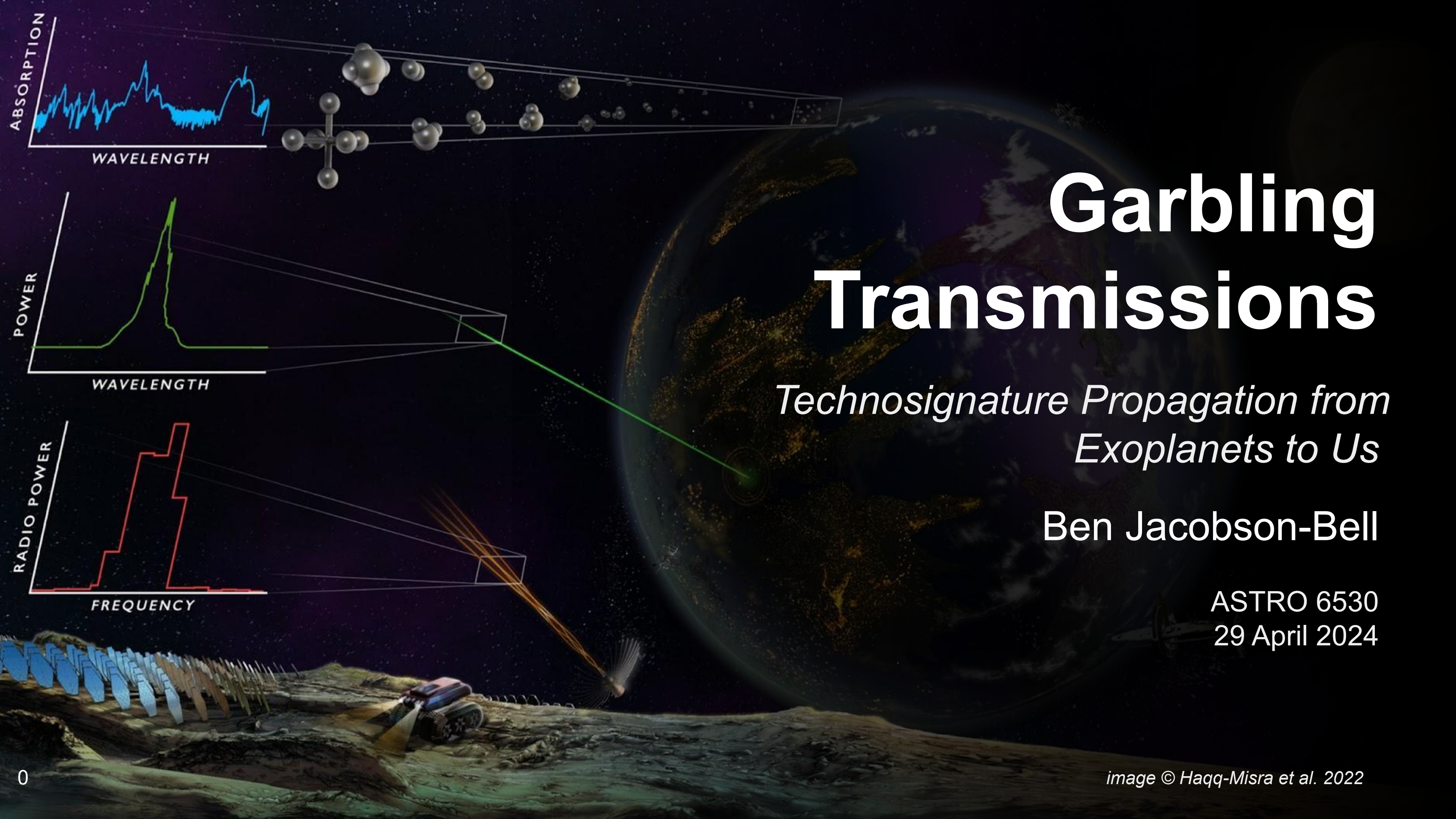

Garbling Transmissions

Technosignature Propagation from Exoplanets to Us

Ben Jacobson-Bell

ASTRO 6530
29 April 2024

image © Haqq-Misra et al. 2022

The Search for (Radio) Technosignatures

Drift rate: Doppler frequency variation due to the exoplanet's radial acceleration

Still a huge diversity of potential signals!
(e.g. in frequency, luminosity, polarization, modulation, etc. …)

How do propagation effects add to this diversity of potential technosignatures?

