A Radio Telescope Search For Dark Matter in the L and S Bands

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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

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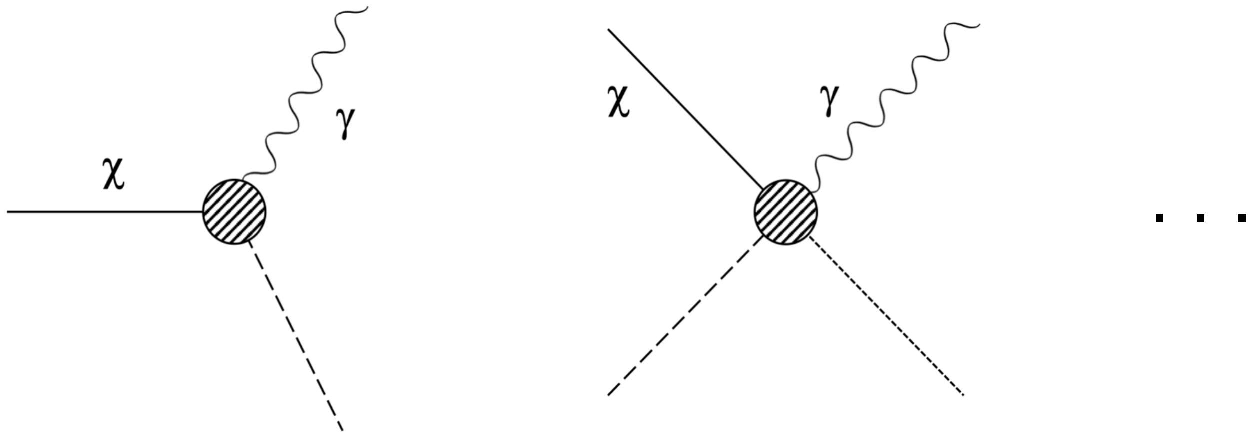
General Concept & Assumptions

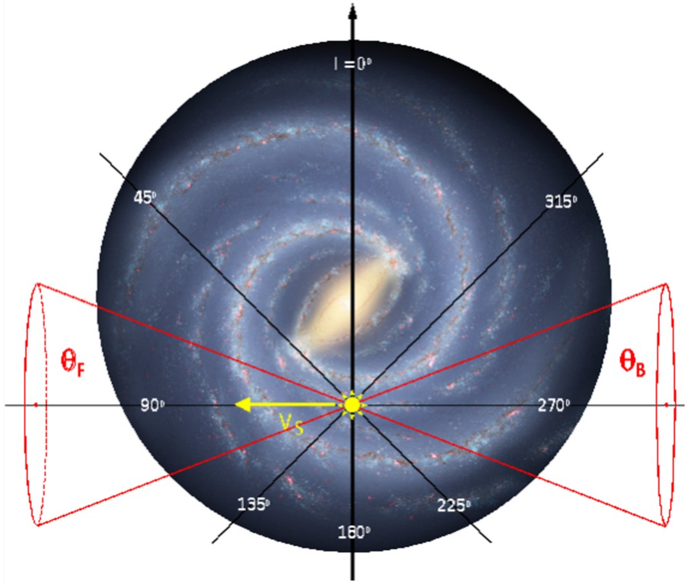
- Dark matter constitutes a static halo through which our solar system is moving with a characteristic velocity $V_S \sim 225$ km/s tangential to our galactic disk, and with a virial velocity $\sigma \sim 250$ km/s
  - A quasi-monochromatic radio line produced by the possible radiative decay or annihilation 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

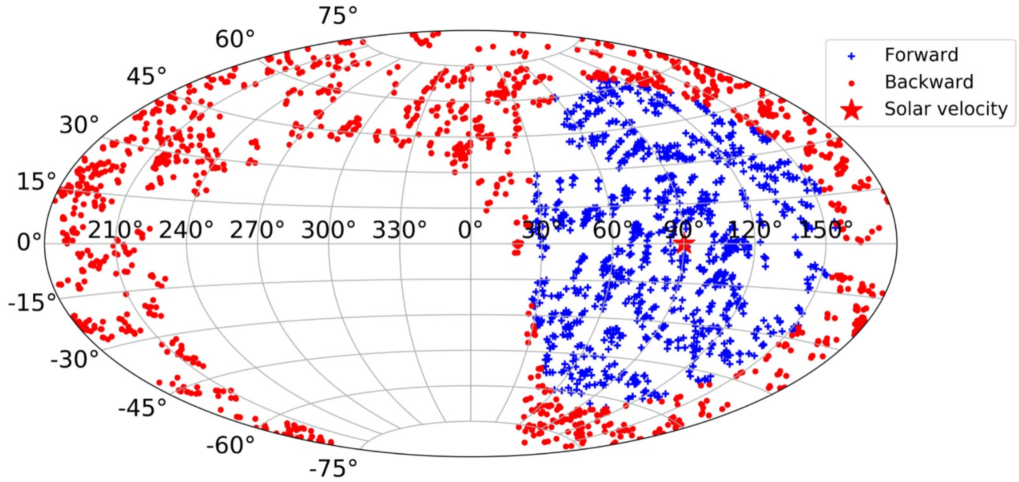


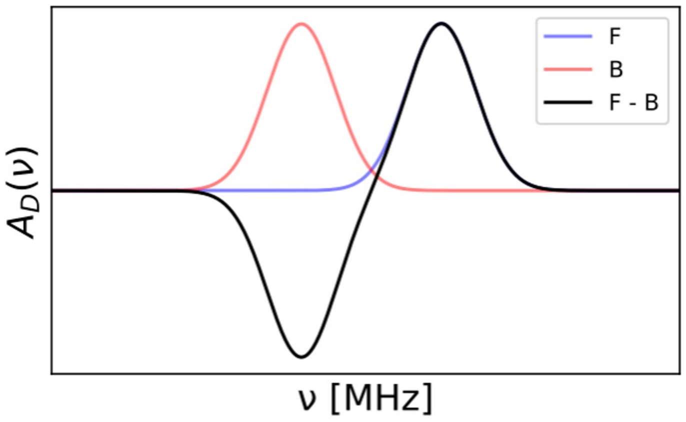
In other words, given this unique database – 3 months observation over ~ 4π – this search asks the question:
"Is there anything with the distribution of the halo that is emitting in the radio spectrum?"

