An L- and S-Band Search for Ultralight Dark Matter Using Green Bank Telescope Data

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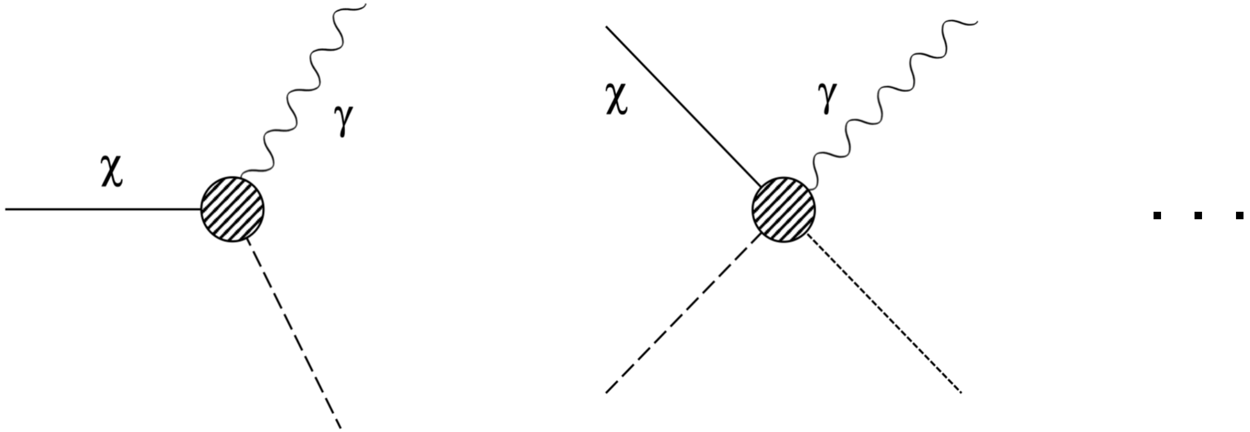
Introduction

- The nature of dark matter is still a mystery
- Broad range of models over many orders of magnitude in mass
- Broadened theoretical scope ⇒ broadened observational approach
- We have developed a *model-independent* search technique relying on two assumptions:
  - Decay or annihilation of virialized dark matter in the halo
  - Frequency and intensity of the line corresponding to the expected phase space structure of the halo
- Using a unique resource, the Breakthrough Listen public data release of ~25,000 spectra (1.1-11.6 GHz) from the Green Bank Telescope

Aya Keller *et al. ApJ* 927 (2022) 71, https://doi.org/10.48550/arXiv.2203.11246

General Concept & Assumptions

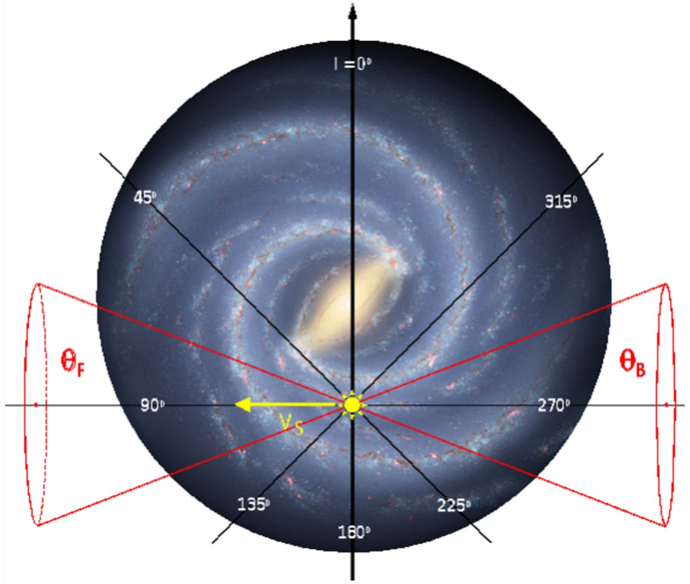
- Dark matter constitutes a static halo through which our solar system is moving with a characteristic velocity $V_S \sim 225$ km/s tangential to our galactic disk, and with a virial velocity $\sigma \sim 250$ km/s
  - A quasi-monochromatic radio line produced by the possible radiative decay or annihilation of ultralight dark matter would be distinguished from any other source by a systematic Doppler shift with respect to the Sun's direction of motion.
- The signal should reflect the spatial distribution as represented by a standard halo model
  - The signal should be proportional to the line-integrated density of the halo ρ for decay, or ρ^2 for a two-body initial state

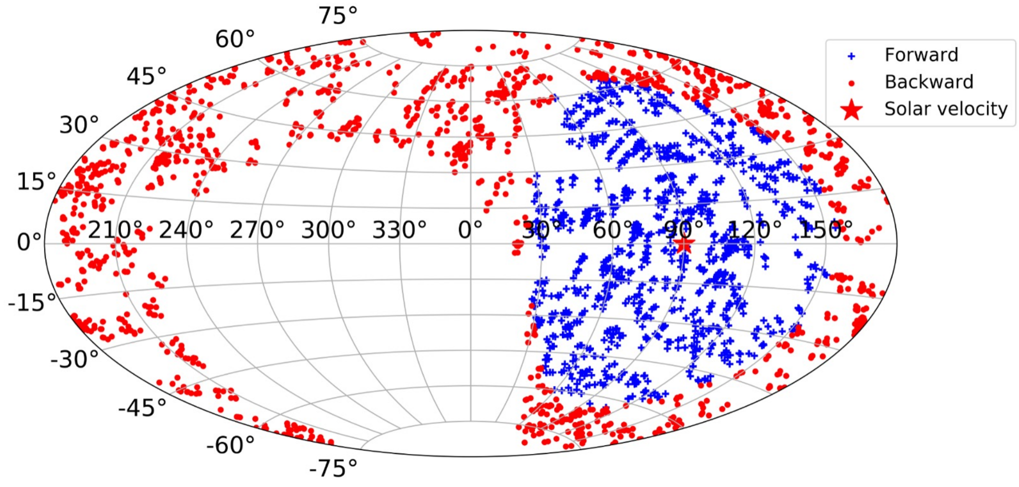


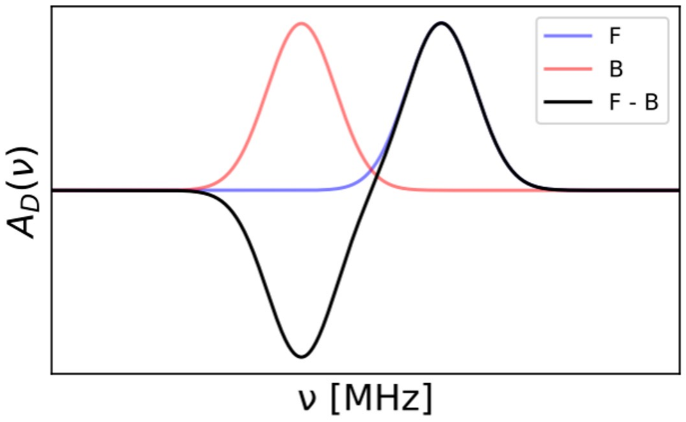
In other words, given this unique database – 3 months observation over ~ 4π – this search asks the question:
"Is there anything with the distribution of the halo that is emitting in the radio spectrum?"

