Scientific Scope of WISPDMX.

Towards a direct detection experiment for WISPy cold dark matter

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HELMHOLTZ
ASSOCIATION

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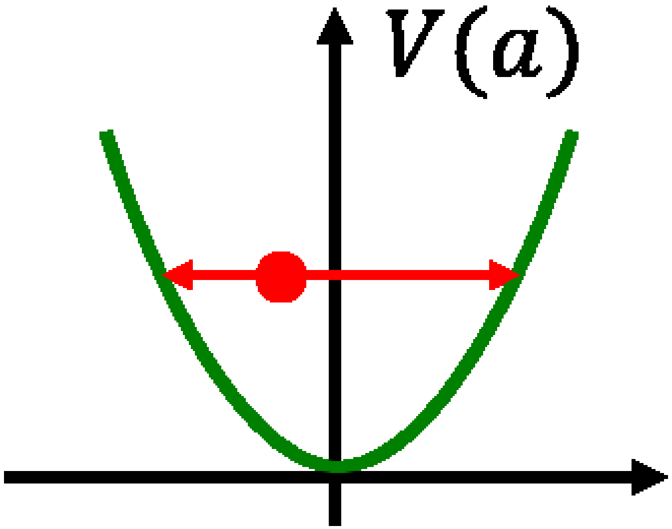
WISPy Cold Dark Matter

> Very weakly interacting slim particles (WISPs), such as

- axions
- axion-like particles (ALPs)
- hidden photons (HPs)



are non-thermally produced in the early universe in the form of non-relativistic classical field oscillations

[...; Arias, Cadamuro, Goodsell, Jaeckel, Redondo, AR, arXiv:1201.5902]