General Concept

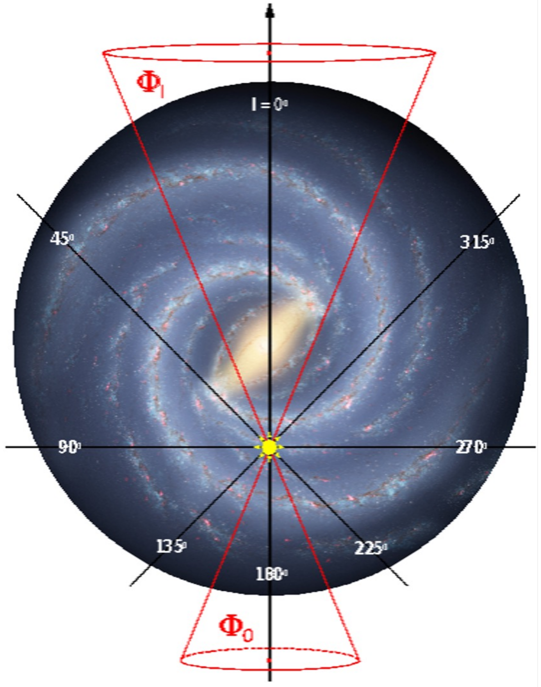
* Mercator projections of targets used in the L-band analysis