General Concept

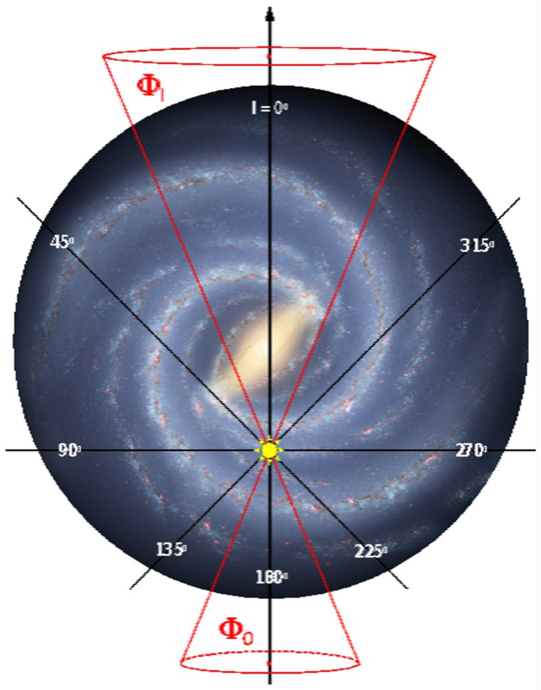
* Mercator projections of targets used in the L-band analysis

