BREAKTHROUGH LISTEN

Our Boldest Effort to Answer Our Oldest Question…

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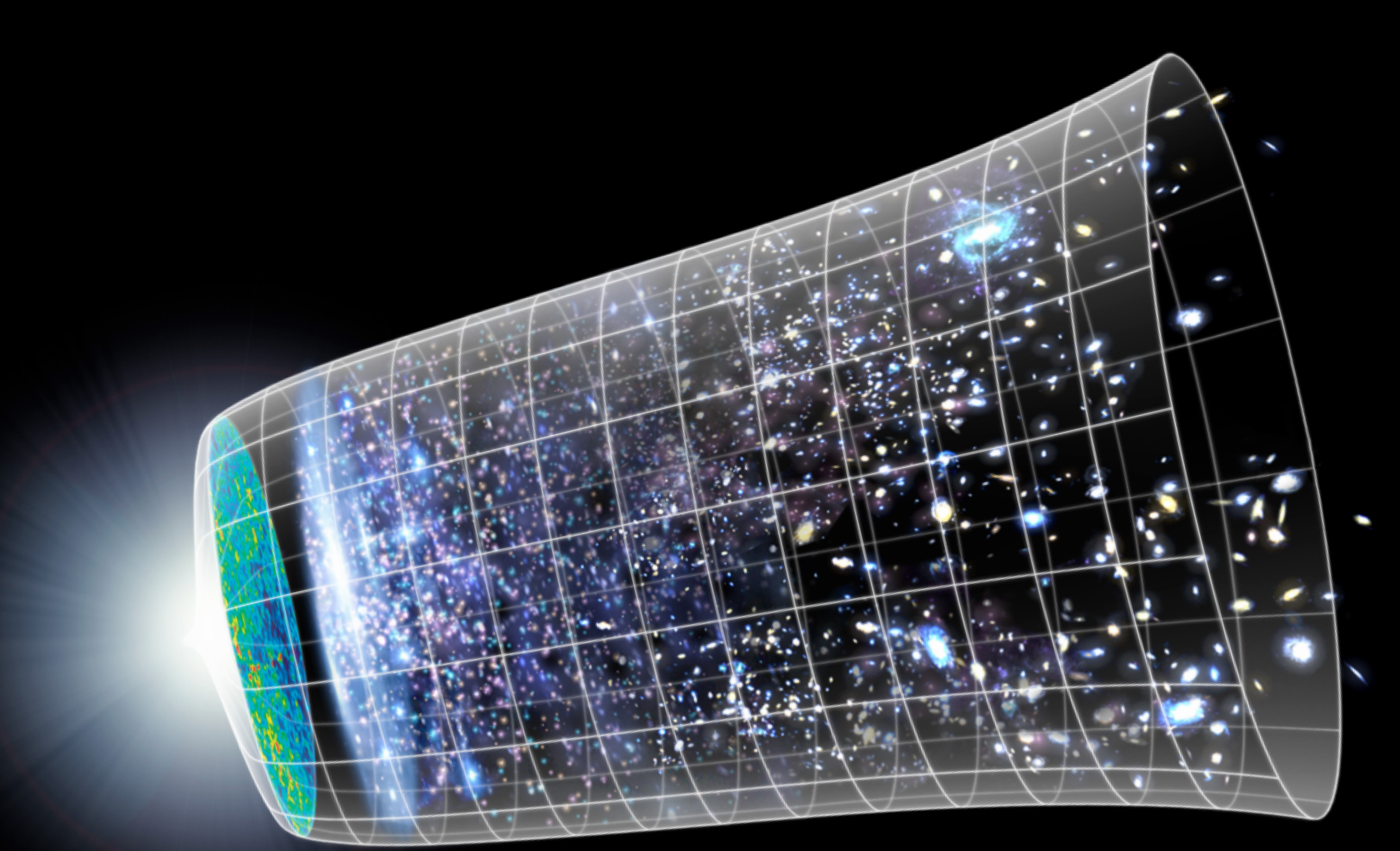
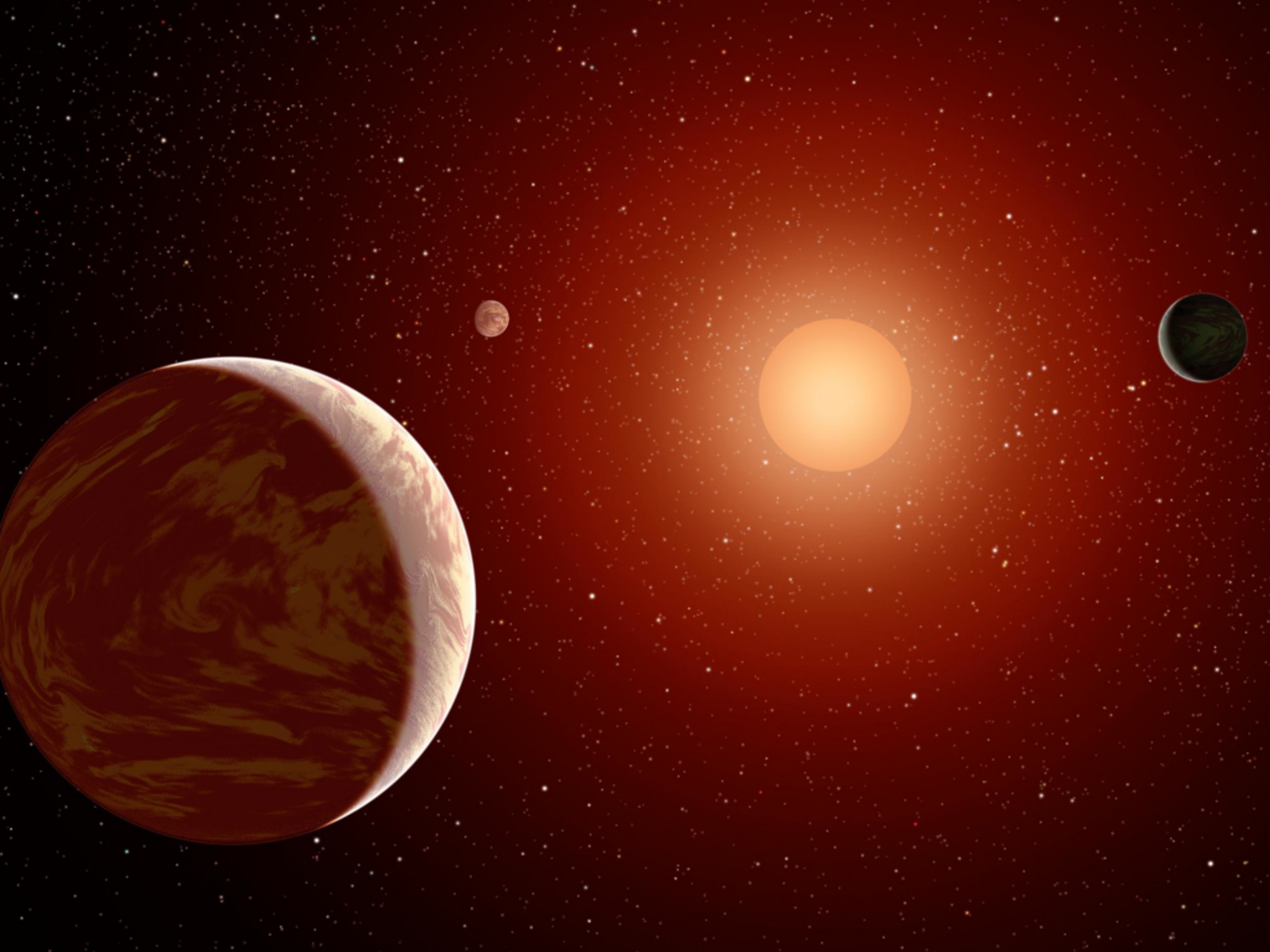
et al.