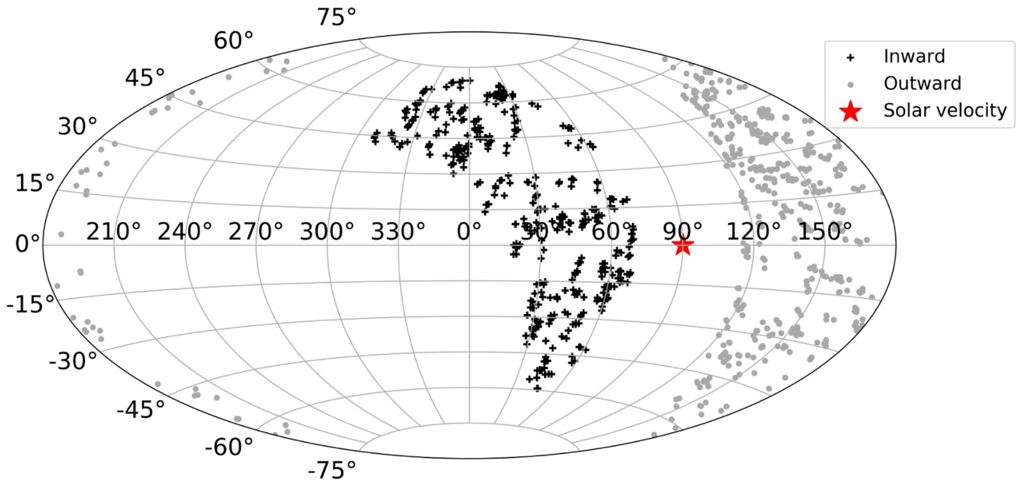


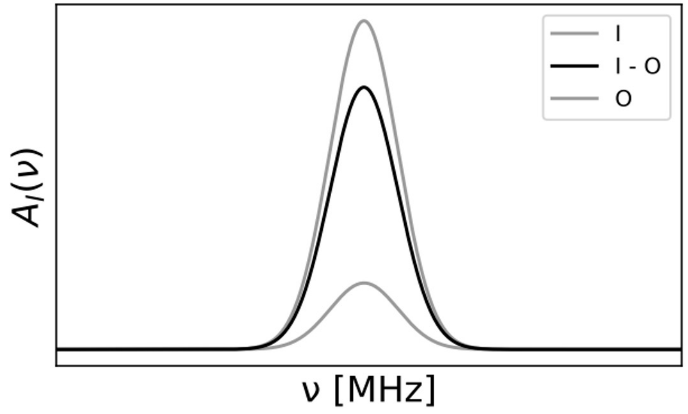




Doppler Asymmetry



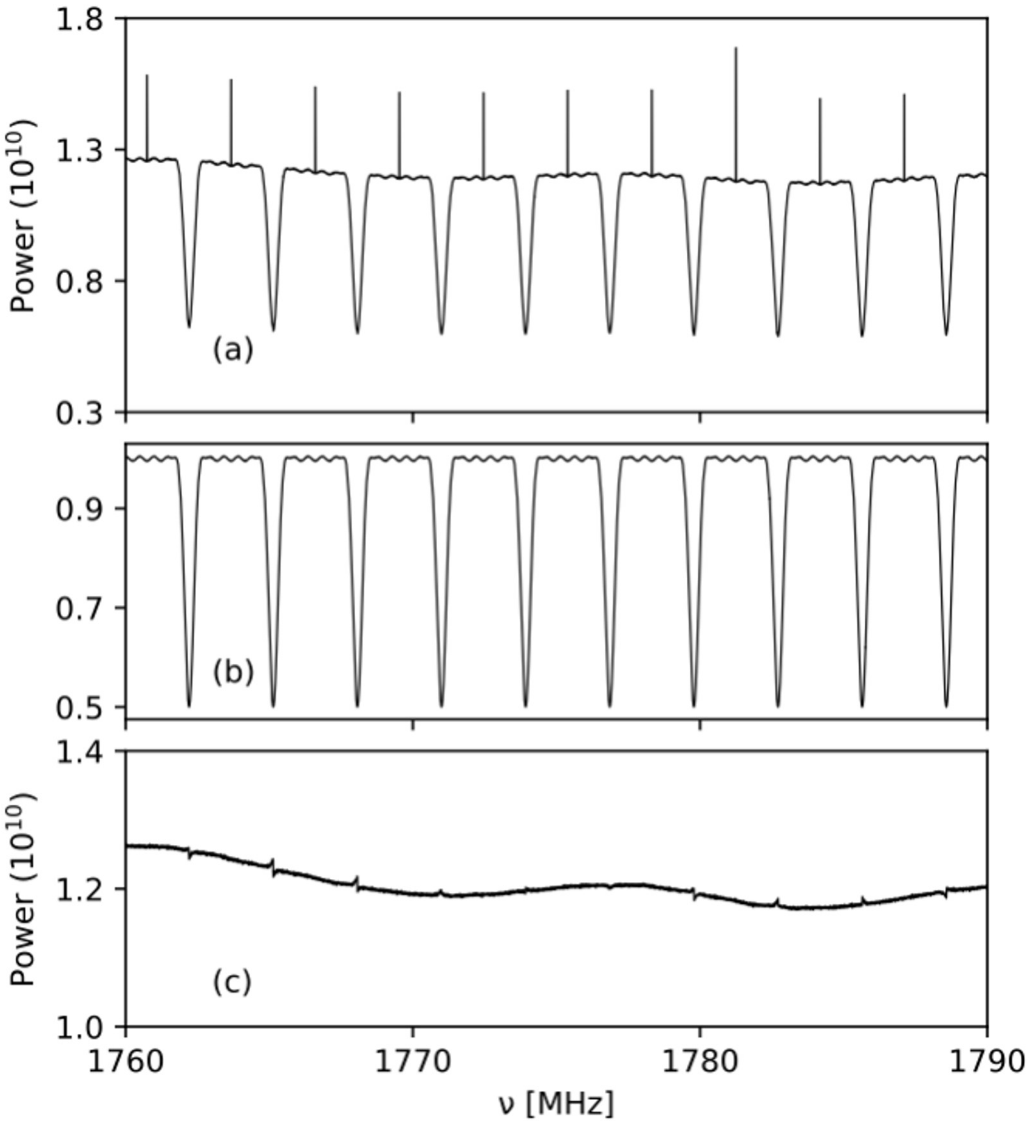




Intensity Asymmetry

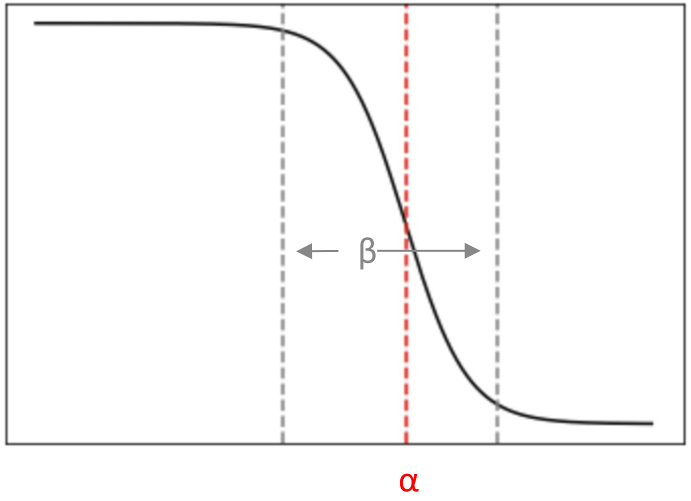
The Breakthrough Listen data set

- 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

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



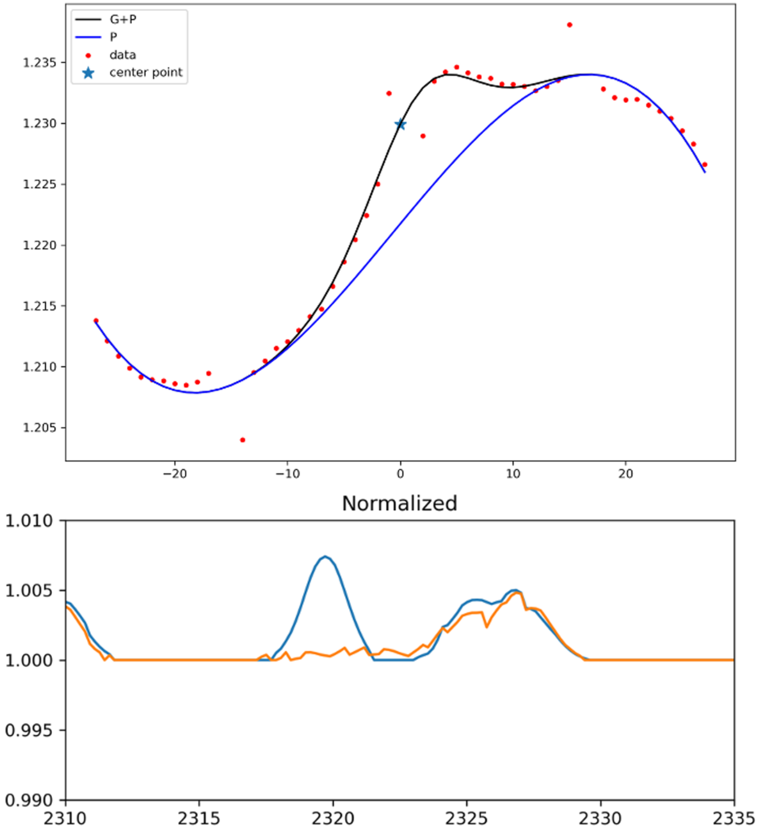
$$N(\nu) = 1 + F(X^2)\frac{G(\nu)}{P(\nu)}$$

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:

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

GBT:

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

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

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

M_χ is the mass of the annihilating dark matter particle

Spectral Flux Density - Decay

General:

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

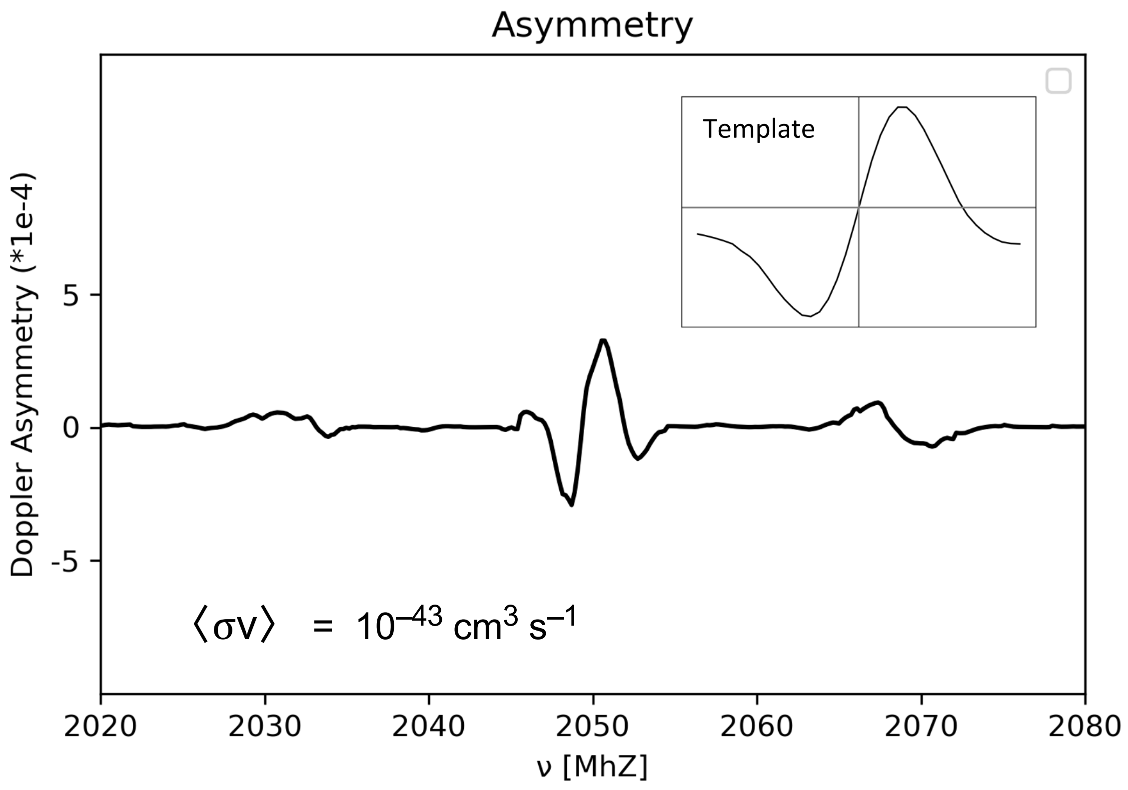
GBT:

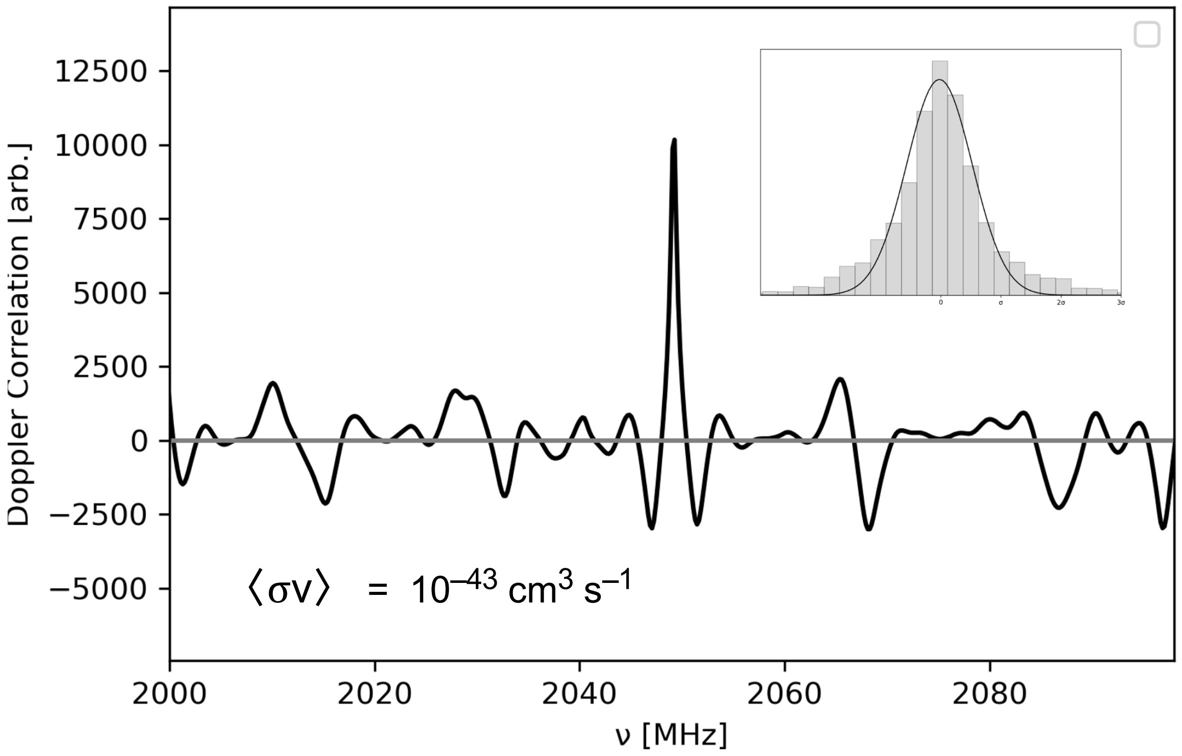
$$\left(\frac{P^D}{\Delta A \cdot \Delta\nu}\right)[W\, m^{-2} Hz^{-1}] = 5.3 \times 10^{-8} \cdot \frac{\lambda\,[s^{-1}]}{\eta^D \cdot (\nu[GHz])^3} \cdot \exp\left[-\frac{1}{2}\left(\frac{\nu-\nu_0}{\eta^D \nu_0}\right)^2\right] \cdot I^D(\mathrm{l,b}) \left[\frac{M_S}{kpc^2}\right]$$

