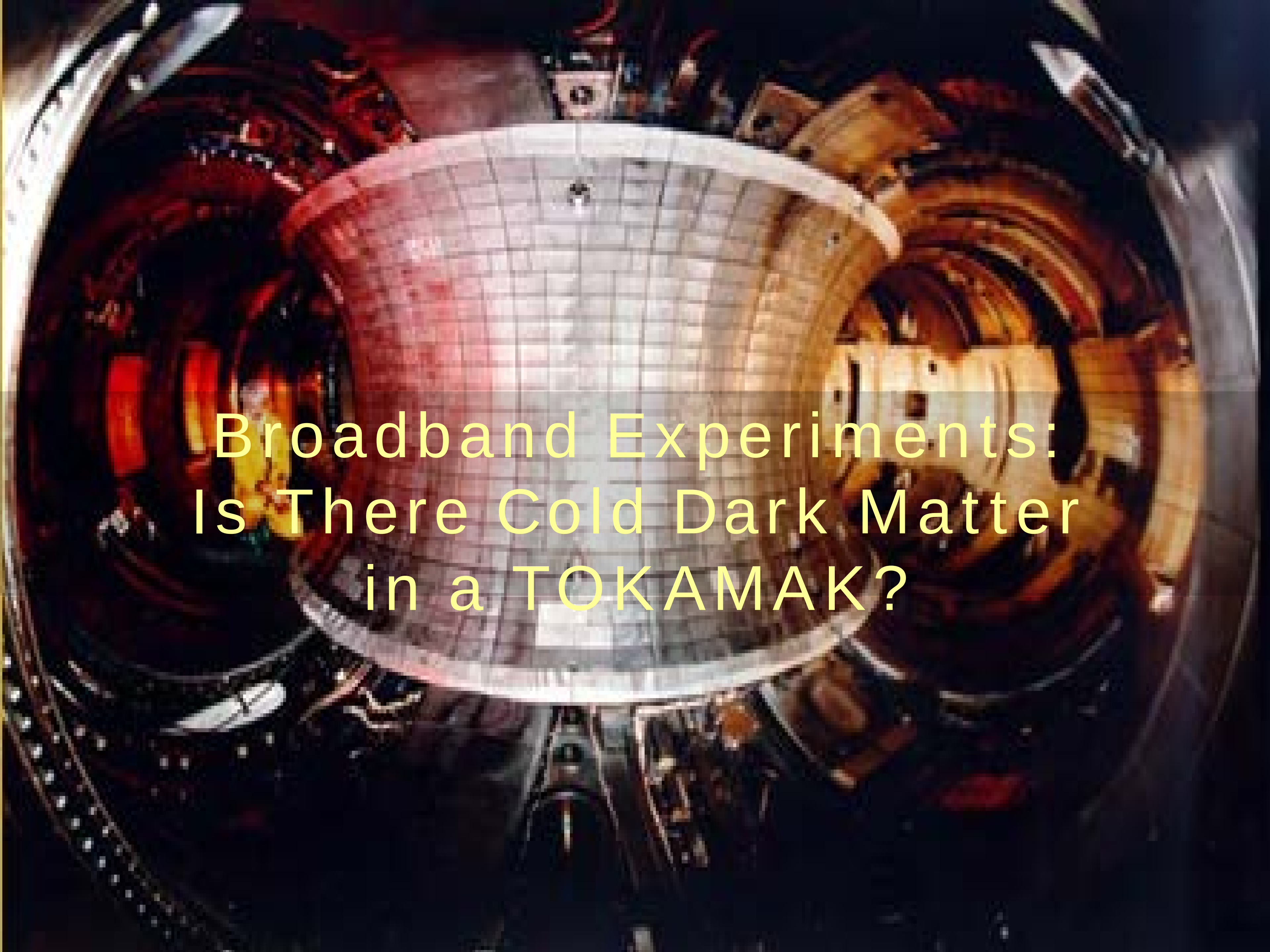
  – increasing measurement time, *t*; *... expensive*

