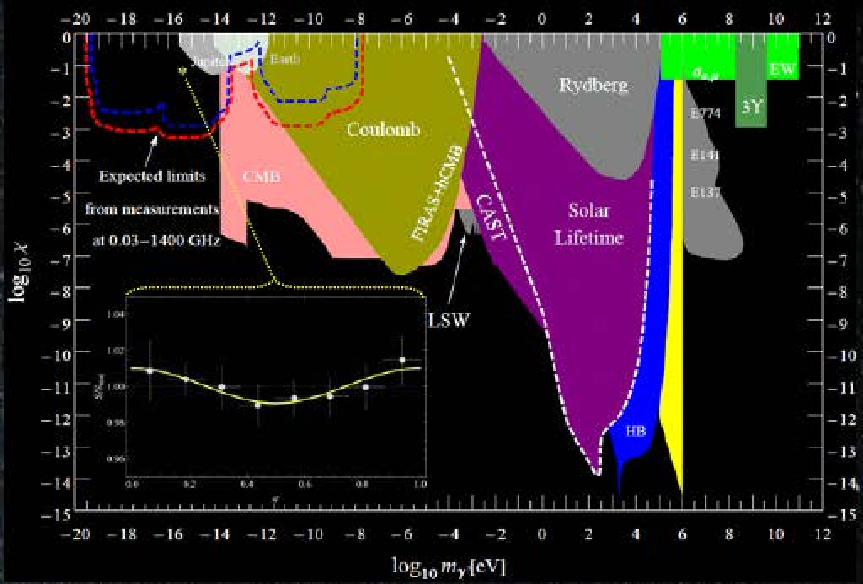


WISPers from the Dark Side:

Radio Probes of Axions and Hidden Photons

Andrei Lobanov
MPIfR Bonn / University of Hamburg

Radio Goes Fundamental

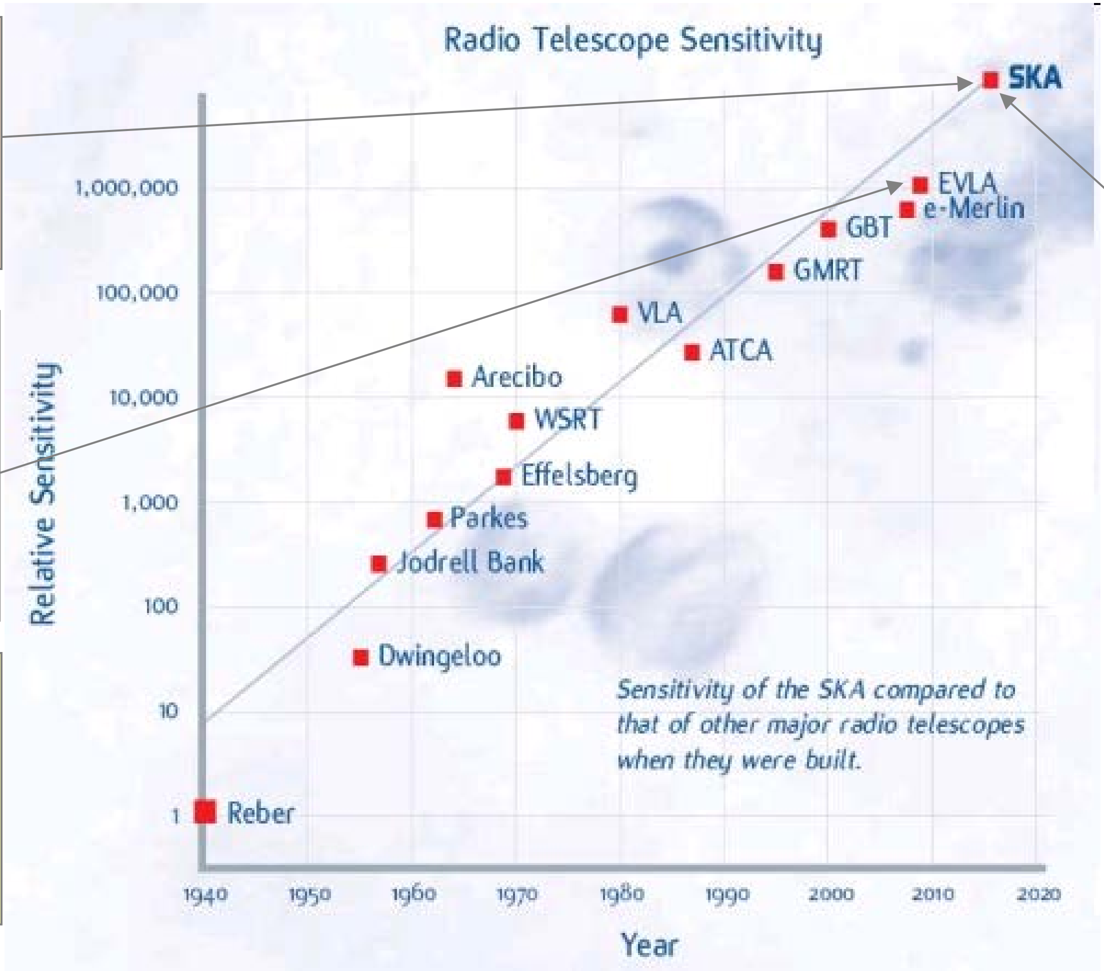
- ☐ Dark matter and dark energy are presently at the focus of many laboratory and astrophysical experiments in the radio.
- ☐ Measurements in radio regime are highly complementary to experiments in other domains.
- ☐ Advances in detection techniques and construction of new facilities in radio astronomy will bring new opportunities for WISP searches.
- ☐ Examples here:
  - – searches for hidden photons in broad-band spectra of astrophysical objects (planets, SNR, AGN);
  - – narrow and broad band laboratory searches for hidden photons and axions at 0.02—2000 GHz (10^{-2}—10^{-7} eV).

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)



Sensitivity of the SKA compared to that of other major radio telescopes when they were built.

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

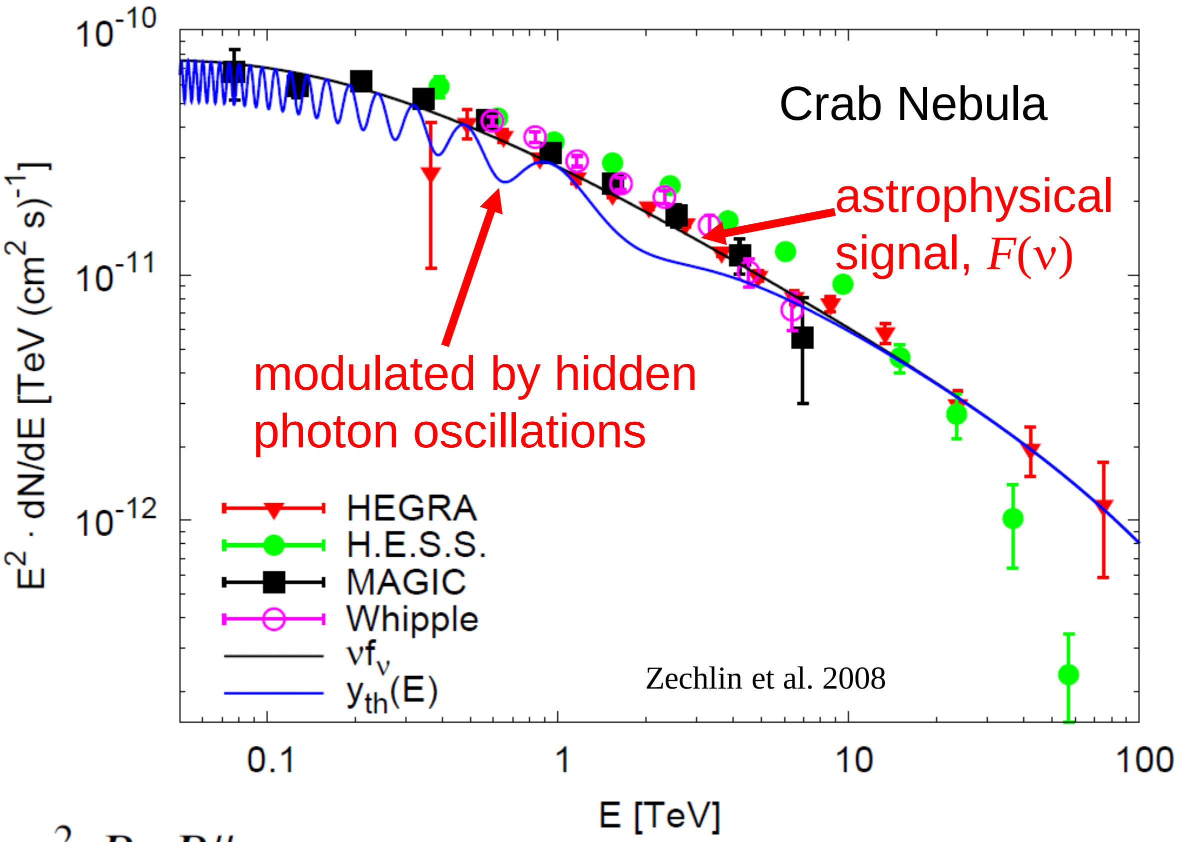
VHE:
1 OMG (10^{20} eV) particle
≈ a tennis ball at 100 km/h