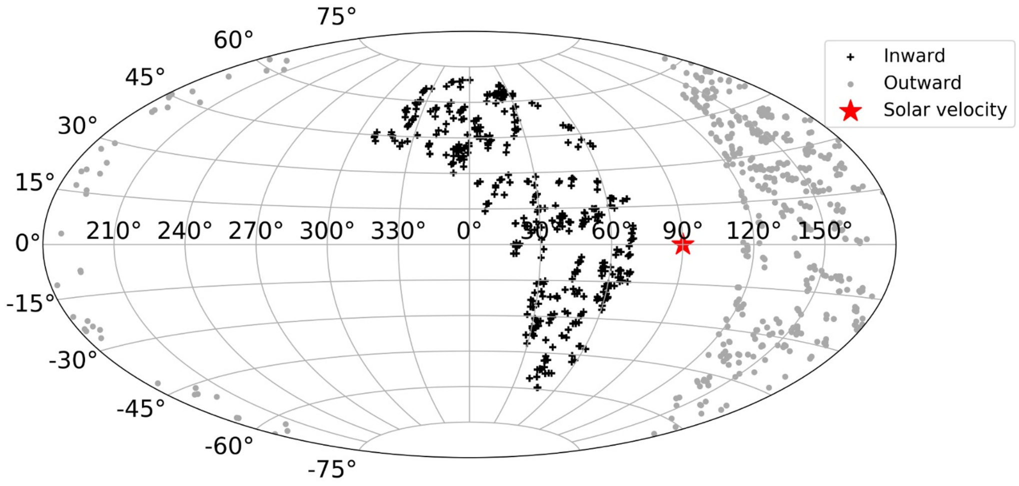


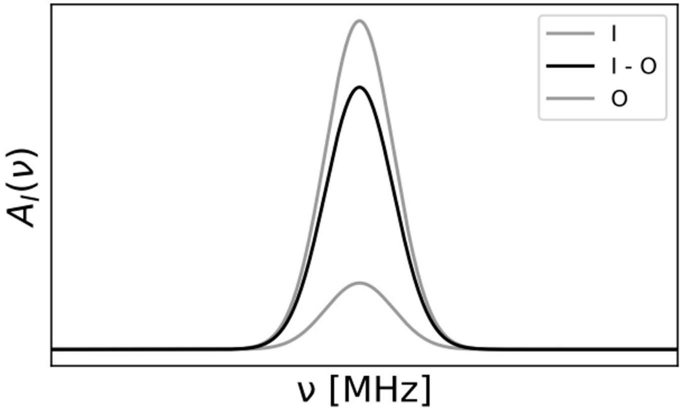




Doppler Asymmetry



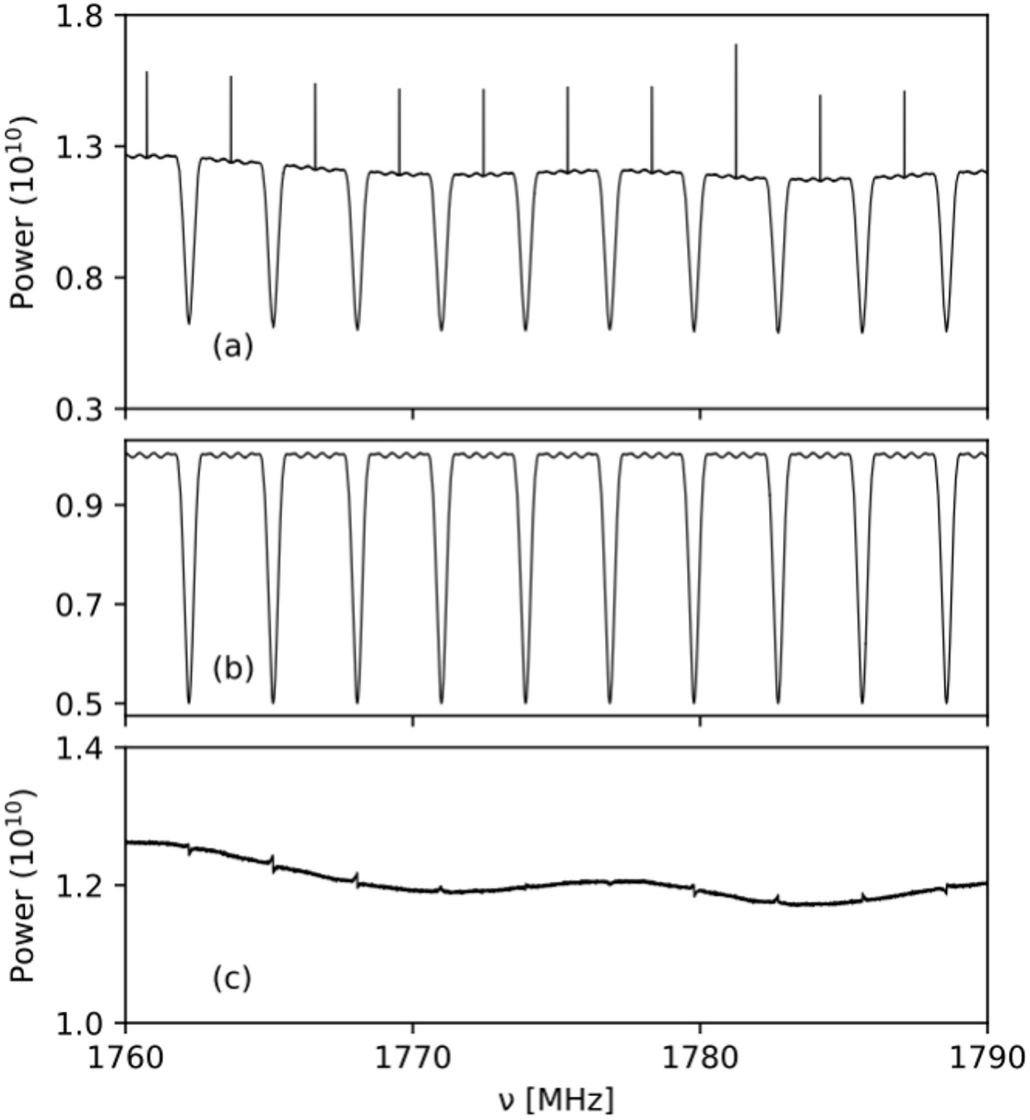




Intensity Asymmetry

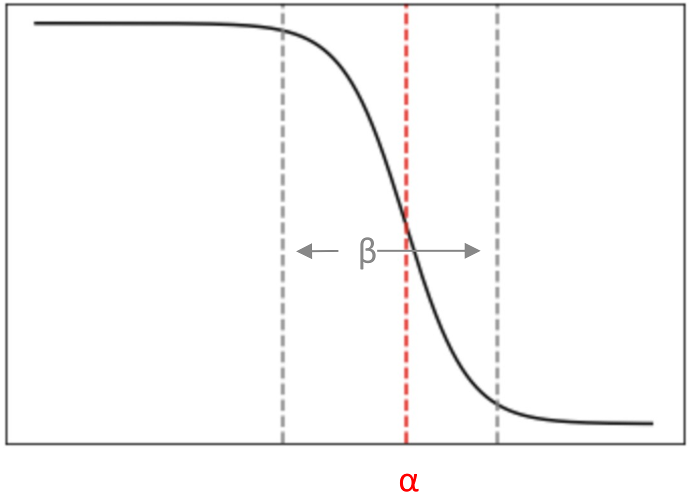
The Breakthrough Listen data set

- Breakthrough Listen public data release from the Green Bank Telescope
  - Spans 3 years
  - ~ 1700 nearby Hipparcos catalog stars and 100 nearby galaxies
  - **L-**, **S-**, C- and X-band (1.1-11.6 GHz)
  - ABACAD on-off target run cadence, 30 min. total
- Raw spectra *(a)* are imprinted with the polyphase filterbank structure repeated every 1024 channels (~2.93 MHz) *(b)*
- Spectra also characterized by quasi-periodic ~15 MHz undulation, ~10% in magnitude *(c)*



Analysis – Normalization Scheme

$$F(\chi^2) = \frac{1}{1+e^{\frac{\log(\chi^2)+\alpha}{\beta}}}$$



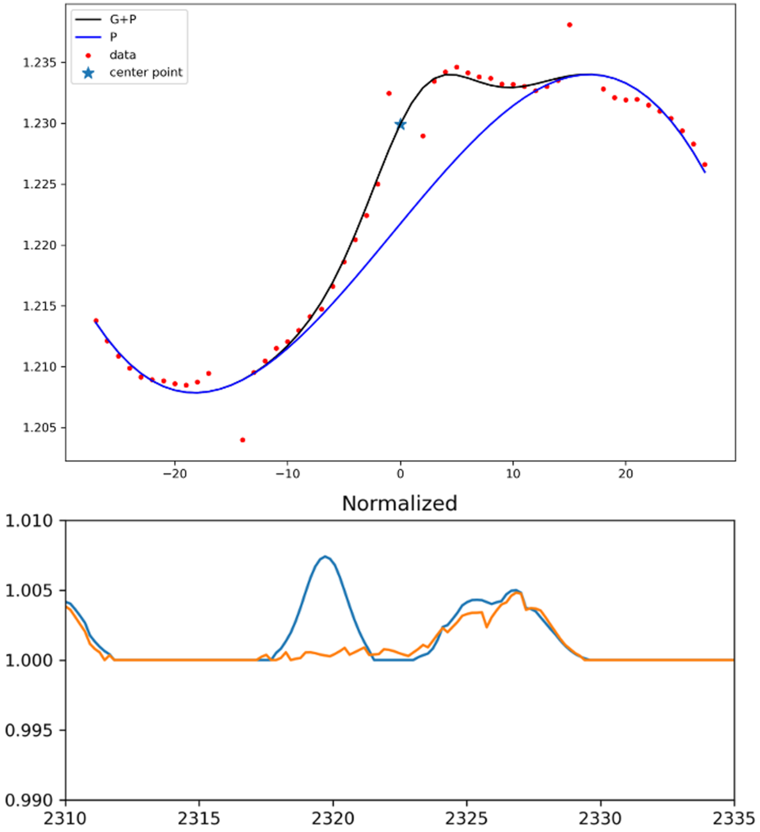
$$N(\nu) = 1 + F(X^2)\,\frac{G(\nu)}{P(\nu)}$$

Where:

G(ν): Fitted Gaussian

P(ν): Fitted polynomial

F(χ²): Fermi function



- The GBT as with all instruments is subject to large environment and time-dependent drifts in response, necessitating a a scheme to unit-normalize all the spectra
- The normalization scheme is a ratio of a fitted polynomial + positive-definite Gaussian, to the polynomial. A chi-squared factor weighting factor is then applied to eliminate the bad fits (noisy regions)

Spectral Flux Density - Annihilation

General:

$$\left(\frac{P^A}{\Delta A\cdot\Delta\nu}\right) = \frac{1}{64}\cdot\sqrt{\frac{\pi}{2}}\cdot\frac{\langle\sigma\cdot v\rangle}{M_\chi\,.\,\eta^A\cdot\nu_0}\cdot(\Delta\vartheta)^2\cdot\exp\left[-\,\frac{1}{2}\left(\frac{\nu-\nu_0}{\eta^A\nu_0}\right)^2\right]\cdot\int_0^\infty\rho^2(\vec{r})\,d\vec{r}$$

GBT:

$$\boxed{\left(\frac{P^A}{\Delta A\cdot\Delta\nu}\right)\left[W\,m^{-2}Hz^{-1}\right] = 0.020\cdot\frac{\langle\sigma\cdot v\rangle\left[cm^3s^{-1}\right]}{\eta^A\cdot M_\chi[\mu eV]\cdot(\nu[GHz])^3}\cdot\exp\left[-\,\frac{1}{2}\left(\frac{\nu-\nu_0}{\eta^A\nu_0}\right)^2\right]\cdot I^A(\mathrm{l,b})\left[\frac{M_S^2}{kpc^5}\right]}$$

where $\eta^A = \frac{1}{\sqrt{6}}\cdot\frac{\sigma}{c}$; this depends on the virial velocity σ ; $\eta^A \approx 3.7 \times 10^{-3}$

$I^A(\mathrm{l,b})$ is the line integral for annihilation

M_χ is the mass of the annihilating dark matter particle

Spectral Flux Density - Decay

General:

$$\left(\frac{P^D}{\Delta A\cdot\Delta\nu}\right) = \frac{1}{64}\cdot\sqrt{\frac{\pi}{2}}\cdot\frac{\lambda}{\eta^A\cdot\nu_0}\cdot(\Delta\vartheta)^2\cdot\exp\left[-\frac{1}{2}\left(\frac{\nu-\nu_0}{\eta^A\nu_0}\right)^2\right]\cdot\int_0^\infty\rho(\vec{r})\,d\vec{r}$$