  – reducing the system noise, T_n; *... reaching quantum limit*

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

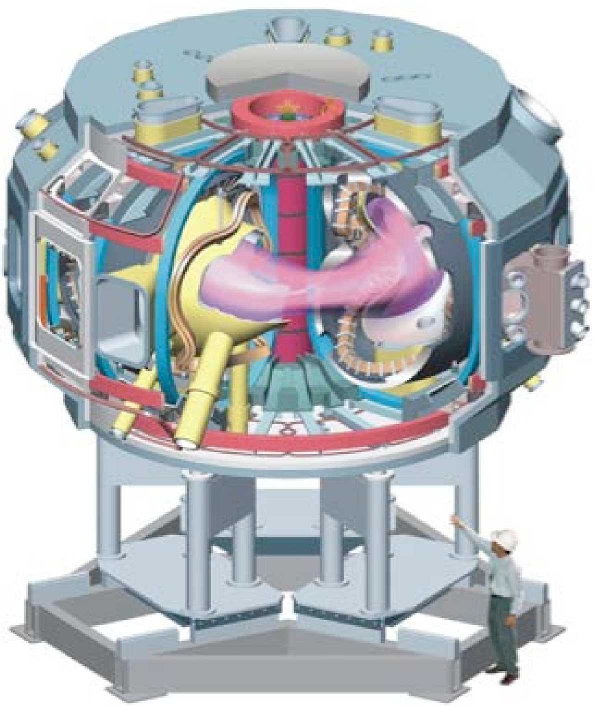
  – increasing the volume, *V*. *... with TOKAMAKs? or dedicated radiometry chambers?*

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



Is This Cheese Free?

Buy This



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Going Away From Resonance

A. Lobanov

- **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 $\lambda \ll V^{1/3}$)

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

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

  -- taking difraction aboard

  -- „dirtying" the particle coupling (especially relevant for axions)

  -- spreading detectors all over

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

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Spherical Reflectors

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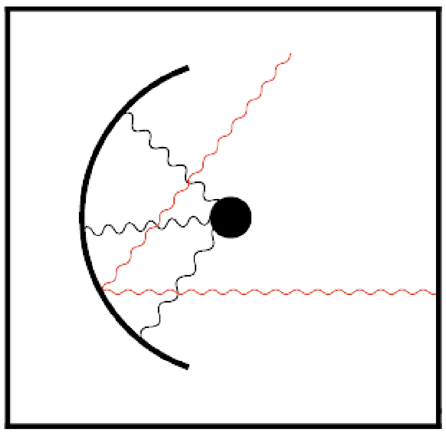
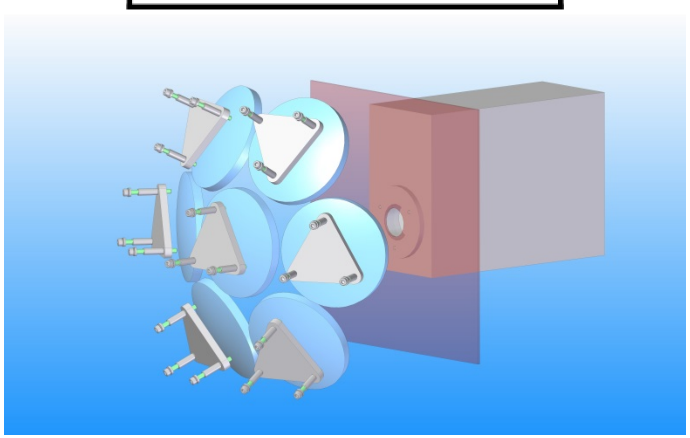
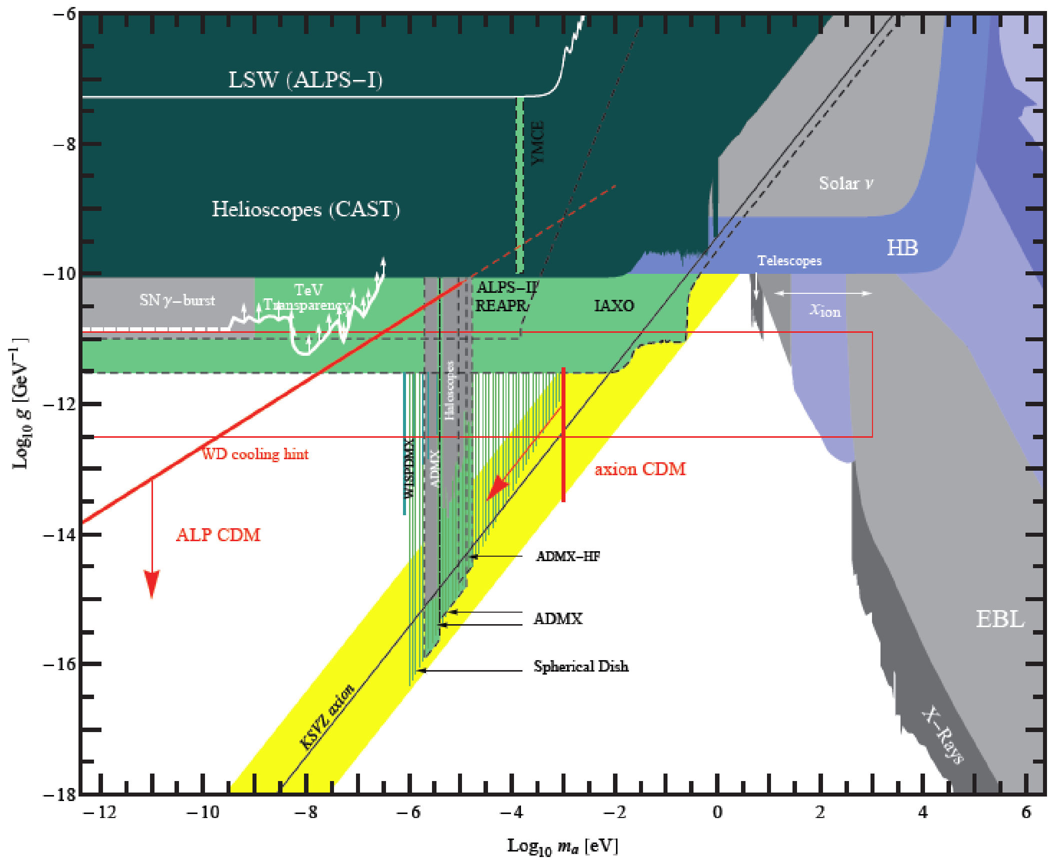
- Employing spherical reflectors enhance (focus) the near field EM signal from the reflector surface which arises due to its interaction with WISP dark matter (Horns et al. 2013). Promising for masses above 10 μeV.
- Pilot study is underway at DESY (Döbrich et al.)







