BREAKTHROUGH LISTEN

Expanding the Search for Life Beyond Earth

Steve Croft, UC Berkeley

with Andrew Siemion and colleagues
and support from the Breakthrough Prize Foundation

BERKELEY SETI RESEARCH CENTER


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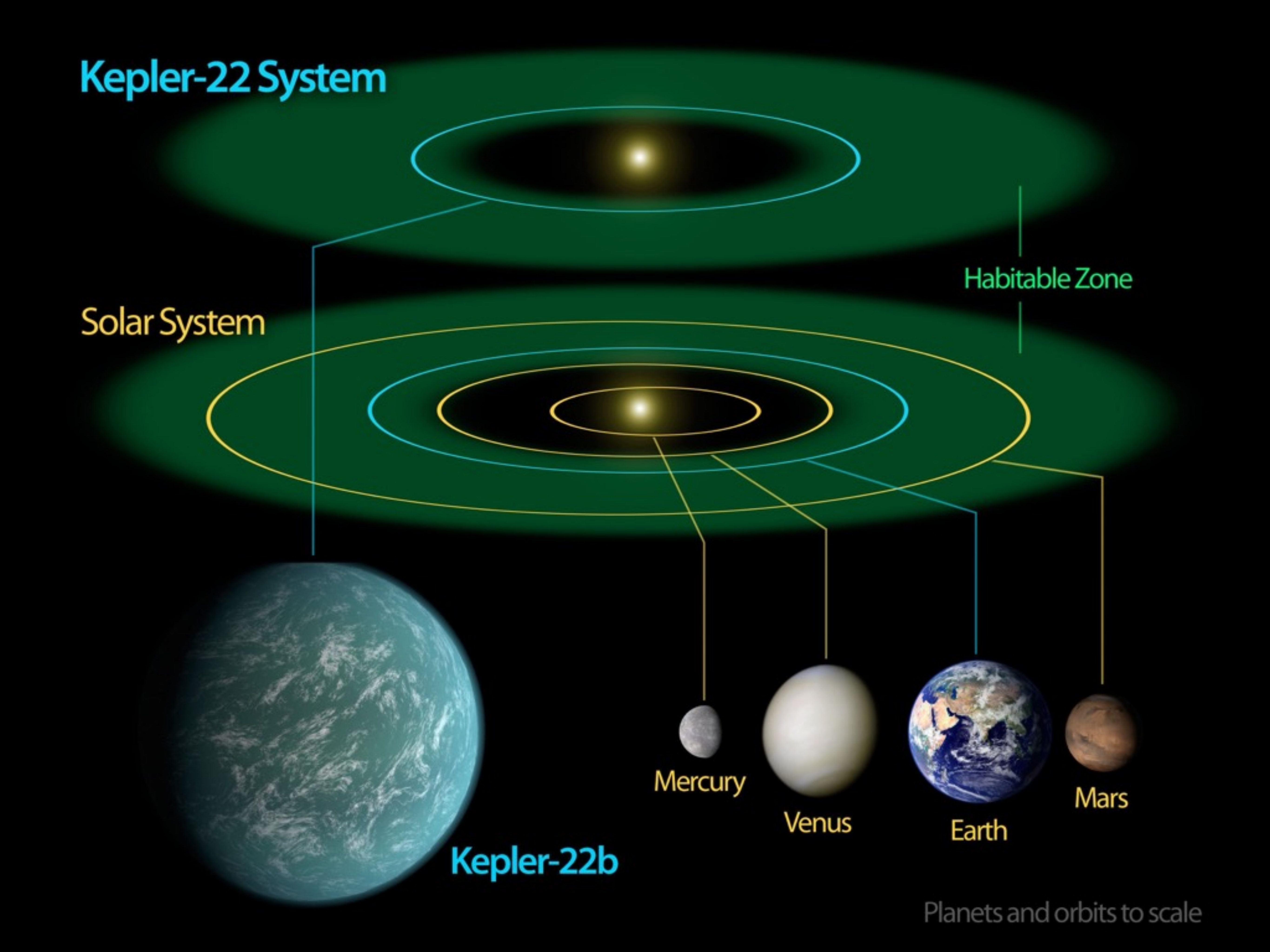
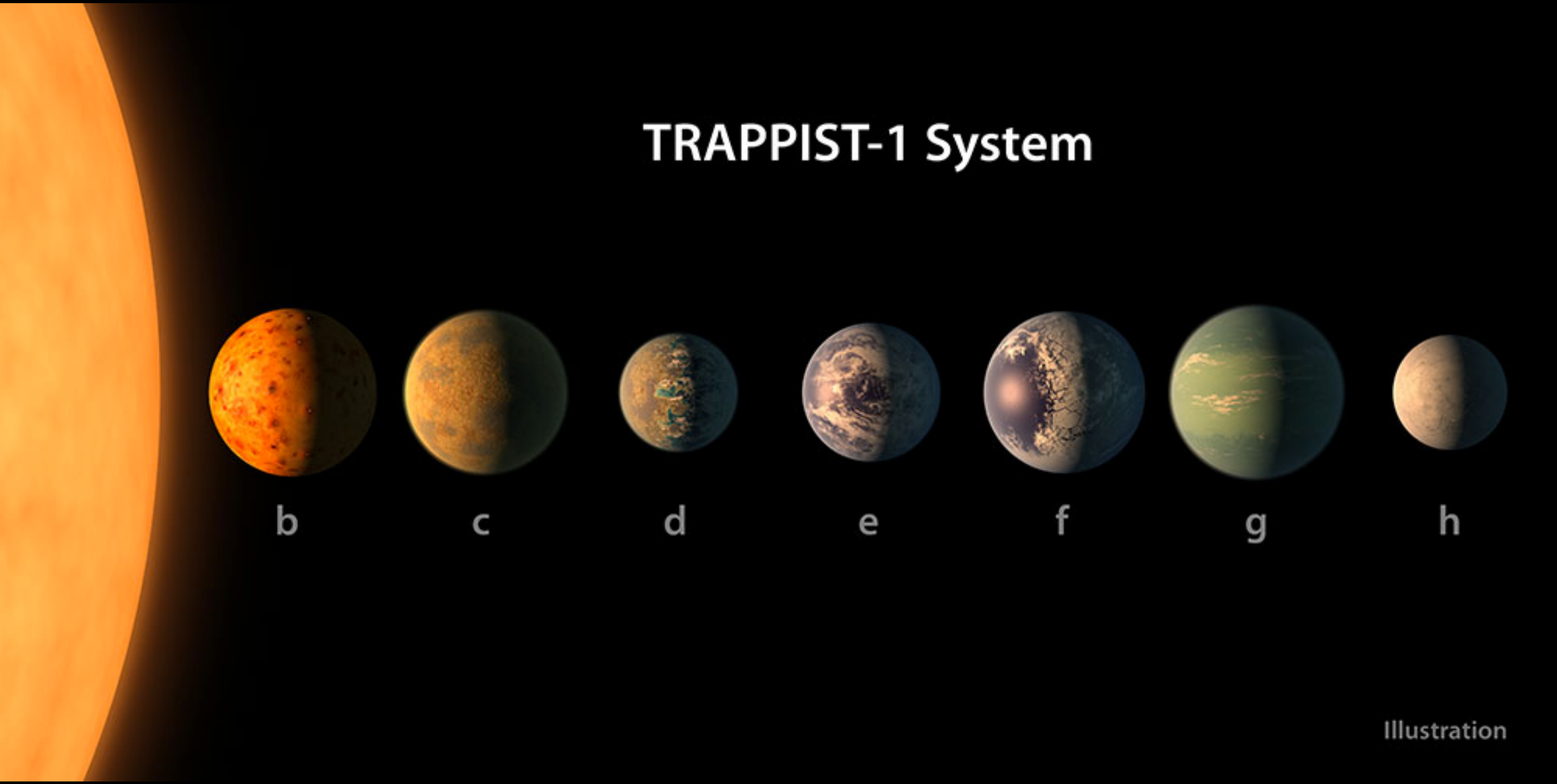
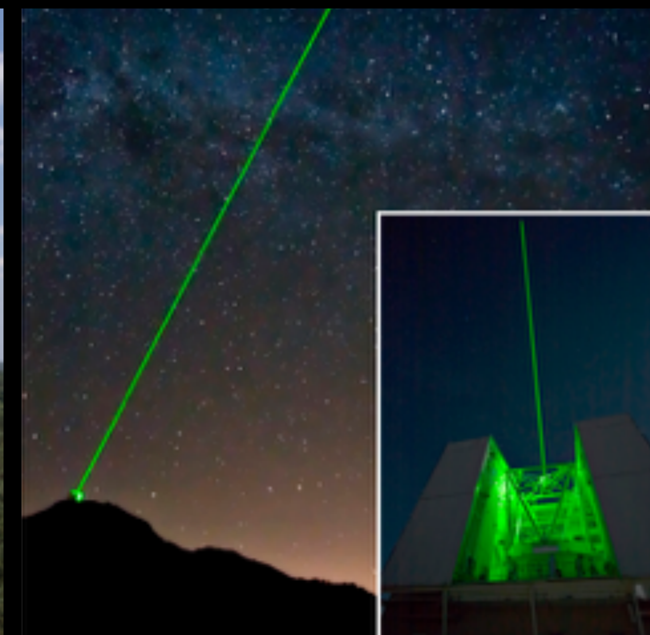
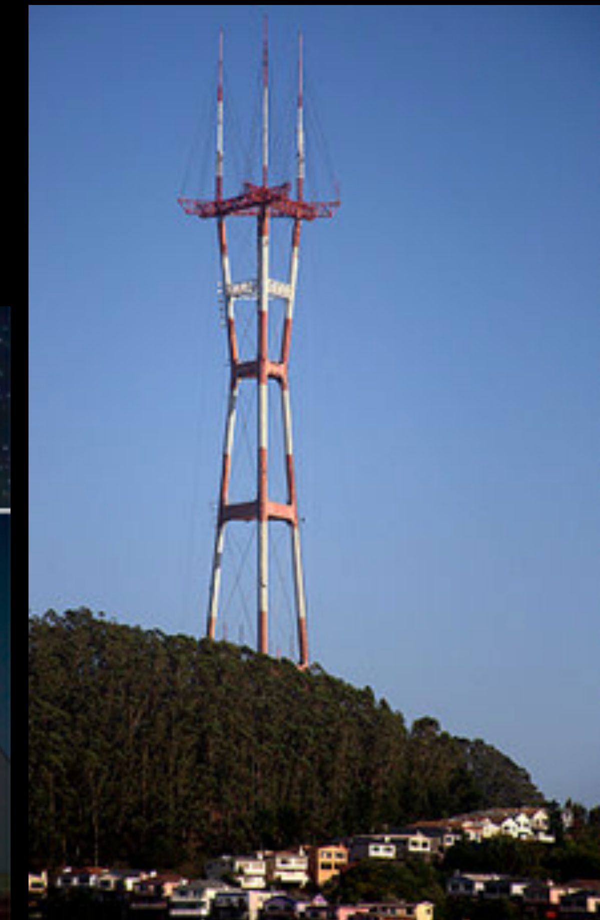
http://extrasolar.spaceart.org


Kepler-22 System
Habitable Zone
Solar System
Kepler-22b
Mercury
Venus
Earth
Mars
Planets and orbits to scale


TRAPPIST-1 System
b
c
d
e
f
g
h
Illustration

Technosignatures






© Laurie Hatch

Image: J. Sarkissian

BL Radio Infrastructure

- 6 GHz bandwith
- 4 PB storage
- 200 TFLOPS
- ~750 MB/sec/compute node
- Observing ~5 hours a day (20% time)
- ~120 TB/day since 1/1/16 - reduced to 0.5 TB / hr