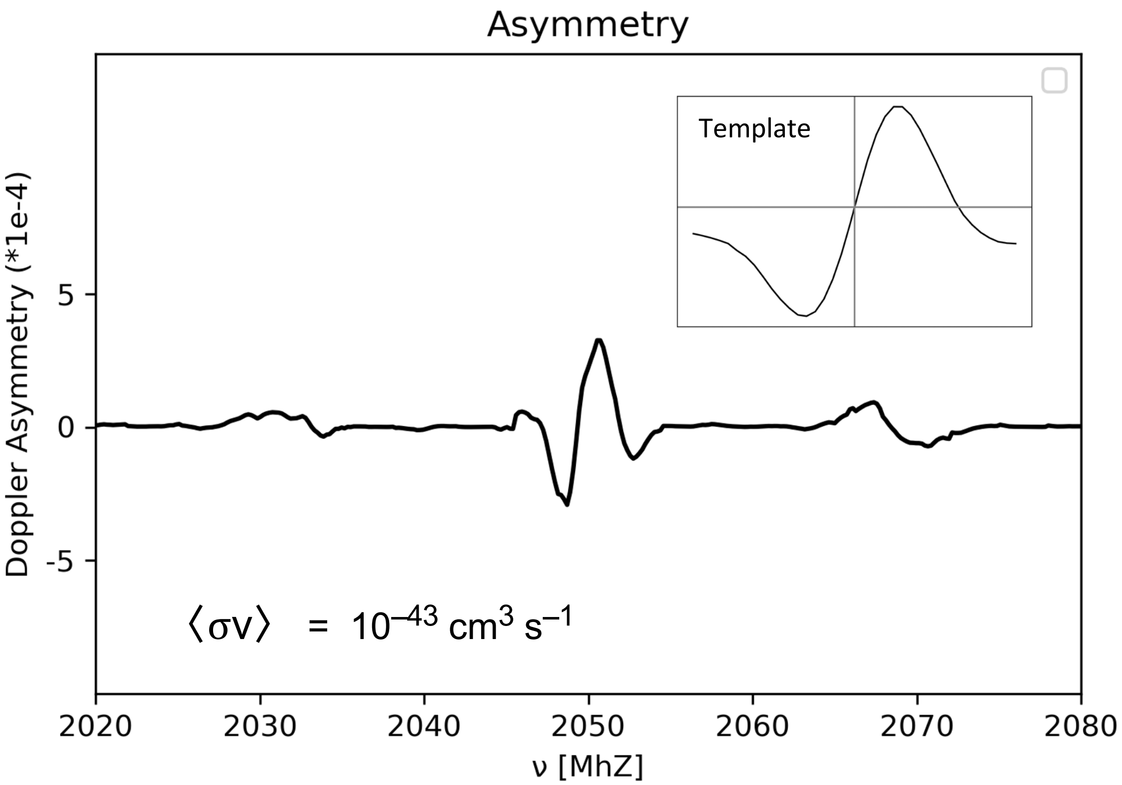
GBT:

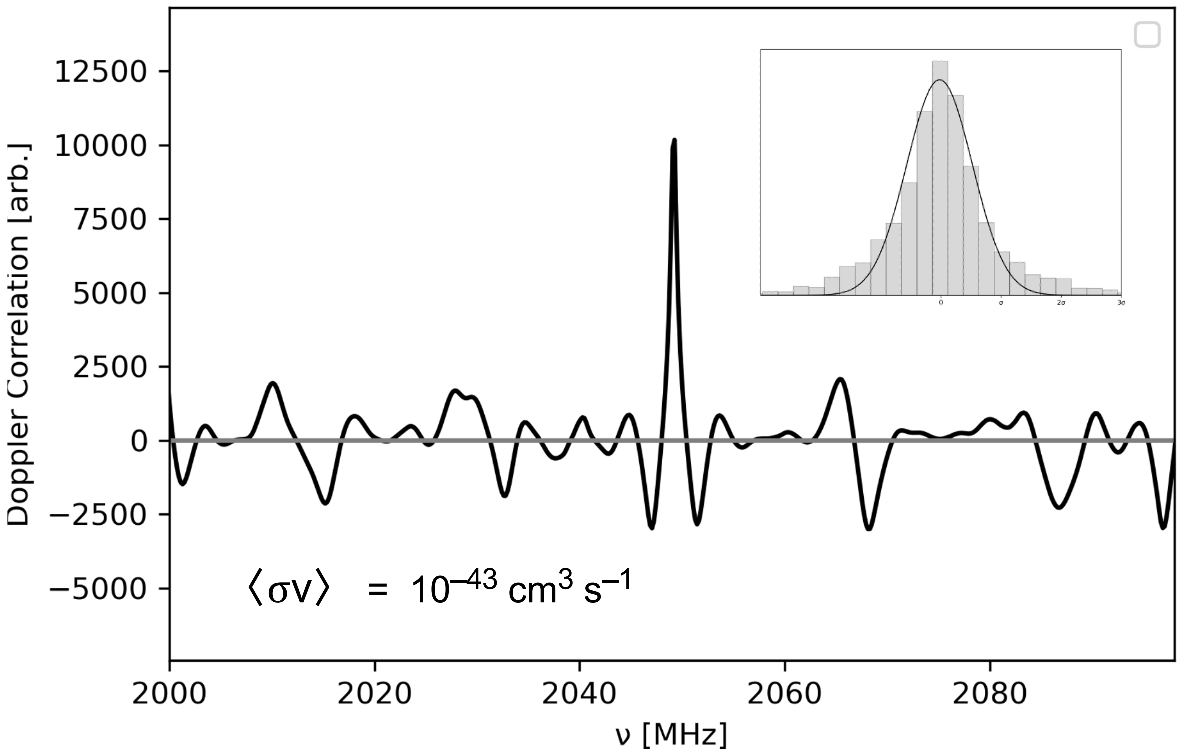
$$\boxed{\left(\frac{P^D}{\Delta A\cdot\Delta\nu}\right)[W\,m^{-2}Hz^{-1}] = 5.3\text{ x }10^{-8}\cdot\frac{\lambda\,[s^{-1}]}{\eta^D\cdot(\nu[GHz])^3}\cdot\exp\left[-\frac{1}{2}\left(\frac{\nu-\nu_0}{\eta^D\nu_0}\right)^2\right]\cdot I^D(\mathrm{l,b})\left[\frac{M_S}{kpc^2}\right]}$$

where $\eta^D = \frac{1}{\sqrt{3}}\cdot\frac{\sigma}{c}$; this depends on the virial velocity σ ; $\eta^D \approx 5.2\text{ x }10^{-4}$