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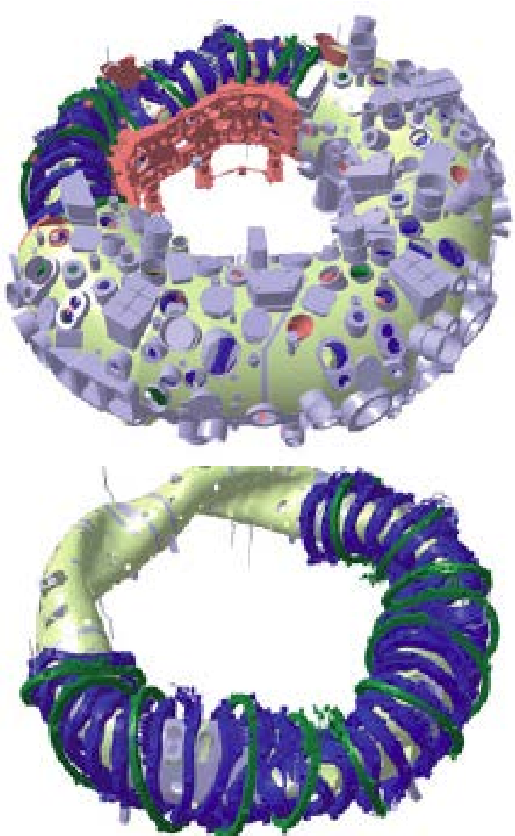
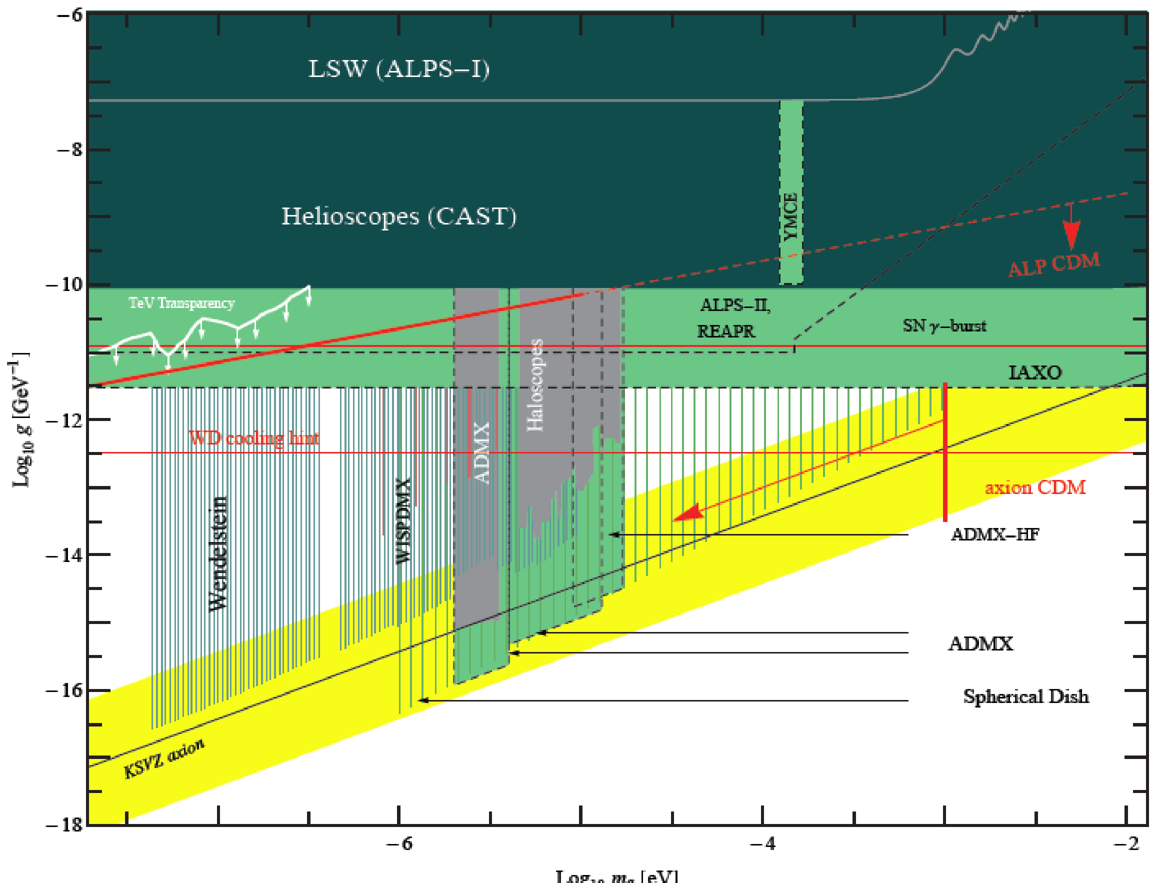
Superconducting Tokamaks