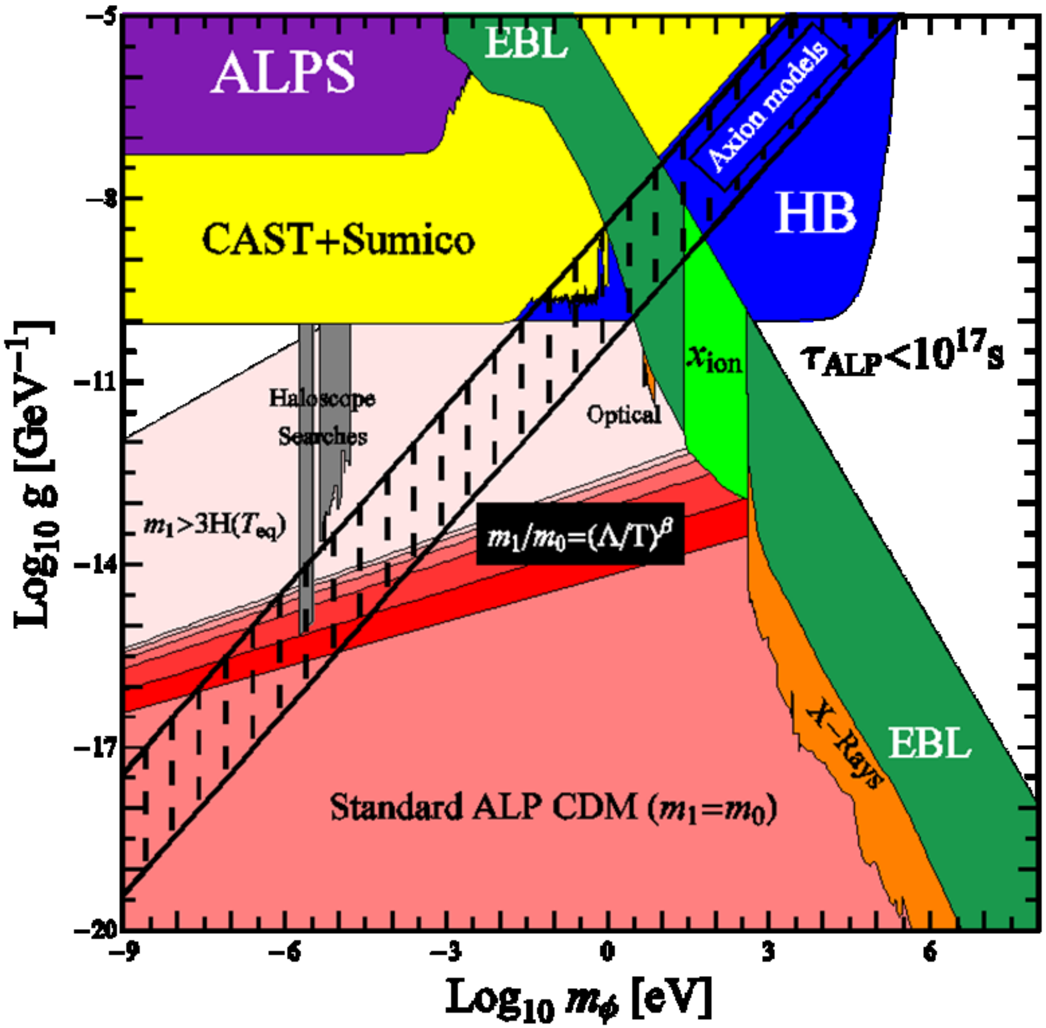
WISPy Cold Dark Matter

- If sufficient weak coupling, e.g. with photons,

$$\mathcal{L} \supset -\frac{g}{4}\,\phi\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L} \supset -\frac{\chi}{2}\, F_{\mu\nu}X^{\mu\nu}$$