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

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

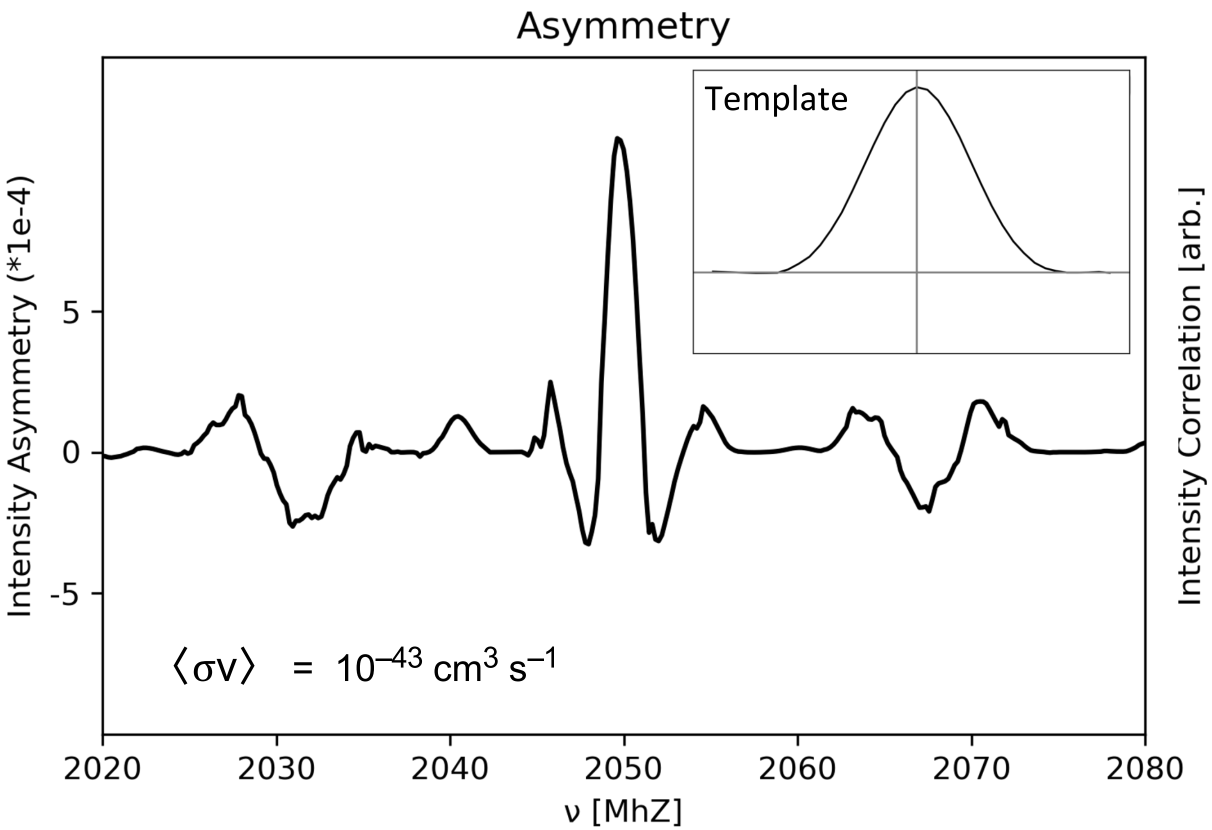
Doppler asymmetry analysis (S Band example)

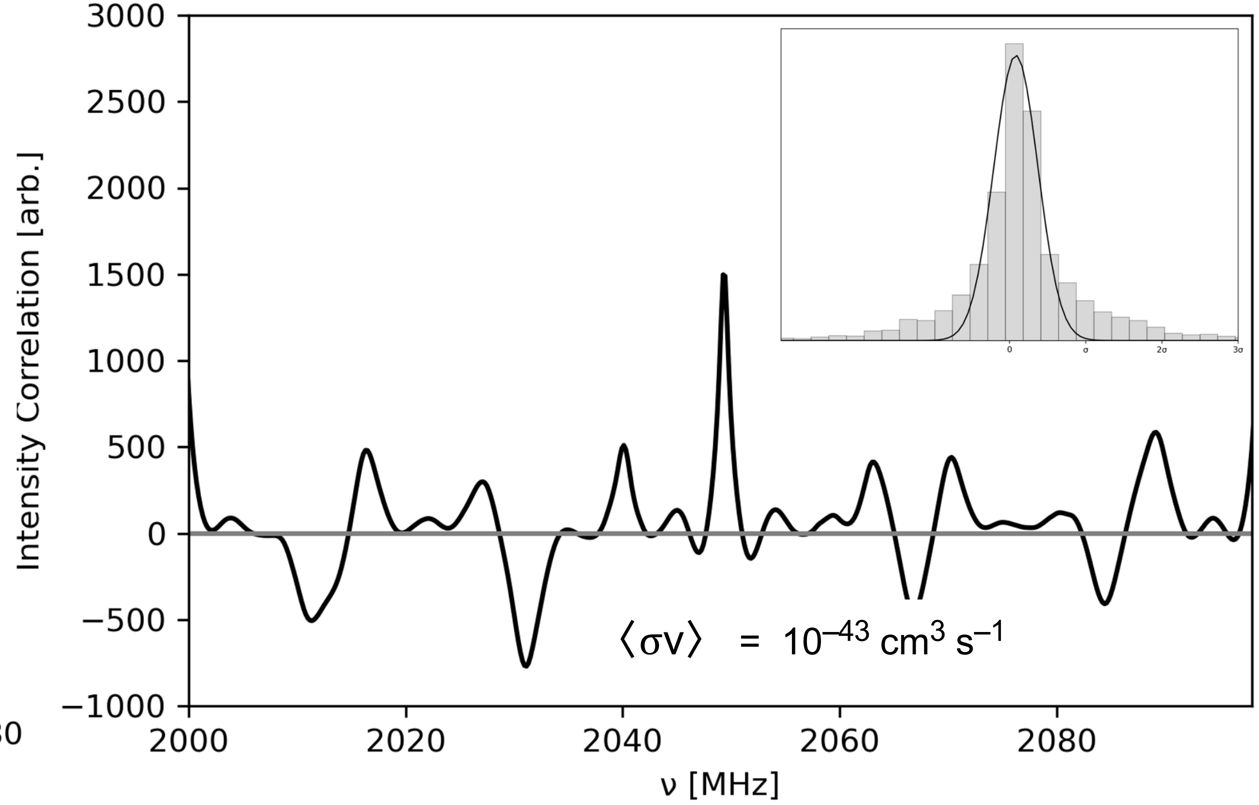




- Target samples: $\theta_F = 69^o$, $\theta_B = 78^o$, total F: 1410, B: 1442 targets
- Form the observed asymmetry spectrum: $A_D(\theta,\nu) = \dfrac{F - B}{F + B}$, $F(\nu) = \dfrac{1}{N} \cdot \sum_i f_i(\nu)$ similarly for *B*
- Form the sample-specific template, with appropriate Doppler shift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