- 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 ~ 100 (ν/1GHz)$^{-1}$ and double shielding of the plasma vessel – but complicated B-field.



W7-X: magnetic coils and plasma vessel



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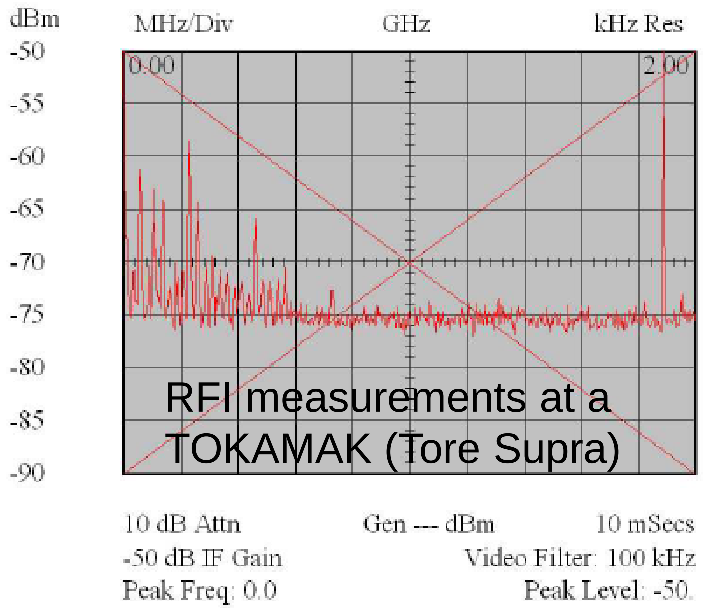
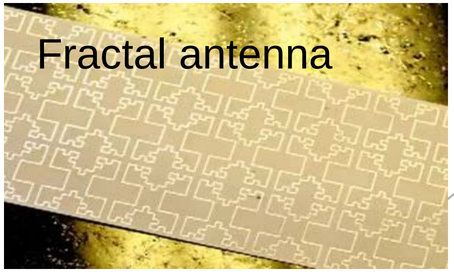
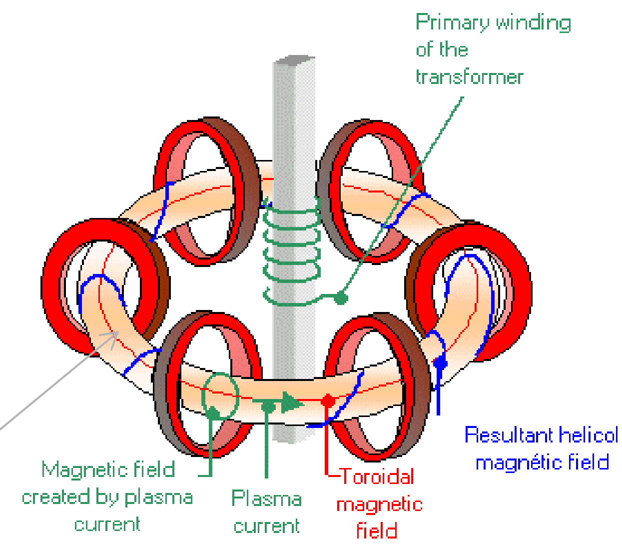
Critical Issues

- 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







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Radiometry Chambers?