they will survive as CDM



WISPy Cold Dark Matter

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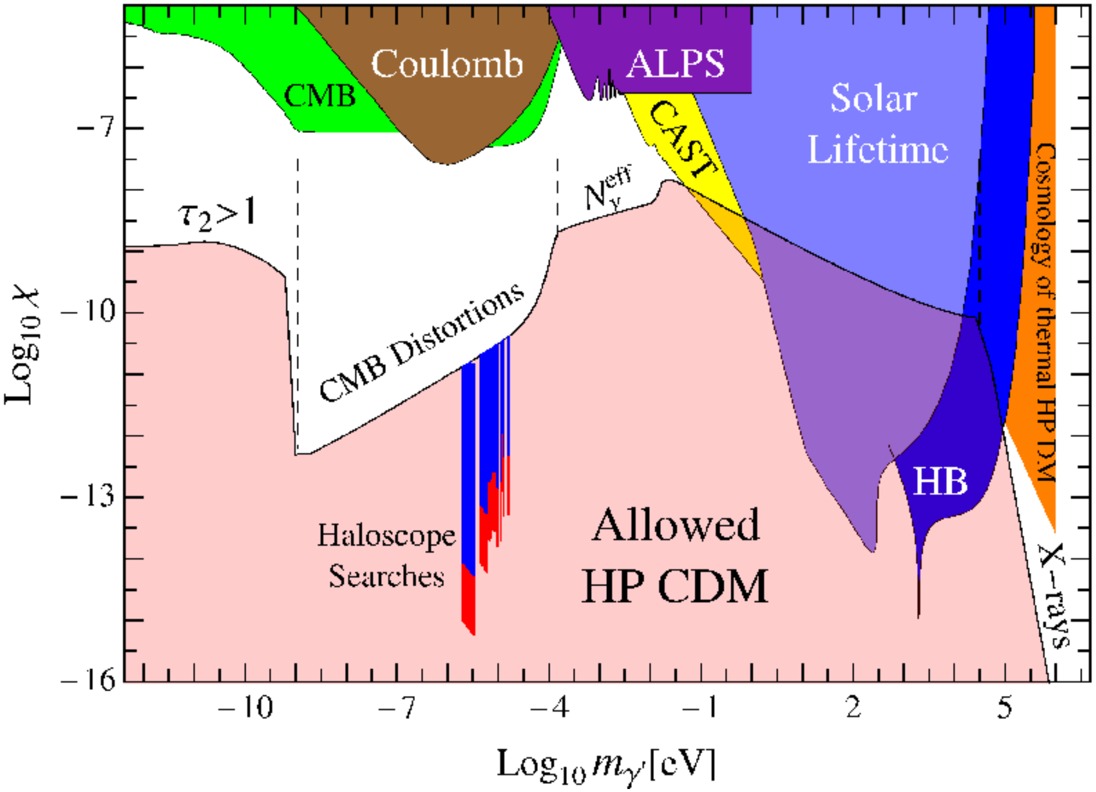
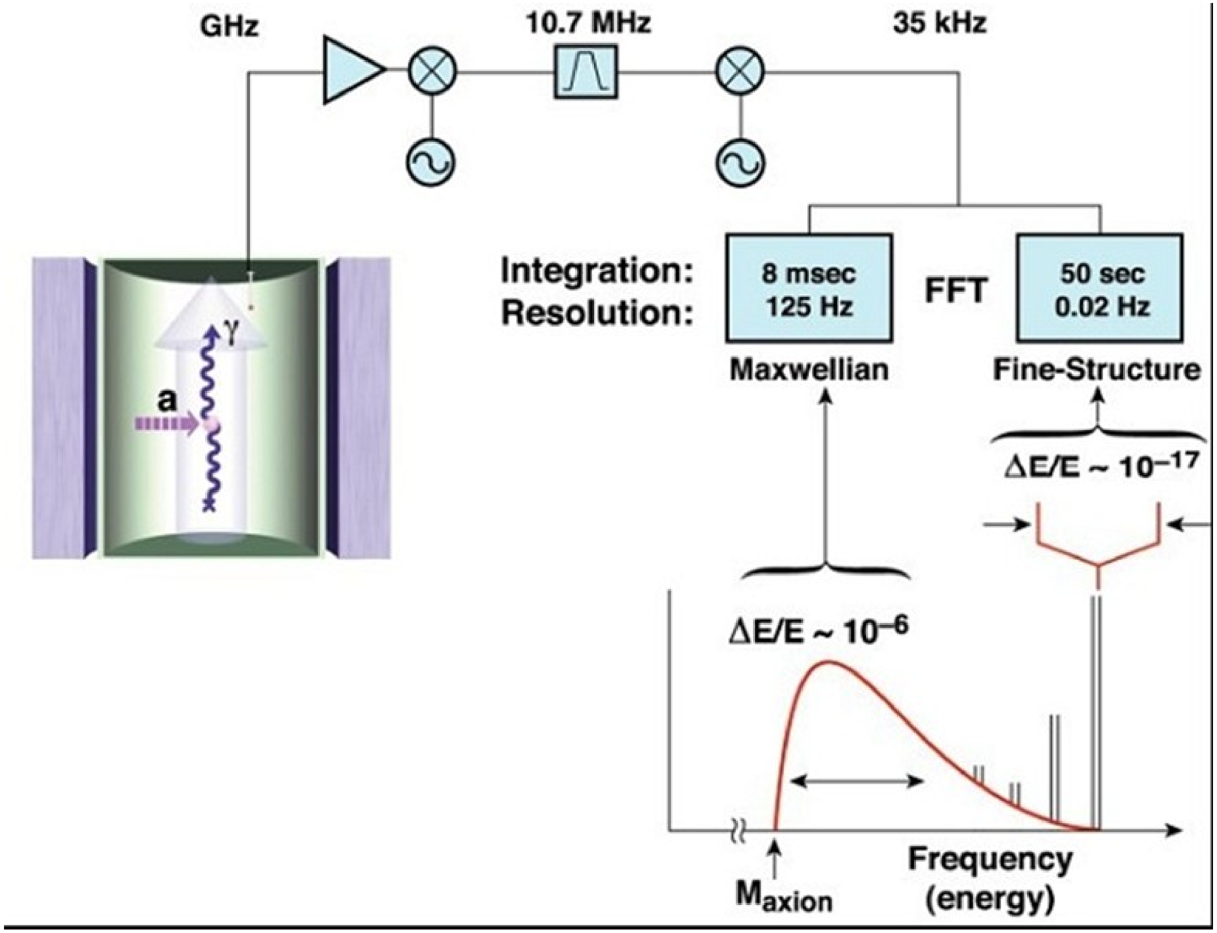


Direct WISPy CDM Searches with Haloscopes

> WISP CDM -> photon conversion in a resonant cavity, e.g. ADMX:



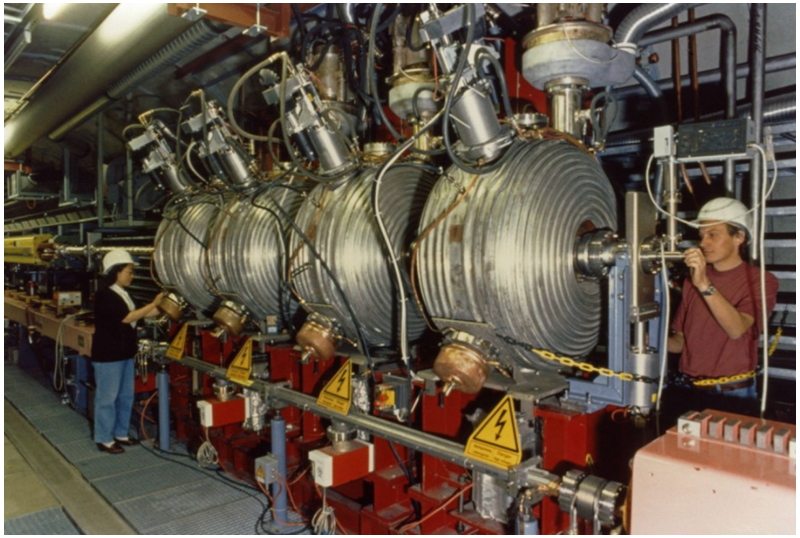
WISPDMX Opportunity

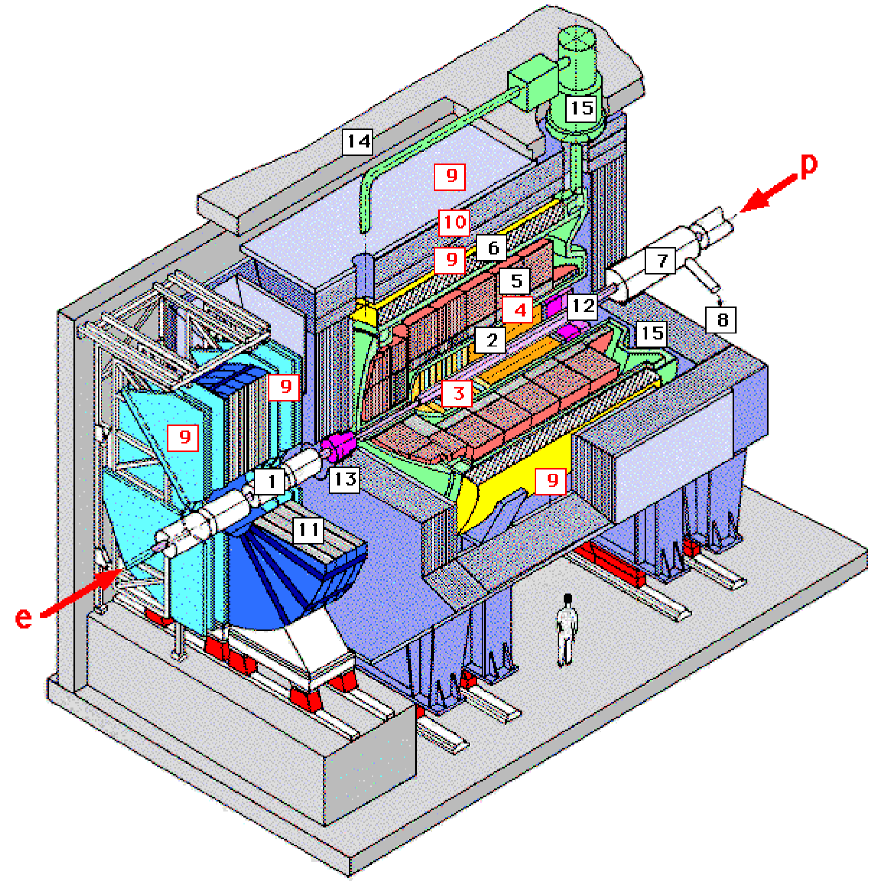
> Available building blocks (DESY)