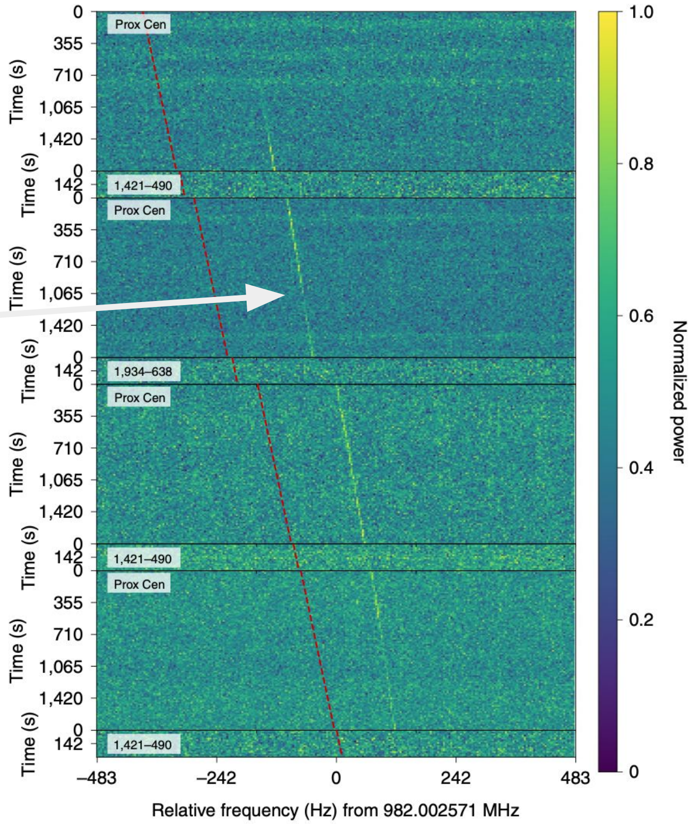

Fig. 4 | The signal of interest, BLC1, from our search of Prox Cen. Here, we plot the dynamic spectrum around the signal of interest over an eight-pointing cadence of on-source and off-source observations. BLC1 passes our coincidence filters and persists for over 2 h. The red dashed line, purposefully offset from the signal, shows the expected frequency based on the detected drift rate (0.038 Hz s^{-1}) and start frequency in the first panel. BLC1 is analysed in detail in a companion paper[23].

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The Search for (Radio) Technosignatures

Drift rate: Doppler frequency variation due to the exoplanet's radial acceleration

Still a huge div

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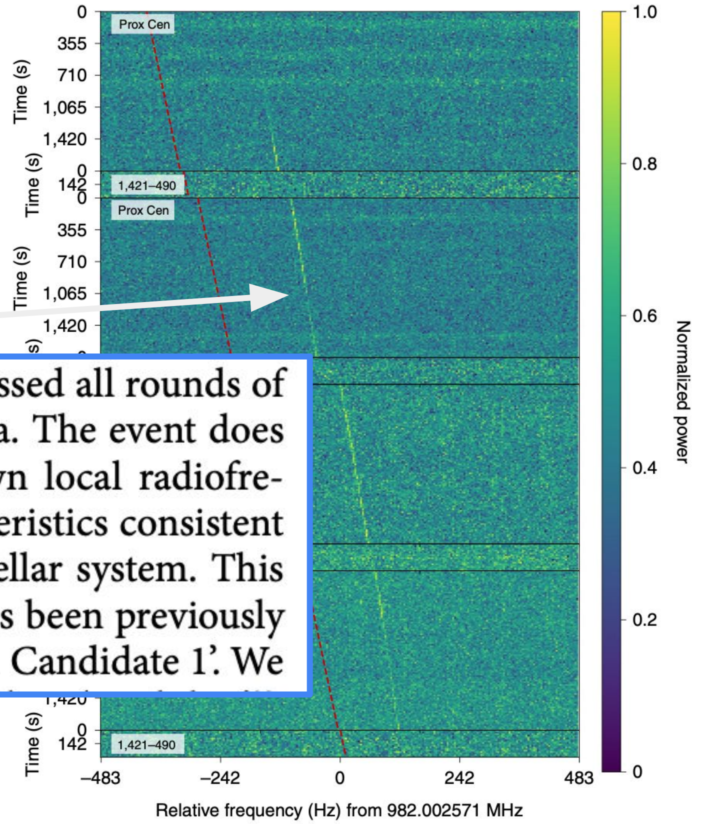
Of the 5,160 events, only one event (Fig. 4) passed all rounds of filtering and visual inspection of dynamic spectra. The event does not lie within the frequency range of any known local radiofrequency interference (RFI), and has many characteristics consistent with a putative transmitter located in another stellar system. This event, which we refer to as a signal of interest, has been previously reported as 'BLC1', short for 'Breakthrough Listen Candidate 1'. We



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The Search for (Radio) Technosignatures

Drift rate: Doppler frequency variation due to the exoplanet's radial acceleration