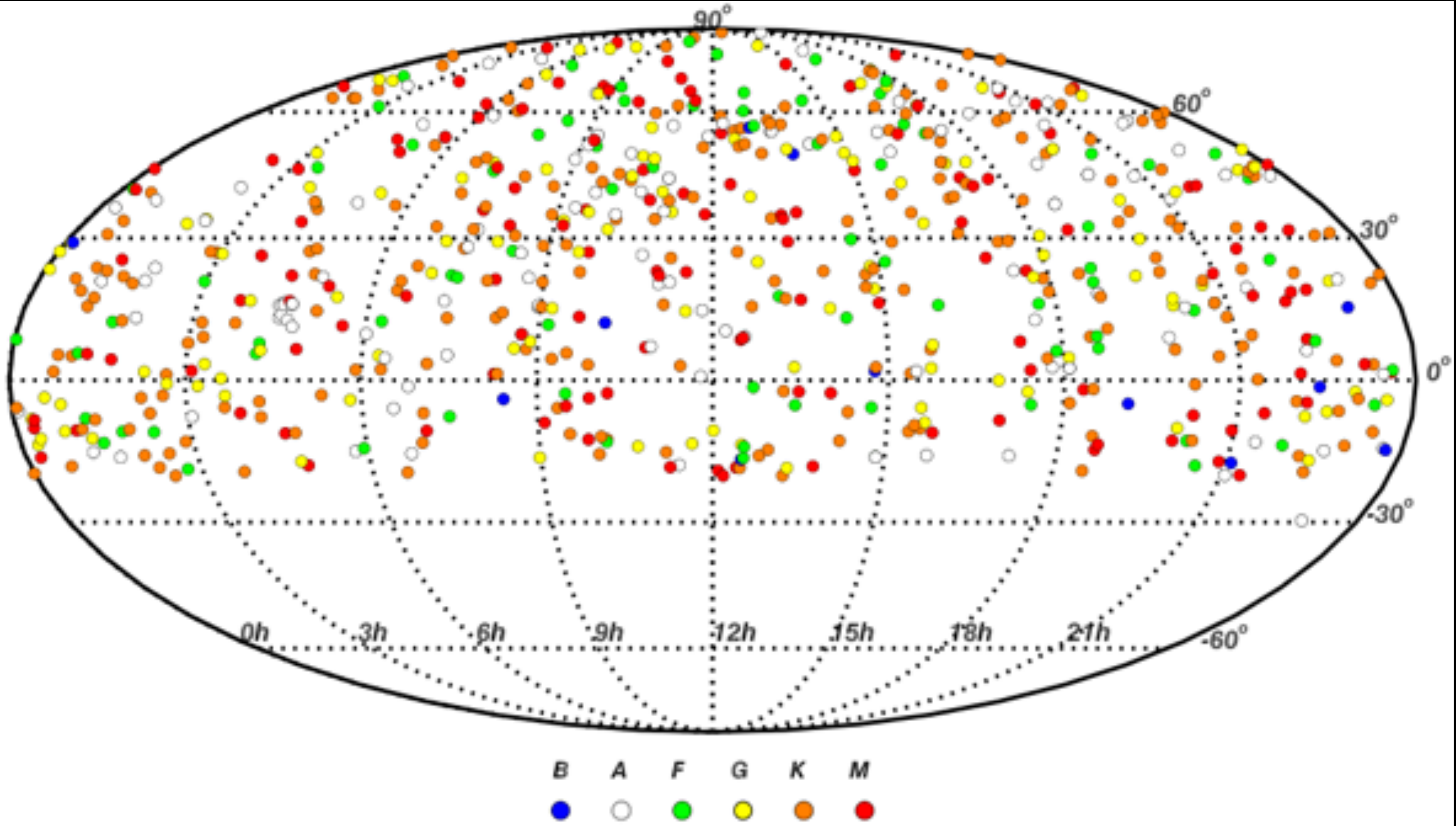
Available for up to 50 hours shared risk in 2018A

Green Bank Data Products

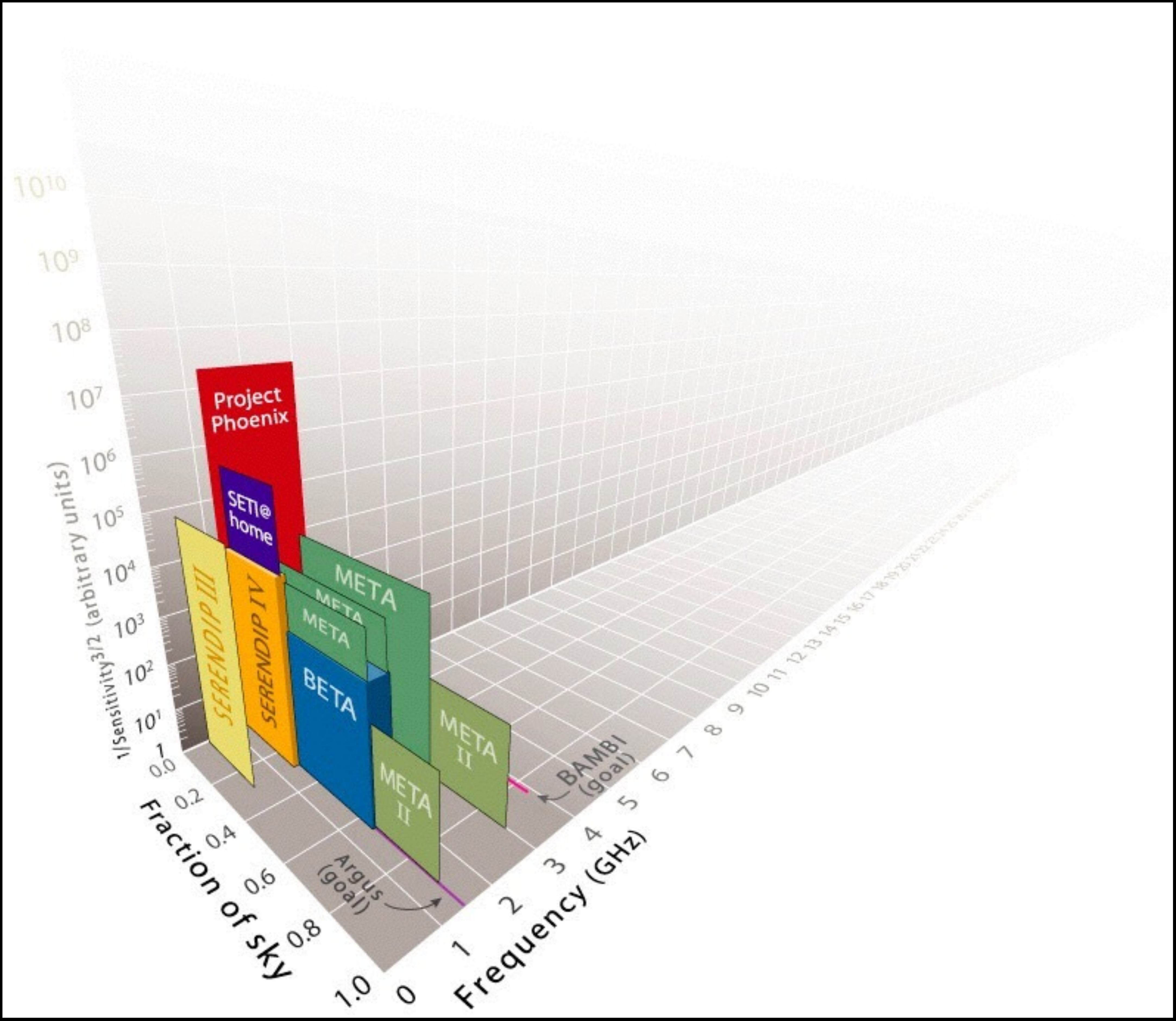
High freq. resolution	~3 Hz frequency bin resolution, ~18 second sample time (SETI)
Medium resolution	~3 kHz frequency bin resolution, ~1 second sample time
High time resolution	~366 kHz frequency bin resolution, ~349 us sample time (pulsar)

Nearby Star and Galaxy Sample

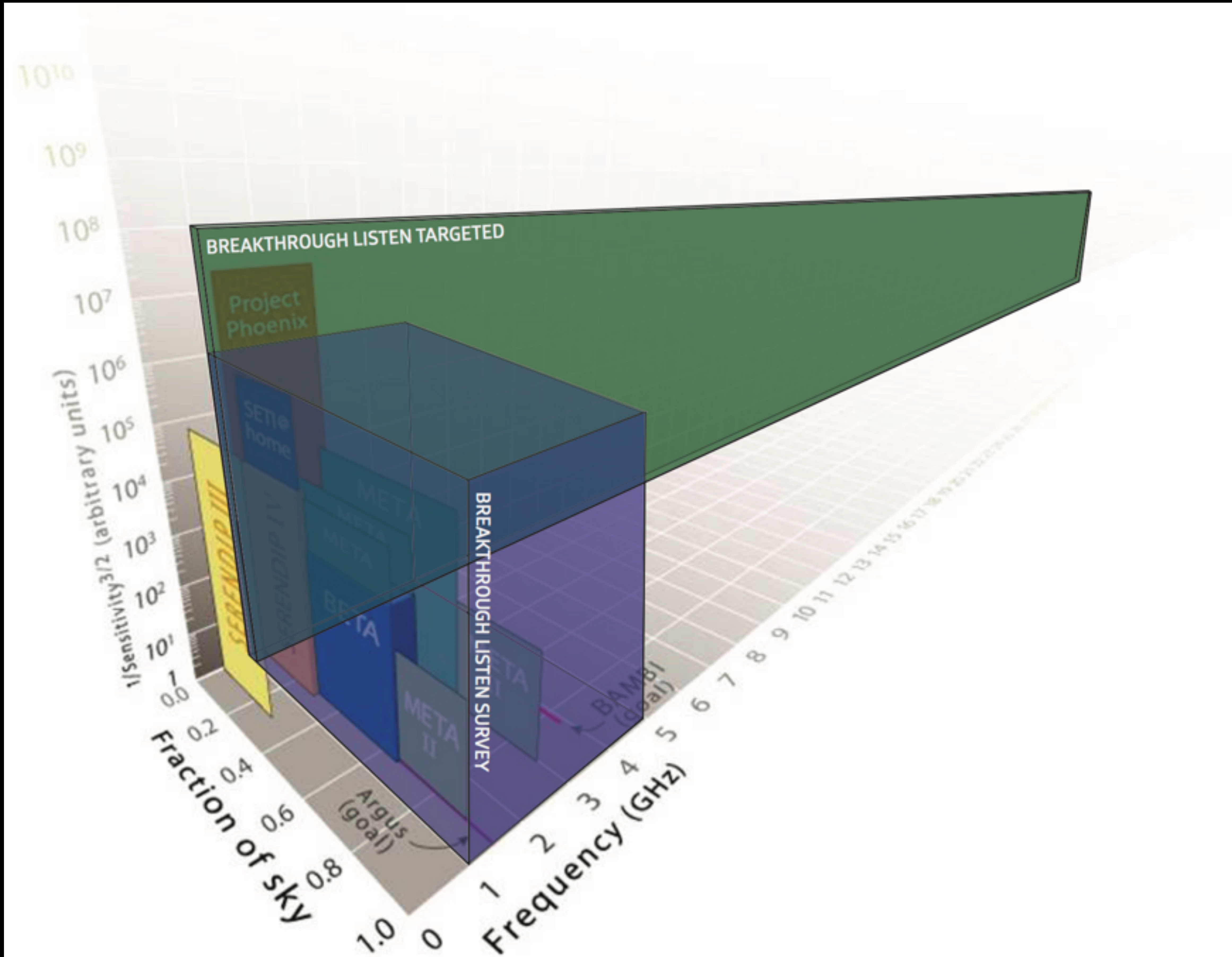
- 60 stars within 5 pc
- 1649 stars 5 - 50 pc sampling all spectral types
- 692 of these observed with GBT in L-band
- 123 nearby galaxies
- Also planning survey observations