- HERA proton ring cavities
- H1 superconducting solenoid

> Available competence (MPIfR)

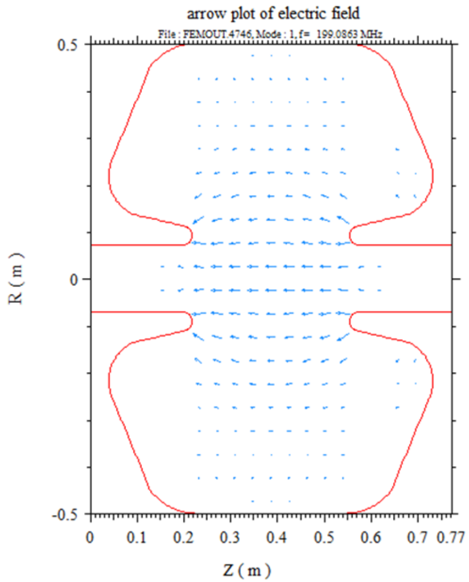
- receiver, amplifier, FFT, …

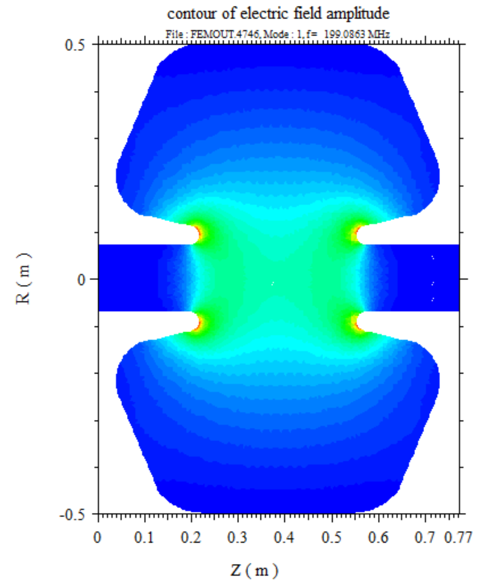




HERA Proton Acceleration Cavity

- Fundamental TM_010 mode: f = 208 MHz and Q_0 = 5.3e4





- Without tuning, sensitive to mass

$$m_{\gamma'} = \omega \equiv 2\pi f = 8.6 \times 10^{-7}\ \mathrm{eV}\ \left(\frac{f}{208\ \mathrm{MHz}}\right)$$

Hidden Photon CDM Experiment

> Power output of cavity,

$$P_{\rm out} = \kappa\chi^2 m_{\gamma'}\rho_0\, Q\, V\, \mathcal{G}_{\gamma'},\ \ \text{with}\ \mathcal{G}_{\gamma'} \equiv \frac{\left(\int dV\, \mathbf{E}_{\rm cav}\cdot\hat{\mathbf{n}}\right)^2}{V\,\int dV\,\mathbf{E}^2_{\rm cav}}$$

with n being the direction between E_cav and the HP field

$$\begin{aligned} P_{\rm out} &= 9.7\times 10^{-21}\ {\rm W}\ \kappa\left(\frac{\chi}{10^{-14}}\right)^2\left(\frac{m_{\gamma'}}{8.6\times 10^{-7}\,{\rm eV}}\right)\left(\frac{Q}{2.7\times 10^4}\right) \\ &\quad \times\left(\frac{V}{460\,\ell}\right)\left(\frac{\mathcal{G}_{\gamma'}}{0.5\times 0.25}\right)\left(\frac{\rho_0}{0.3\,{\rm GeV/cm^3}}\right). \end{aligned}$$