Radio:
70 years of observations
< a falling snowflake

Astrophysical HP Searches

☐ 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



astrophysical signal, $F(\nu)$

modulated by hidden photon oscillations

Zechlin et al. 2008

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

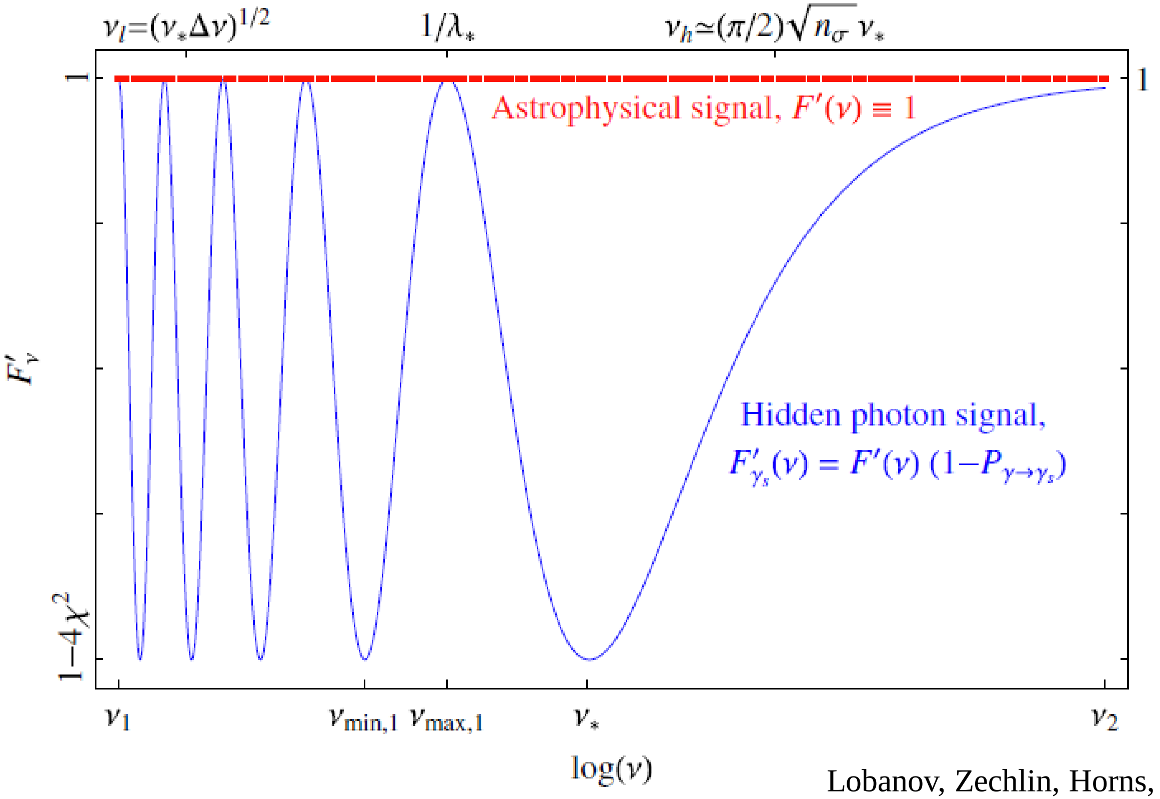
$$F_{\gamma_s}(\nu) = F(\nu)(1 - P_{\gamma\rightarrow\gamma_s})$$

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

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

Photon-Photon Oscillations

- Oscillations can be detected around the primary frequency ν_*, within a „useful range“ of frequencies (ν_l, ν_u).
- Can search for photon oscillations in galactic SNR and in AGN.
- Can stack multiple objects, substantially improving detection limits.



$$\nu_\star = \frac{m_{\gamma_s}^2 L}{4\pi^2} = 6.02\left(\frac{m_{\gamma_s}}{10^{-15}\ \mathrm{eV}}\right)^2\left(\frac{L}{\mathrm{pc}}\right)\ \mathrm{MHz}$$

$$\lambda_\star = \frac{8\pi^2}{m_{\gamma_s}^2 L} = 99.64\left(\frac{m_{\gamma_s}}{10^{-15}\ \mathrm{eV}}\right)^{-2}\left(\frac{L}{\mathrm{pc}}\right)^{-1}\ \mathrm{m}$$

$$\nu_1 = \sqrt{\nu_\star\Delta\nu + (\Delta\nu/4)^2} \approx \sqrt{\nu_\star\Delta\nu}$$

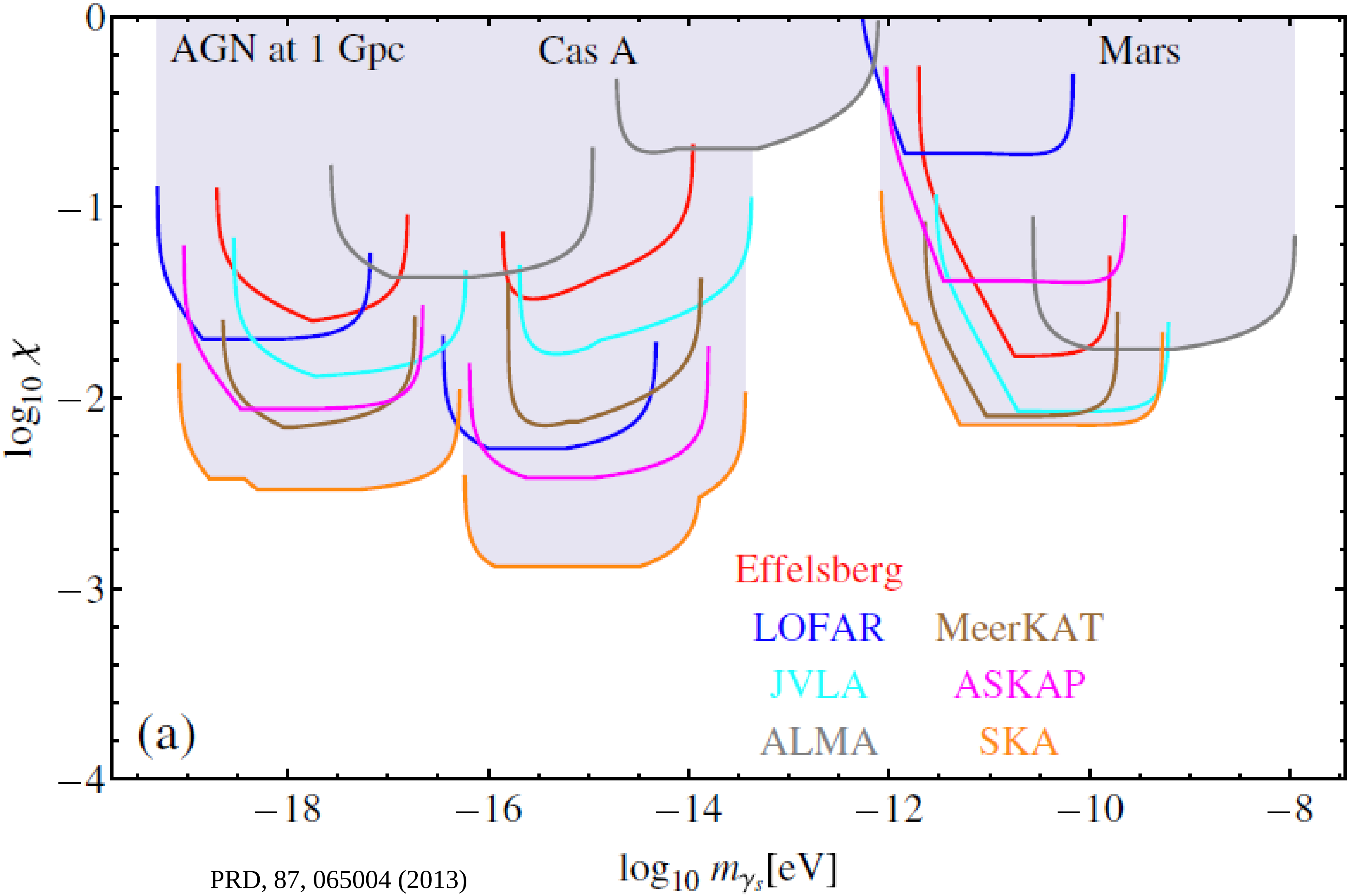
$$\nu_\mathrm{h} \approx 2\, n_\sigma\, \nu_\star$$

If detected, would provide exceptionally good distance measure (via λ_*)!