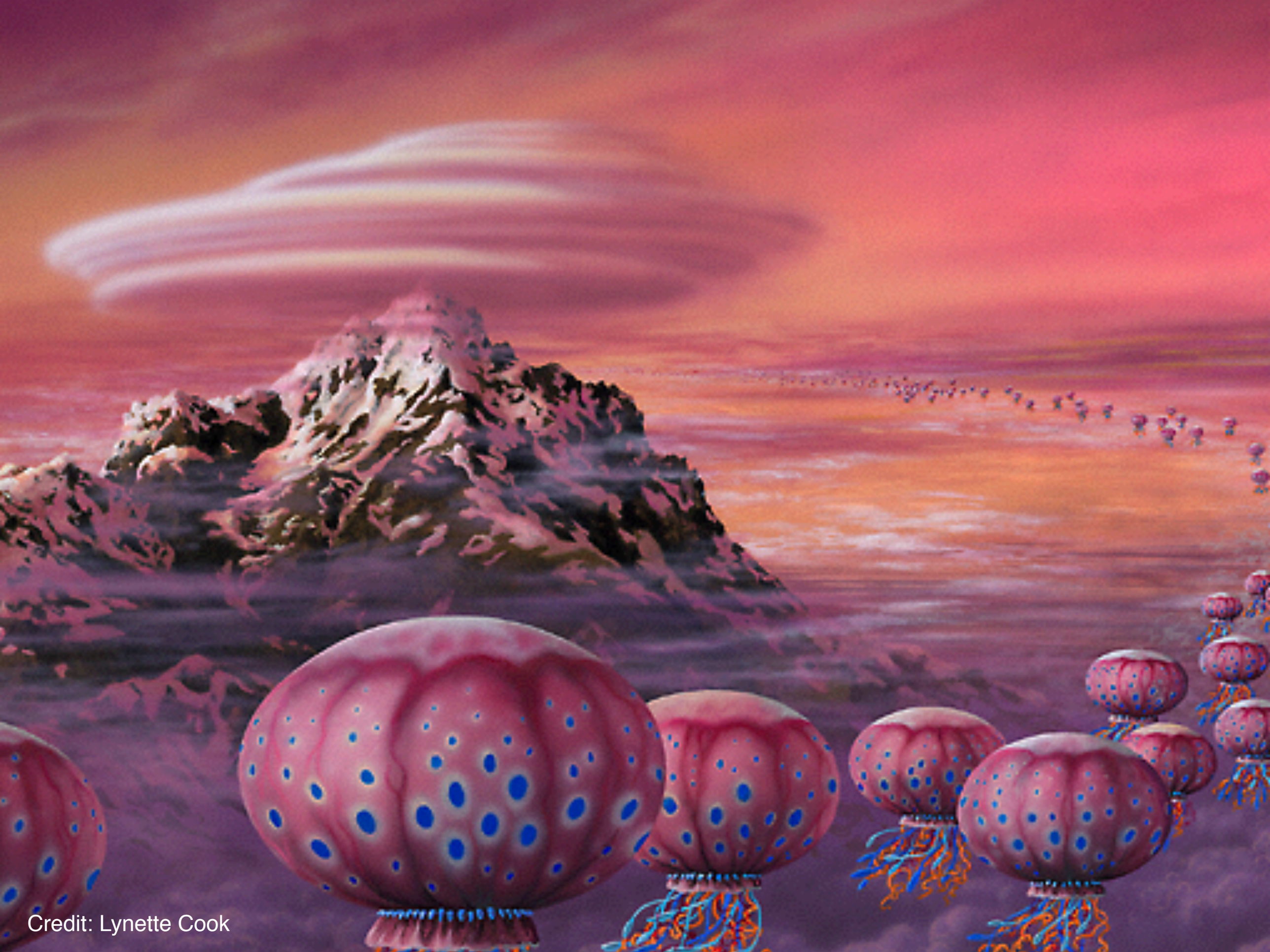
ANDREW P. V. SIEMION



Credit: NASA

Credit: Richard Arculus

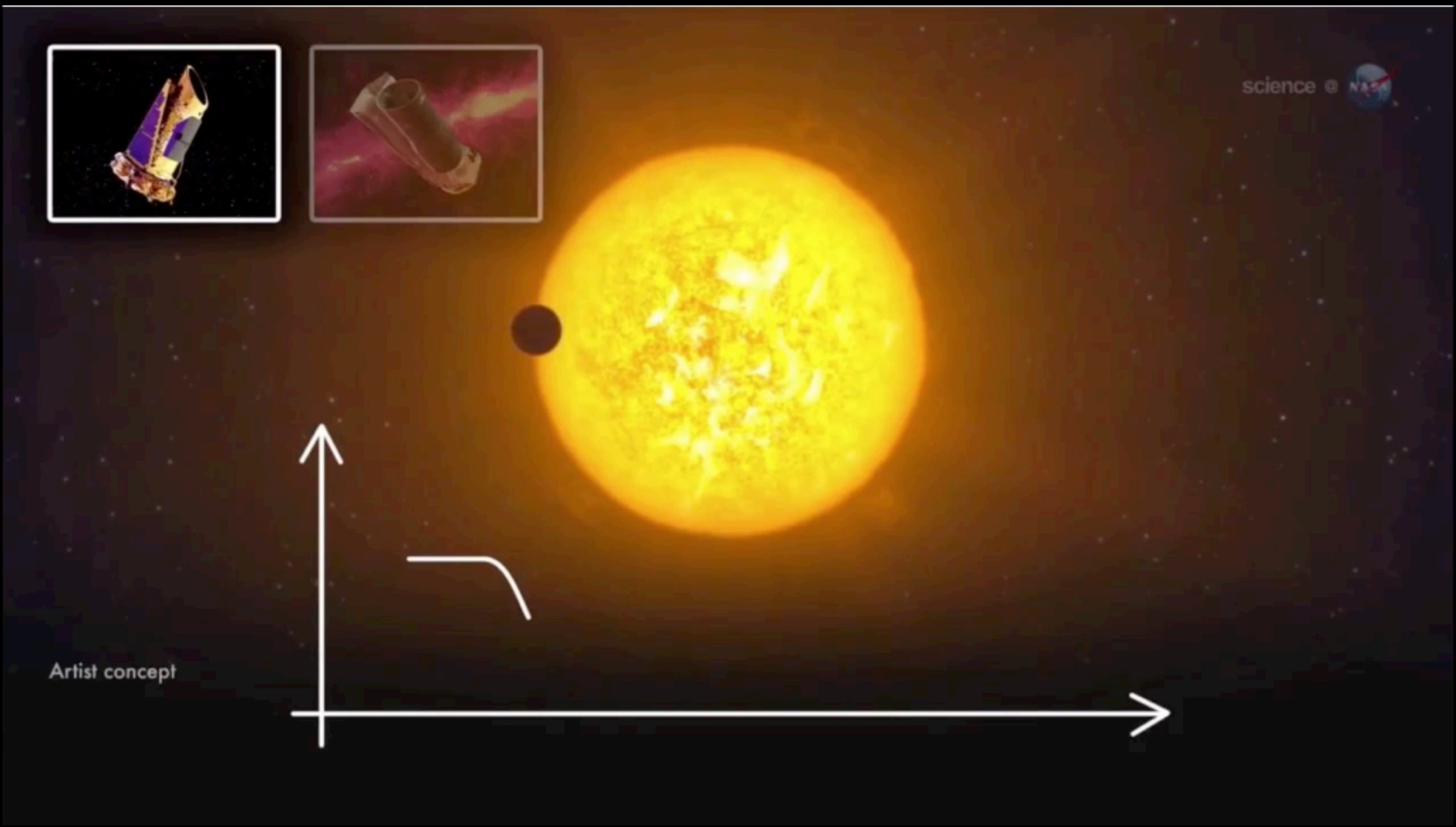




Credit: Lynette Cook

Credit: Lynette Cook

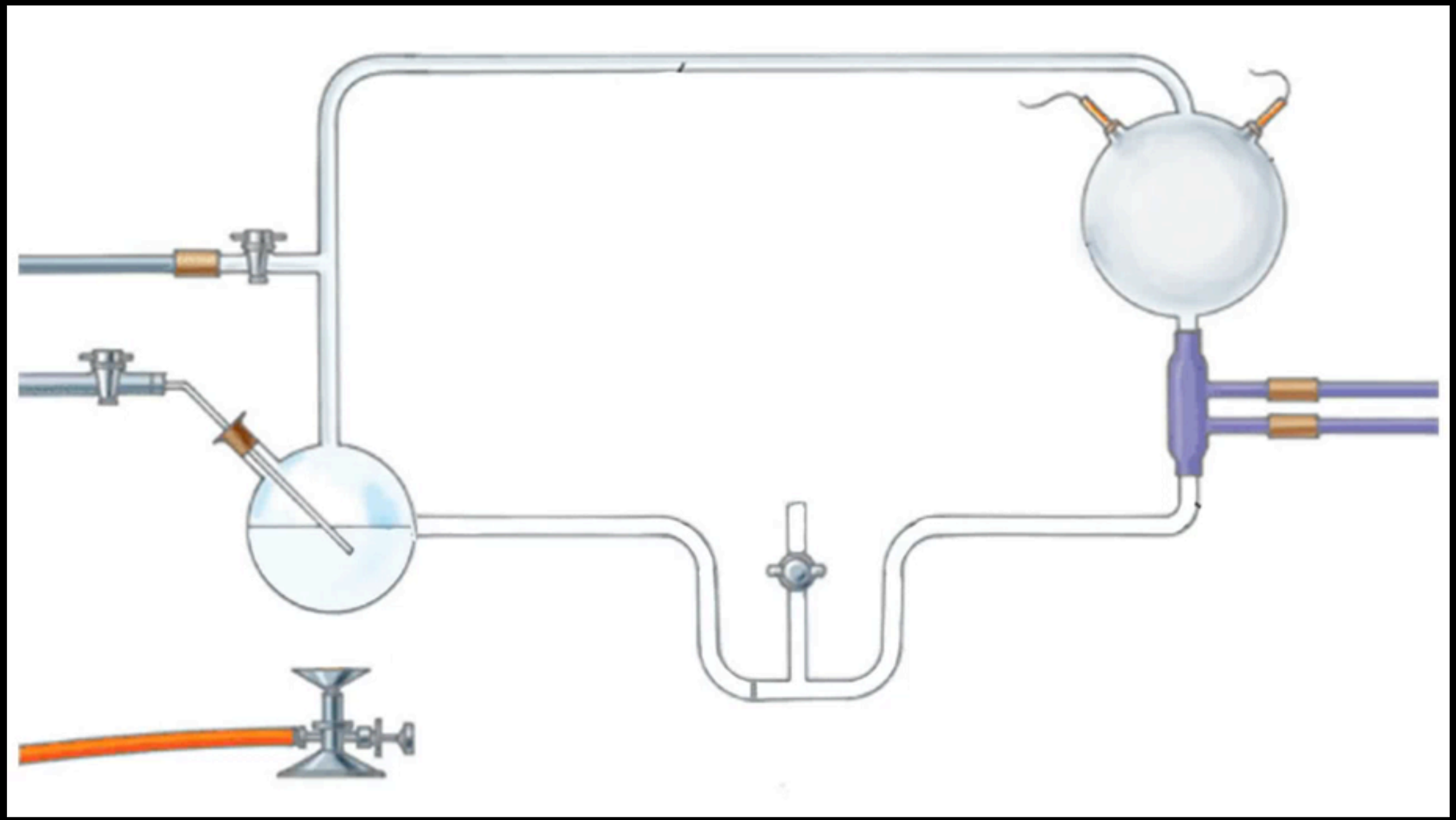
Kepler - An Exoplanet Bonanza…



1 in 5 stars harbors an Earth-sized planet in Habitable Zone

Earth-sized planet
in Habitable Zone

The Biochemical Origin of Life

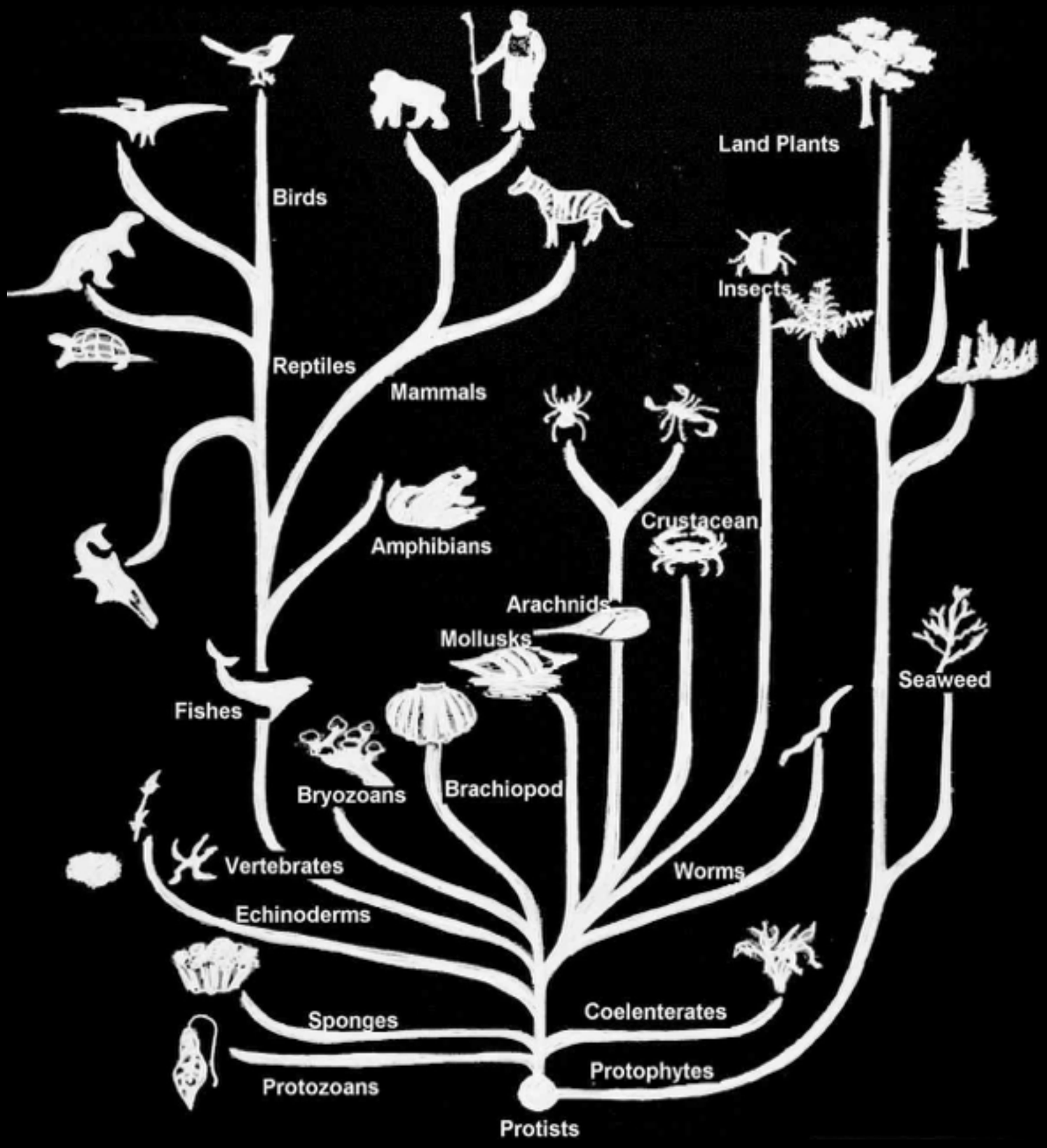


"Miller-Urey" experiments: the building blocks of life from basic ingredients.