Hidden Photon CDM Experiment

- Required measurement time,

$$t = (\mathrm{SNR})^2 \left(\frac{k_B T_n}{P_{\mathrm{out}}}\right)^2 b_{\gamma'} = (\mathrm{SNR})^2 \left(\frac{k_B T_n}{P_{\mathrm{out}}}\right)^2 \frac{f}{Q_{\gamma'}}$$

$$\sim 6.0 \times 10^2\,\mathrm{s} \left(\frac{\mathrm{SNR}}{4}\right)^2 \left(\frac{T_n}{300\,\mathrm{K}}\right)^2 \left(\frac{\chi}{10^{-14}}\right)^{-4} \left(\frac{V}{460\,\ell}\right)^{-2} \left(\frac{\mathcal{G}_{\gamma'}}{0.5 \times 0.25}\right)^{-2}$$

$$\times \left(\frac{\rho_0}{0.3\,\mathrm{GeV/cm^3}}\right)^{-2} \left(\frac{10^6}{Q_{\gamma'}}\right) \left(\frac{8.6 \times 10^{-7}\,\mathrm{eV}}{m_{\gamma'}}\right)^{-3} \left(\frac{Q}{2.7 \times 10^4}\right)^{-2}$$

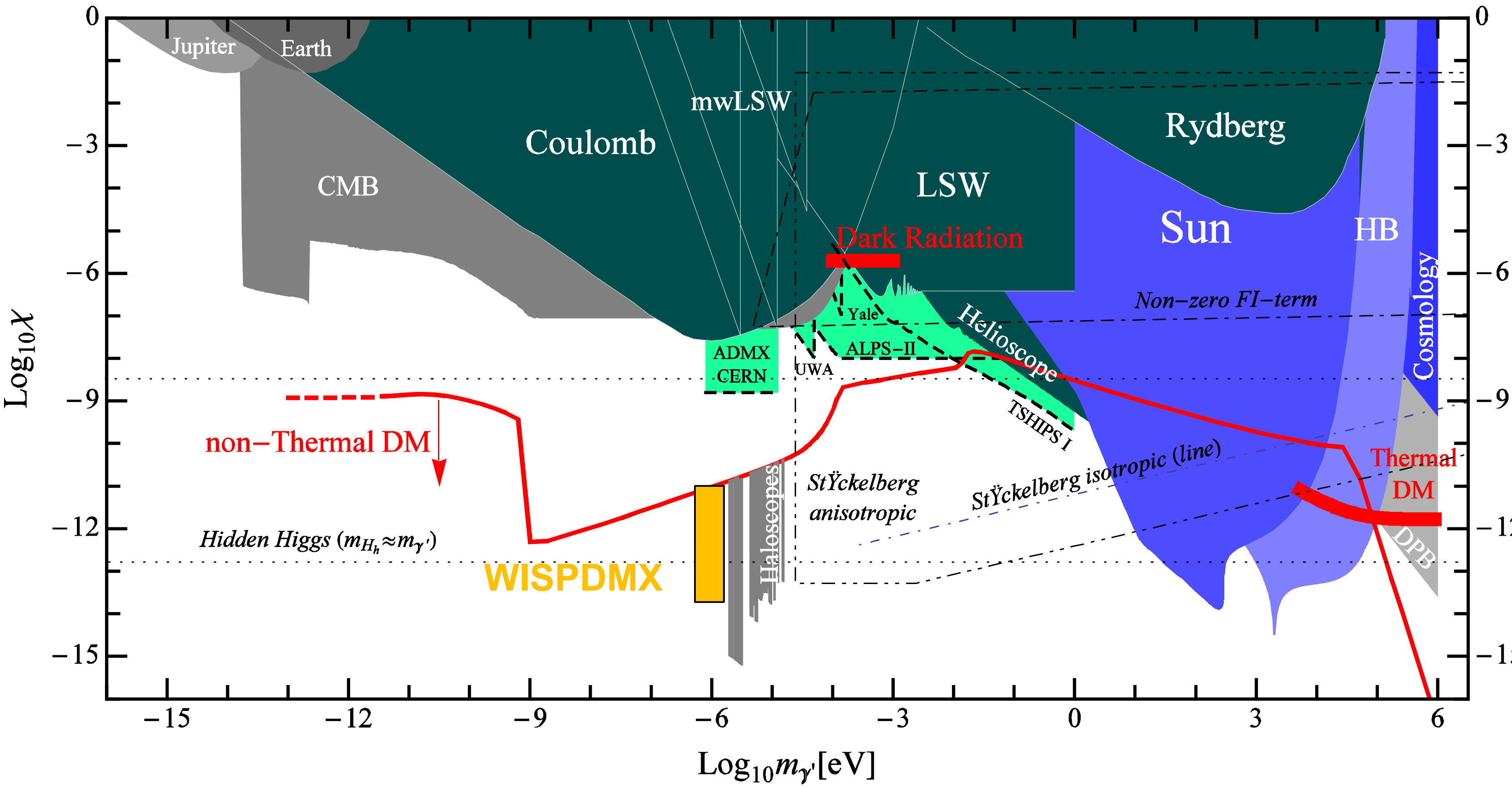
- Scanning speed,

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

$$\times \left(\frac{208\,\mathrm{MHz}}{f}\right)^2 \left(\frac{Q}{2.7 \times 10^4}\right) \left(\frac{10^6}{Q_{\gamma'}}\right) \left(\frac{\rho_0}{0.3\,\mathrm{GeV/cm^3}}\right)^2$$