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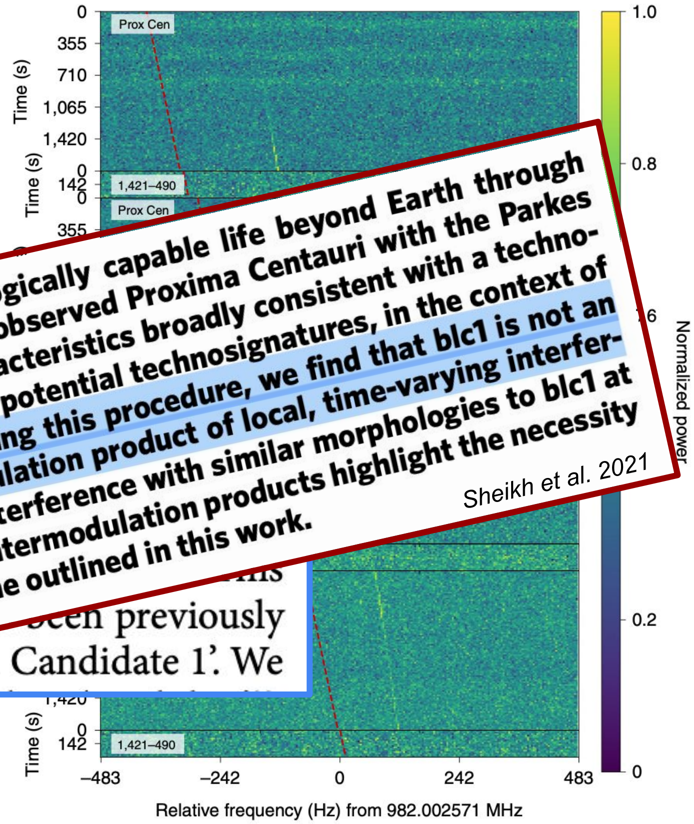
The aim of the search for extraterrestrial intelligence (SETI) is to find technologically capable life beyond Earth through their technosignatures. On 2019 April 29, the Breakthrough Listen SETI project observed Proxima Centauri with the Parkes 'Murriyang' radio telescope. These data contained a narrowband signal with characteristics broadly consistent with a techno-signature near 982 MHz ('blc1'). Here we present a procedure for the analysis of potential technosignatures, in the context of the ubiquity of human-generated radio interference, which we apply to blc1. Using this procedure, we find that blc1 is not an extraterrestrial technosignature, but rather an electronically drifting intermodulation product of local, time-varying interferers aligned with the observing cadence. We find dozens of instances of radio interference with similar morphologies to blc1 at frequencies harmonically related to common clock oscillators. These complex intermodulation products highlight the necessity for detailed follow-up of any signal of interest using a procedure such as the one outlined in this work.

Sheikh et al. 2021



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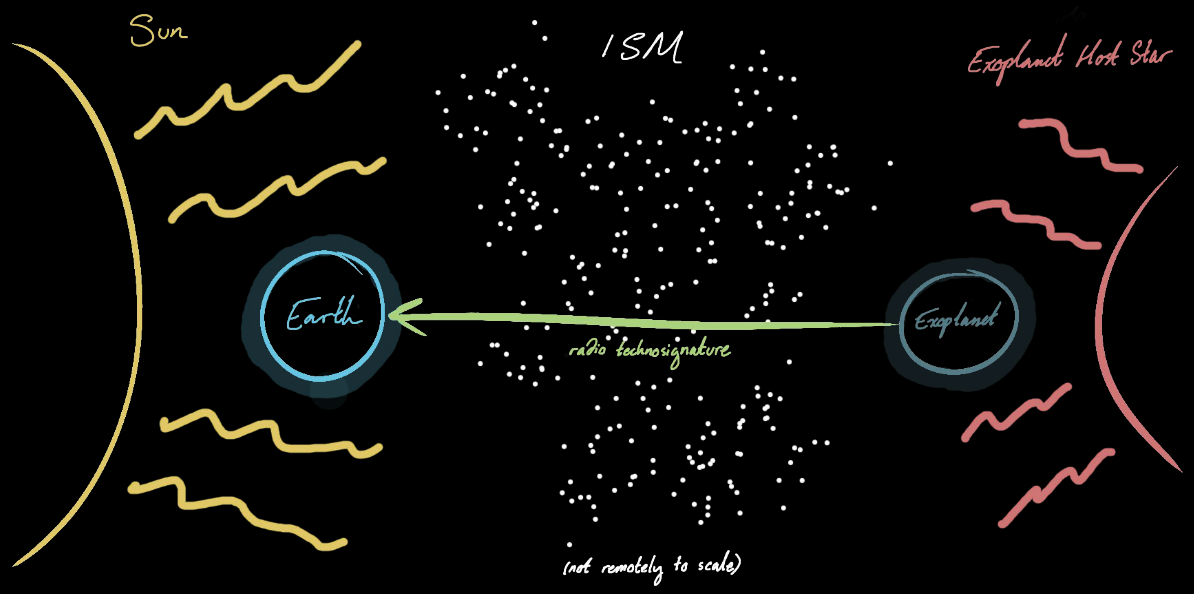
Technosignature Propagation

Like all signals, radio technosignatures travel through different media as they propagate from extraterrestrial transmitters to our receivers on Earth.

- Exoplanet's atmosphere, ISM, Earth's atmosphere, respective solar winds …

How do these media change radio signals that pass through them?