Habitability…

Extreme ecosystems - life thrives in the most inhospitable environments on Earth

Is Intelligence a Common Outcome?



Detectable Signatures of Intelligence

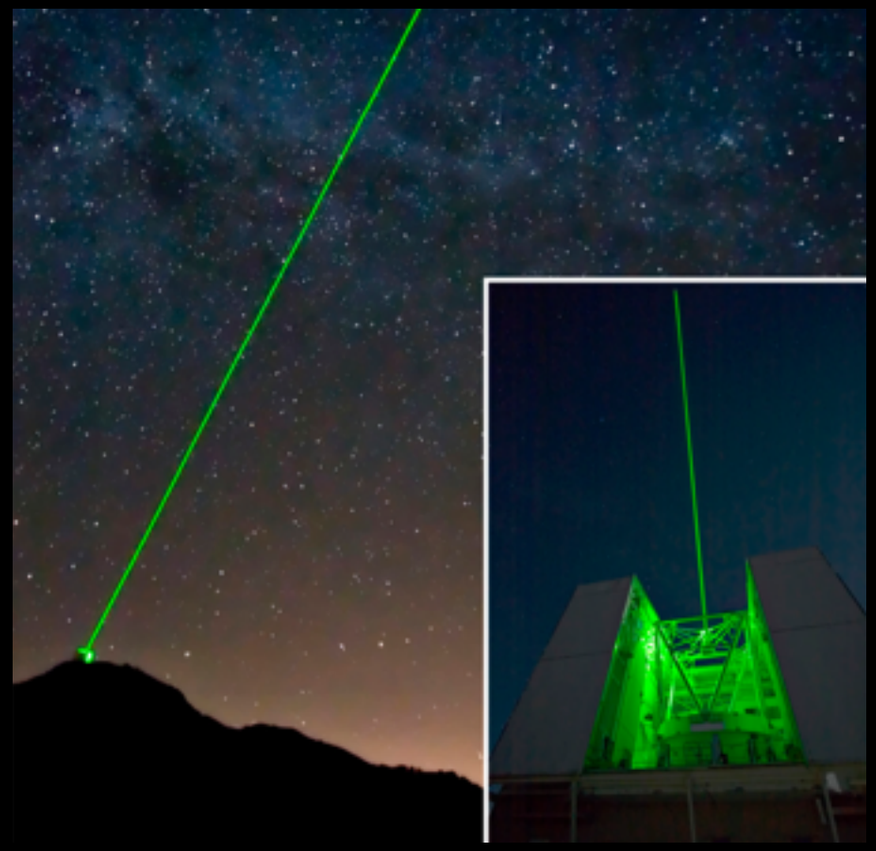
High-power TV and Radio

Hundreds of transmitters detectable at a few lightyears

Planetary Radar Systems

A few radar systems on Earth detectable across the galaxy

High-power Lasers



Lasers can outshine the Sun by thousands of times

Leakage?