Lobanov, Zechlin, Horns, PRD, 87, 065004 (2013)

Limits on χ

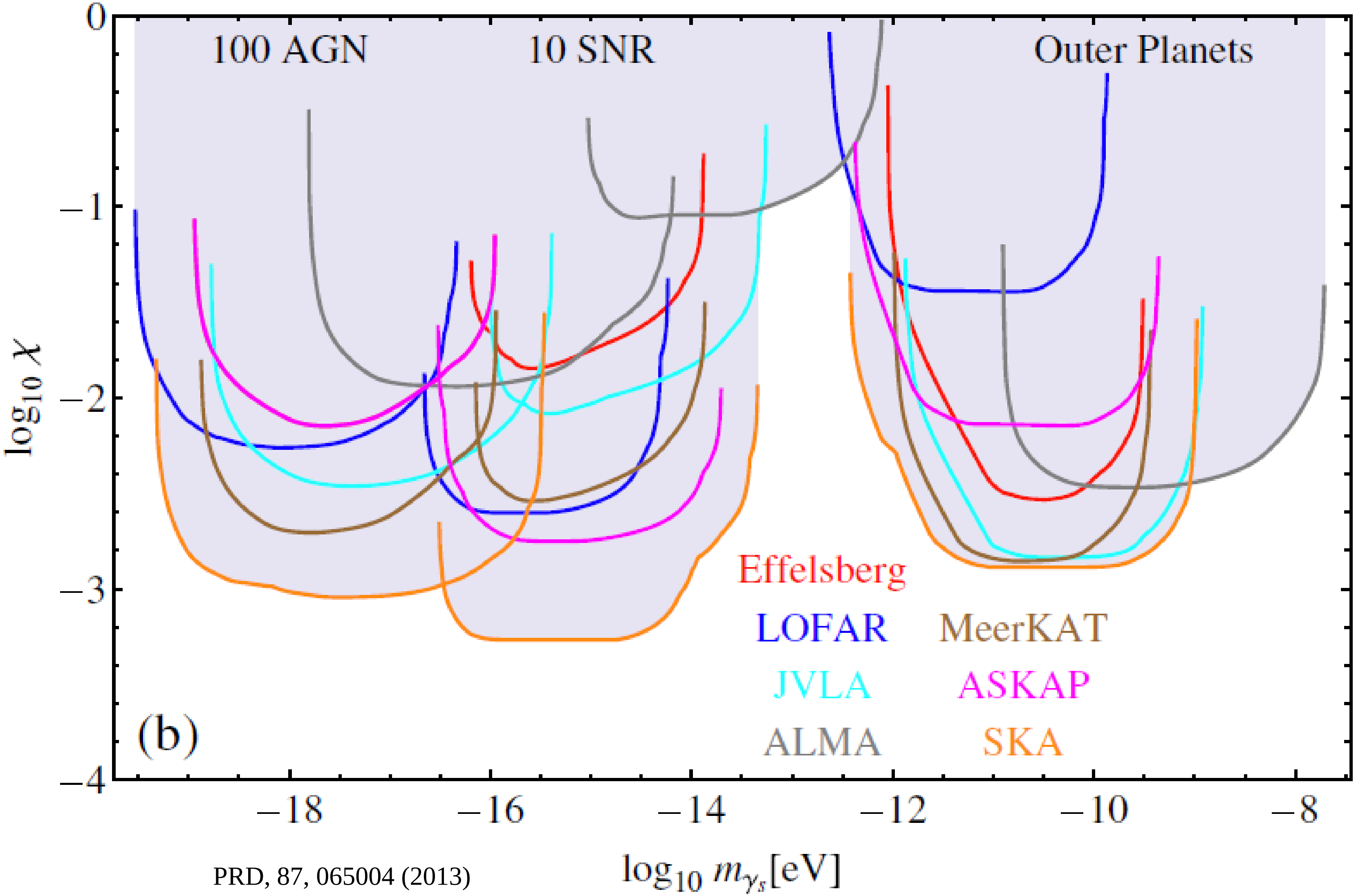
☐ Expected limits on χ from measurements in different target objects



PRD, 87, 065004 (2013)

Data Stacking

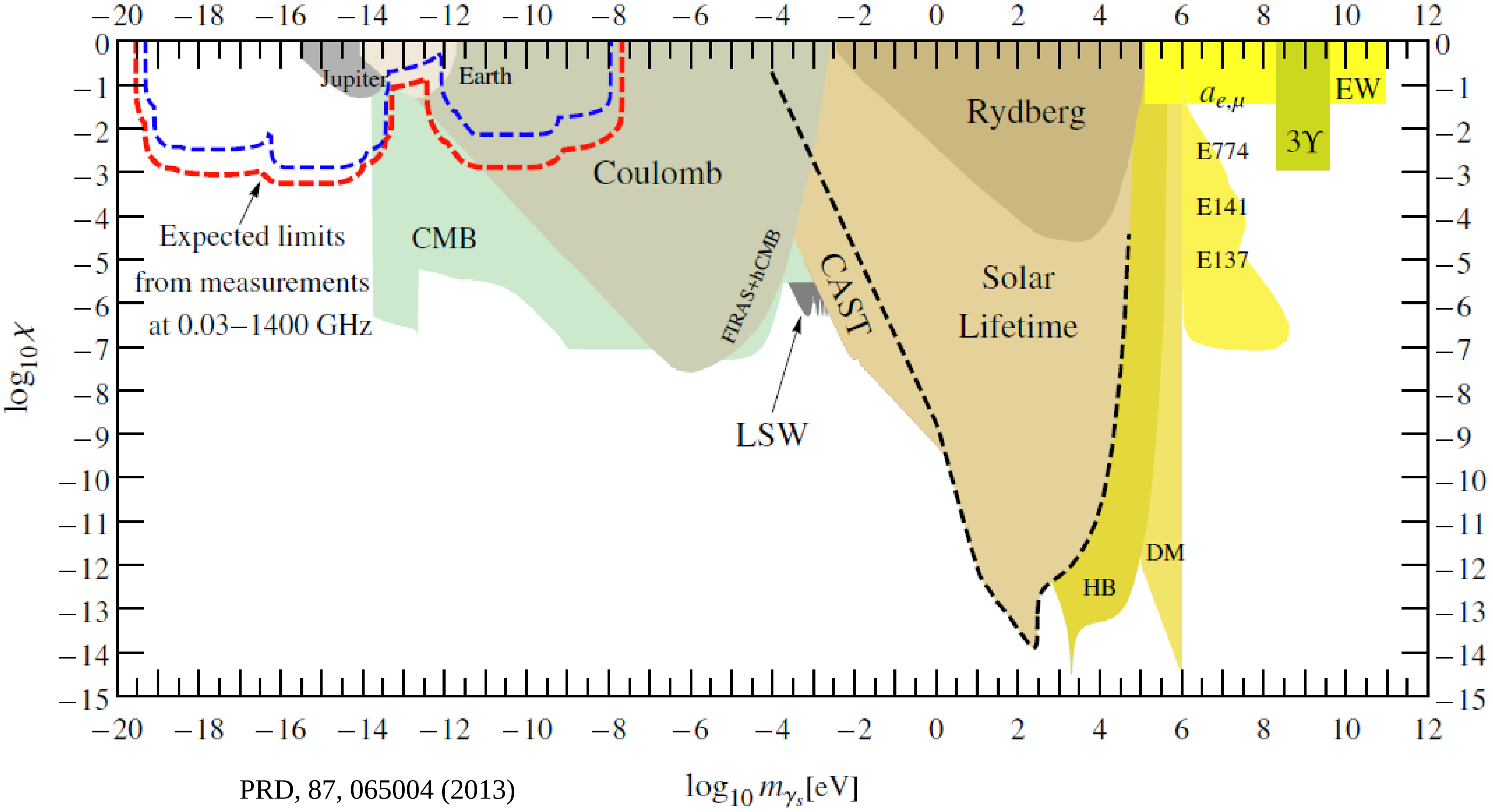
- Expected limits on χ from data stacking on different target objects



PRD, 87, 065004 (2013)

Expected Impact

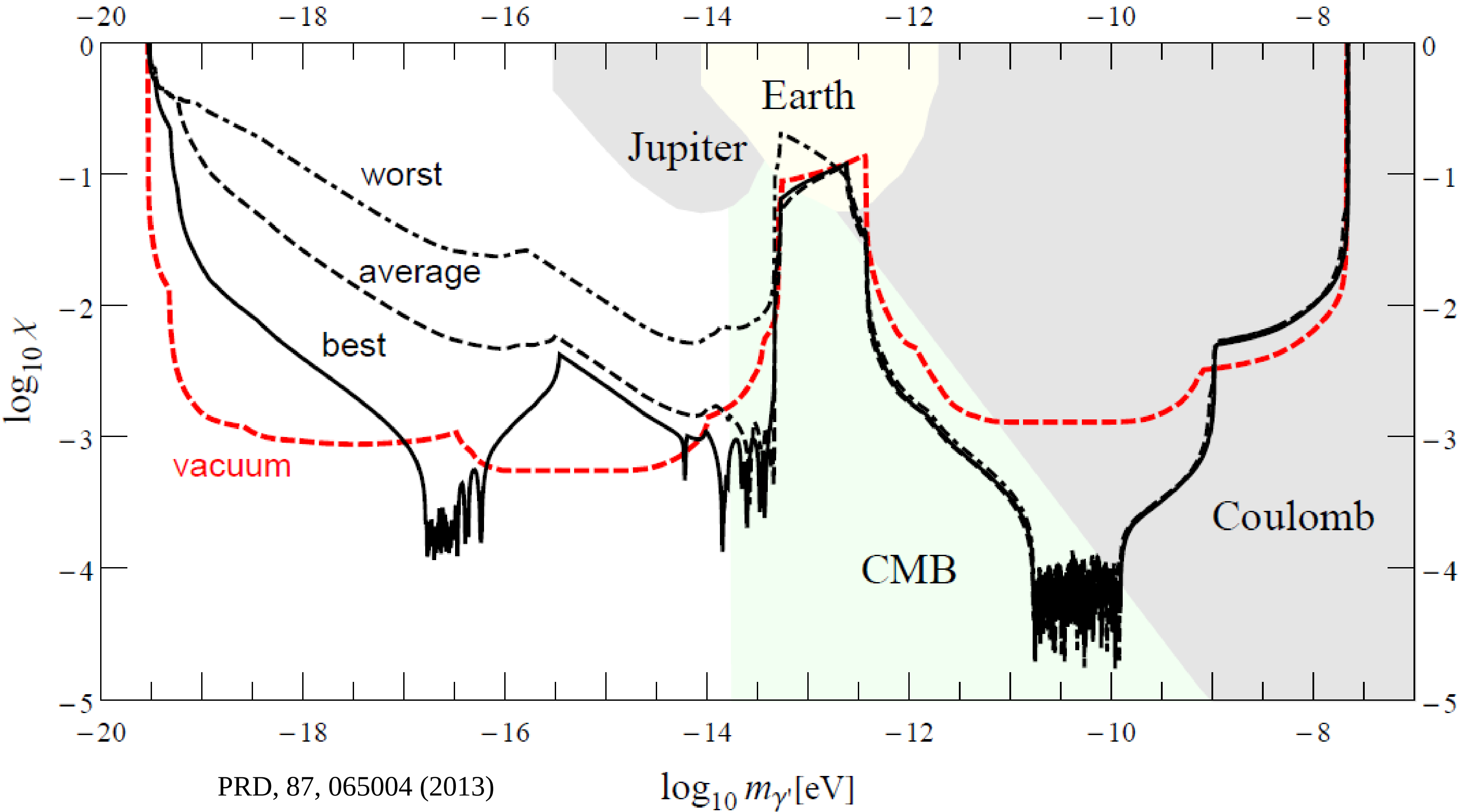
- ☐ Single source observations should provide $\chi < 10^{-2}$ bounds; stacking of 10–100 objects would yield $\chi < 10^{-3}$ bounds down to $m_{\gamma_s} \approx 10^{-19}$ eV.
- ☐ SKA surveys: broad band measurements of 100000+ radio sources.