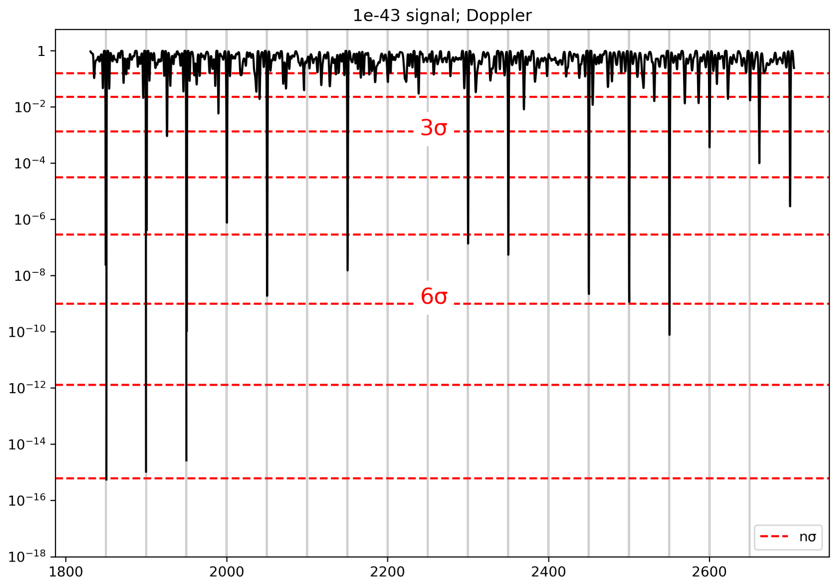
Intensity asymmetry analysis (S Band example)