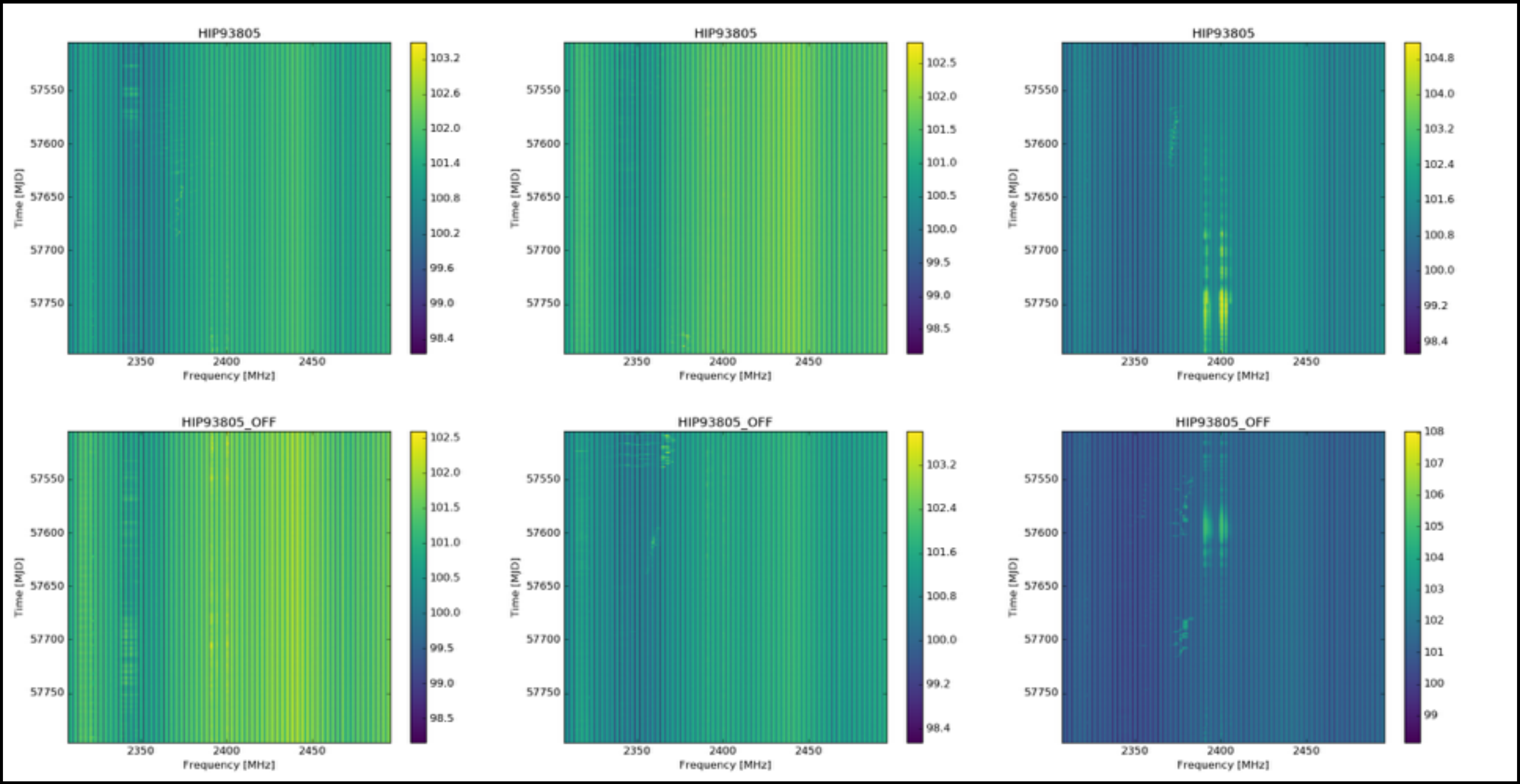
Isaacson et al. (2017)

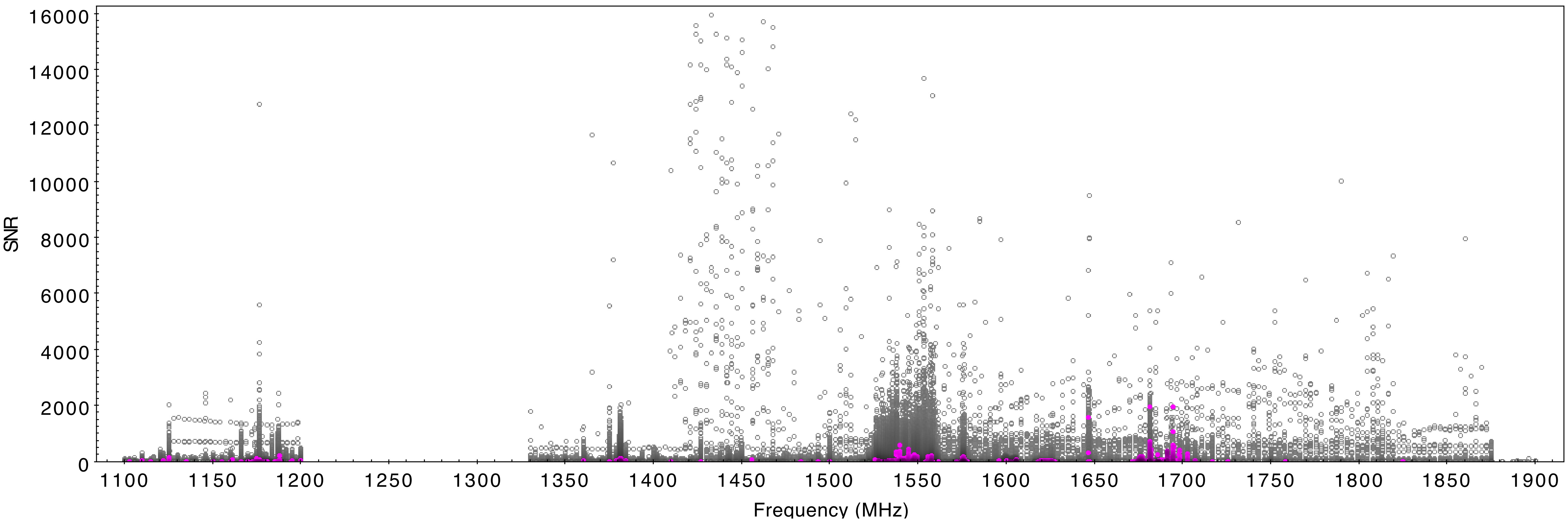


Project Phoenix
SETI@home
SERENDIP III
SERENDIP IV
META
META
META
BETA
META II
META II
BAMBI (goal)
Argus (goal)
1/Sensitivity3/2 (arbitrary units)
1
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
10¹⁰
Fraction of sky
0.0
0.2
0.4
0.6
0.8
1.0
Frequency (GHz)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17



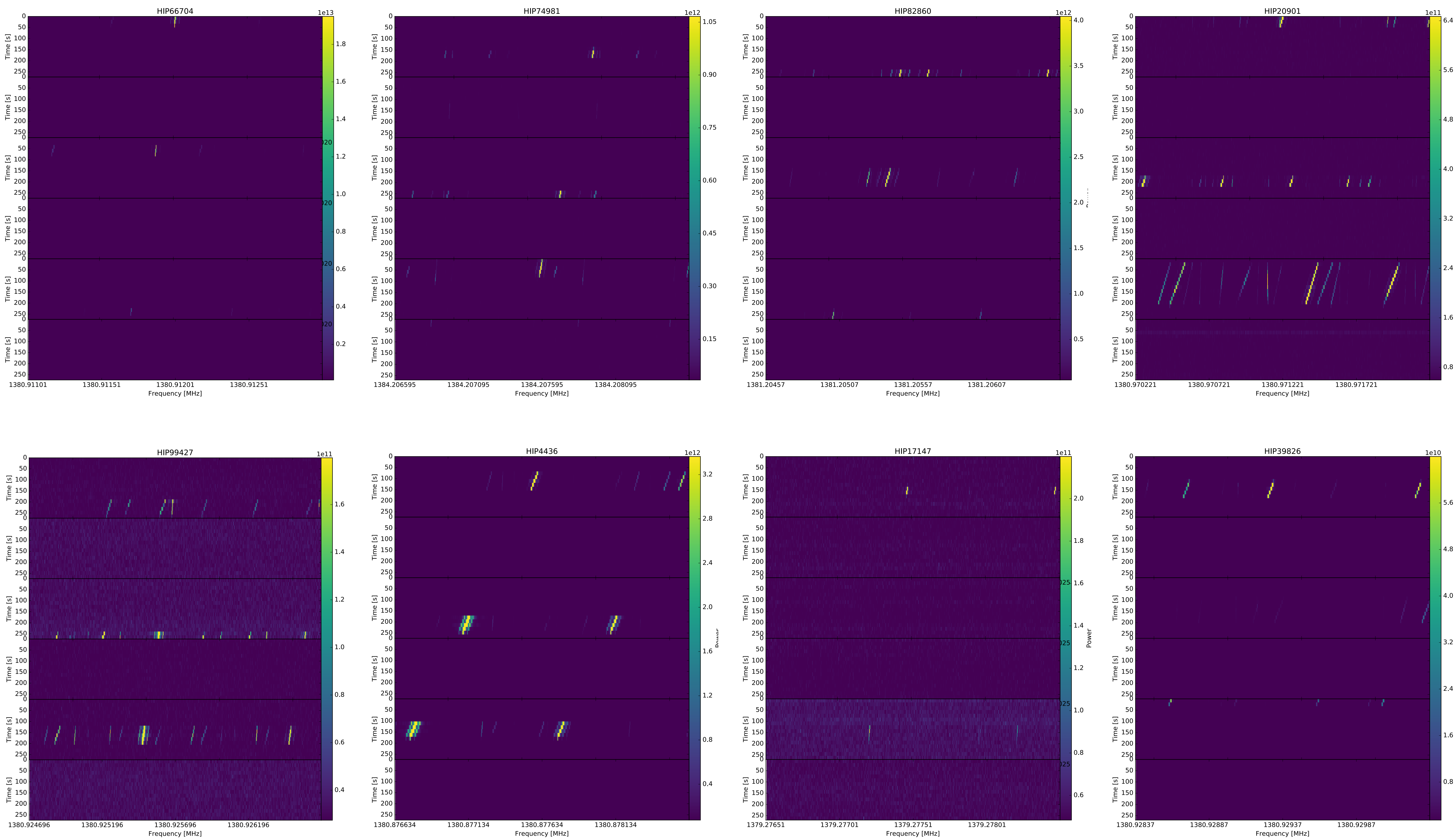
BREAKTHROUGH LISTEN TARGETED
BREAKTHROUGH LISTEN SURVEY
Project Phoenix
SETI@home
SERENDIP III
SERENDIP IV
META
META
META
BETA
META II
META II
BAMBI (goal)
Argus (goal)
1/Sensitivity3/2 (arbitrary units)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
Fraction of sky
0.0
0.2
0.4
0.6
0.8
1.0
Frequency (GHz)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


HIP93805
HIP93805
HIP93805
HIP93805_OFF
HIP93805_OFF
HIP93805_OFF
Time [MJD]
Frequency [MHz]
57550
57600
57650
57700
57750
2350
2400
2450



SNR
16000
14000
12000
10000
8000
6000
4000
2000
0
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
Frequency (MHz)

MULTIPLE HIT EVENTS - ENRIQUEZ ET AL. (2017)