PRD, 87, 065004 (2013)

Propagation Effects

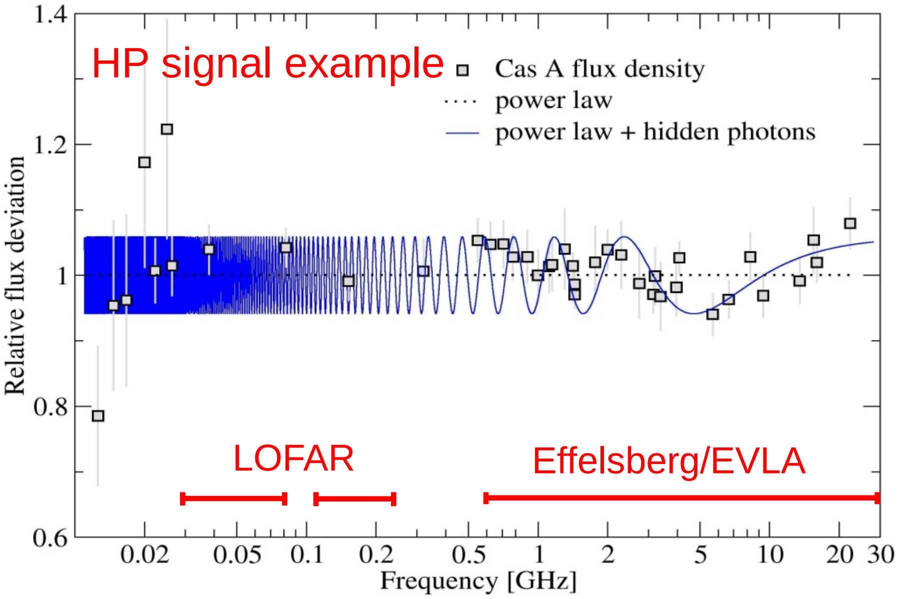
- ☐ Propagation through ISM/IGM affects the hidden photon signal, leading to a resonance at $m_{\gamma_s} = m_p$ and damping the oscillations at lower m_{γ_s} .
- ☐ This effect modifies the expected limits on χ from radio measurements.



PRD, 87, 065004 (2013)

Toy Example: HP in SNR

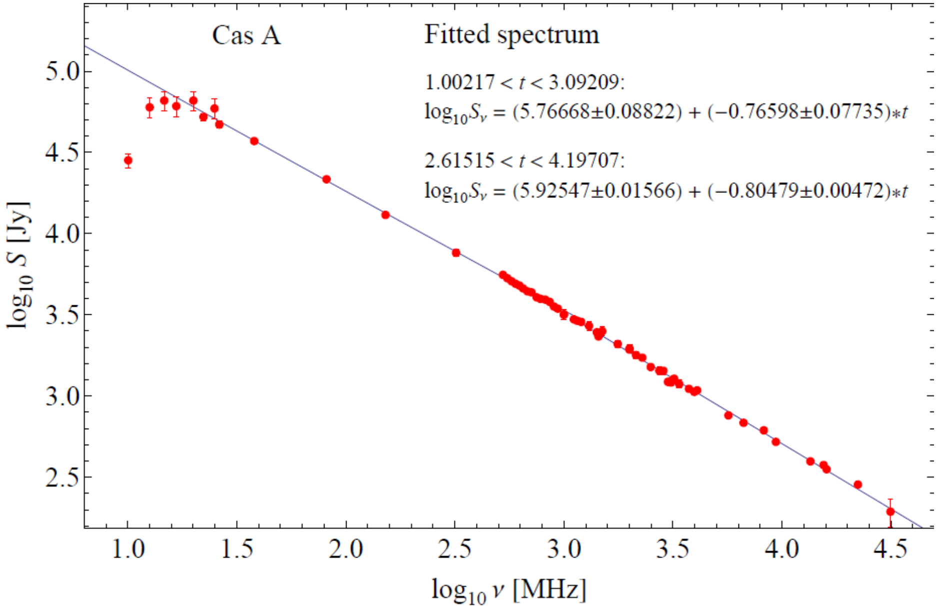
- ❑ Broad-band, absolute flux density measurements in Cas A, Tau A. Absolute calibration is an issue.
- ❑ In-band, relative measurements would be preferred (can be made now with LOFAR, EVLA, and Effelsberg).