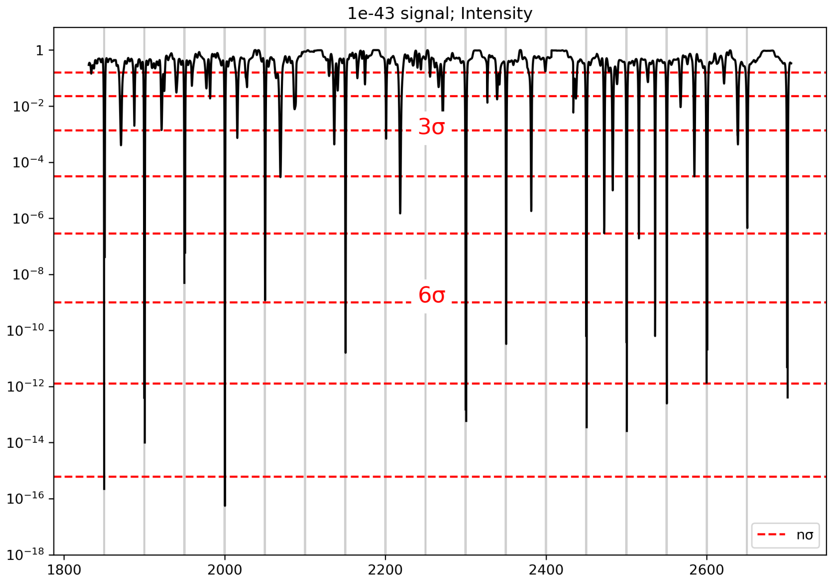


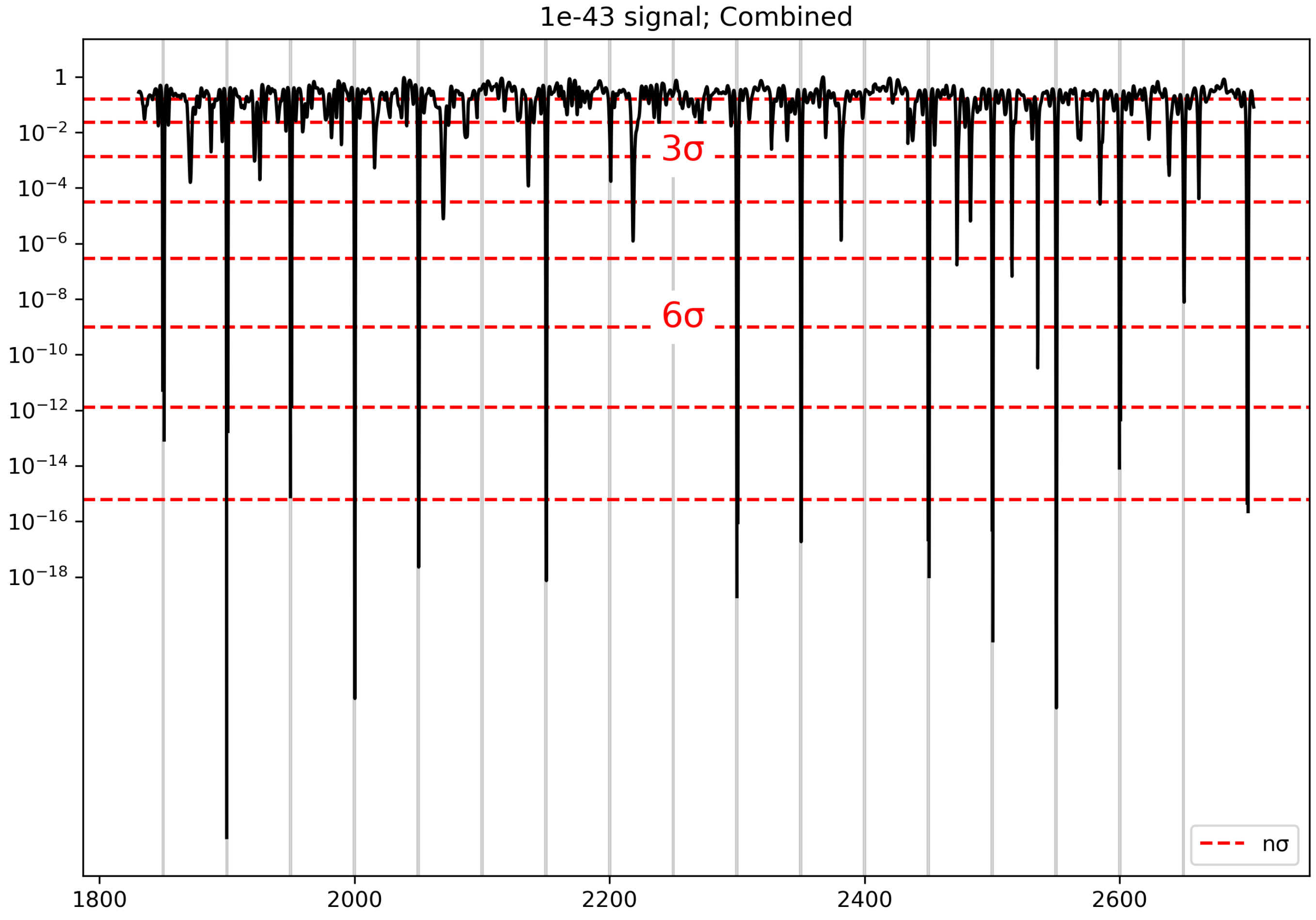


- Analysis follows in a completely analogous way to the Doppler asymmetry: $A_I(\Phi,\nu) = \dfrac{I - O}{I + O}$, etc.
- $\Phi_I = 45^o$ (171 spectra) , $\Phi_O = 133^o$ (917 spectra)

P-value analysis



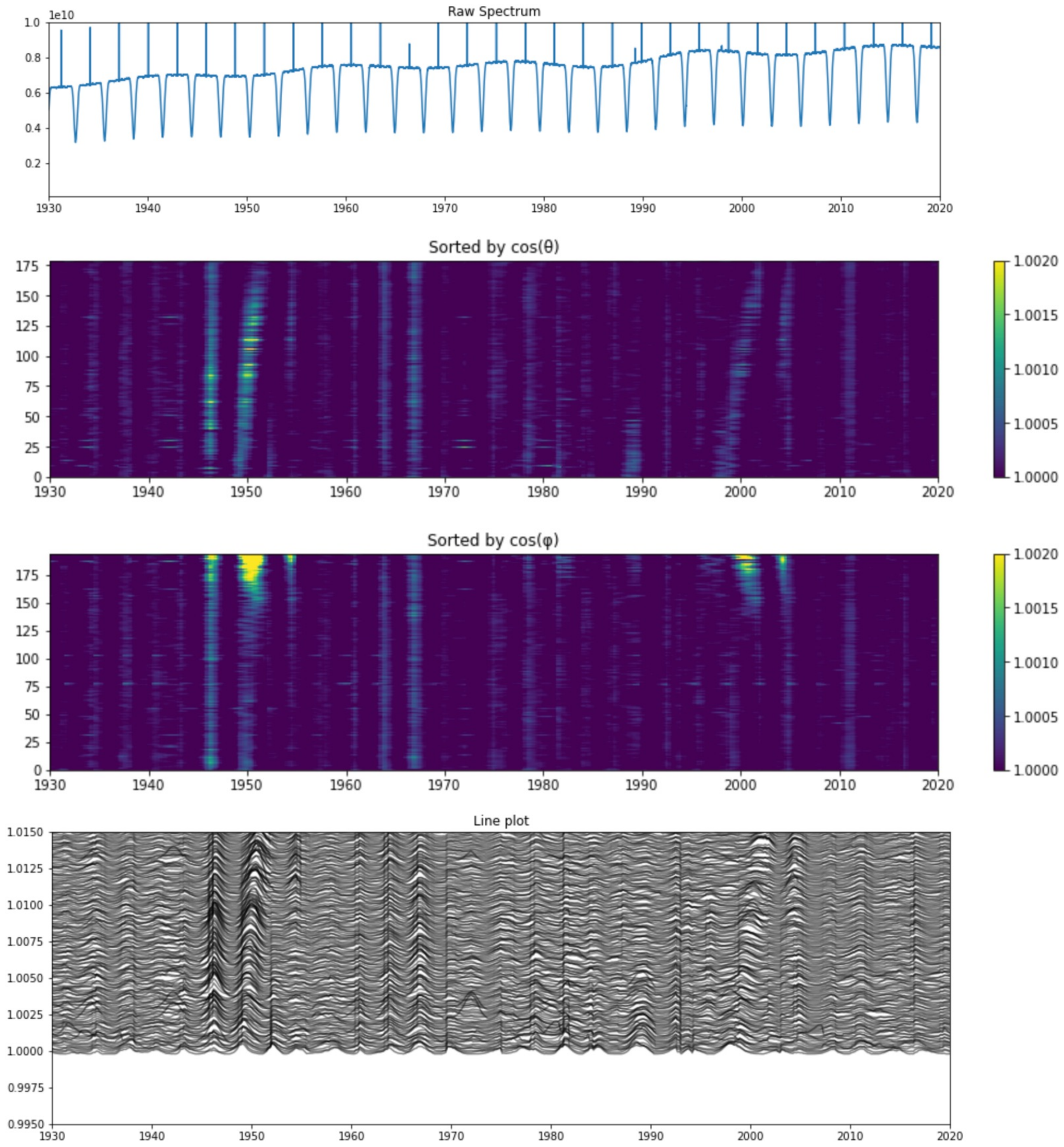




- A signal was injected at 50 MHz intervals starting from 1850 MHz
- The STD for the p-value calculation was a rolling STD with a 35 MHz window