PUBLIC DATA

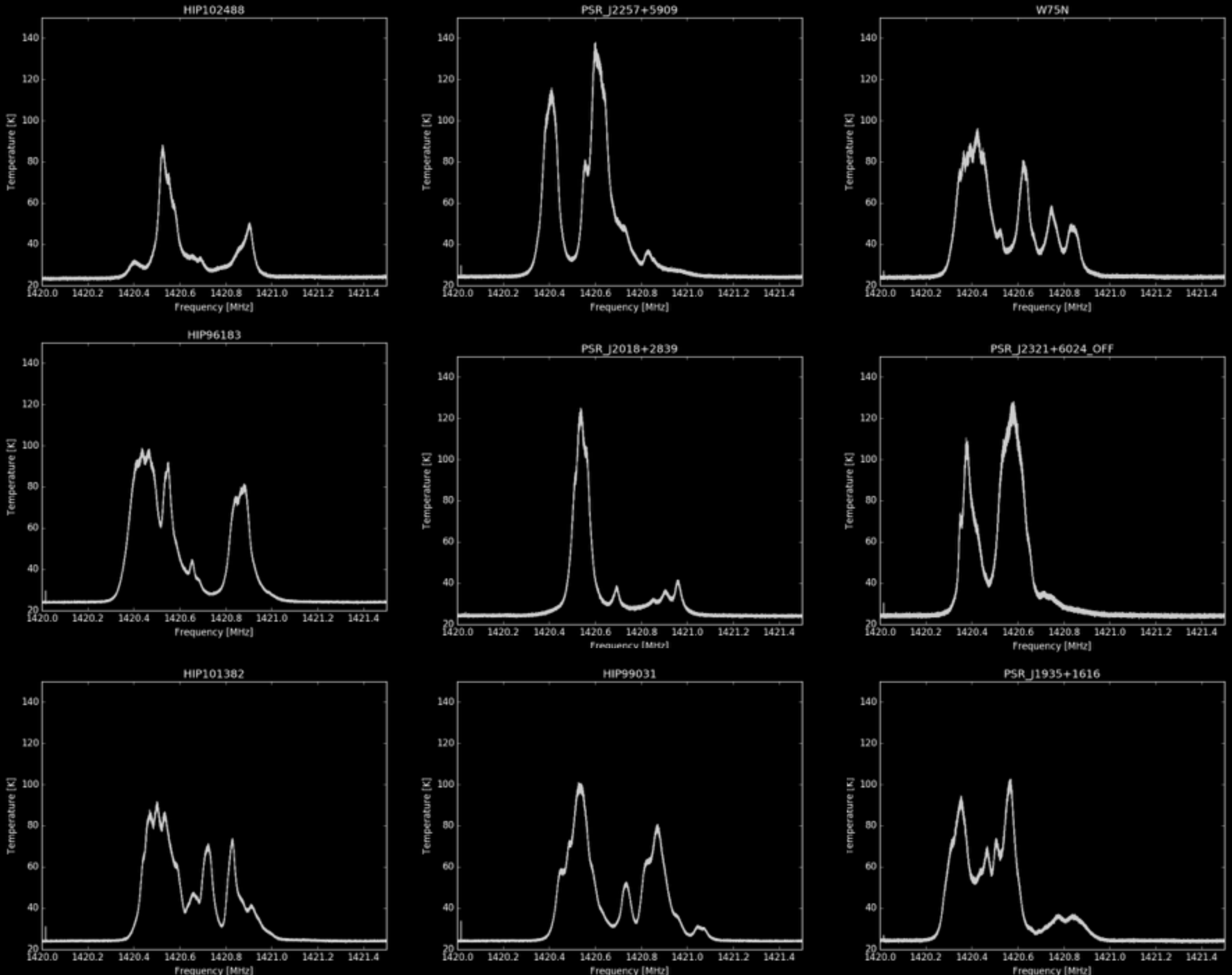
SEARCH FORM

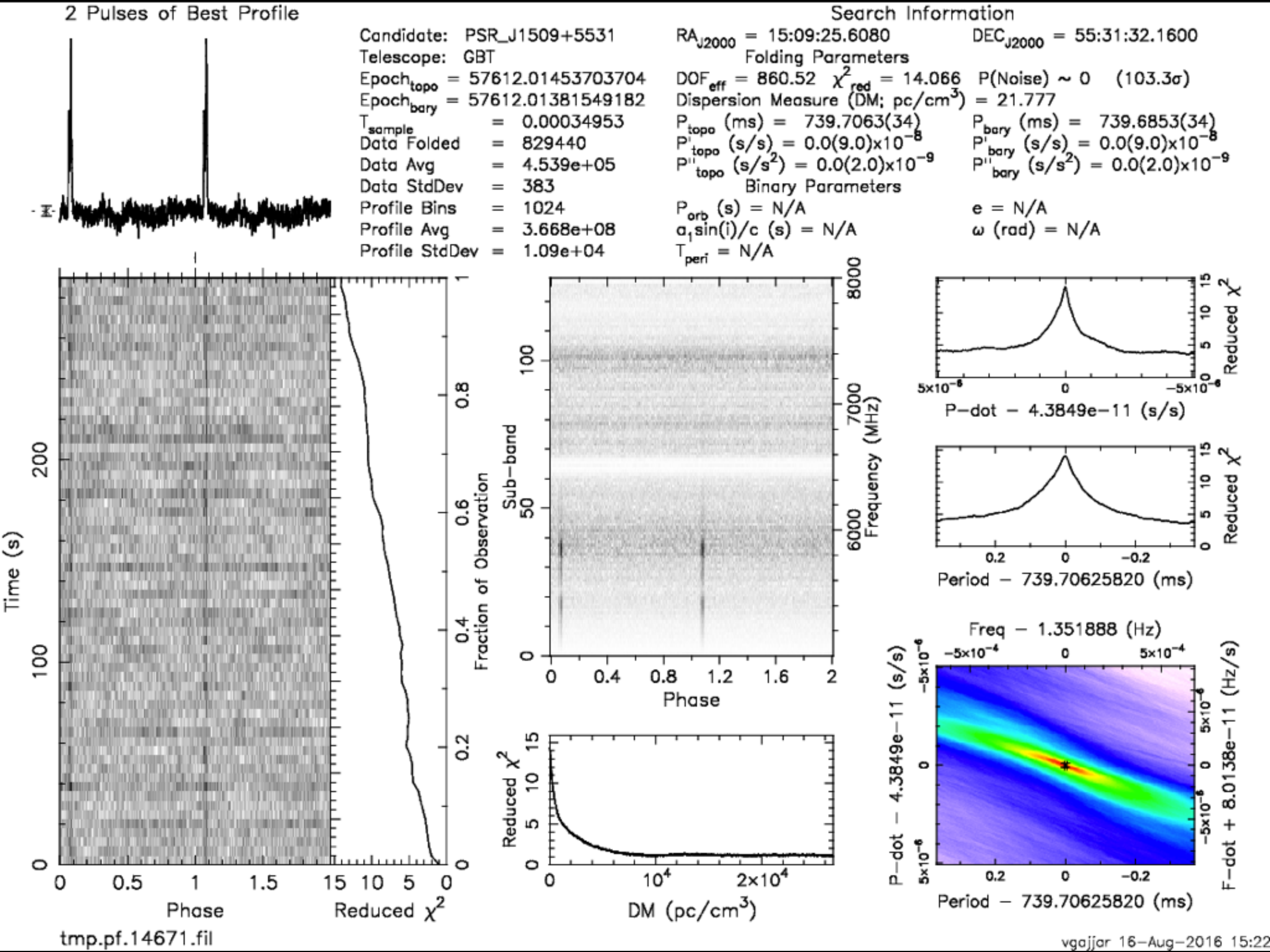
Project	All Projects
Sky coordinates:	
Right Ascension (in degrees)	
Declination (in degrees)	
Time (in MJD)	
Center Frequency (in MHz)	
Target Name	All Targets

SEARCH

RESULTS

UTC	MJD	Project	Target	RA	Decl	Center Freq	File Type	Size	Md5sum	Download
2016-08-28 05:36:07	57628.2334	GBT	HIP88194	270.3922	29.5819	10482.71	baseband data	671121920	9a72304a683c4595421ebdf691c15ae0	↓
2016-08-28 05:36:07	57628.2334	GBT	HIP88194	270.3922	29.5819	11045.21	baseband data	671121920	c834c3dc3106db7917d64fb37d9fe698	↓
2016-08-28 05:36:07	57628.2334	GBT	HIP88194	270.3922	29.5819	11420.21	baseband data	671121920	75d1c877f48612ec3e3ee8185cda2fc6	↓
2016-08-28 05:36:07	57628.2334	GBT	HIP88194	270.3922	29.5819	10295.21	baseband data	671121920	5525639bf051702f1792ff1cb78de0ec	↓
2016-08-28 05:36:07	57628.2334	GBT	HIP88194	270.3922	29.5819	11232.71	baseband data	671121920	770c0fb0577cd8dda4fae7d16b5eba34	↓
2016-08-28 05:36:07	57628.2334	GBT	HIP88194	270.3922	29.5819	11607.71	baseband data	671121920	b41b1812449f3f360ca54d5053fa5d11	↓
2016-08-28 05:36:07	57628.2334	GBT	HIP88194	270.3922	29.5819	10857.71	baseband data	671121920	9c6b5d15927869ac430120a956eac5d6	↓
2016-08-28 05:36:07	57628.2334	GBT	HIP88194	270.4111	29.5817	10670.21	baseband data	671121920	a5d5cf2e1673c4371a6fe5ecf30795b8	↓
2016-08-28 05:35:45	57628.2332	GBT	HIP88194	269.9512	29.5821	11420.21	baseband data	17180721152	4f7760b6a5fde1f1080e849b42d4d743	↓
2016-08-28 05:35:45	57628.2332	GBT	HIP88194	269.9512	29.5821	11607.71	baseband data	17180721152	896086bf9c06cb9dfe138411d49d371f	↓
2016-08-28 05:35:45	57628.2332	GBT	HIP88194	269.9703	29.582	10482.71	baseband data	17180721152	45deb50cf73f0e14f746b8a9b964afbf	↓


HIP102488
PSR_J2257+5909
W75N
HIP96183
PSR_J2018+2839
PSR_J2321+6024_OFF
HIP101382
HIP99031
PSR_J1935+1616
Temperature [K]
Frequency [MHz]
20
40
60
80
100
120
140
1420.0
1420.2
1420.4
1420.6
1420.8
1421.0
1421.2
1421.4


2 Pulses of Best Profile
Search Information
Candidate: PSR_J1509+5531
RA$_{J2000}$ = 15:09:25.6080
DEC$_{J2000}$ = 55:31:32.1600
Telescope: GBT
Folding Parameters
Epoch$_{topo}$ = 57612.01453703704
DOF$_{eff}$ = 860.52 χ^2_{red} = 14.066 P(Noise) ~ 0 (103.3σ)
Epoch$_{bary}$ = 57612.01381549182
Dispersion Measure (DM; pc/cm^3) = 21.777
T$_{sample}$ = 0.00034953
P$_{topo}$ (ms) = 739.7063(34)
P$_{bary}$ (ms) = 739.6853(34)
Data Folded = 829440
P'$_{topo}$ (s/s) = 0.0(9.0)x10^{-8}
P'$_{bary}$ (s/s) = 0.0(9.0)x10^{-8}
Data Avg = 4.539e+05
P''$_{topo}$ (s/s^2) = 0.0(2.0)x10^{-9}
P''$_{bary}$ (s/s^2) = 0.0(2.0)x10^{-9}
Data StdDev = 383
Binary Parameters
Profile Bins = 1024
P$_{orb}$ (s) = N/A
e = N/A
Profile Avg = 3.668e+08
a$_1$sin(i)/c (s) = N/A
ω (rad) = N/A
Profile StdDev = 1.09e+04
T$_{peri}$ = N/A
Time (s)
Phase
Reduced χ^2
Fraction of Observation
Sub-band
Frequency (MHz)
Phase
Reduced χ^2
DM (pc/cm^3)
P-dot − 4.3849e-11 (s/s)
Period − 739.70625820 (ms)
Freq − 1.351888 (Hz)
P-dot − 4.3849e-11 (s/s)
F-dot + 8.0138e-11 (Hz/s)
Period − 739.70625820 (ms)
tmp.pf.14671.fil
vgajjar 16-Aug-2016 15:22

README.md

How to find ET

This README is intended as an introduction to anyone with experience programming in Python who is interested in delving deeper into analysis of data from the Green Bank Telescope. It assumes little or no knowledge of radio astronomy or of techniques used in the search for extraterrestrial intelligence. Intended audiences include those who may be interested in running machine learning or other sophisticated analyses on Breakthrough Listen data.

First, if you haven't already read the five-page introduction on our webpage, please visit seti.berkeley.edu/listen (you can gloss over the parts about optical SETI and the Automated Planet Finder on page 3, and on the second halves of pages 4 and 5). We're going to concentrate on radio searches here, specifically those that we're doing with the 100-meter diameter Green Bank Telescope (GBT) in West Virginia - the largest fully-steerable radio telescope on the planet. When you're comfortable with the material on seti.berkeley.edu, come back here and we'll get into more of the details.