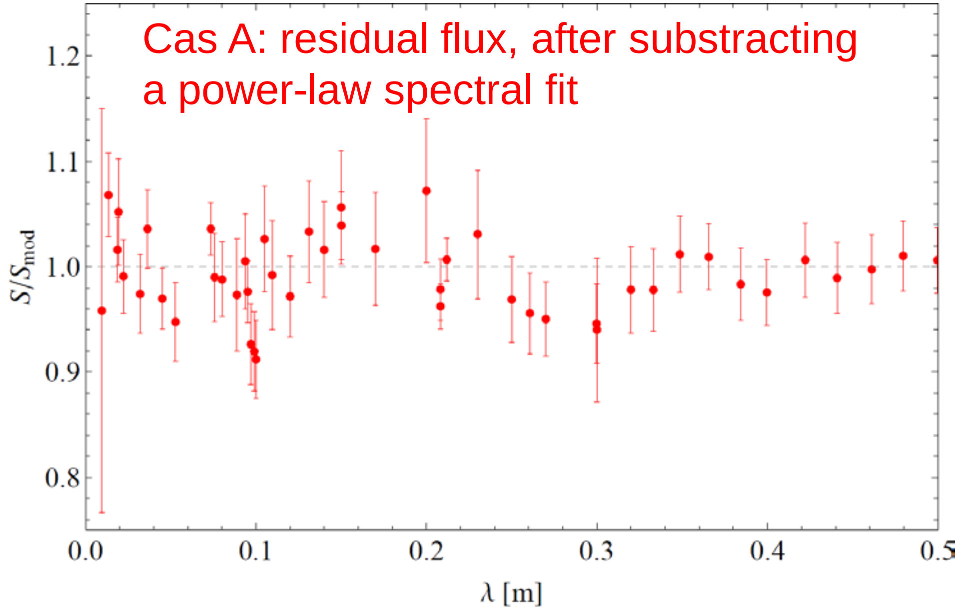


HP signal example

LOFAR

Effelsberg/EVLA

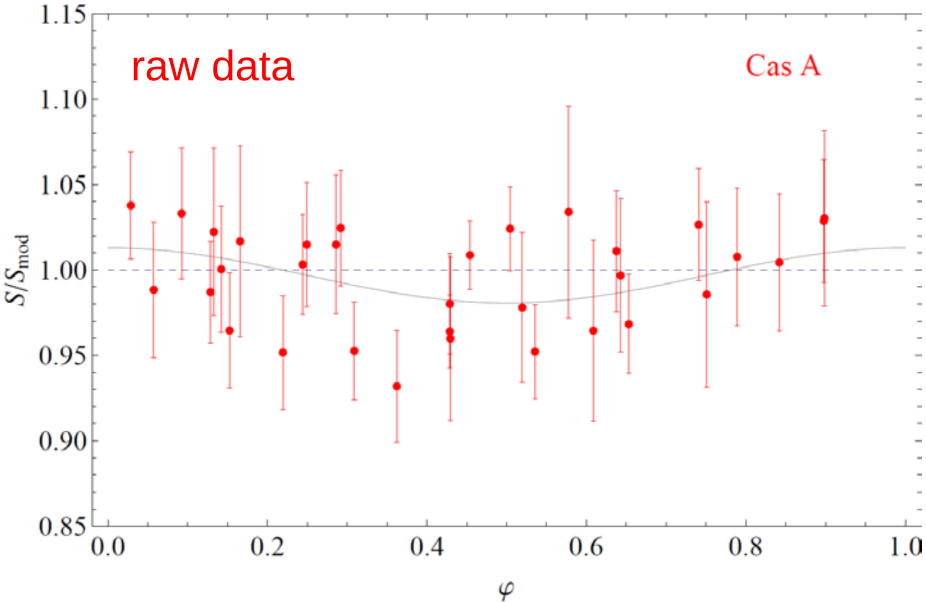


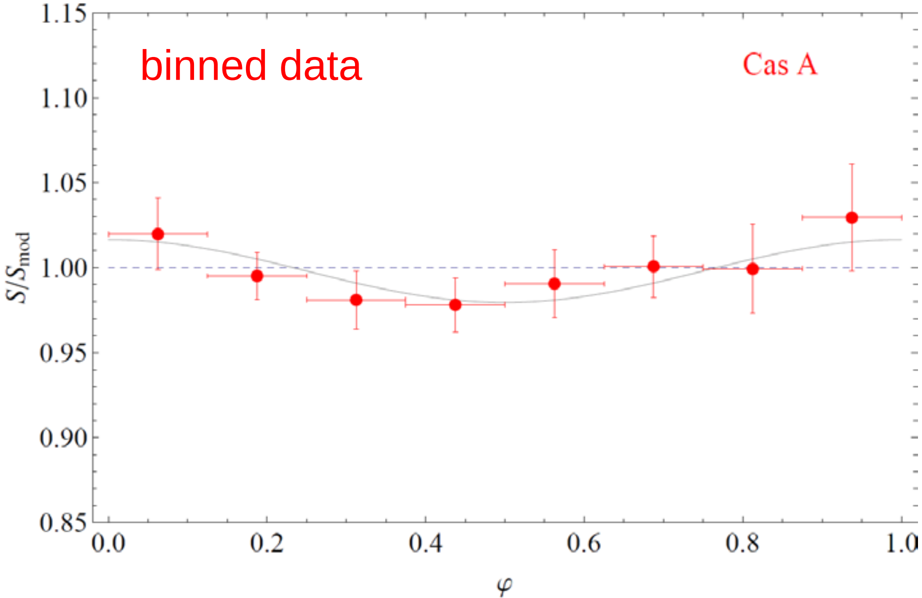


Cas A: residual flux, after substracting a power-law spectral fit

Periodic Oscillations

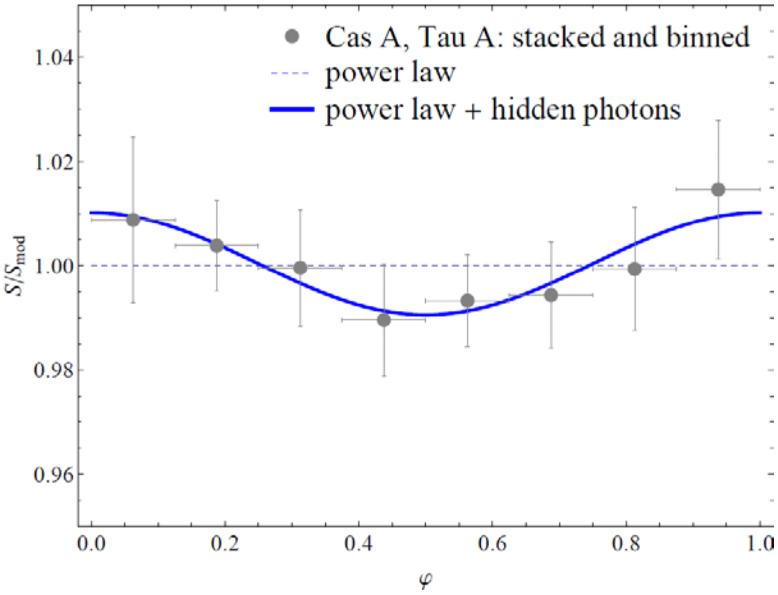
- Weak (<2σ in amplitude) detections in Cas A ($\lambda_* = 0.15$ m) and Tau A ($\lambda_* = 0.19$ m). Wavelength ratio (1.3±0.3) agrees well with the distance ratio of 1.4±0.5.
- Hence it could indeed be the same signal in both objects.
- Could try stacking all data together.

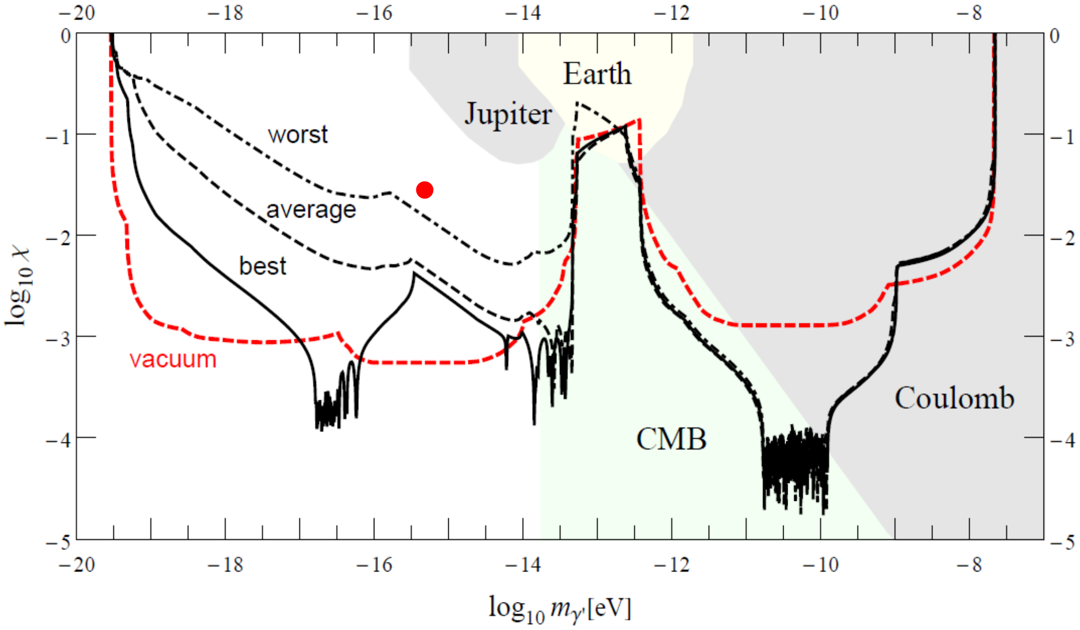




Results from Stacked Data

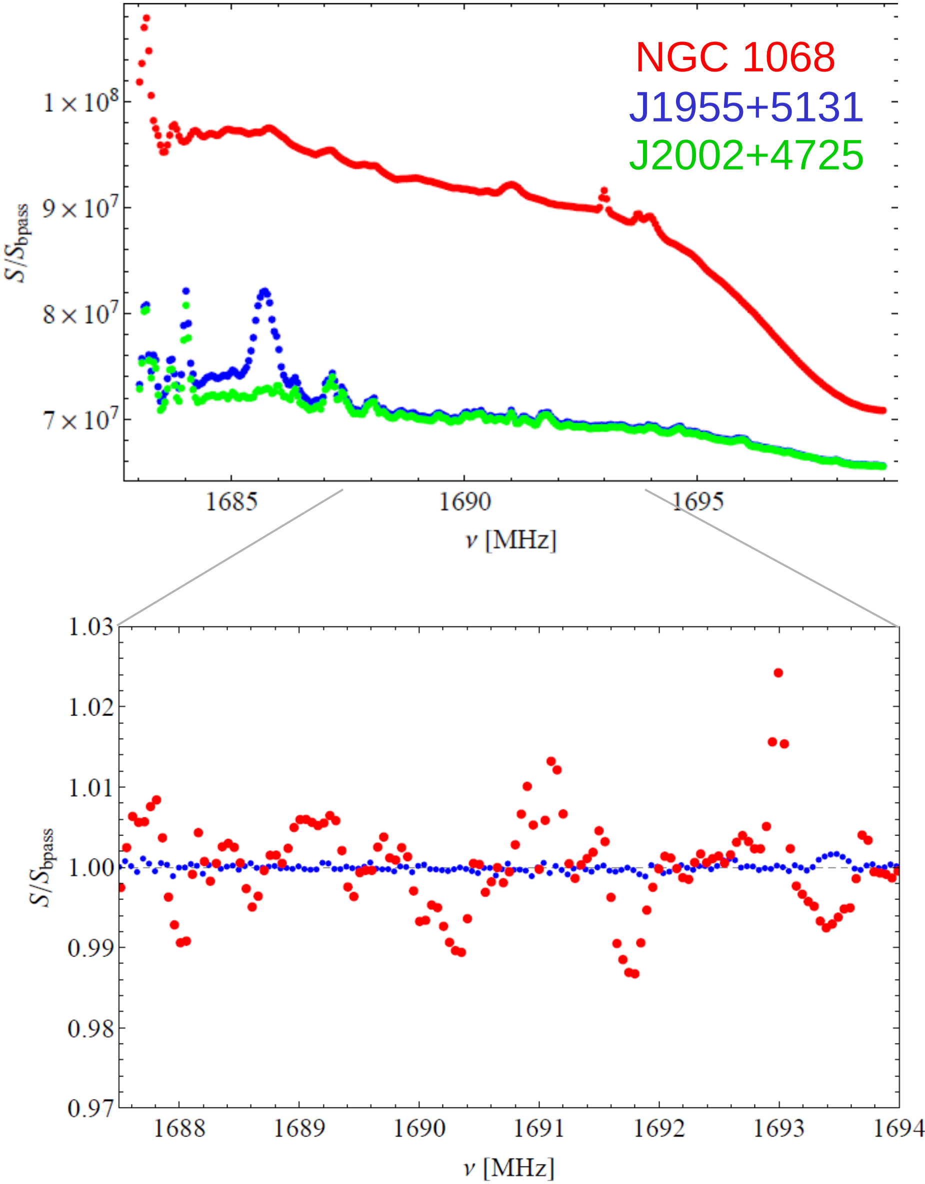
- Stacked data yield a ~2σ detection of a signal with
  $\chi = 0.02 \pm 0.01$ and $\lambda_{*} = 0.41 \pm 0.04$ m $[L/\mathrm{kpc}]^{-1}$.
- This would correspond to a signal from hidden photons with
  $m_{\gamma_s} = (4.9 \pm 0.5) \times 10^{-16}$ eV
  which is not excluded by existing measurements.
- Analysis of new in-band observations of AGN is underway.