$I^D(\mathrm{l,b})$ is the line integral for decay

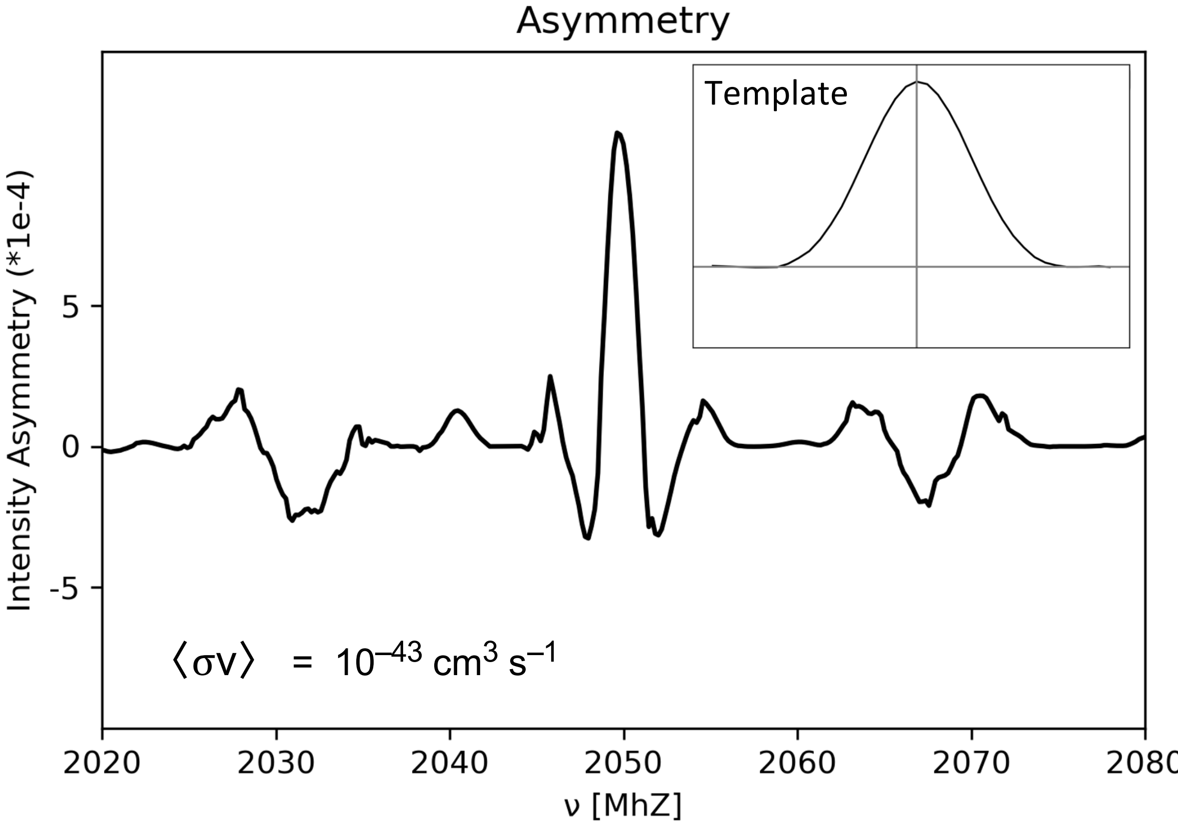
Doppler asymmetry analysis

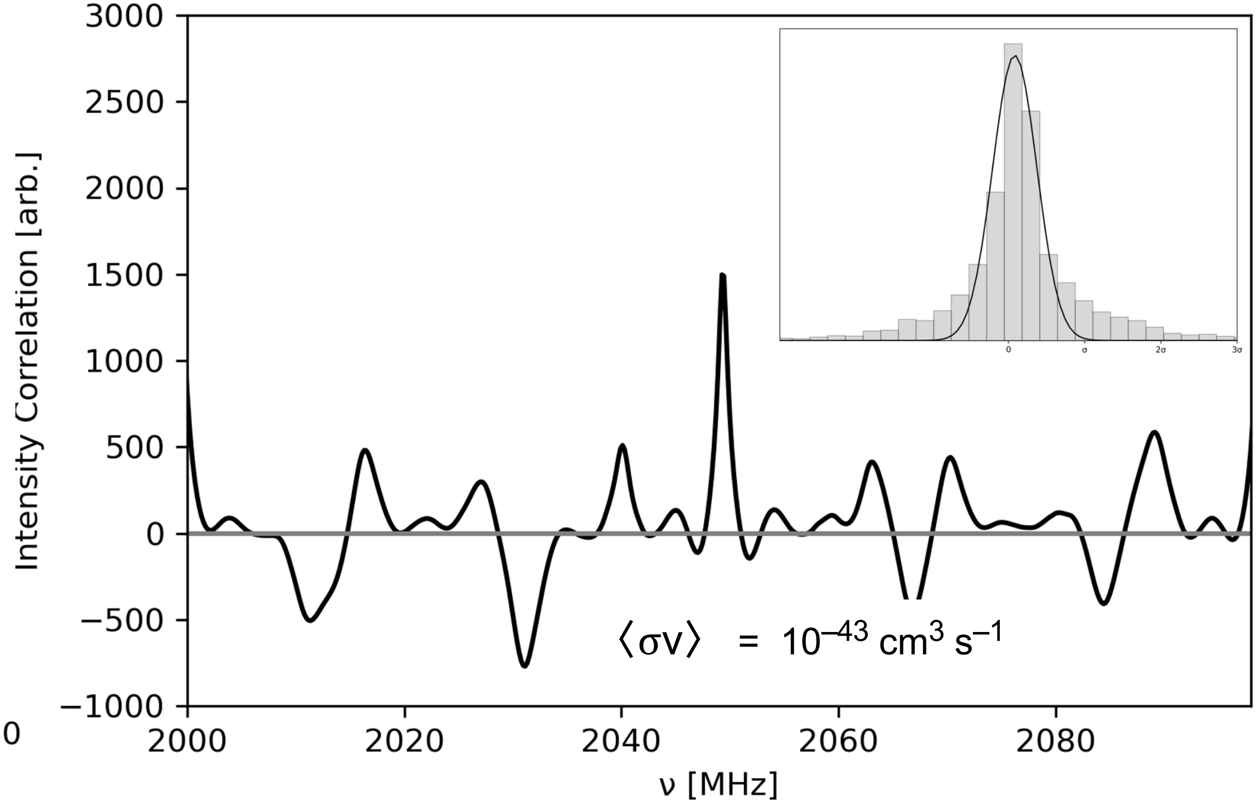




- Target samples: $\theta_F = 69^o$, $\theta_B = 78^o$, total F: 1410, B: 1442 targets
- Form the observed asymmetry spectrum: $A_D(\theta,\nu) = \dfrac{F - B}{F + B}$, $F(\nu) = \dfrac{1}{N} \cdot \sum_i f_i(\nu)$ similarly for *B*
- Form the sample-specific template, with appropriate Doppler shift $\nu' = \nu \cdot (1 \pm \dfrac{V_o}{c} \cdot \cos\theta)$ & line-integrals for each target
- Create the correlation spectrum by taking the dot-product of the template with the asymmetry: $R_D(\nu) = \boldsymbol{T} \cdot \boldsymbol{A_D}(\nu)$