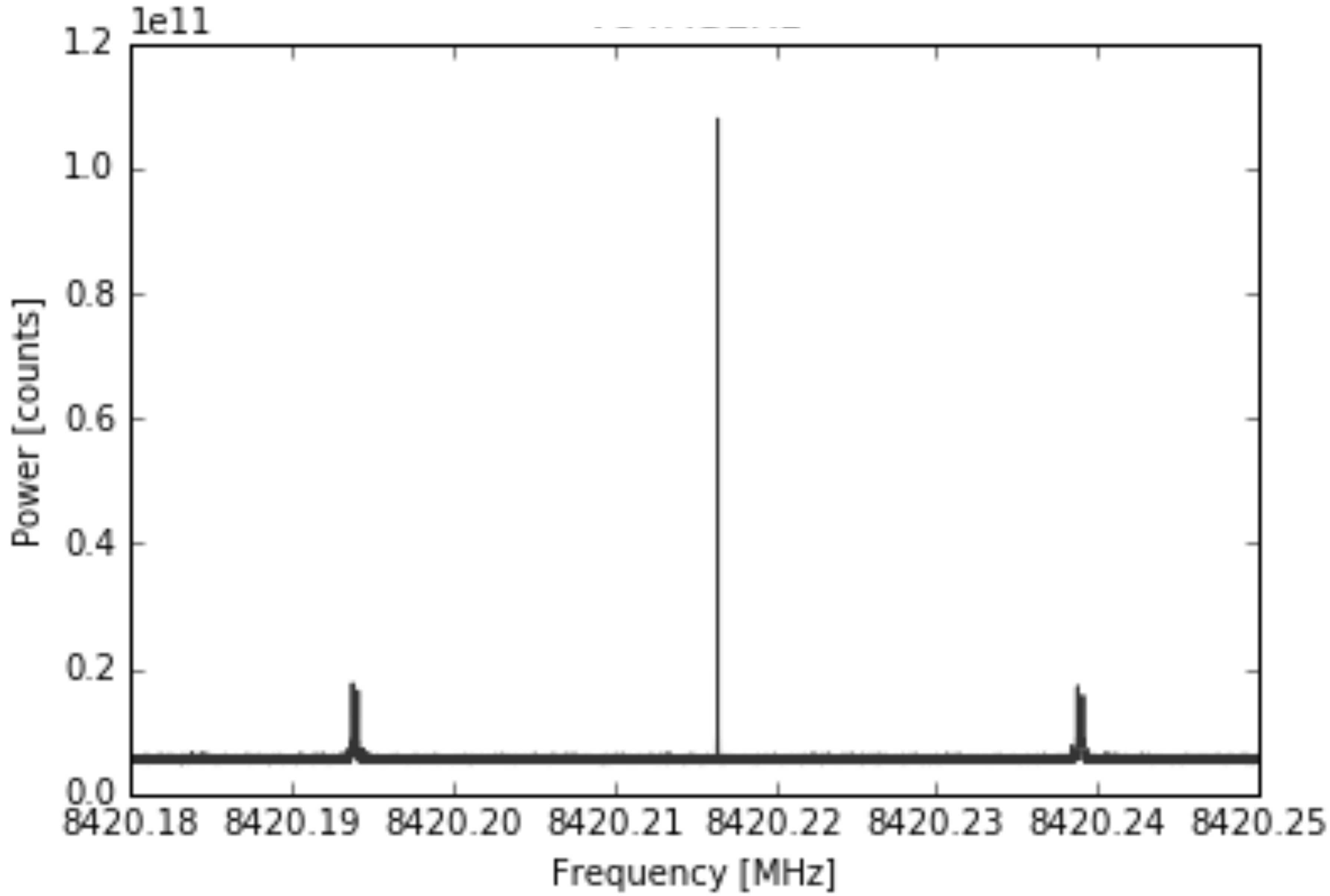
As noted in the introductory materials, the basics of searching for signatures of extraterrestrial technology are actually quite simple, but the confounding factors are:

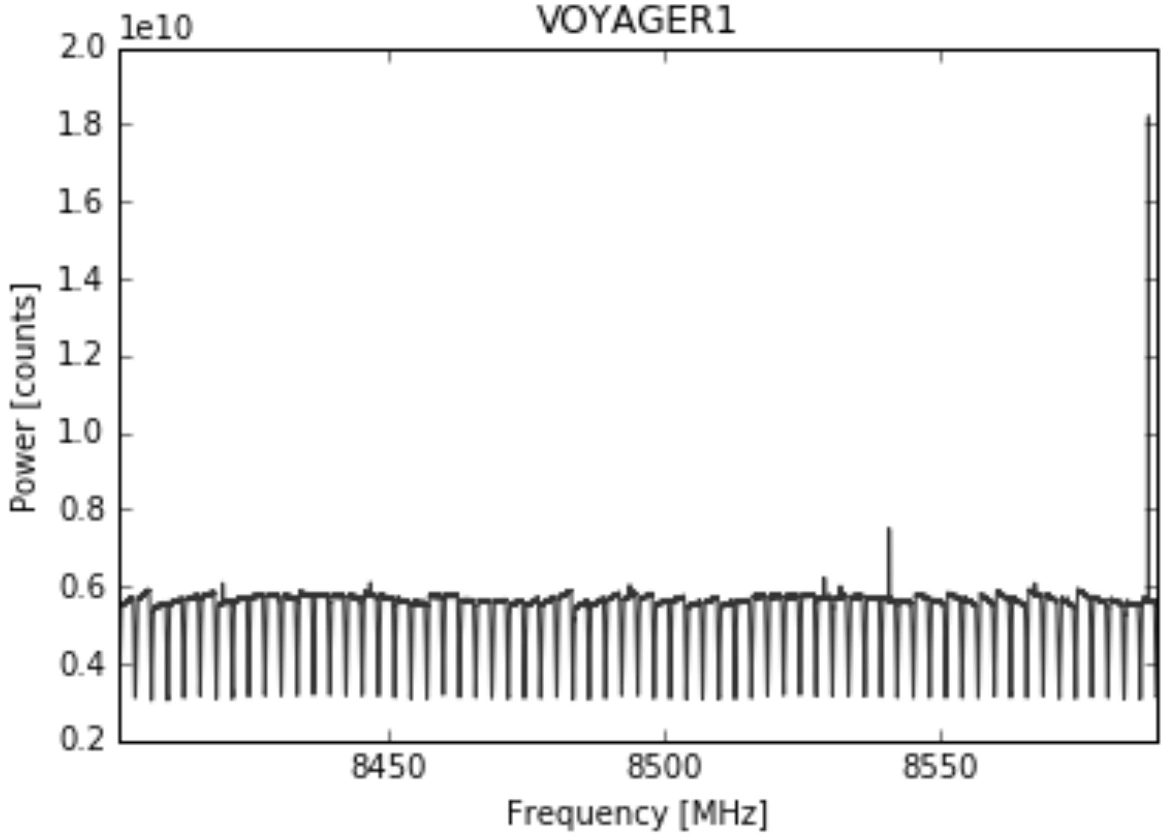
1. Human technology gives off signals like the ones we are looking for (radio frequency interference)
2. Data volumes are too large to run brute force analysis on the whole dataset

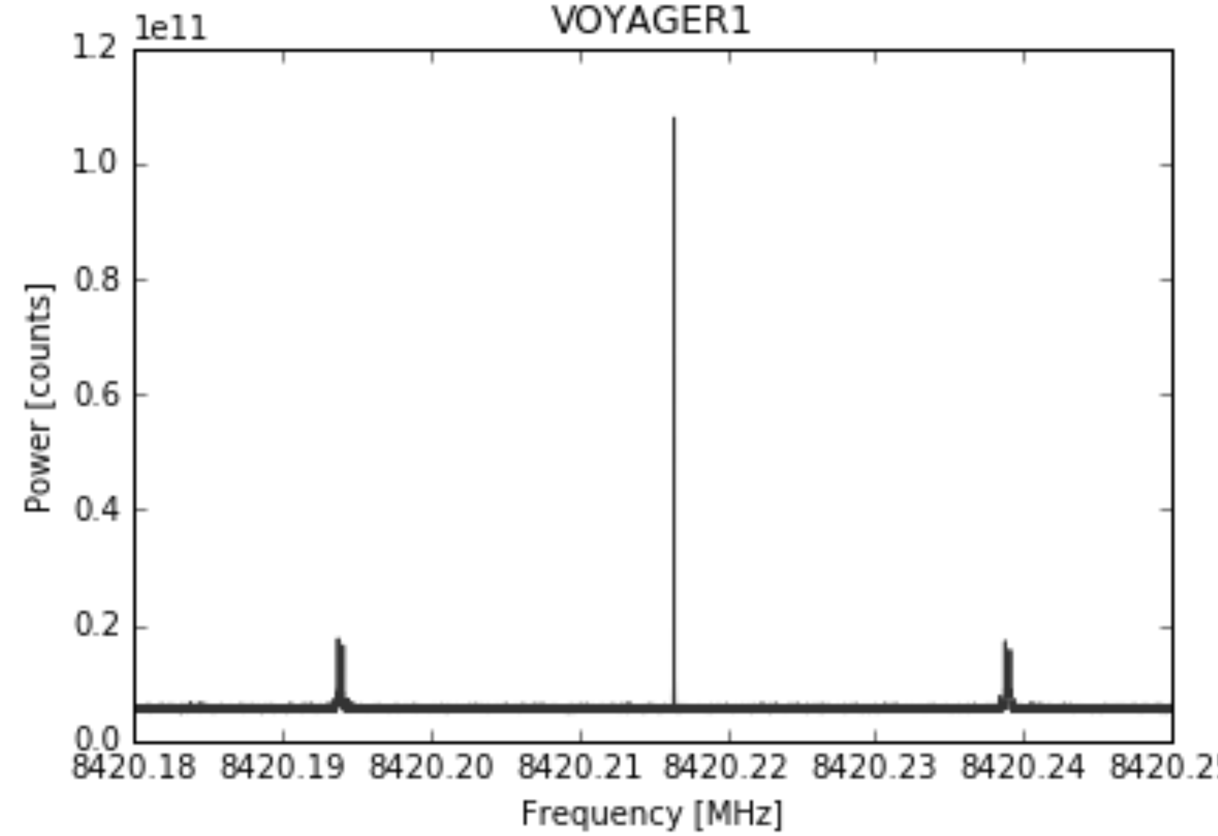
Here's how we deal with these problems:

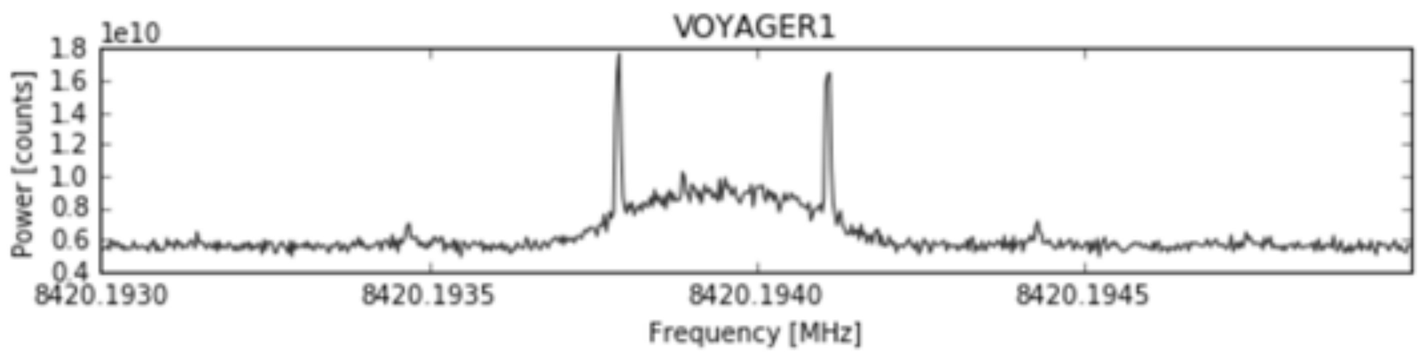
Radio Frequency Interference

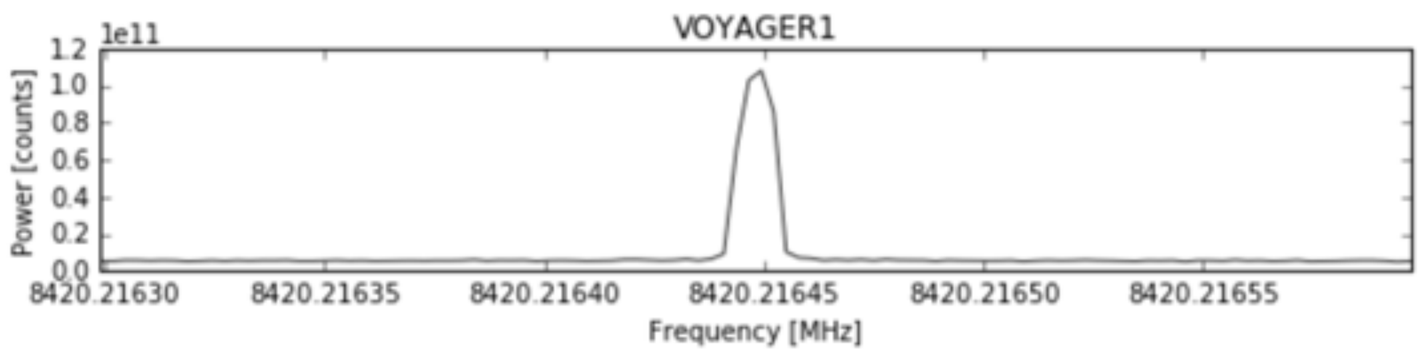
RFI is emitted by our own transmitters - not just radio stations, but wifi routers, cellphones, and even electronics that are not deliberately designed to transmit radio signals. So searching for extra-terrestrial intelligence (ETI) signals is very much a needle in a haystack problem. There are three main methods that we can use to weed out signals of interest.