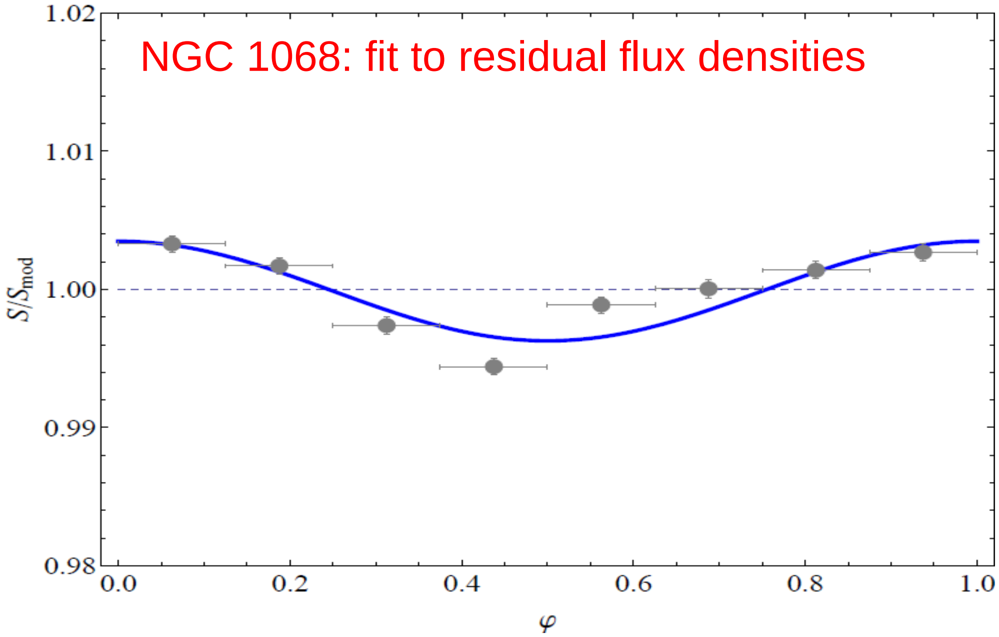




In-band Measurements

- ☐ In-band measurements: NGC 1068, with bandpass from J1955+5131 and J2002+4725.
- ☐ A fit to NGC 1068 corresponds to
  $m_{\gamma_s} = (2.08 \pm 0.08) \times 10^{-16}$ eV
  $\chi = 0.008 \pm 0.003$
- ☐ … to be verified with new data.

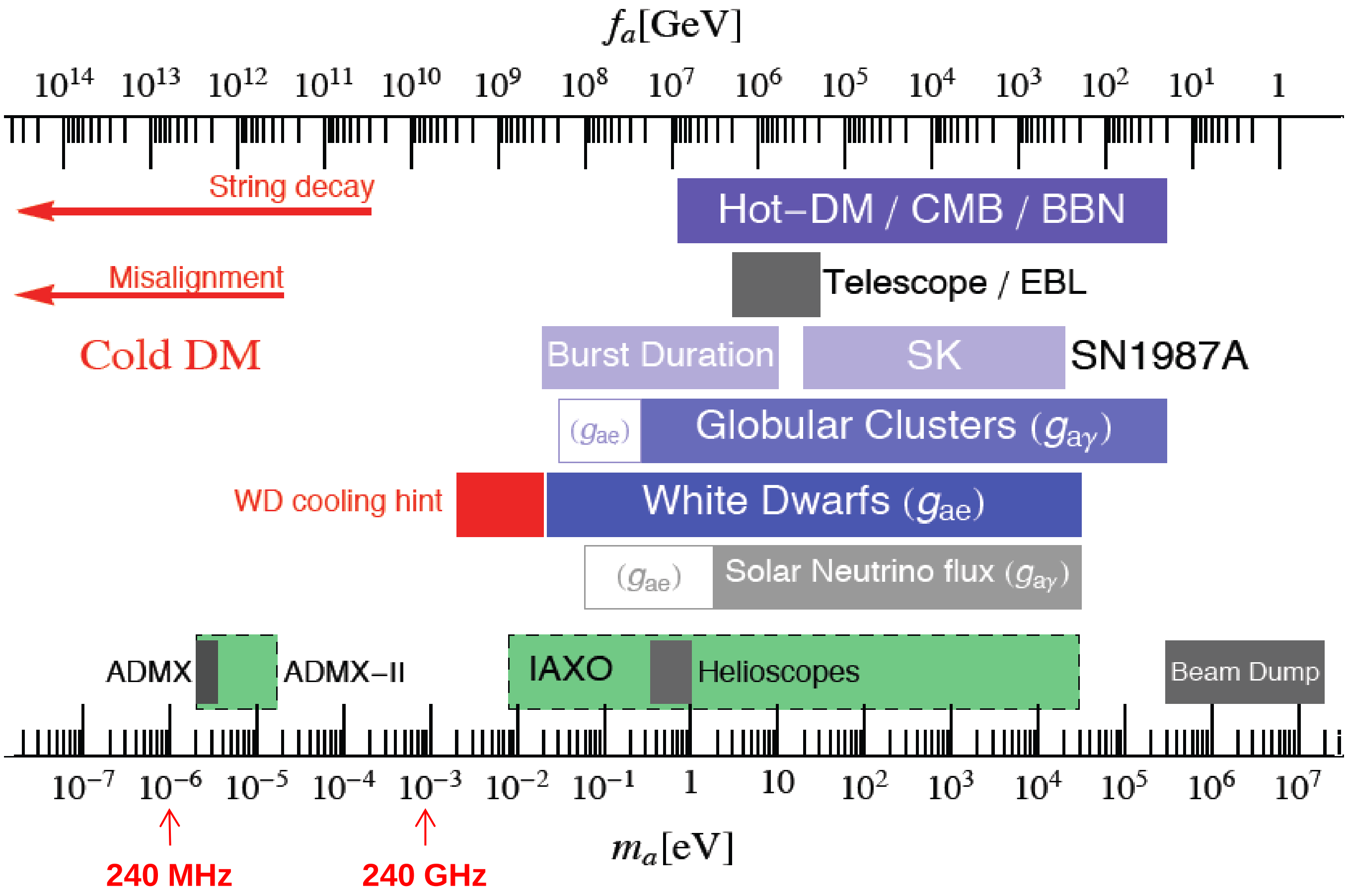




Taking it Closer to Home: Laboratory Searches for WISP

WISP DM Searches in Radio

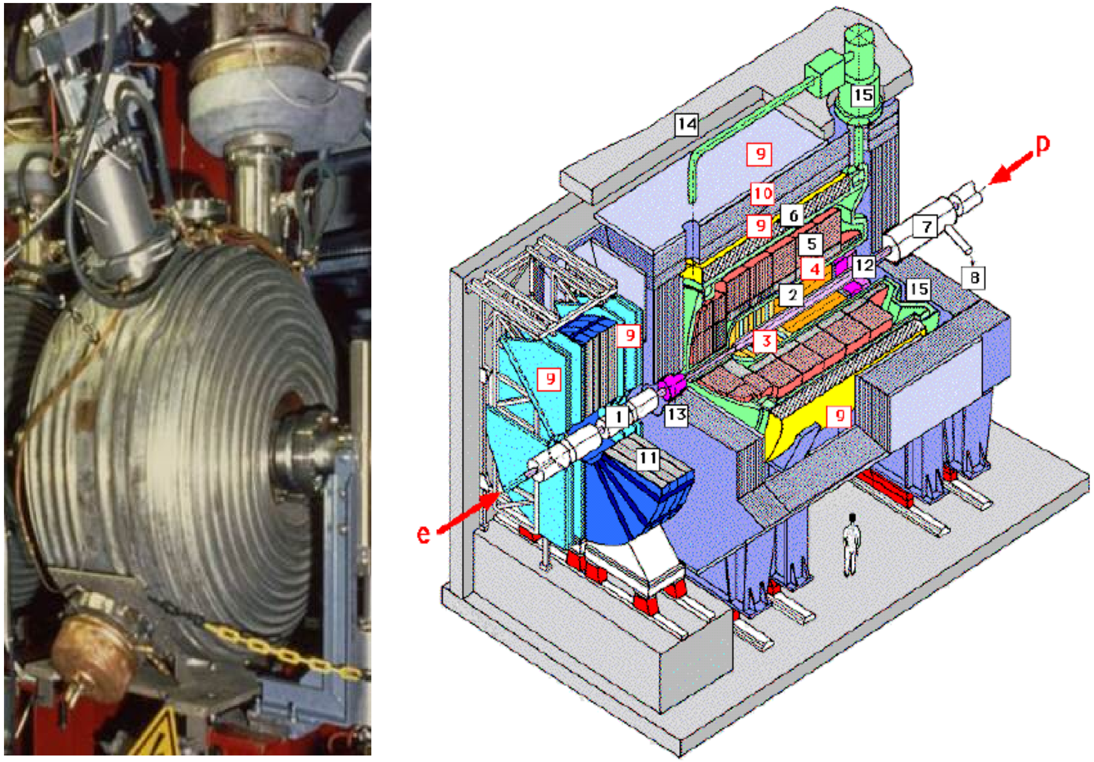
- ☐ (arguably) The best motivated mass range for axion DM ($10^{-2} - 10^{-7}$ eV) is probed by measurements in the 20 MHz – 2 THz frequency range.
- ☐ Highly sensitive experiments in this range are needed: narrow band searches with tunable microwave cavities and new, broadband methods.