Arecibo Planetary radar

- Brightest terrestrial radio transmitter.
- 2 MW at S-band
- Frequently used in CW mode
- EIRP ~2×10^{13} W

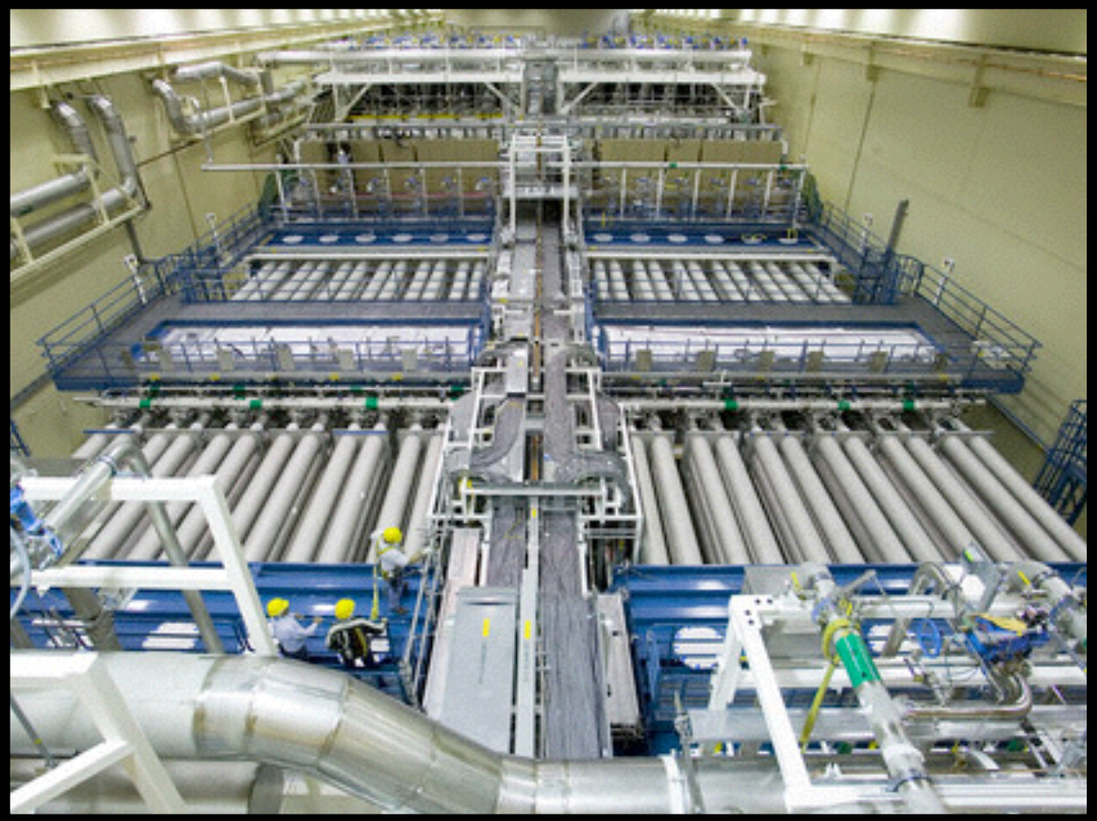
Detectable Across the Galaxy!

Leakage?

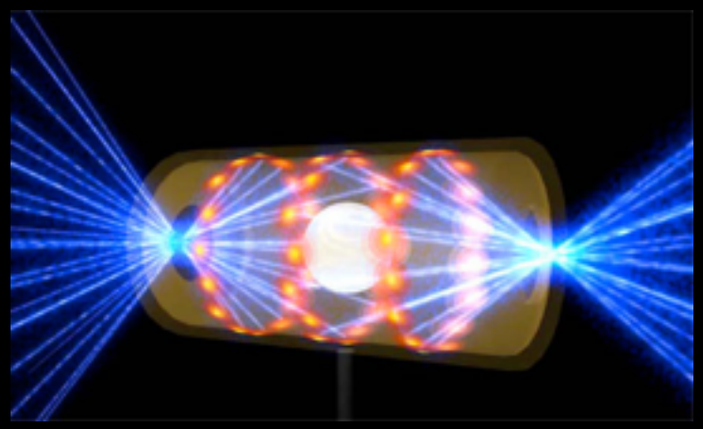
United States Air Force Space Surveillance System
"Space Fence"

- 768 kW @ 217 MHz (originally 108 MHz)
- Pure continuous wave (CW) sinusoid
- EIRP ~10^{10} W
- 120° x 1.5' Fan Beam
  (3000 times the solid angle of Arecibo Planetary Radar)

Could outshine the Sun by three orders of magnitude at 1000 lightyears…



National Ignition Facility - LLNL, Livermore



5 MJ pulsed laser +
10m reflector at 1000ly

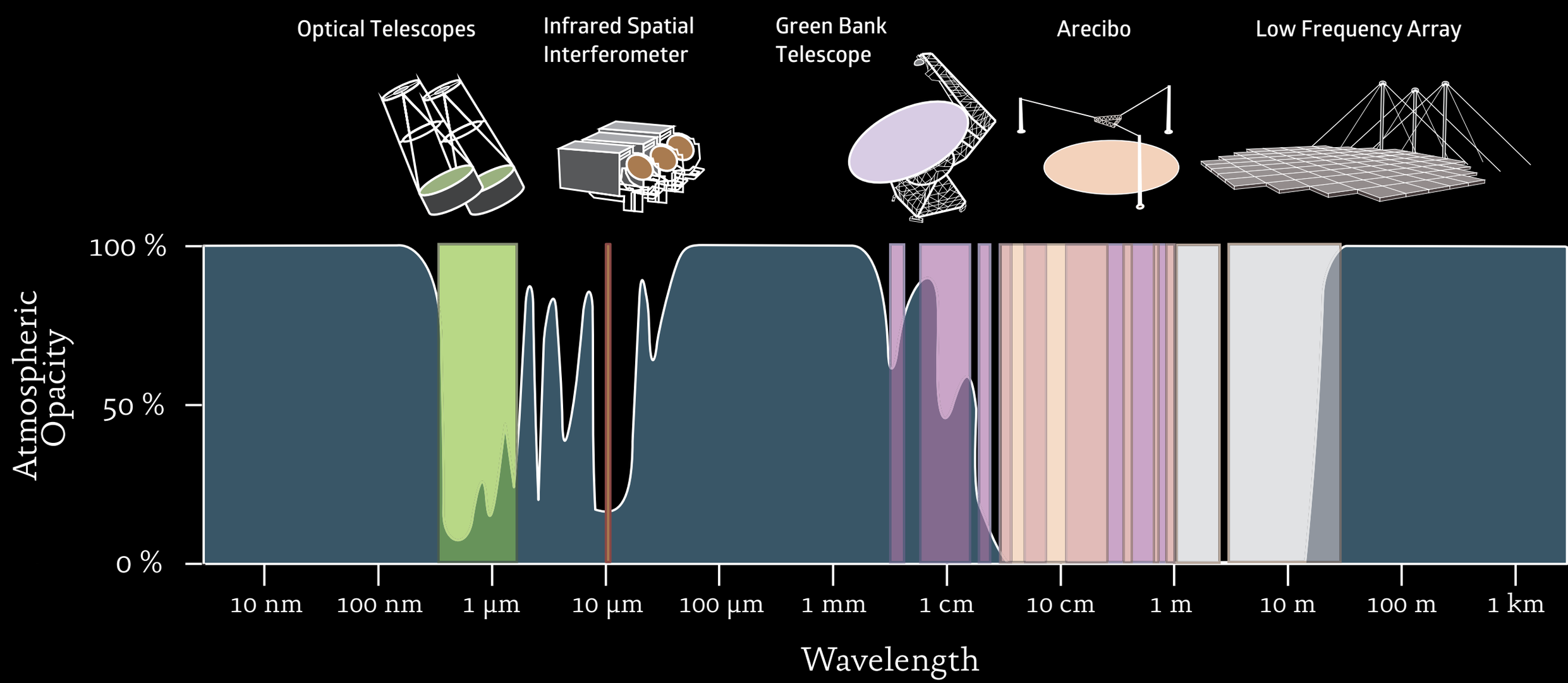
$$\sim 5 \frac{\gamma}{\mathrm{ns\ m^2}}$$

Keck Twin 10m Telescopes - Mauna Kea, Hawaii

Solar-type star at 1000 ly

$$\sim 10^{-3} \frac{\gamma}{\mathrm{ns\ m^2}}$$

Searching Across the Electromagnetic Spectrum



Using multiple telescopes, we can search across the electromagnetic spectrum for indicators of advanced technology.

A Unique Moment in our History

Arecibo Observatory, Puerto Rico

The most sensitive single radio telescope in the world.

Arecibo Observatory, Puerto Rico

National Science Foundation Senior Review:

…the NSF Review Committee recommends that Arecibo be closed or operate with a much smaller budget…

The most sensitive single radio telescope in the world.


The Robert C. Byrd
Green Bank Telescope,
West Virginia
Fully steerable with very
wide frequency coverage.