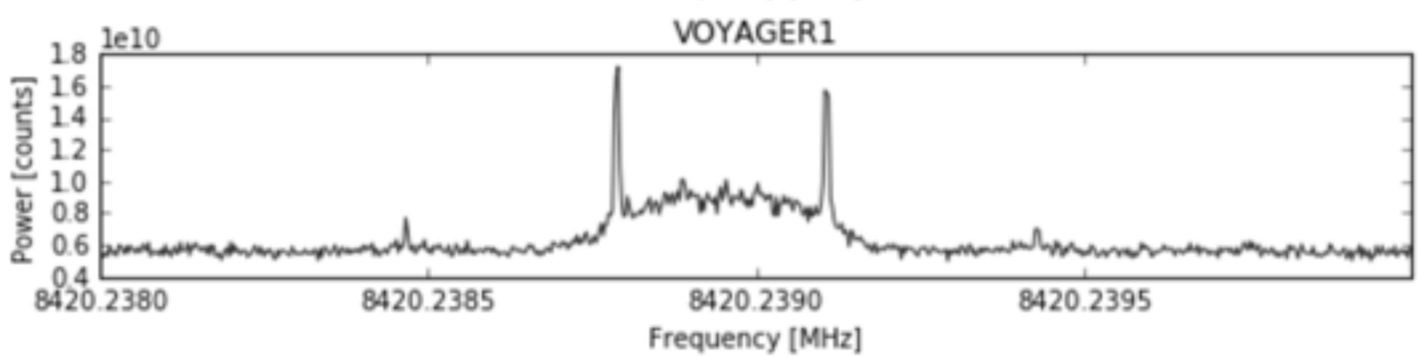

1e11
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Power [counts]
8420.18
8420.19
8420.20
8420.21
8420.22
8420.23
8420.24
8420.25
Frequency [MHz]











http://bit.do/BL_voyager

Breakthrough Listen: Voyager 1 Observations

Voyager 1 is the most distant man-made object from Earth. Launched by NASA in 1977, it has travelled at fantastic speed (roughly 17,000 m/s), past the outer boundaries of our Solar System and into interstellar space (>12.5 billion miles from the Sun).

Remarkably, 38 years on, Voyager 1 is still sending telemetry data from the depths of interstellar space. This makes it a great systems test for the Breakthrough Listen signal processing pipeline.

In this tutorial, we load, read, and plot some Breakthrough Listen (BL) observations of Voyager 1. The data were taken using the Robert C. Byrd Greenbank Telescope in West Virginia.

About this tutorial

This tutorial introduces you to BL filterbank data. It is intended for intermediate to advanced users, who have experience with Python, Numpy and basic astronomy. You'll need to have Jupyter installed, along with a scientific Python installation (numpy, scipy, matplotlib, and astropy).

About the data

We used the Greenbank X-band receiver (8.0-11.6 GHz) on December 30, 2015, to observe the known position of Voyager 1. The BL digital signal processing system saves digitized data in a 'raw' format, which we have converted into 'filterbank' format using our `gpuspec` code (see guppi2spectra.c in https://github.com/UCBerkeleySETI/gbt_seti/tree/master/src). For *advanced users* who want to start from scratch, the specific command is:

```
time /gbt_seti/bin/gpuspec -i ./blc3_2bit_guppi_57386_VOYAGER1_0004.0000.raw \
    -B 2 -f 1032192 -t 15 -V -o /datax2/scratch/dprice/
```

For the purposes of this tutorial, we suggest that you download the 504 MB file `voyager_f1032192_t300_v2.fil` from the BL data archive.

Filterbank format

The voyager data is stored in *filterbank format*, a simple binary file format that is detailed in the SIGPROC user guide. For this tutorial, we've provided a simple Python class to load and interpret the filterbank file into a numpy array.

Let's get started!

Firstly, let's setup the notebook and import the `Filterbank()` class to read the data.

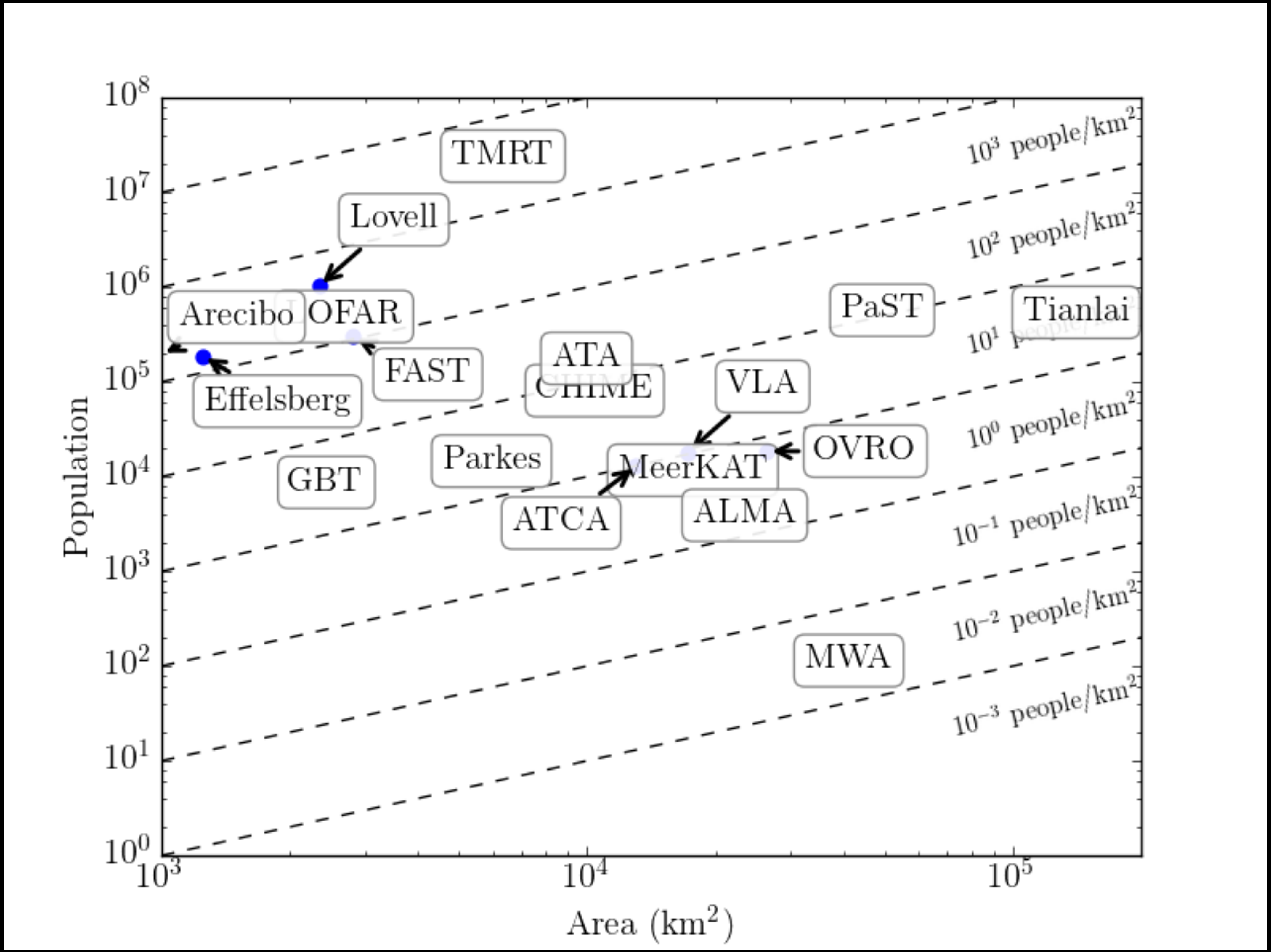
In [1]:
```
%matplotlib inline
```

In [3]:
```
import pylab as plt
from filterbank import Filterbank
```

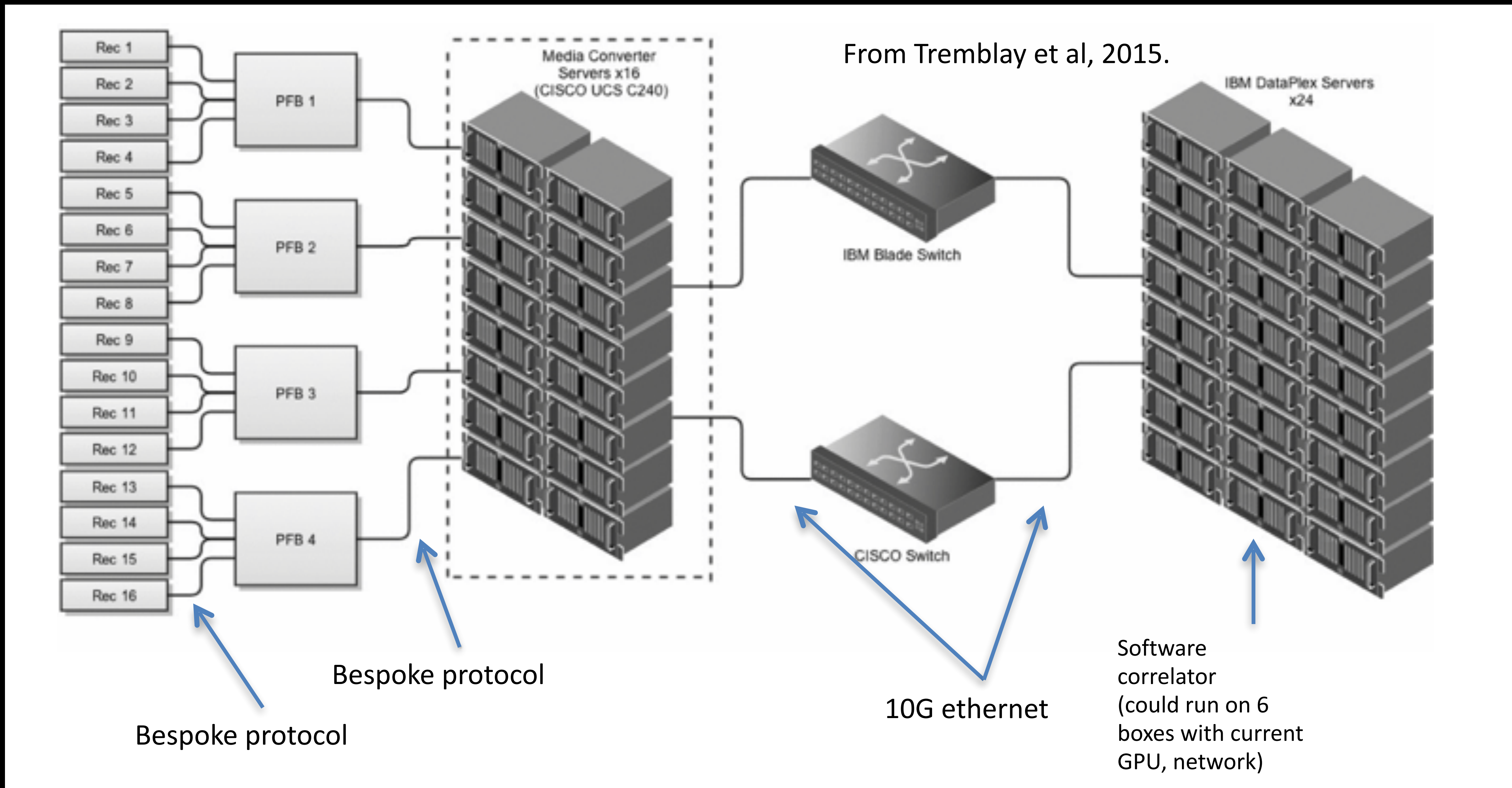
Now, let's read the observation data using `Filterbank()`:

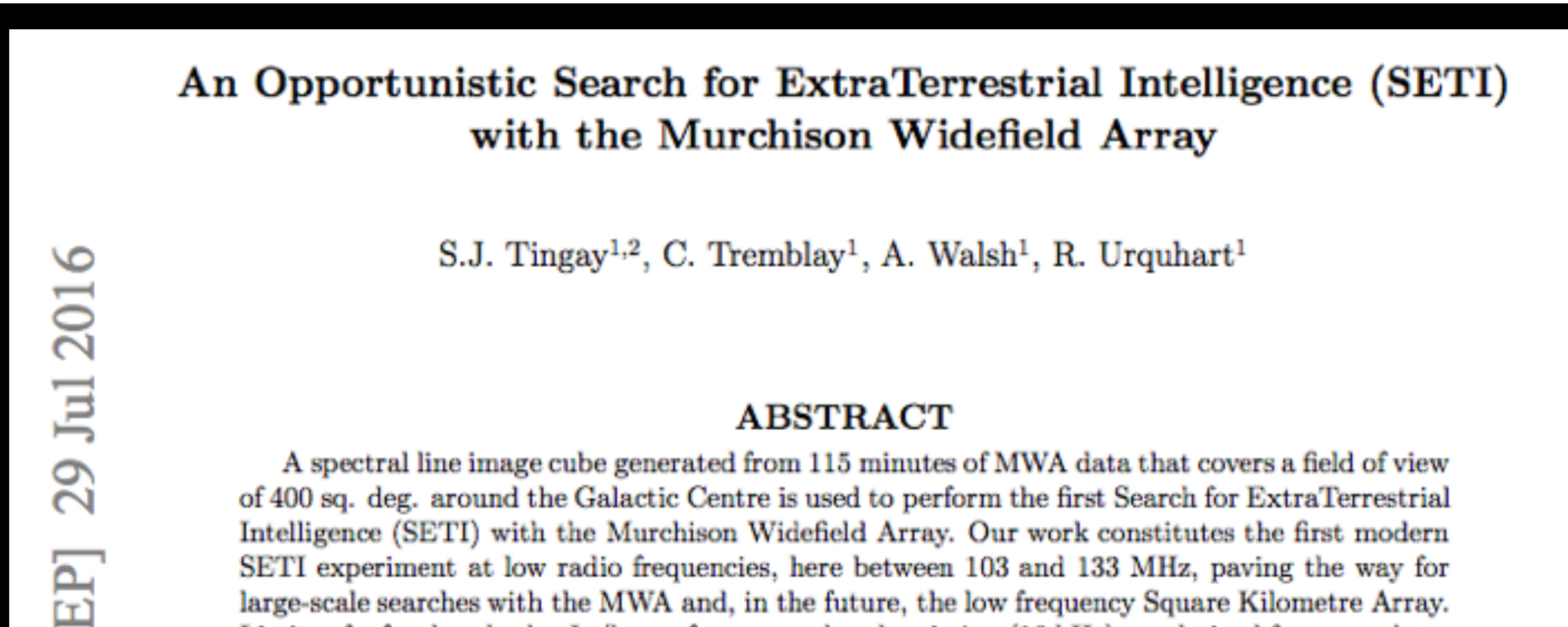
MeerKAT - South Africa
64 15m dishes

MWA - Australia
2048 dipole antennas


TMRT
Lovell
Arecibo
OFAR
FAST
Effelsberg
ATA
CHIME
PaST
Tianlai
VLA
OVRO
MeerKAT
Parkes
GBT
ATCA
ALMA
MWA
10^3 people/km^2
10^2 people/km^2
10^1 people/km^2
10^0 people/km^2
10^{-1} people/km^2
10^{-2} people/km^2
10^{-3} people/km^2
Population
Area (km^2)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^3
10^4
10^5

D. Kaplan





An Opportunistic Search for ExtraTerrestrial Intelligence (SETI) with the Murchison Widefield Array

S.J. Tingay[1,2], C. Tremblay[1], A. Walsh[1], R. Urquhart[1]

EP] 29 Jul 2016

ABSTRACT

A spectral line image cube generated from 115 minutes of MWA data that covers a field of view of 400 sq. deg. around the Galactic Centre is used to perform the first Search for ExtraTerrestrial Intelligence (SETI) with the Murchison Widefield Array. Our work constitutes the first modern SETI experiment at low radio frequencies, here between 103 and 133 MHz, paving the way for large-scale searches with the MWA and, in the future, the low frequency Square Kilometre Array. Limits of a few hundred mJy/beam for narrow band emission (10 kHz) are derived from our data

Pilot MWA Program

- 100 Gbit / s link between MRO and Curtin
- Total data rate is 80 Gbit / s (5 + 5 bit), corresponding to 130 Gbit / s in 8 + 8 bit, dual pol, from 128 tiles
- Aim to deploy 4 GPU compute chassis (each 4U), each with 24 x 5 TB hard drives, and a 1080 GPU
- Each chassis will handle 2 x 1.28 MHz from the switch (for a total ~10 MHz of bandwidth in this initial system)

Observing Modes

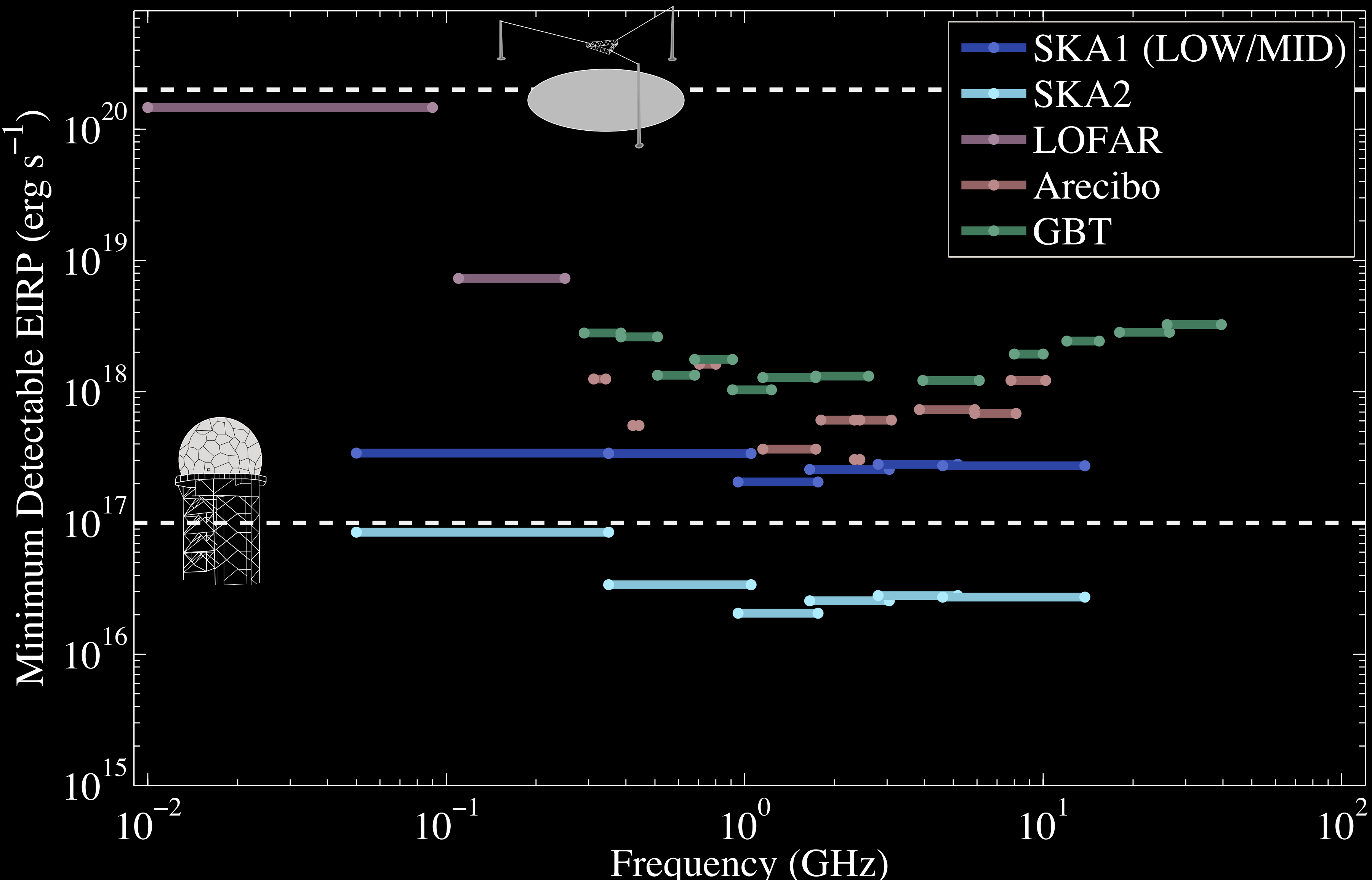
- Tied-array targeted observations of stars, commensally within the MWA primary beam
- High-resolution spectroscopy and thresholding over the whole primary beam, with incoherent summing of subsets of 32 tiles for interference rejection.
- Fly's-eye observations (subarrays pointed in different directions to tile the entire sky with reduced sensitivity)

Commensal and / or complementary to fast transients, flare stars, VCS, pulsars, spectroscopy.

SKA
SQUARE KILOMETRE ARRAY

For an Extraterrestrial Transmitter @ 50 ly

($t_{integration}$ = 10 min, SNR = 15)



TARGETED SETI WITH SKA

Most thorough targeted SETI search previously conducted: Project Phoenix: 1000 stars over 1-3 GHz to a luminosity limit of ~ 2 x 10^{19} ergs/sec.

SKA1: In a five year commensal campaign, could survey e*very star* within 100pc to a luminosity limit an order of magnitude fainter, ~ 2 x 10^{18} ergs/sec over a larger band.