Discovery Reach for HP CDM Experiment

- Even without cooling, can probe HP CDM with chi ~ 1e-14 up to ADMX
  [Jaeckel,Lindner,Lobanov,Möller,AR,Sekutowicz,Trines,Westphal]



Axion and ALP CDM Experiment

- Power output of cavity,

$$P_{\rm out} = \kappa\, g^2 V\, |\mathbf{B}_0^2|\, \rho_0\, \mathcal{G}_\phi\, \frac{1}{m_\phi}\, Q, \ \ \text{with}\ \mathcal{G}_\phi = \frac{\left(\int dV\, \mathbf{E}_{\rm cav}\cdot \mathbf{B}_0\right)^2}{V|\mathbf{B}_0|^2 \int dV\, \mathbf{E}_{\rm cav}^2}$$

in numbers:

$$\begin{aligned} P_{\rm out} &= 2.7\times 10^{-23}\ \mathrm{W}\, \kappa \left(\frac{g}{10^{-15}/\mathrm{GeV}}\right)^2 \left(\frac{V}{460\,\ell}\right) \left(\frac{B_0}{1.15\,\mathrm{T}}\right)^2 \left(\frac{Q}{2.7\times 10^4}\right) \\ &\times \left(\frac{8.6\times 10^{-7}\,\mathrm{eV}}{m_\phi}\right) \left(\frac{\mathcal{G}_\phi}{0.5}\right) \left(\frac{\rho_0}{0.3\,\mathrm{GeV/cm^3}}\right) \end{aligned}$$