The Robert C. Byrd
Green Bank Telescope,
West Virginia

…the NSF Review Committee recommends divestment from the Robert C. Byrd Green Bank Telescope…

Fully steerable with very
wide frequency coverage.

“The only black tie event in Silicon Valley”

FOUNDERS:

Sergey Brin - Priscilla Chan -Jack Ma - Julia Milner -
Yuri Milner - Anne Wojcicki - Cathy Zhang
Mark Zuckerberg

BREAKTHROUGH INITIATIVES

"All the News That's Fit to Print"

The New York Times

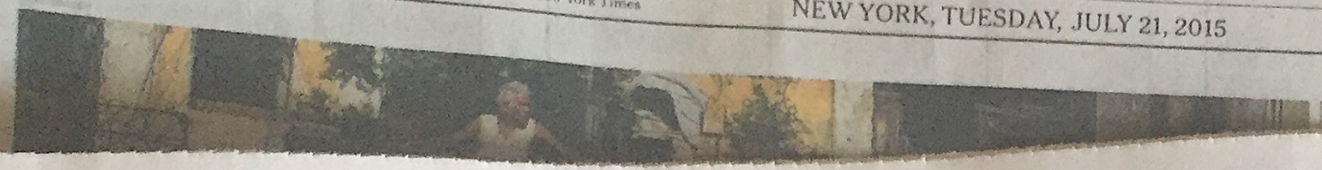
VOL. CLXIV . . . . No. 56,934

NEW YORK, TUESDAY, JULY 21, 2015

Late Edition

Today, clouds, sun, hot, high 90. **Tonight,** early evening shower or storm, clear late, low 72. **Tomorrow,** plenty of sunshine, less humid, high 84. Weather map is on Page A22.

$2.50

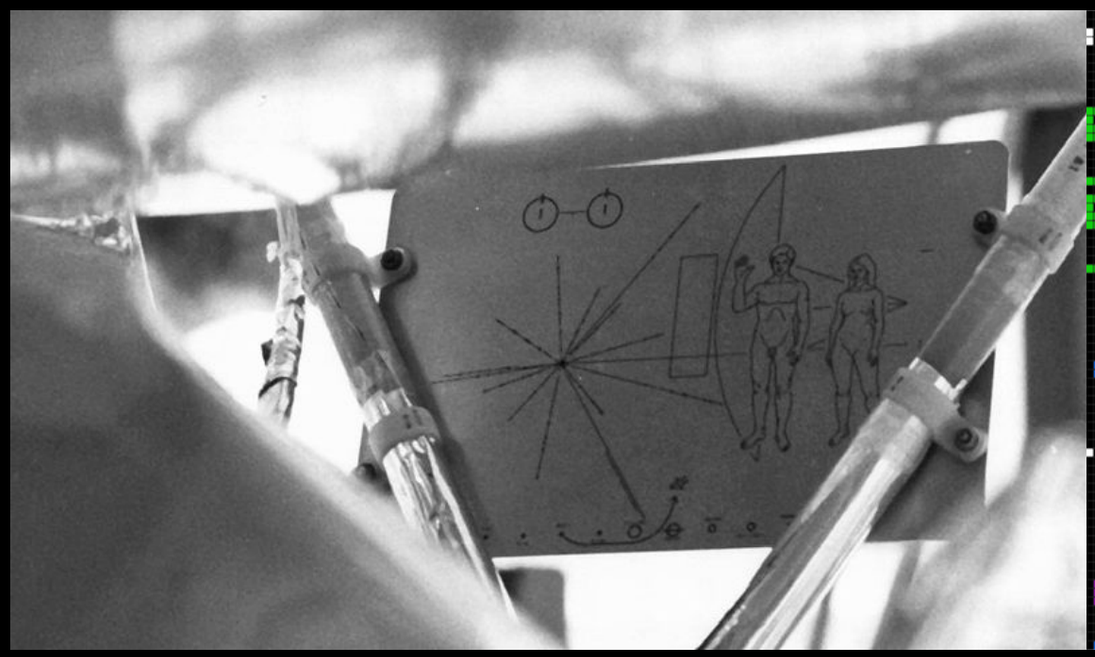


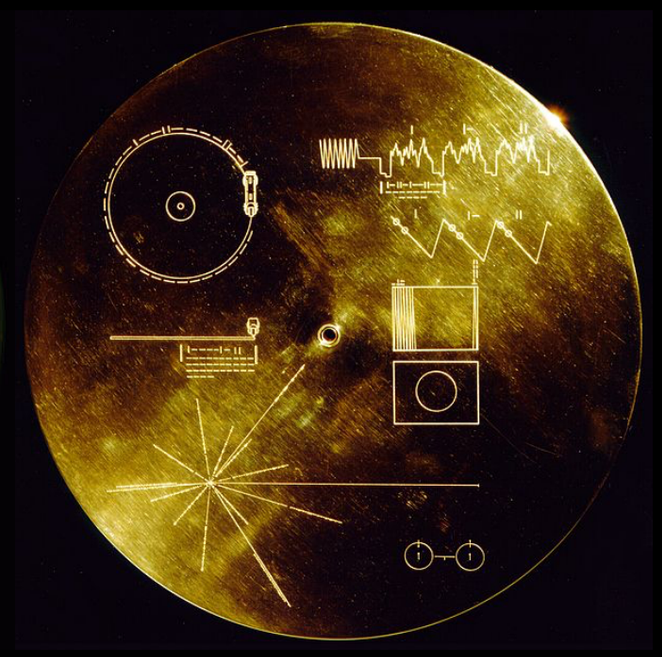
Are we alone?

Now is the time to find out

Yuri Milner
Cori Bargmann
Sarah Brightman
Magnus Carlsen
Ding Chen
Frank Drake
Ann Druyan
Stephen Hawking
Paul Horowitz
Garik Israelian
Lisa Kaltenegger
Nikolay Kardashev
Mark Kelly
Eric Lander
Alexey Leonov
Avi Loeb
Seth MacFarlane
Geoff Marcy
Lord Martin Rees
Kenneth Rogoff
Dimitar Sasselov
Sara Seager
Sujan Sengupta
Seth Shostak
Thomas Stafford
Jill Tarter
Kip Thorne
James Watson
Steven Weinberg
Edward Witten
Pete Worden
Shinya Yamanaka

BREAKTHROUGH MESSAGE



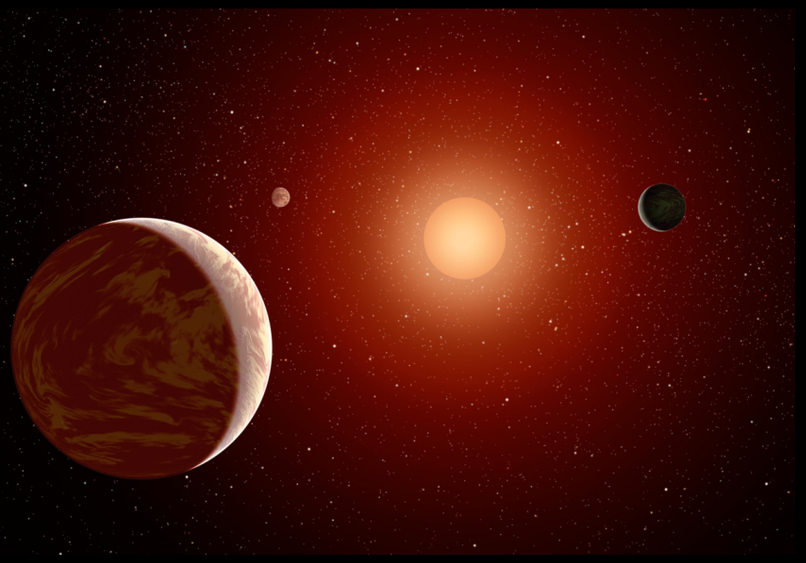


What message would you send to represent Earth to ET?