WISPDMX

- WISP Dark Matter eXperiment (WISPDMX) is a pilot search for hidden photons and axions with masses below 2 μeV, probing well into the dark matter-favored coupling strengths and aiming at exploring the axion masses below the mass range covered by ADMX.

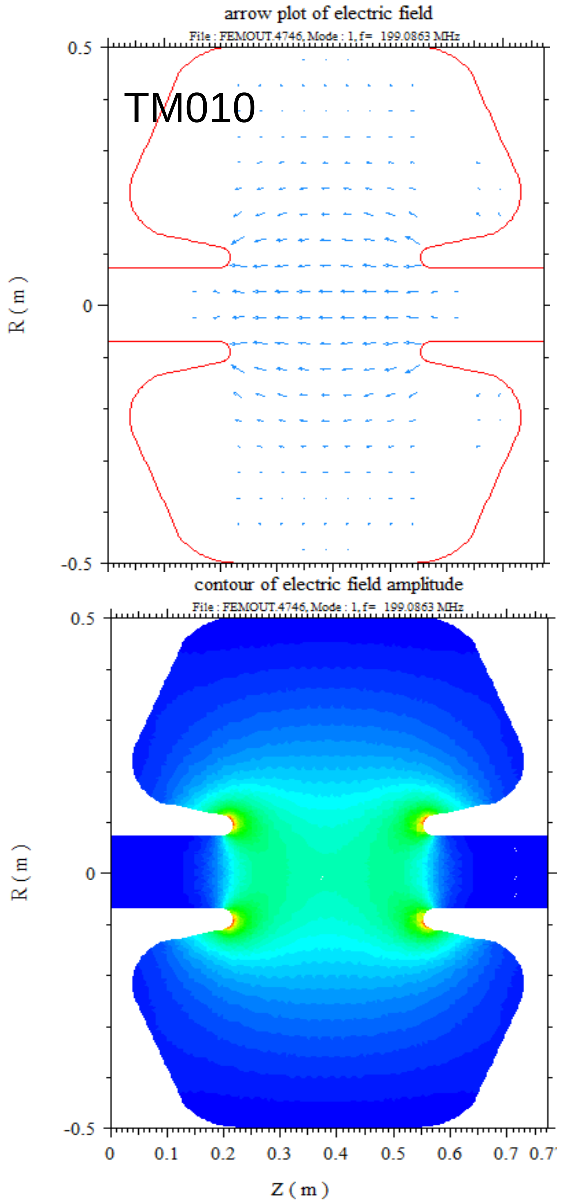
- WISPDMX utilizes a 208-MHz resonant cavity designed for the HERA accelerator at DESY and plans to make use of the H1 dipole magnet. The signal is amplified by a broadband 0.2-1.0 GHz amplifier from the MPIfR.



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

Specifics of WISPDMX

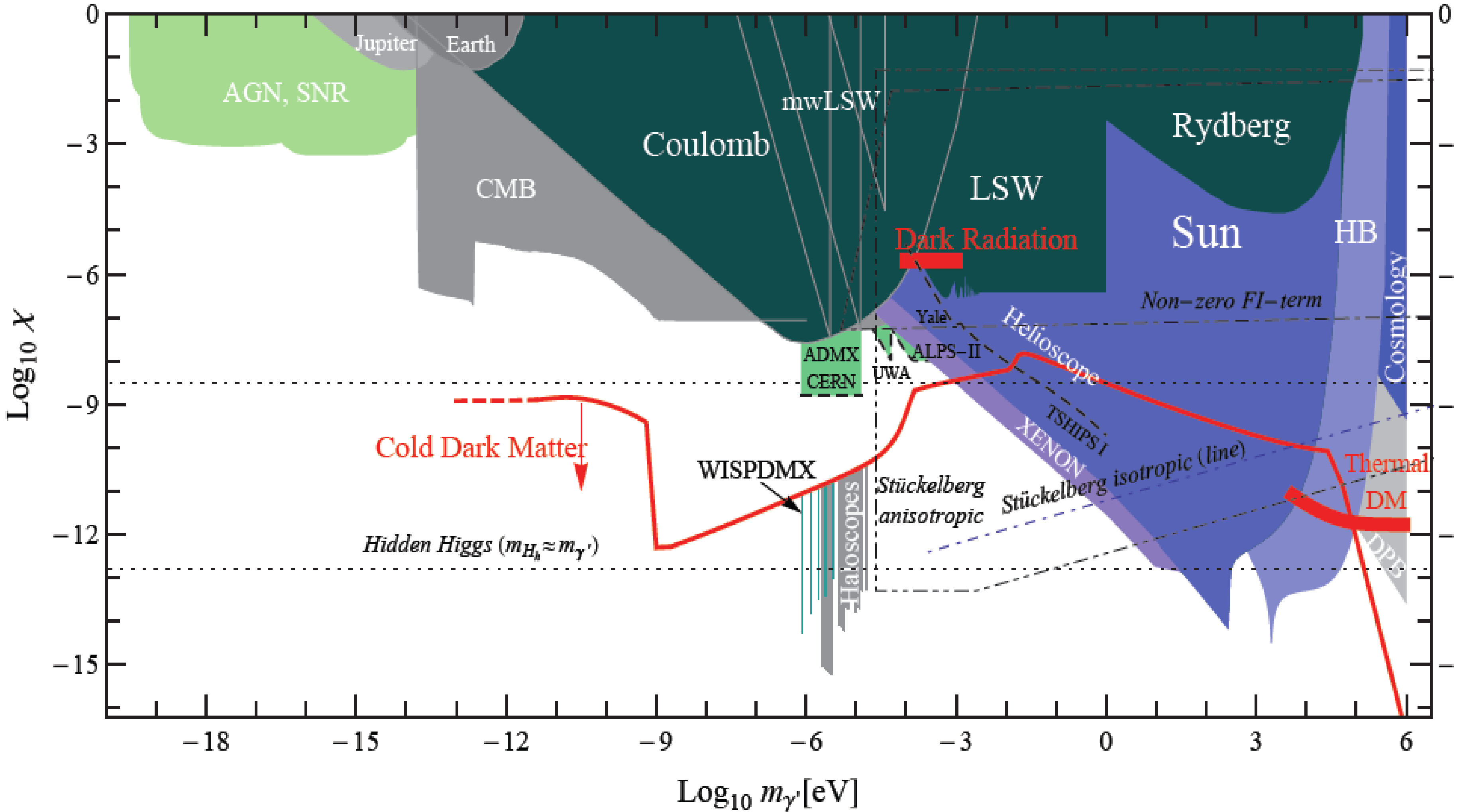
- Combining existing elements (cavity, amplifier, downconverter, magnet, plunger).
- H1 magnet: provides *B* = 1.15 Tesla in a volume of 7.2 m^3 and the total chamber volume of ~100 m^3
- HERA 208-MHz proton ring accelerator cavity: *V* = 460 l., TM010 at 207.9 MHz, with *Q* = 46000.
- Presently, limited tuning and no cooling.
- Planning to measure at several resonant modes simultaneously: using TM0n0 and TM0n1 modes.
- 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 reaching ~10 % tuning range.