The Equation of Radiative Transfer*

intensity of signal

absorption coefficient: related to number density n and collision cross-section σ_ν

$$\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu$$

differential propagation length

emission coefficient: related to source function S_ν and absorption coefficient α_ν

***I'm neglecting scattering here.** Rybicki & Lightman give a detailed review in §1.7–1.8 of *Radiative Processes in Astrophysics*, the gist of which is that the scattering term makes the above an integrodifferential equation, which is solved numerically. Scattering does change the problem significantly and is worth considering in general, but it's outside the scope of this project. Following R&L's derivation could probably have been a project unto itself!

Solving the Equation of Radiative Transfer

Need to solve in 3* media: **exoplanet atmosphere, ISM, and Earth atmosphere.**

*really 2, if we approximate the exoplanet atmosphere as Earthlike

Given certain assumptions, the solution has the same form in all three media.

$$\frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu$$

substitute optical depth to simplify RHS, then solve using an integrating factor

$$I_\nu(\tau_\nu) = I_\nu^{(0)} e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)} S_\nu(\tau'_\nu) d\tau'_\nu$$

How good is this assumption? Not terrible, but not great. An interesting extension would be to instead derive the spatial dependence of the source function from (a) the atmospheric PT profile and (b) a Galactic electron density model (e.g. Cordes & Lazio 2002).

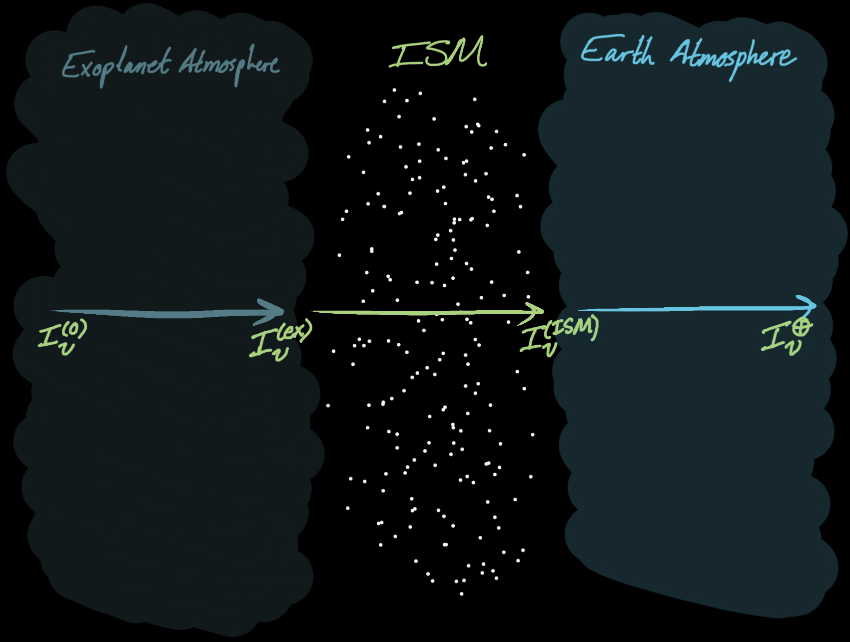
assume a spatially invariant source function, then integrate second term

$$\boxed{I_\nu(\alpha_\nu, S_\nu, L) = I_\nu^{(0)} e^{-\alpha_\nu L} + S_\nu \left(1 - e^{-\alpha_\nu L}\right)}$$

Here *L* is the total distance the beam travels through the medium — about 100 km for each atmosphere and on the order of pc–kpc for the ISM.

Solving the Equation of Radiative Transfer

$$\boxed{I_\nu(\alpha_\nu, S_\nu, L) = I_\nu^{(0)} e^{-\alpha_\nu L} + S_\nu \left(1 - e^{-\alpha_\nu L}\right)}$$



At each successive stage we get the following:

$$\begin{aligned}
I_\nu^{(\mathrm{ex})} &= I_\nu^{(0)} e^{-\alpha_\nu^{(\mathrm{atm})} L^{(\mathrm{atm})}} && + S_\nu^{(\mathrm{atm})} \left(1 - e^{-\alpha_\nu^{(\mathrm{atm})} L^{(\mathrm{atm})}}\right) \\
I_\nu^{(\mathrm{ISM})} &= I_\nu^{(\mathrm{ex})} e^{-\alpha_\nu^{(\mathrm{ISM})} L^{(\mathrm{ISM})}} && + S_\nu^{(\mathrm{ISM})} \left(1 - e^{-\alpha_\nu^{(\mathrm{ISM})} L^{(\mathrm{ISM})}}\right) \\
I_\nu^{\oplus} &= I_\nu^{(\mathrm{ISM})} e^{-\alpha_\nu^{(\mathrm{atm})} L^{(\mathrm{atm})}} && + S_\nu^{(\mathrm{atm})} \left(1 - e^{-\alpha_\nu^{(\mathrm{atm})} L^{(\mathrm{atm})}}\right)
\end{aligned}$$

Or, revising our notation a little for brevity:

$$\begin{aligned}
I_\nu^{(\mathrm{ex})} &= I_\nu^{(0)} e^{-\alpha_\nu z} && + S_\nu^{(\mathrm{atm})} \left(1 - e^{-\alpha_\nu z}\right) \\
I_\nu^{(\mathrm{ISM})} &= I_\nu^{(\mathrm{ex})} e^{-\beta_\nu d} && + S_\nu^{(\mathrm{ISM})} \left(1 - e^{-\beta_\nu d}\right) \\
I_\nu^{\oplus} &= I_\nu^{(\mathrm{ISM})} e^{-\alpha_\nu z} && + S_\nu^{(\mathrm{atm})} \left(1 - e^{-\alpha_\nu z}\right)
\end{aligned}$$

Putting it all together …

We have to assume forms for the source functions.