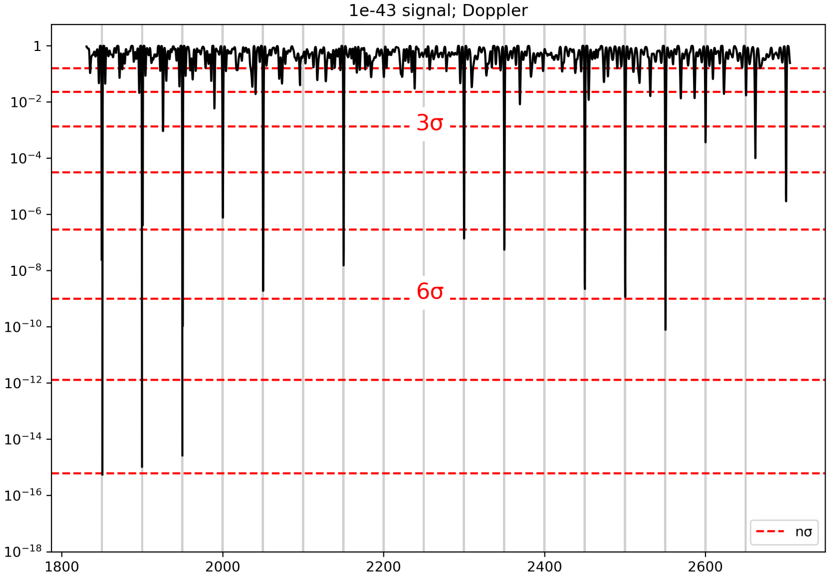
Intensity asymmetry analysis

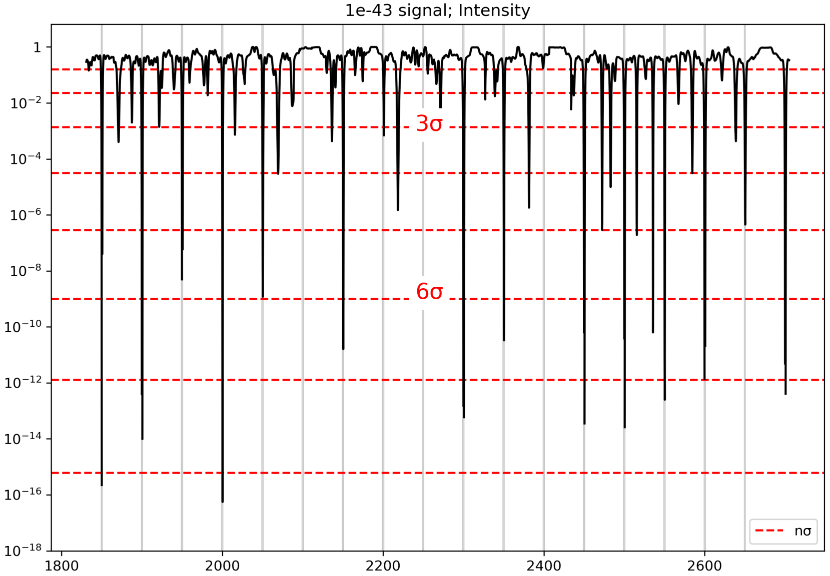


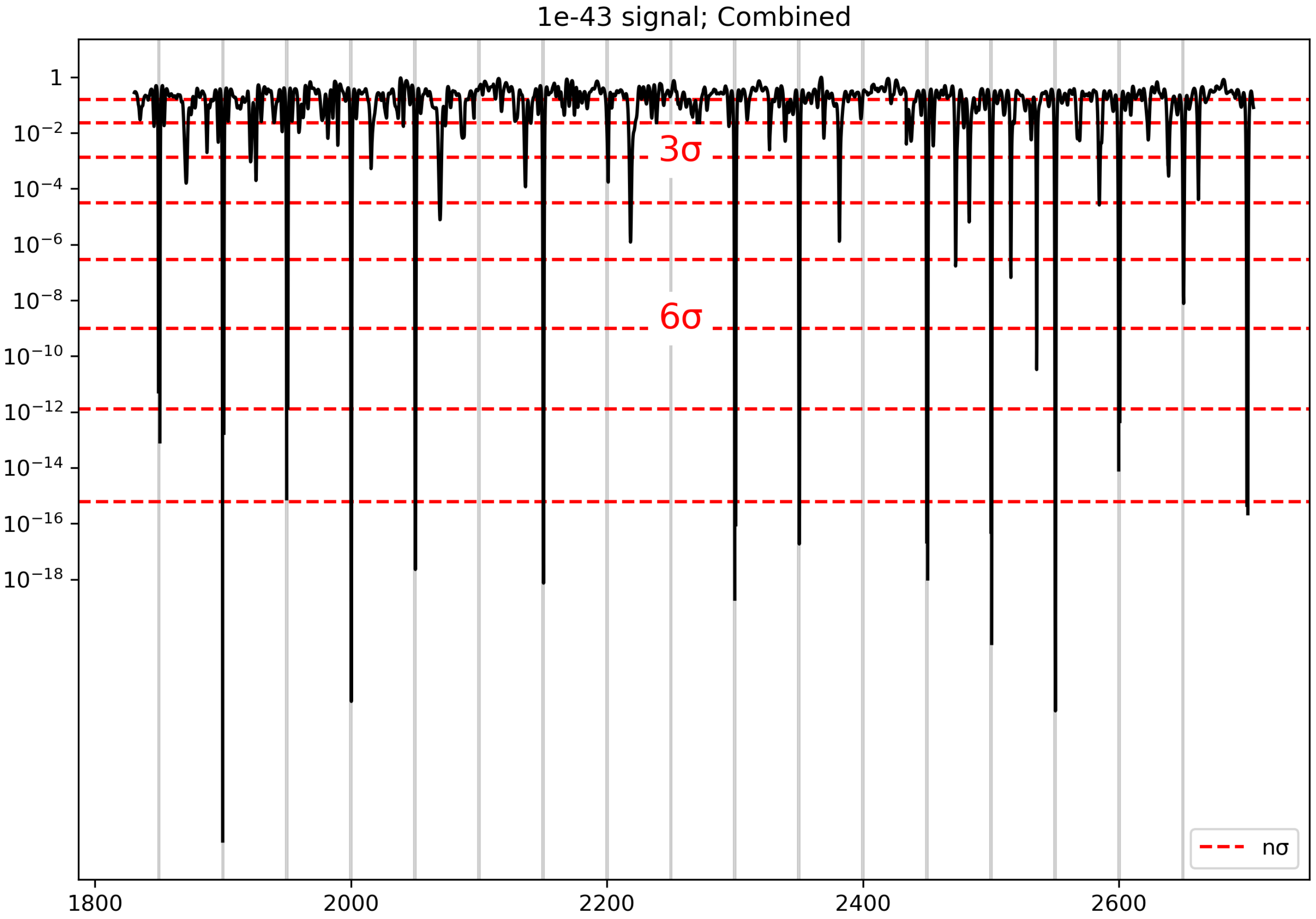


- Analysis follows in a completely analogous way to the Doppler asymmetry: $A_I(\Phi,\nu) = \frac{I-O}{I+O}$, etc.
- $\Phi_I = 45^o$ (171 spectra) , $\Phi_O = 133^o$ (917 spectra)