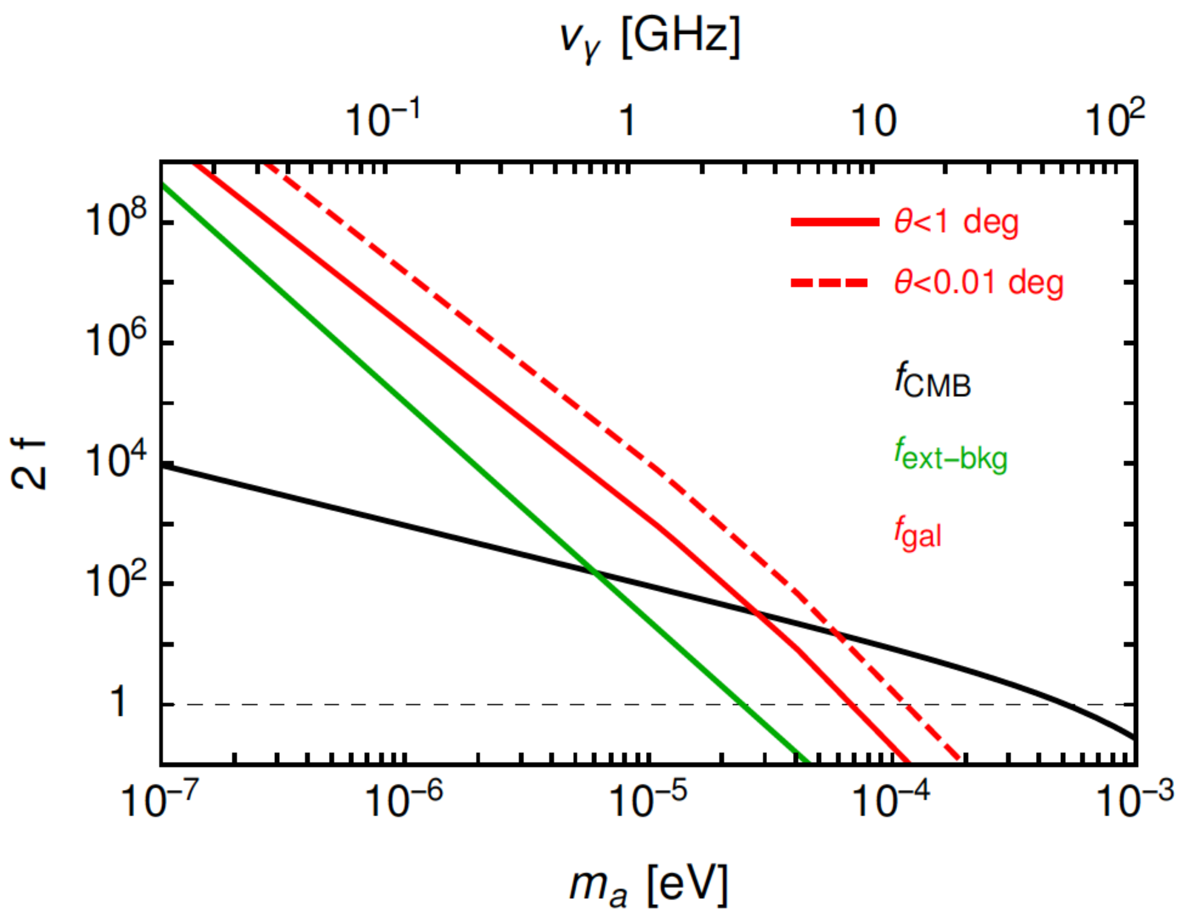
Example heatmap with signal at 1950 MHz and 2000 MHz

1e-43



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

Correction for stimulated emission

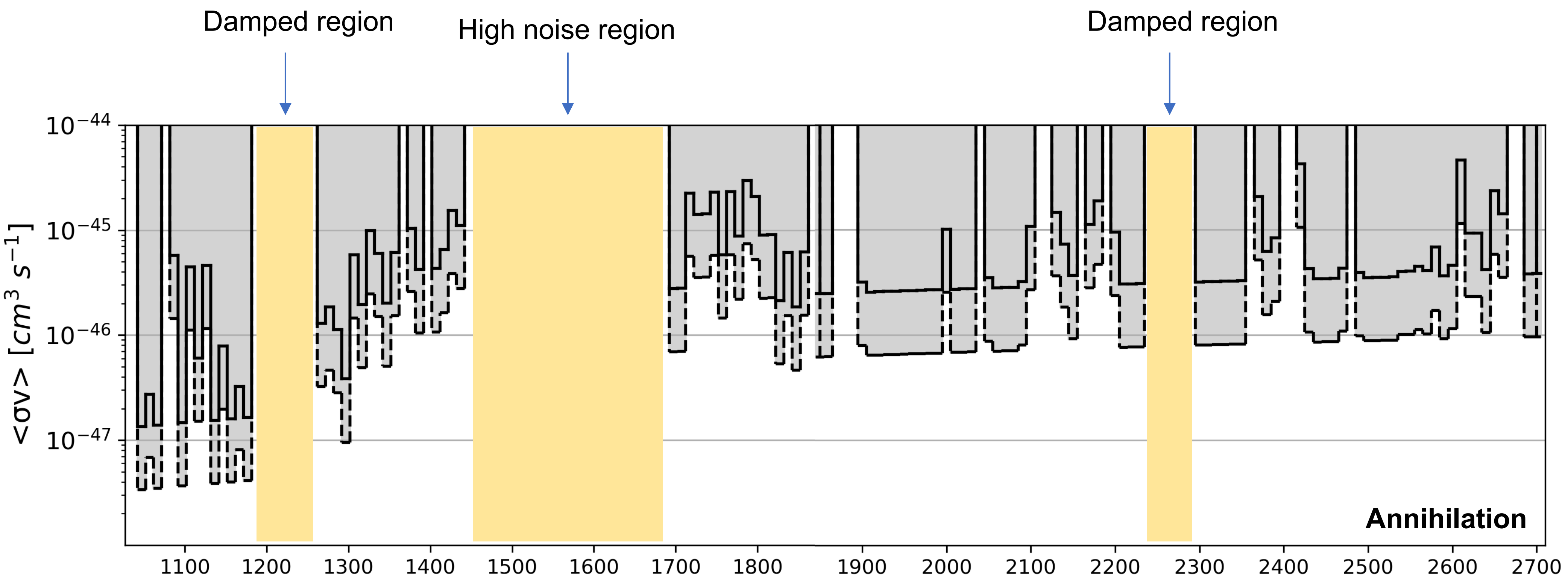


- For any one- or two-photon process, the flux is enhanced (and thus the limits strengthened) by stimulated emission from all sources of photons in the galactic halo.
- The three dominant terms are (i) the diffuse galactic emission (strongly peaked towards the galactic center), (ii) the extra-galactic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

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

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

Limits



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

Future plans

- Exploration of sensitivity for different cases of solar and virial velocities
- Decay 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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