1 Million USD Prize

BREAKTHROUGH LISTEN

The Breakthrough Listen Initiative: *Overview*



1 Million Stars

Milky Way Galactic Plane Survey

100 Galaxies

1 day of Breakthrough Listen = 1 year of any previous search

More scientific data publicly available than any project in history

HTTP://BREAKTHROUGHINITIATIVES.ORG

The Breakthrough Listen Initiative: *Telescopes*

Automated Planet Finder (Lick Observatory)

- Search for extremely narrow emission lines from artificial lasers
- Extremely high resolution “Levy Spectrometer”
  374 - 950 nm, $\lambda/\Delta\lambda = 10^5$

· *10%*

Green Bank Telescope (Green Bank, WV)

- Radio search focusing on targeted and raster observations
- Nearly continuous frequency coverage 300 MHz - 100 GHz
- Flexible IF system can deliver up to 10 GHz dual-pol analog bandwidth
- Extremely radio quiet (Federally protected radio quiet zone)

· *~20%*

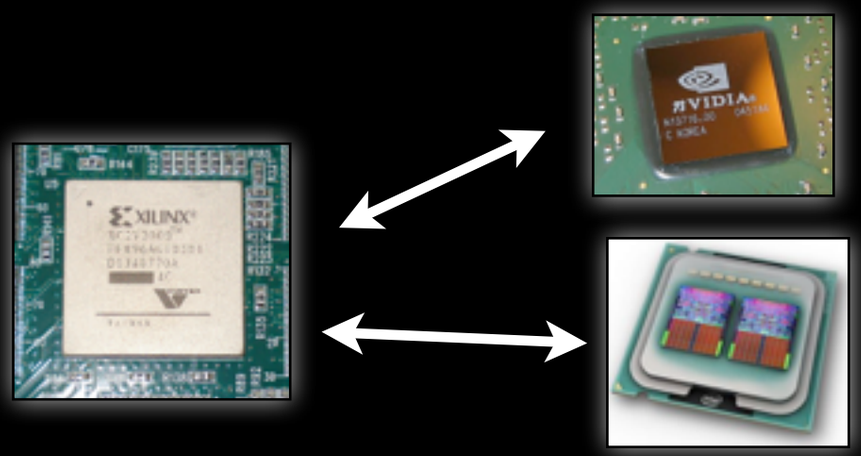
Parkes Telescope (New South Wales, Australia)

- Radio search focusing on surveys
- Southern hemisphere location gives great access to galactic plane
- Multi-beam receiver allows very efficient L-band (1.2 - 1.5 GHz) galactic plane surveys (Parkes Multibeam Receiver)
- Wide-band single-pixel and Phased Array Feed upgrades possible.

· *~20%*

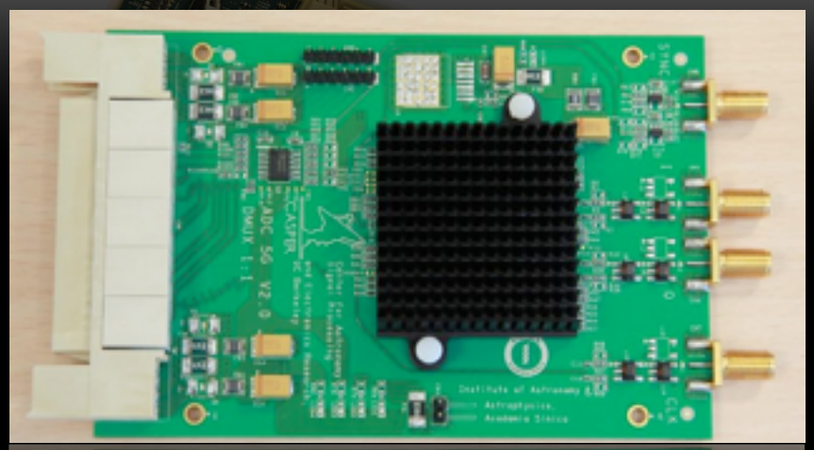

Time Progression:
10,000y
per second

The Breakthrough Listen Initiative: *Technology*



Commodity Compute Elements

FPGA Computing Boards



High Speed Digitizers

Many-GHz processing capability

200 - 400 Gbps data recording

10^{10} channel spectroscopy

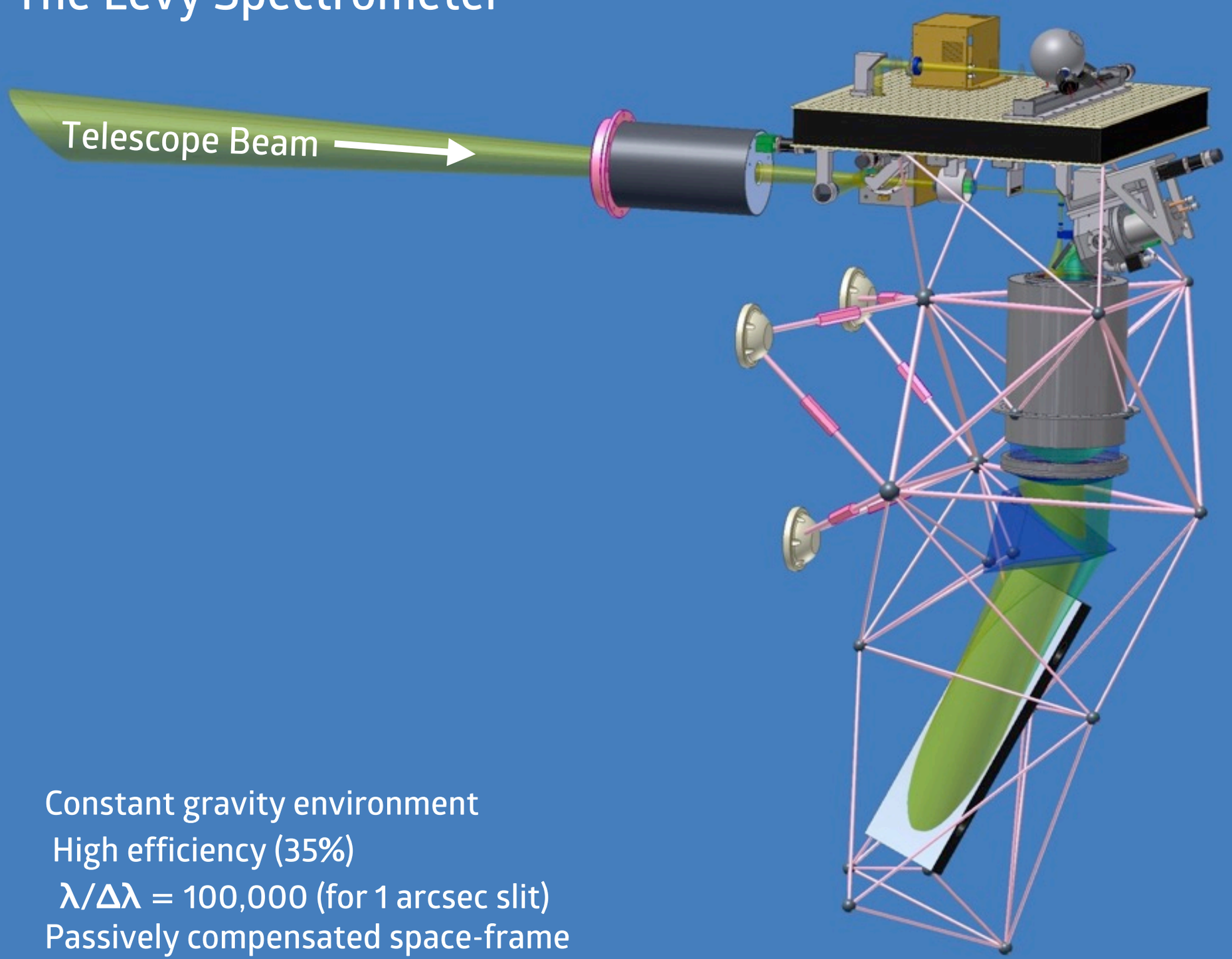
GPU-accelerated multi-parameter search pipeline (dispersion, Doppler effects)

Interference identification, classification

CASPER

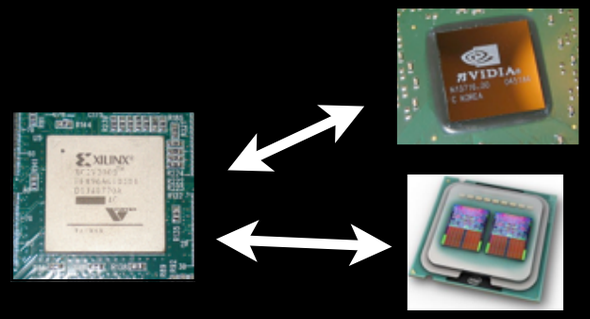
The Breakthrough Listen Initiative: *Technology*

The Levy Spectrometer



Constant gravity environment
High efficiency (35%)
$\lambda/\Delta\lambda$ = 100,000 (for 1 arcsec slit)
Passively compensated space-frame
1 m/s velocity precision
Cost: $2.6 million (NASA and Ken and Gloria Levy)