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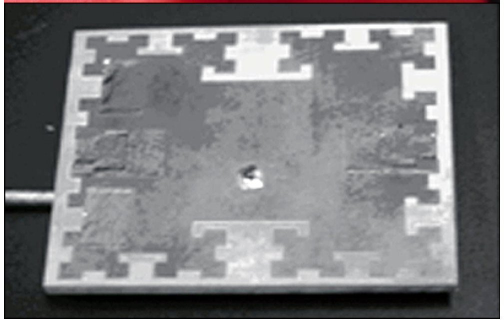
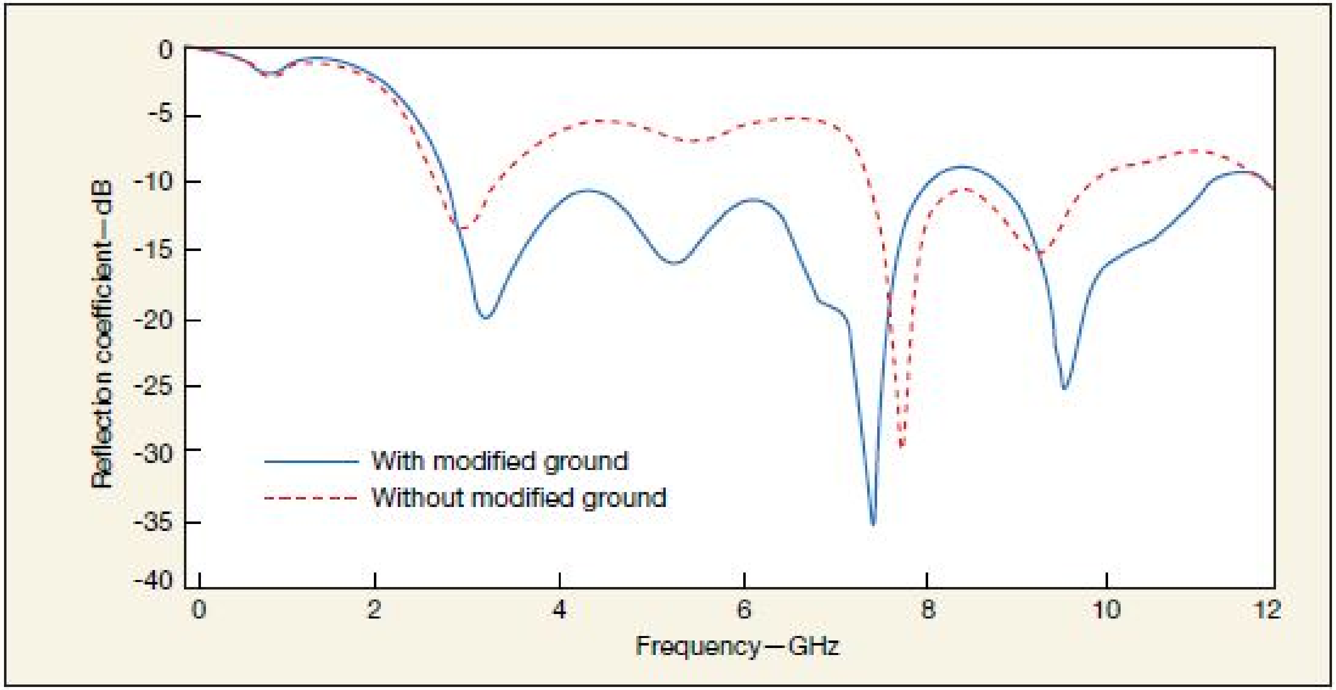
- „Squashing the cauliflower“ and going to Q=1 with a detection chamber „coated“ on the inside with fractal antennas.
- Should get a decent bandpass over a broad range of frequencies.
- Should get the sensitivity of the total inner surface area by adding (correlating) signals from individual fractal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





Radiometry Chambers

A. Lobanov

- 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.