- In the **atmosphere**, we assume LTE, so the source function is the Planck distribution (Kirchhoff's Law).
- In the **ISM**, LTE is not a good assumption.

Putting the source functions together with the three radiative transfer solutions from the previous slide (and simplifying), we get the following:

$$I_\nu^\oplus = I_\nu^{(0)} e^{-(2\alpha_\nu z + \beta_\nu d)} + \frac{2\nu^2 k_B T}{c^2}\left(1 - e^{-\alpha_\nu z}\right)\left(1 + e^{-(\alpha_\nu z + \beta_\nu d)}\right) + \frac{h\nu^3}{c^2}\left(\frac{1 - e^{-\beta_\nu d}}{e^{\alpha_\nu z}}\right)$$

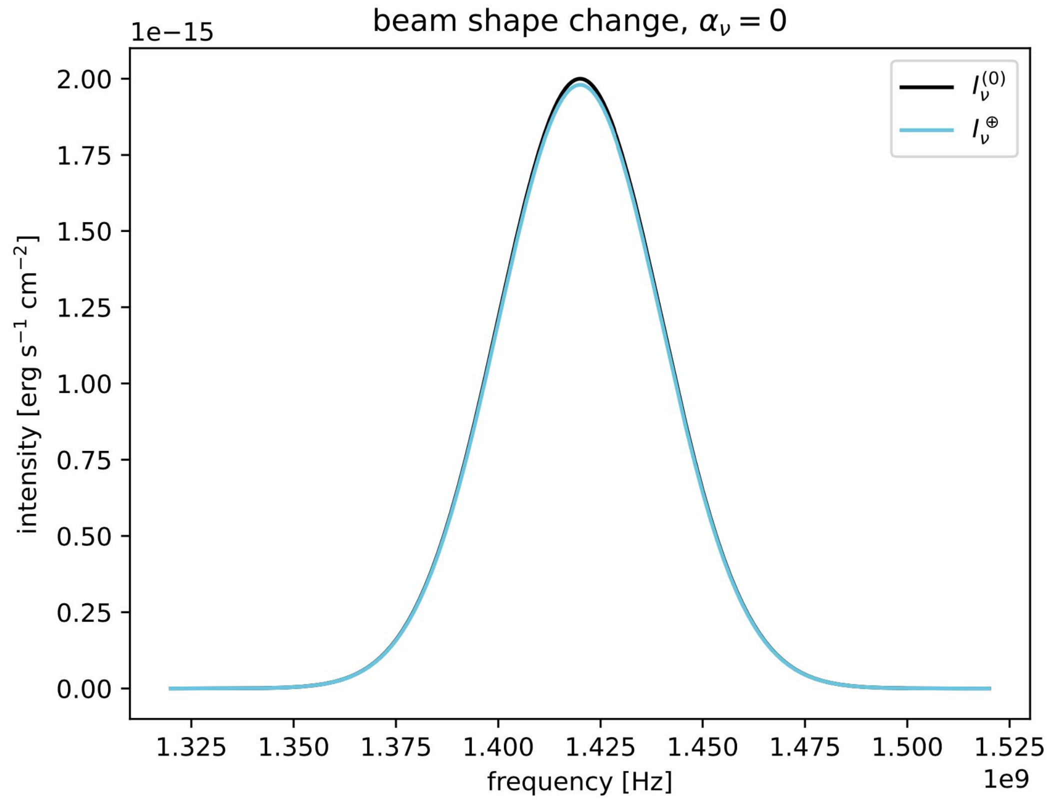
Here, because we're in the radio regime, I've used Wien's approximation to say $(e^{h\nu/k_B T} - 1) \approx h\nu/k_B T$.