Axion and ALP CDM Experiment

> Required measurement time,

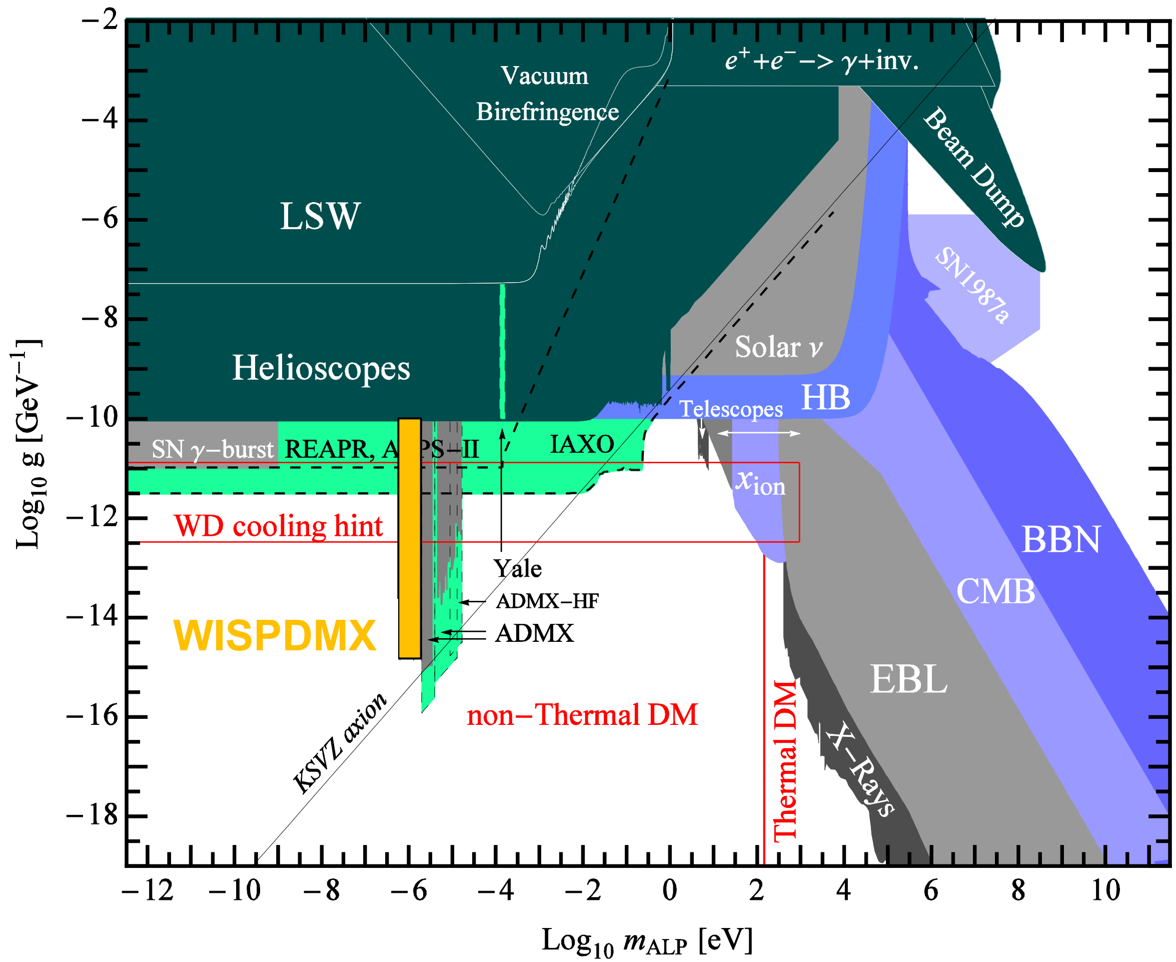
$$
\begin{aligned}
t &= (\mathrm{SNR})^2 \left(\frac{k_B T_n}{P_{\rm out}}\right)^2 b_\phi = (\mathrm{SNR})^2 \left(\frac{k_B T_n}{P_{\rm out}}\right)^2 \frac{f}{Q_\phi} \\
&\sim 7.6\times 10^3\,\mathrm{s}\left(\frac{\mathrm{SNR}}{4}\right)^2 \left(\frac{T_n}{3\,\mathrm{K}}\right)^2 \left(\frac{B_0}{1.15\,\mathrm{T}}\right)^{-4} \left(\frac{V}{460\,\ell}\right)^{-2} \left(\frac{\mathcal{G}_\phi}{0.5}\right)^{-2} \left(\frac{g}{10^{-15}/\mathrm{GeV}}\right)^{-4} \\
&\quad \times \left(\frac{\rho_a}{0.3\,\mathrm{GeV/cm^3}}\right)^{-2} \left(\frac{10^6}{Q_\phi}\right) \left(\frac{8.6\times 10^{-7}\,\mathrm{eV}}{m_\phi}\right)^{-3} \left(\frac{Q}{2.7\times 10^4}\right)^{-2}
\end{aligned}
$$

> Scanning speed,

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

Discovery Reach of Axion and ALP CDM Experiment

- Can probe even proper QCD Axion CDM up to ADMX mass region:
  [Jaeckel,Lindner,Lobanov,Möller,AR,Sekutowicz,Trines,Westphal]



Conclusions

- Unique opportunity: exploiting available equipment and joining forces with the MPIfR it is possible to explore WISPy CDM in a previously unexplored, but well motivated parameter range
- May do WISPDMX in well separated stages:
  - Start with HP CDM search: even with modest investment (do not need magnet for it; cooling of the cavity and receiver is not necessary in the beginning) one has great discovery potential.
  - Continue HP CDM search, but now with cooled cavity and receiver
  - Extend it later to Axion or ALP CDM search, by putting the previous apparatus in the H1 solenoid: this may even be sensitive to proper QCD Axion CDM