Phase I: Hidden Photons

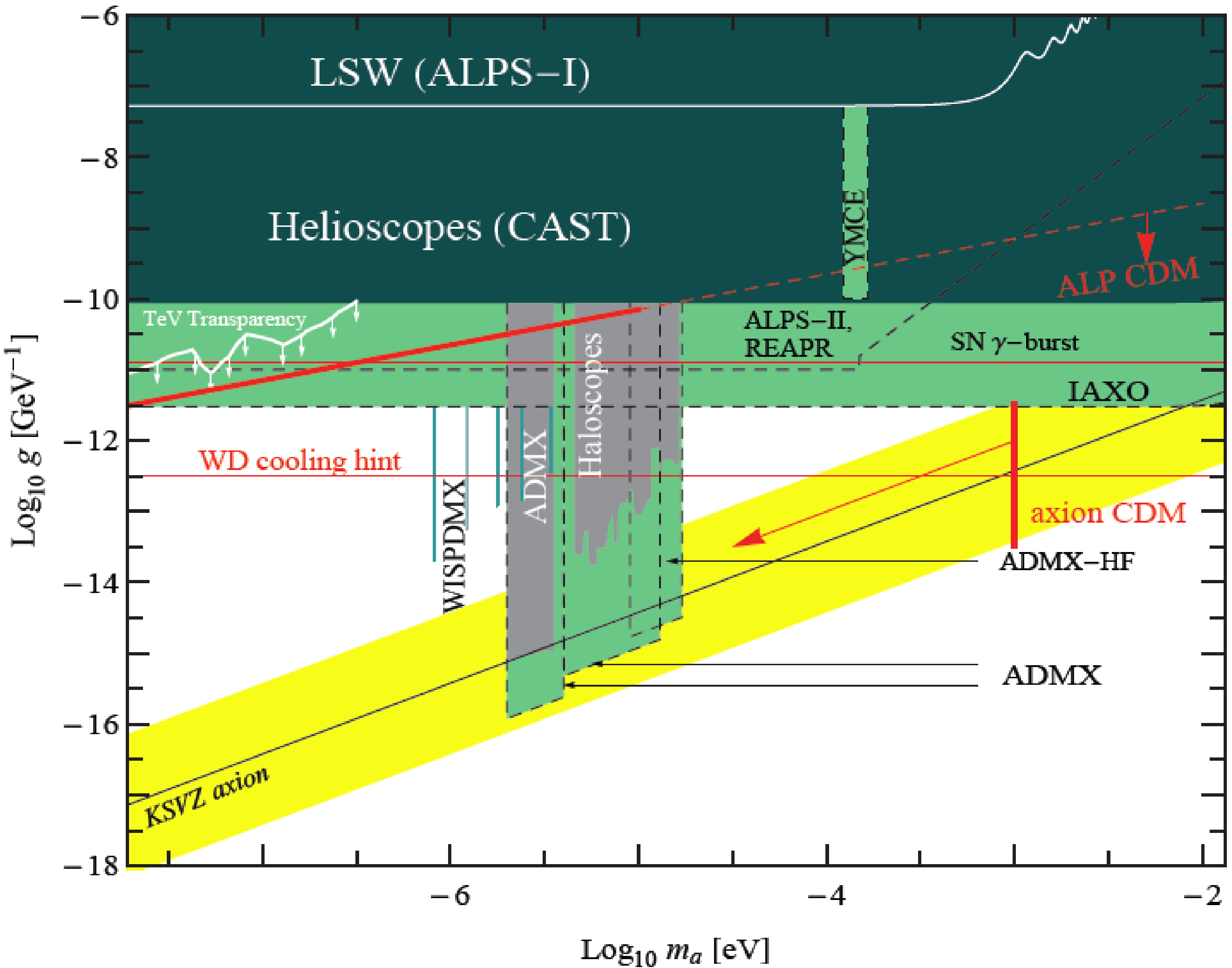
☐ First stage measurements will probe hidden photon coupling down to $\chi \approx 10^{-14}$.

☐ Plunger assembly will be used to provide a ≈ 2% frequency tuning range



Phase II: Axions

- ☐ Second stage measurements made with the H1 magnet should provide robust axion-photon coupling constraints for masses below $2\mu\text{eV}$.



Broad Band Mess:
Is It Worth a Try?

Broad/Narrow Band Tradeoffs

- 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:

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

- 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

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

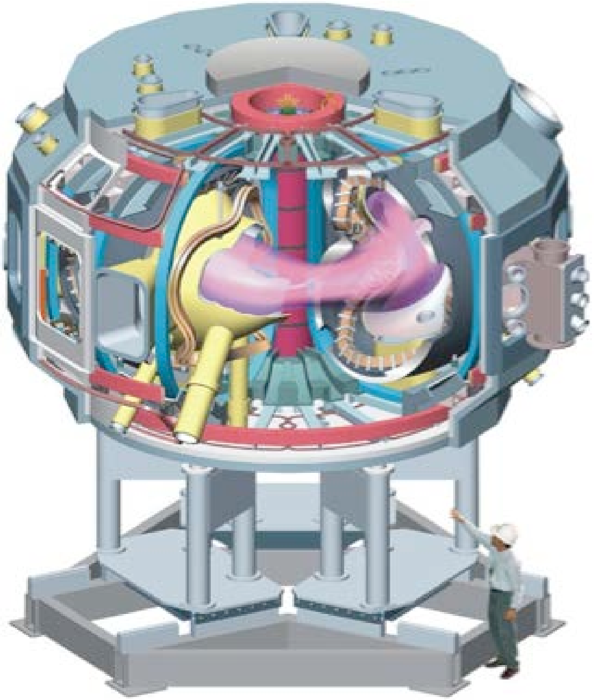
- If a narrow band measurement has large Q, this implies

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

- 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?

Is This Cheese Free?

Buy This



Get This Free

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

  -- 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

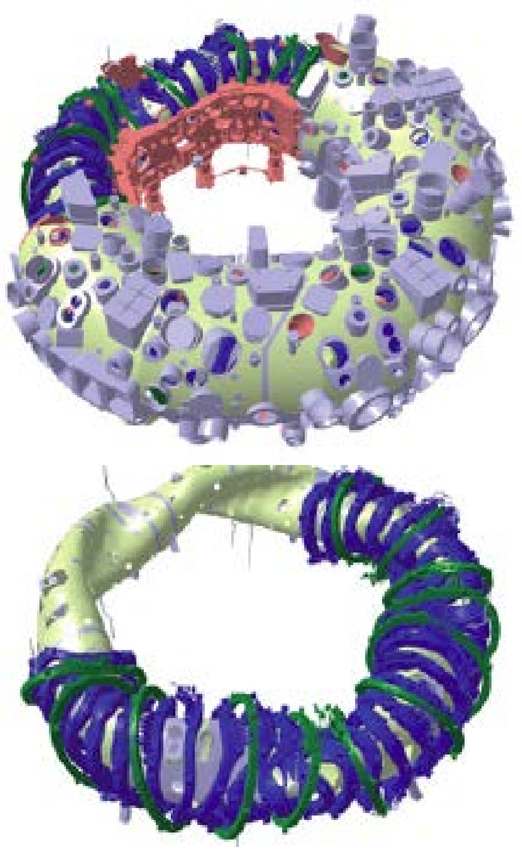
Max-Planck-Institut für Radioastronomie

A. Lobanov

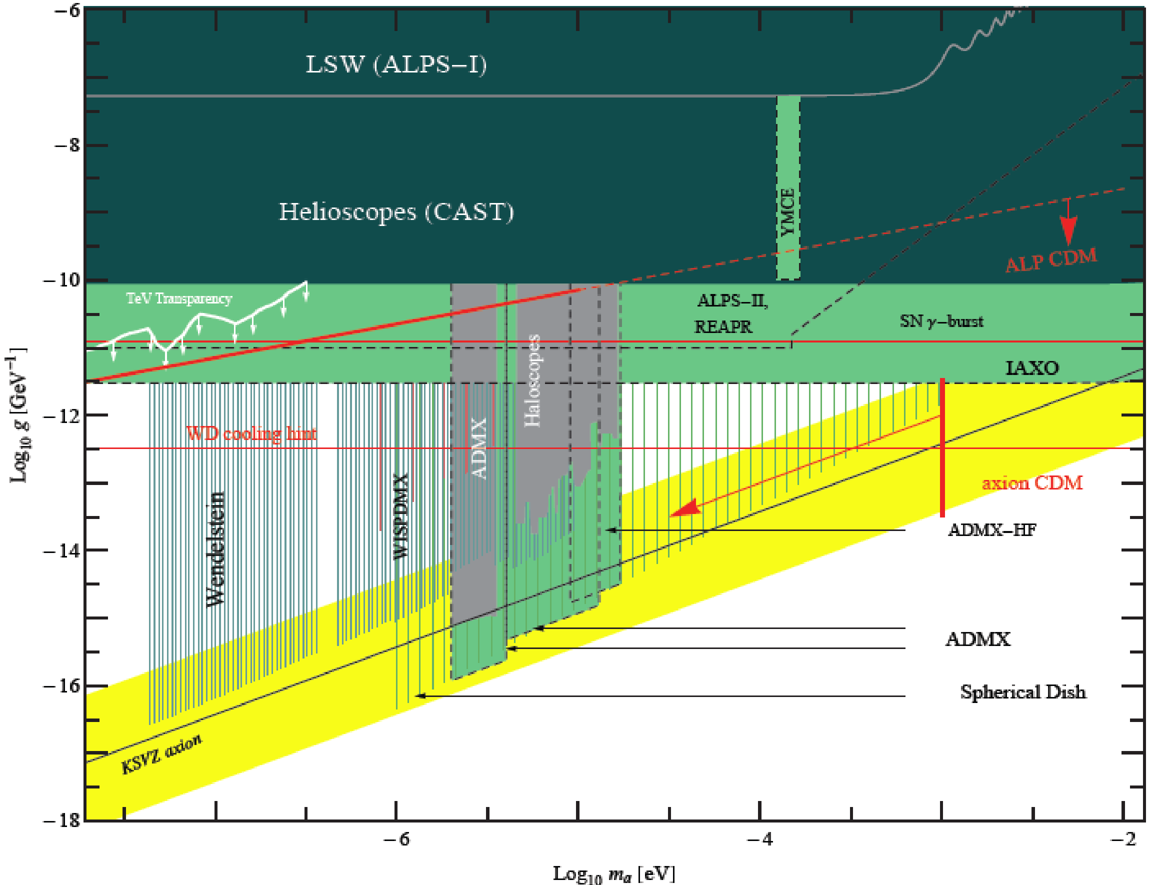
MAX-PLANCK-GESELLSCHAFT

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



Summary

- WISP detection relies on low energy experiments, particularly in the radio regime crucial.
- 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:
  - Systematic searches for hidden photon oscillations at 0.03 – 40 GHz.
  - Definitive microwave cavity experiments for axion and hidden photon searches at 0.2 – 1.0 GHz (1 – 5 μeV).
  - 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. Cross-field collaborations are essential for this research.