P-value analysis


1e-43 signal; Doppler

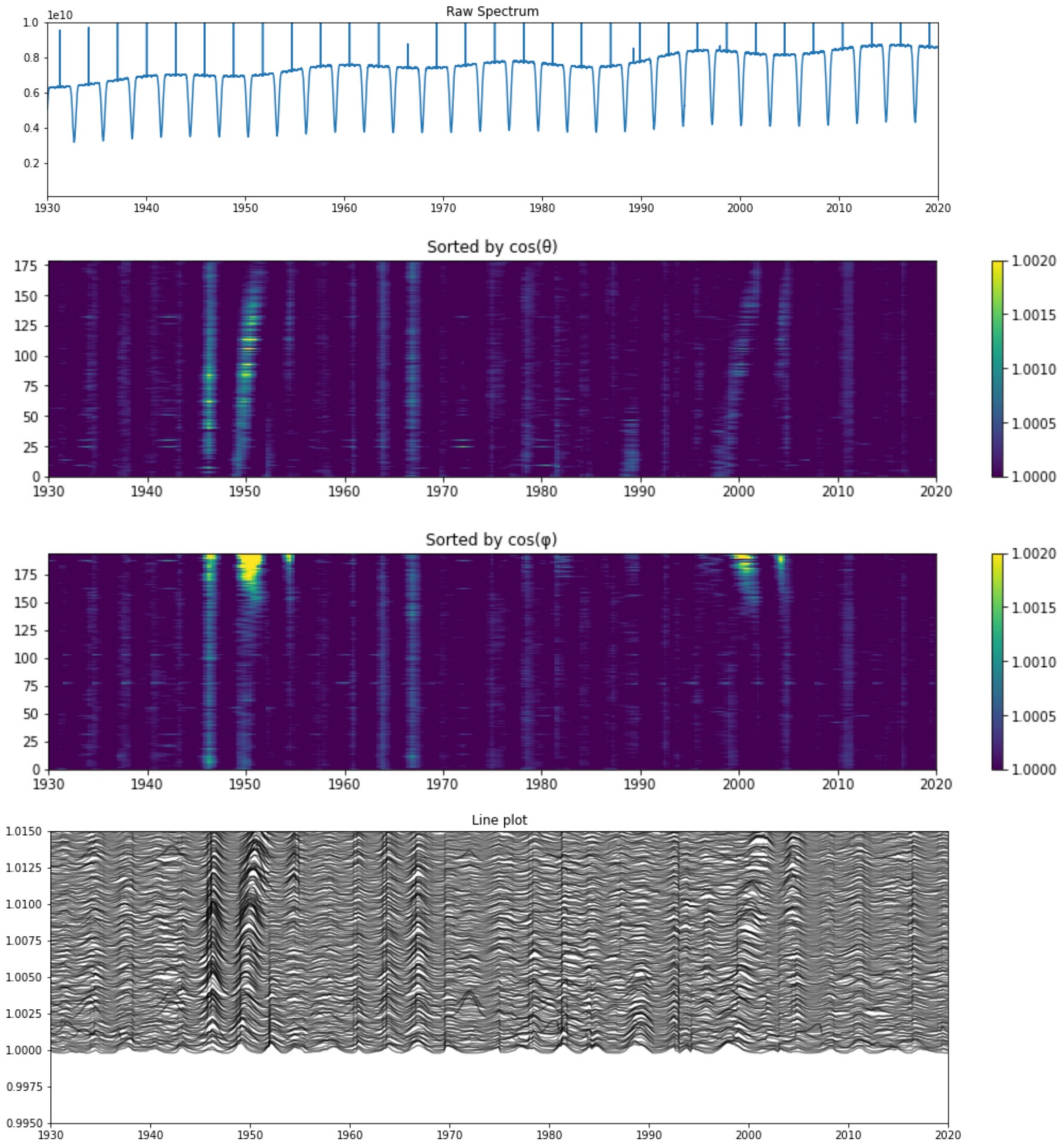

1e-43 signal; Intensity


1e-43 signal; Combined

- A signal was injected at 50 MHz intervals starting from 1850 MHz
- The STD for the p-value calculation was a rolling STD with a 35 MHz window

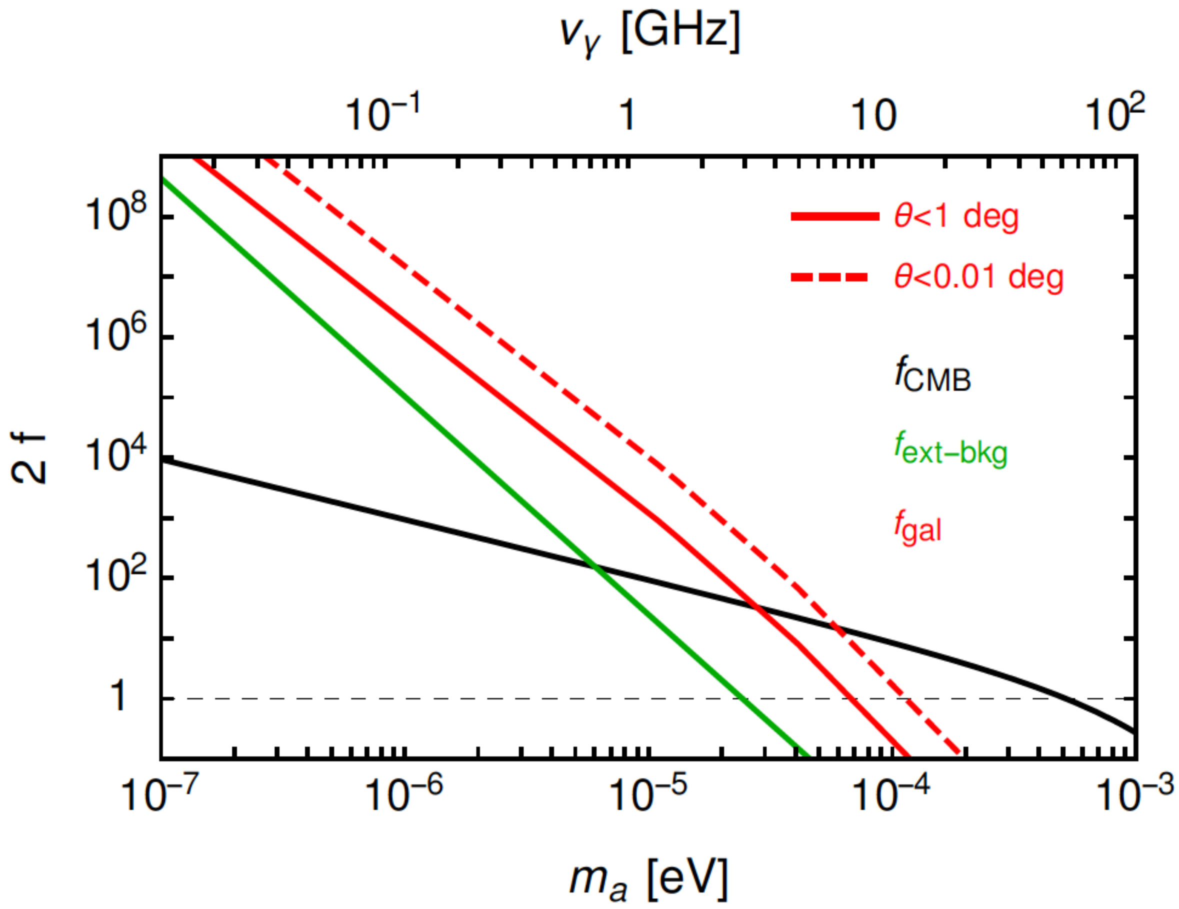
Example heatmap with signal at 1950 MHz and 2000 MHz

1e-43



$$\langle \sigma v \rangle = 1 \times 10^{-43} cm^3 sec^{-1}$$

Correction for stimulated emission



- For any one- or two-photon process, the flux is enhanced (and thus the limits strengthened) by stimulated emission from all sources of photons in the galactic halo.
- The three dominant terms are (i) the diffuse galactic emission (strongly peaked towards the galactic center), (ii) the extra-galactic radio background, and (iii) the CMB.
- The first two dominate but fall strongly with frequency.