The Breakthrough Listen Initiative: *Timeline*



August 2015
Instrumentation development and observation planning

November 2015
APF Observations Begin

January 2016
GBT Observations Begin

October 2016
Parkes Observations Begin

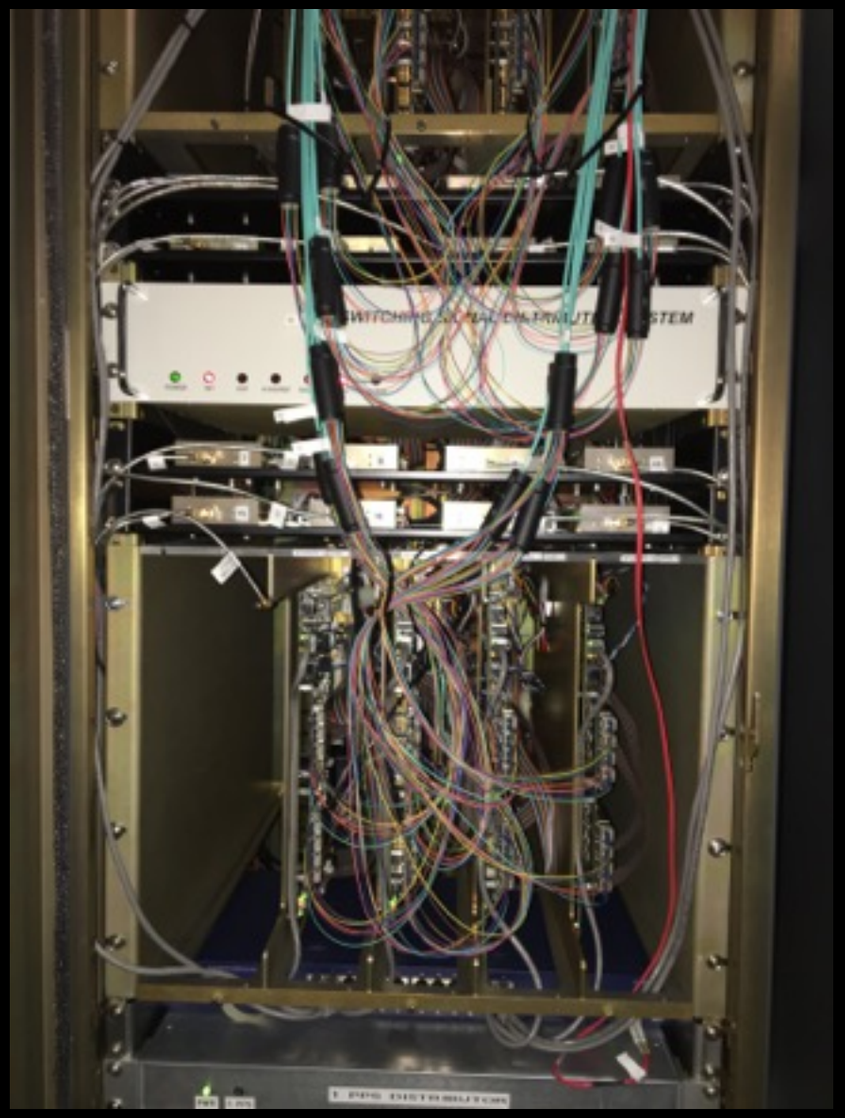
How to Build a SETI Instrument in 6 Months

- Step 1: Use existing antenna

(Courtesy Breakthrough Listen Chief Engineer Dave MacMahon)

How to Build a SETI Instrument in 6 Months

- Step 2: Use existing digitizers and gateware



How to Build a SETI Instrument in 6 Months

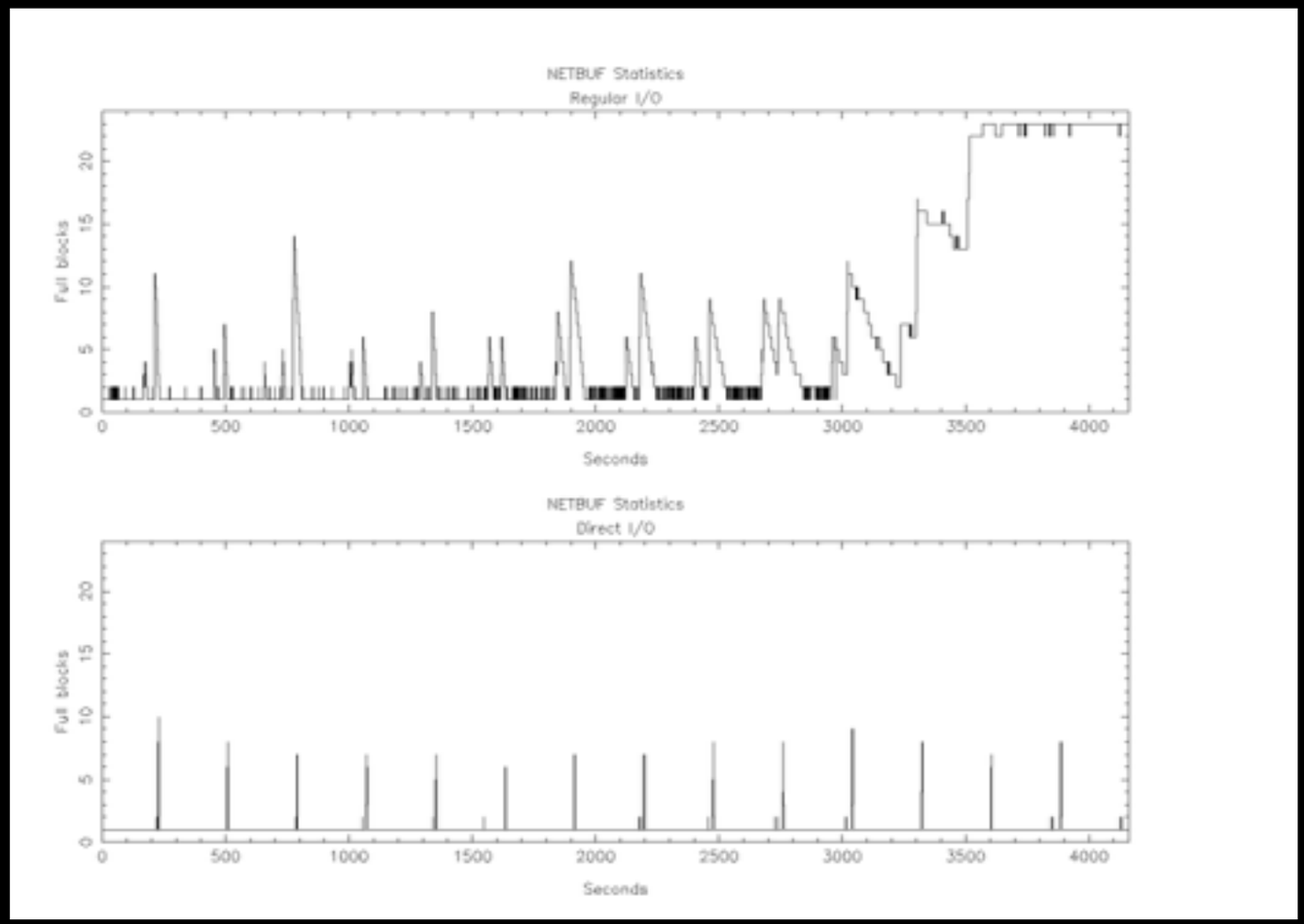
- Step 3: Upgrade observatory's 10 GbE switch

How to Build a SETI Instrument in 6 Months

- Step 4: Install cluster
  - 1 head node
  - 8 compute nodes
    24 x 5 TB disks each
    TITAN X GPU
  - 1 storage node
    36 x 5 TB disks

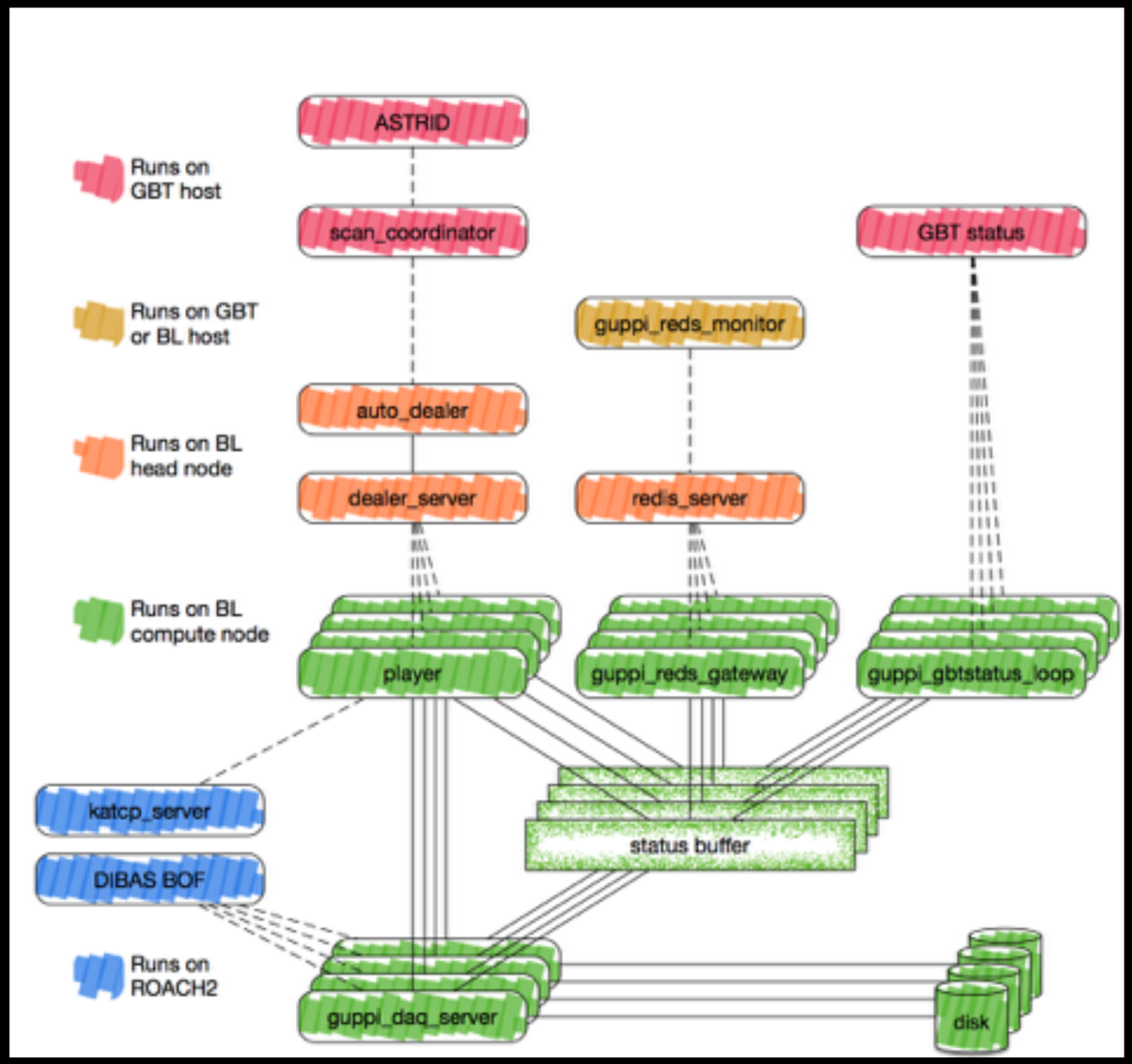
How to Build a SETI Instrument in 6 Months