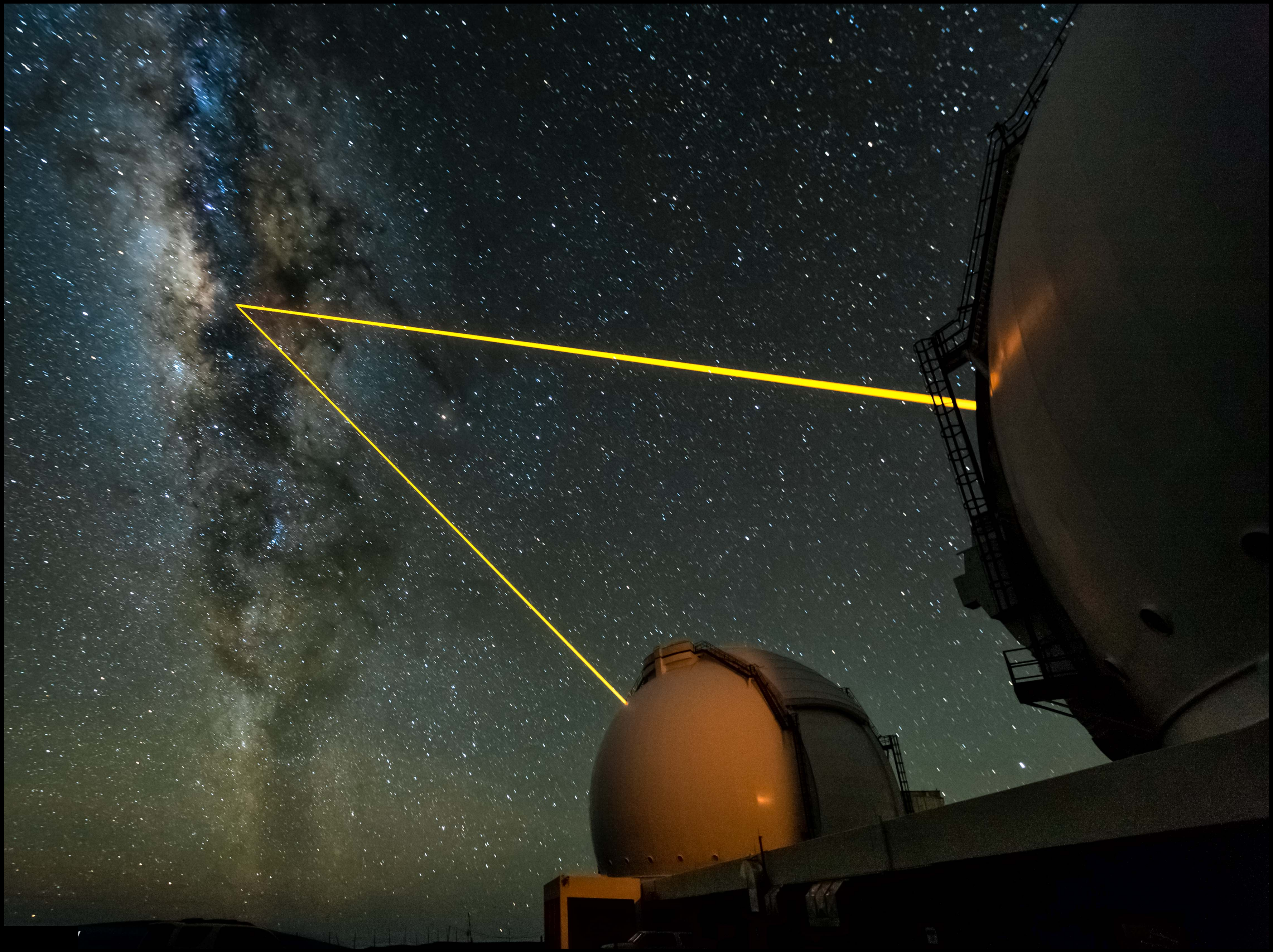
SKA2: In ten years (conservatively) could survey every star within 100pc to a luminosity limit equal to the EIRP of terrestrial aircraft radars (10^{17} ergs/sec) over the entire terrestrial microwave window.

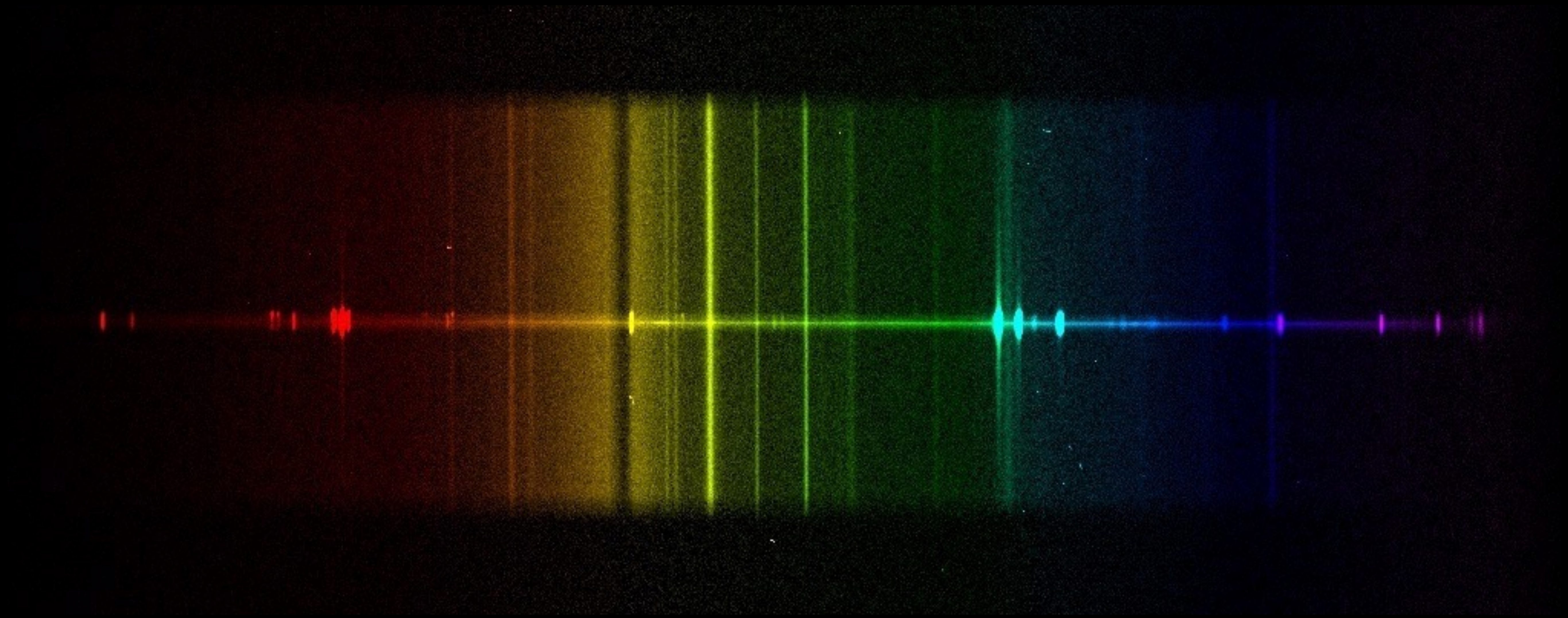
seti.berkeley.edu

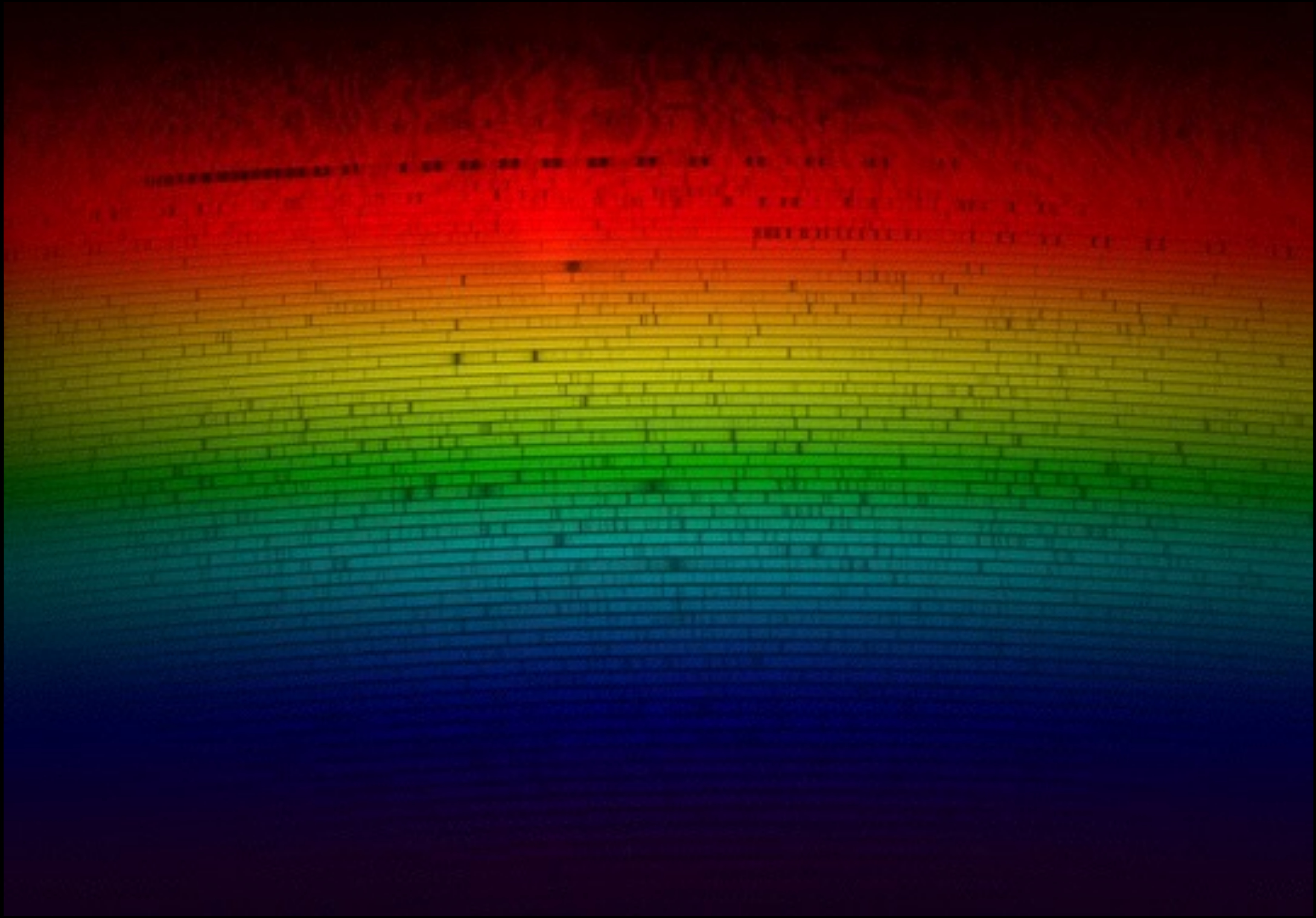
@BerkeleySETI

Watch for job ads

Laser searches







Last edited: June 17, 2016

Working with APF Data

By Haynes Stephens

About this tutorial

This tutorial introduces you to APF fits format data. It is intended for beginners with little to no Python experience. You'll need to have Jupyter installed, along with a scientific Python installation (numpy, scipy, matplotlib [specifically pyplot], astropy, and lmfit). This focus of this tutorial is to help you understand how to:

- work with a `.fits` file
- plot the full spectrum
- indentify and plot the H-alpha absorption feature from the full spectrum
- create a reduced spectrum
- indentify and plot the H-alpha absorption feature from the reduced spectrum
- perform a gaussian fit on the reduced H-alpha absorption feature
- create an algorithm to identify cosmic rays

About the data

For the purposes of this tutorial, we suggest that you download `ucb-amp194.fits` from this Breakthrough Listen webpage. Click on "DOWNLOAD APF SAMPLE DATA" and the '.fits' file should automatically download to your computer. Put the .fits file in the same directory that this Jupyter notebook is stored in. That way it can be opened as you run the commands in this tutorial.

Let's get started!

Working with a `.fits` file

First, we're going to want to import the pyfits, matplotlib, and numpy libraries. The pyfits library allows us to open and explore the data in '.fits' file. The matplotlib library is used for plotting data, including spectra. The numpy library helps with modifying arrays, which is how the data in our '.fits' file will be organized.

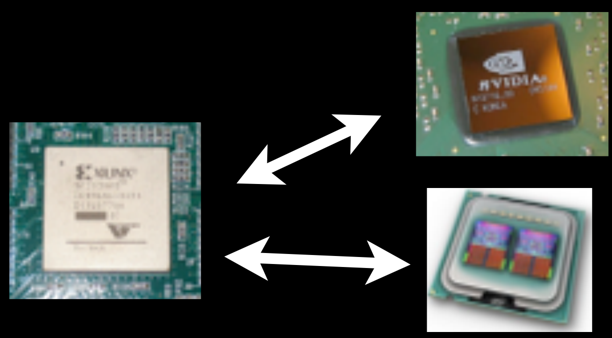
In [1]:
```
%matplotlib inline
```

In [2]:
```
import numpy as np
import pyfits as pf
import matplotlib
from matplotlib import pyplot as plt
import lmfit
from lmfit import minimize, Parameters, report_fit, fit_report
from IPython.display import Image
```

Now that we have imported the necessary libraries, let's open the APF data file.

In [3]:
```
apf_file = pf.open('ucb-amp194.fits copy')
```

The Breakthrough Listen Initiative: *Timeline*



<u>August 2015</u>
Instrumentation development and observation planning

<u>Early 2016</u>
GBT Observations began

<u>Early 2016</u>
APF observations began

<u>October 2016</u>
Parkes observations begin