Observables

$$I_\nu^{\oplus} = I_\nu^{(0)} e^{-(2\alpha_\nu z + \beta_\nu d)} + \frac{2\nu^2 k_B T}{c^2}\left(1 - e^{-\alpha_\nu z}\right)\left(1 + e^{-(\alpha_\nu z + \beta_\nu d)}\right) + \frac{h\nu^3}{c^2}\left(\frac{1 - e^{-\beta_\nu d}}{e^{\alpha_\nu z}}\right)$$

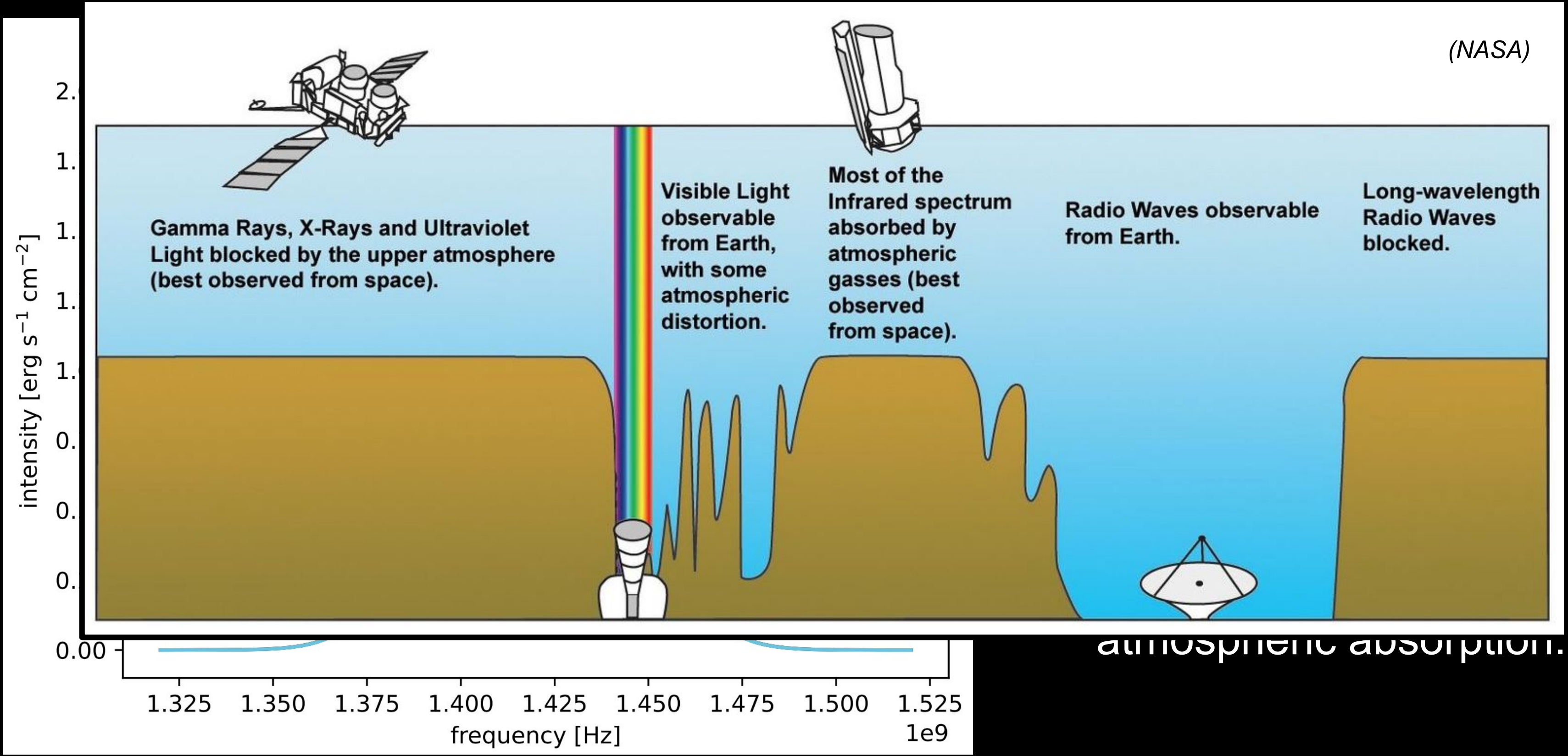
- α_ν, the absorption coefficient of the atmosphere
  - obtained from atmospheric absorption spectra
- β_ν, the absorption coefficient of the ISM
  - = $n\sigma$, where n is the electron density of the ISM and σ is the Thomson cross-section
- z, the height of the atmosphere
  - ~100 km for an Earthlike atmosphere
- d, the line-of-sight distance to the exoplanet through the ISM
  - generally well known for well-studied exoplanets, on the order of 10s–100s of pc
- T, the atmospheric temperature
  - 300 K not a bad approximation

How does this propagation affect the beam’s shape?



- Simulated “beam” as Gaussian centered on 1420 MHz (HI/21-cm line)
- Amplitude is 10^6 times stronger than the Arecibo transmitter at d = 30 pc
- … Not very exciting, because the radio spectrum is sort of all-or-nothing on atmospheric absorption.

How does this propagation affect the beam's shape?