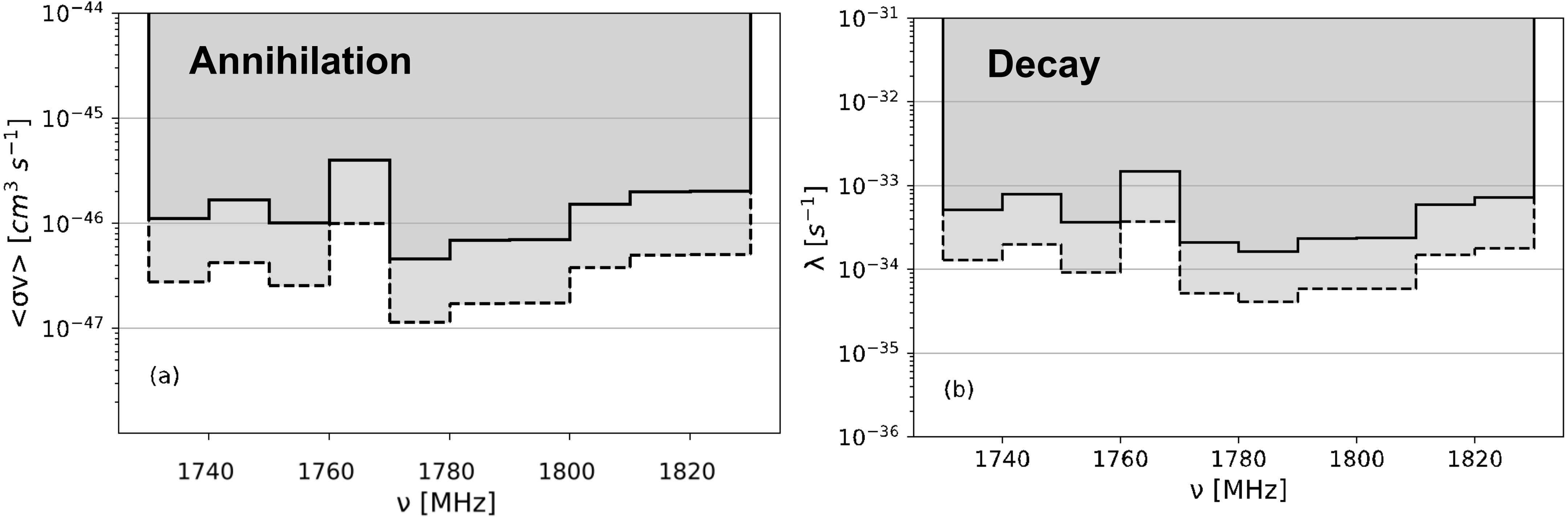
$$\boxed{f_\gamma(\ell,\Omega,m_a) \simeq f_{\gamma,\rm CMB}(m_a) + f_{\gamma,\rm gal}(\ell,\Omega,m_a) + f_{\gamma,\rm ext-bkg}(m_a)}$$

Andrea Caputo *et al.* JCAP 03 (2019) 027

Published limits (L Band)

(Aya Keller *et al.* *ApJ* 927 (2022) 71)

Solid line: 1-photon final states; Dashed line: 2-photon final states

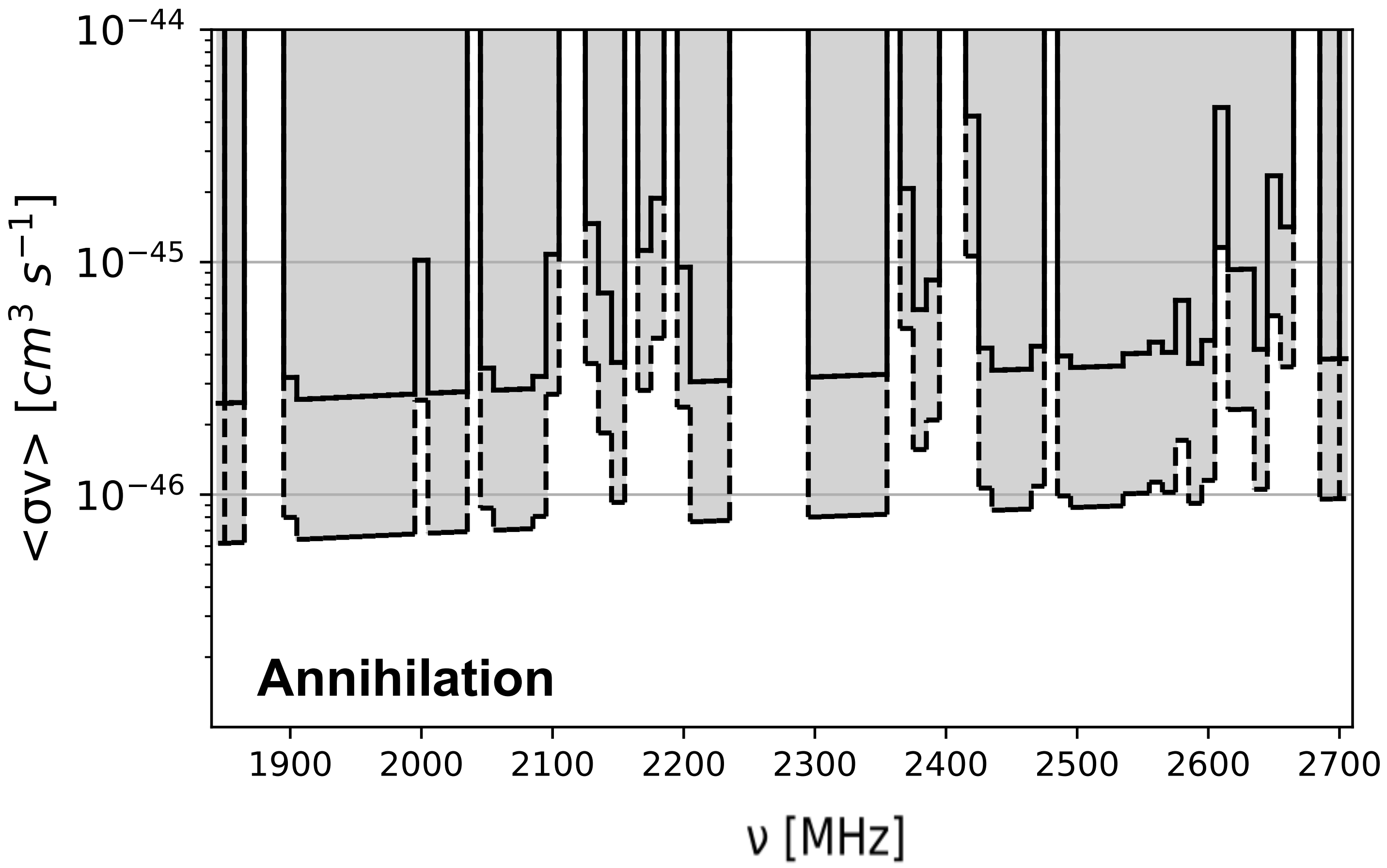


Notes:

- Annihilation at V_{virial} ~ 225 km/sec corresponds to a cross section of $\sigma \sim 4 \times 10^{-54}$ cm^2
- For the two-photon decay, $g_{a\gamma\gamma} \sim 10^{-7}$ GeV^{-1}, already strongly excluded
- Final states $\phi\gamma$ may not be immune from stellar cooling limits for masses ~ T (E. Vitagliano)

Preliminary limits (S Band)

Solid line: 1-photon final states; Dashed line: 2-photon final states



- Preliminary results are conservative; final limits will be significantly stronger; regions of significant RFI have been excluded for the moment, but will be analyzed later

Future plans

- Exploration of sensitivity for different cases of solar and virial velocities
- S-band decay analysis
- Complete full range of L-band analysis
- Will incorporate Parkes data to provide full galactic coverage
- Other hypothesis-driven searches may benefit from techniques to selectively detect very weak, broad signals

Acknowledgments

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- Furthermore, we thank Kathryn Zurek, Sam Witte, Edoardo Vitagliano, Ben Safdi and Hitoshi Murayama for many clarifying conversations throughout the course of the project

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