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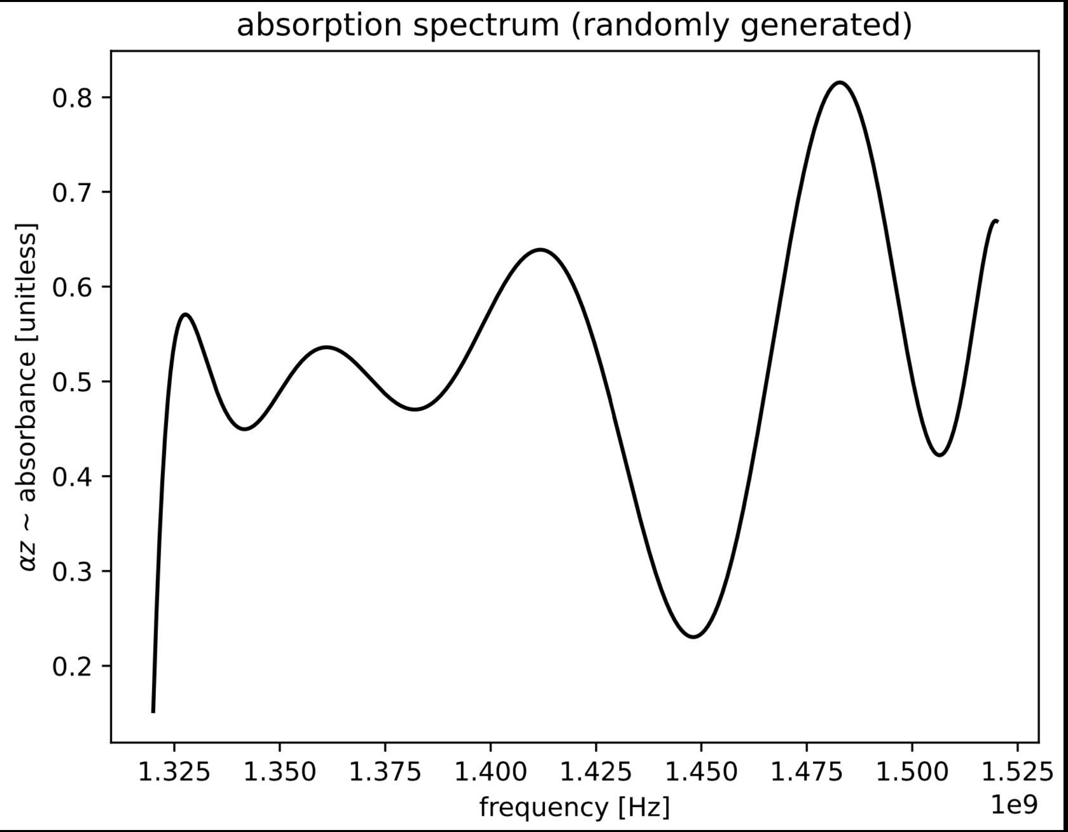
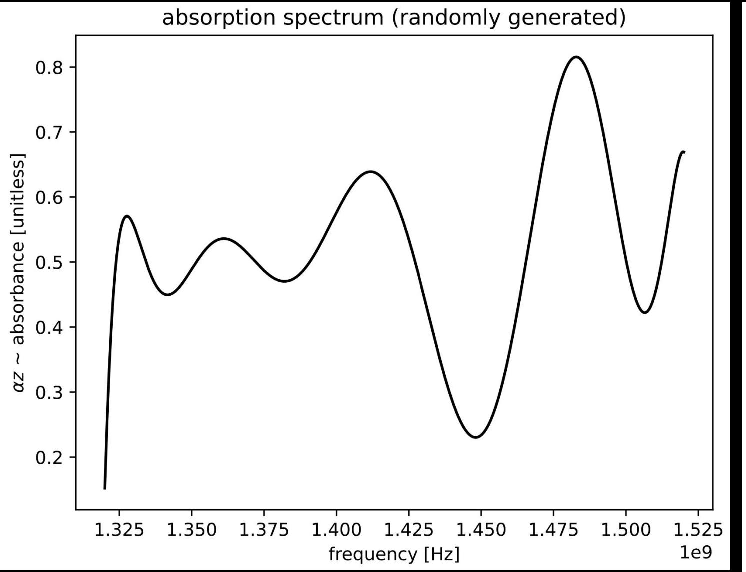
atmospheric absorption.

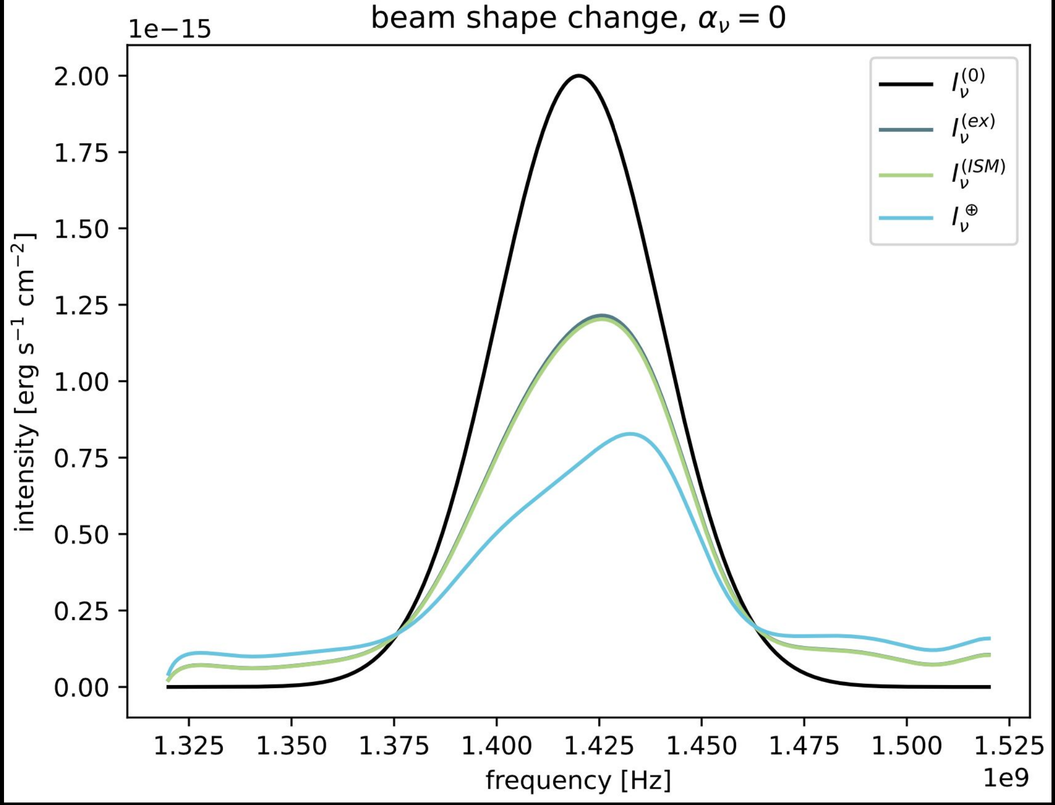
Suppose we invent a more interesting spectrum?



- 10th-order polynomial with pseudo-randomly generated coefficients
- Not intended to be especially realistic (just for illustration)

Suppose we invent a more interesting spectrum?

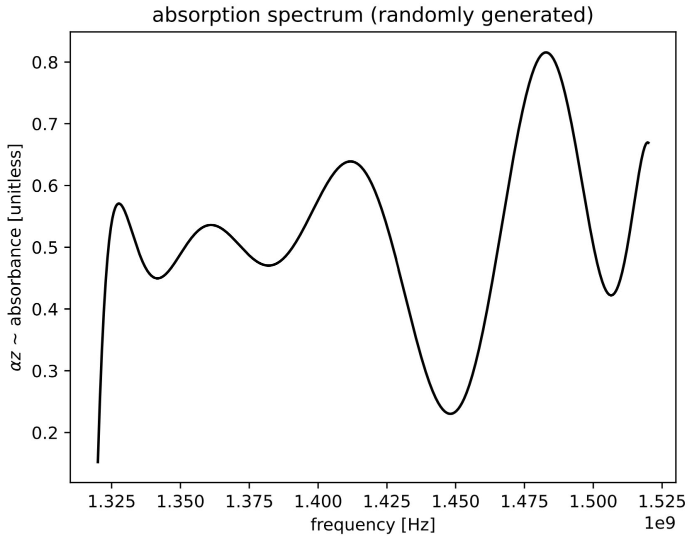


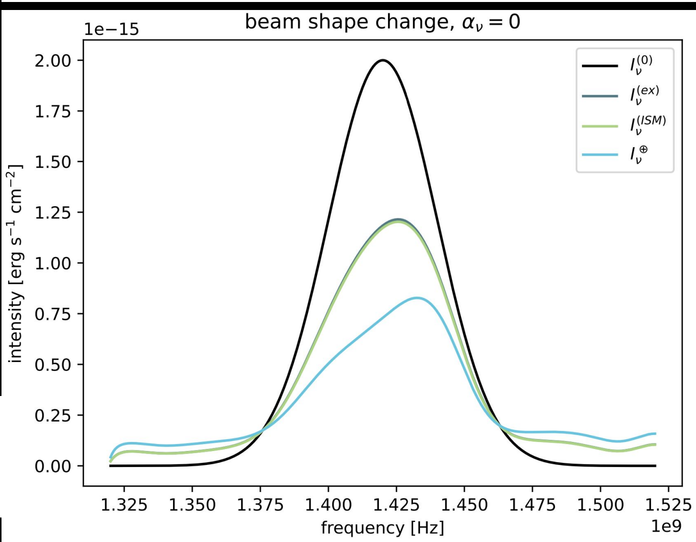


- More significant effects on beam shape!
- Notably, the ISM is still a very small effect compared to the atmosphere.

Takeaways

- This is the effect of atmospheric and ISM absorption/emission on the shape of a beam that propagates through them.
- Granted, there are a few caveats:
  - neglected scattering
  - assumed spatially invariant atmospheres + ISM
  - assumed exoplanet ≈ Earth
  - ISM source function? (relatively small contribution overall)
- Still a useful model for illustration, and many of these caveats can be mitigated by further calculations.





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