- Step 5: Tune existing software (guppi_daq)
  - Packet Sockets
  - Direct I/O
  - RAID0
  - XFS
  - 6 Gbps to disk (750 MB/s) per compute node



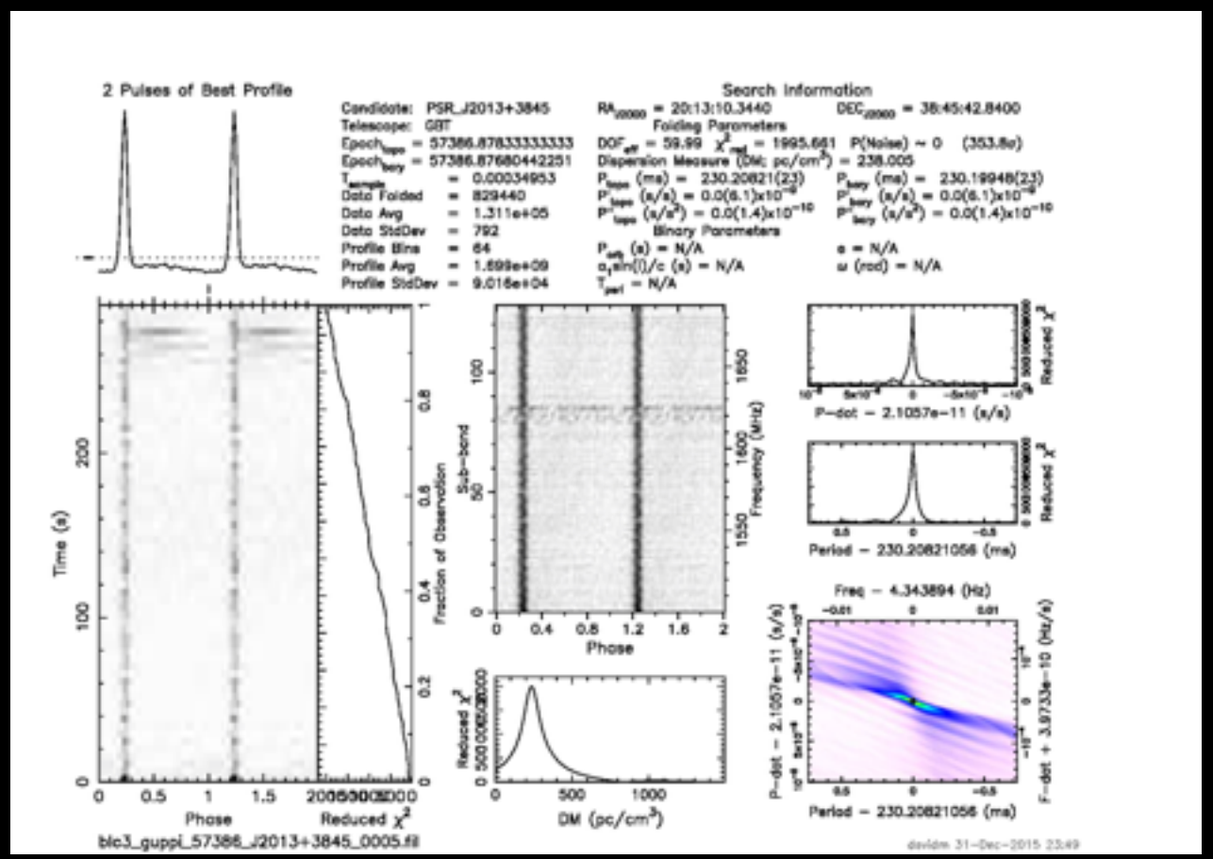
How to Build a SETI Instrument in 6 Months

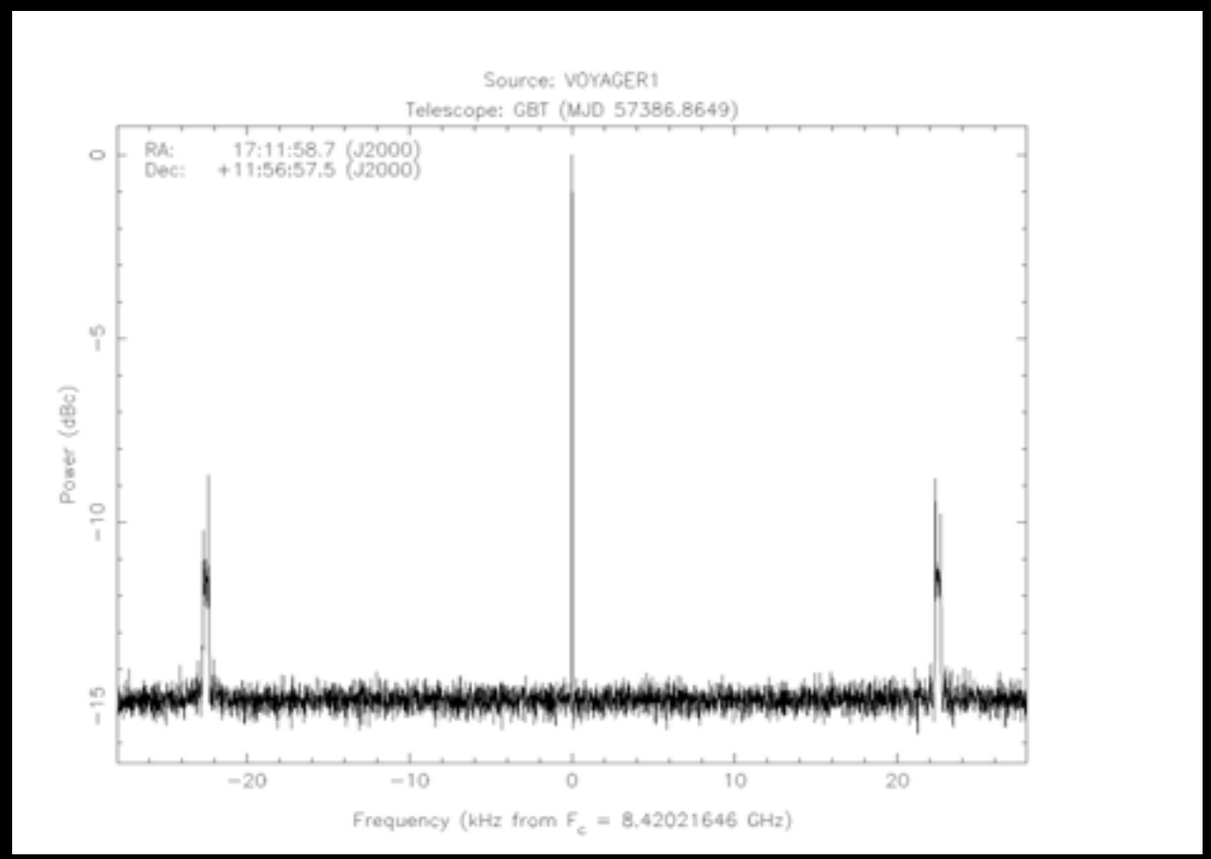
- Step 6: Integrate with telescope control system



How to Build a SETI Instrument in 6 Months

- Step 7: Take data!
  BL@GBT First Light December 30, 2015

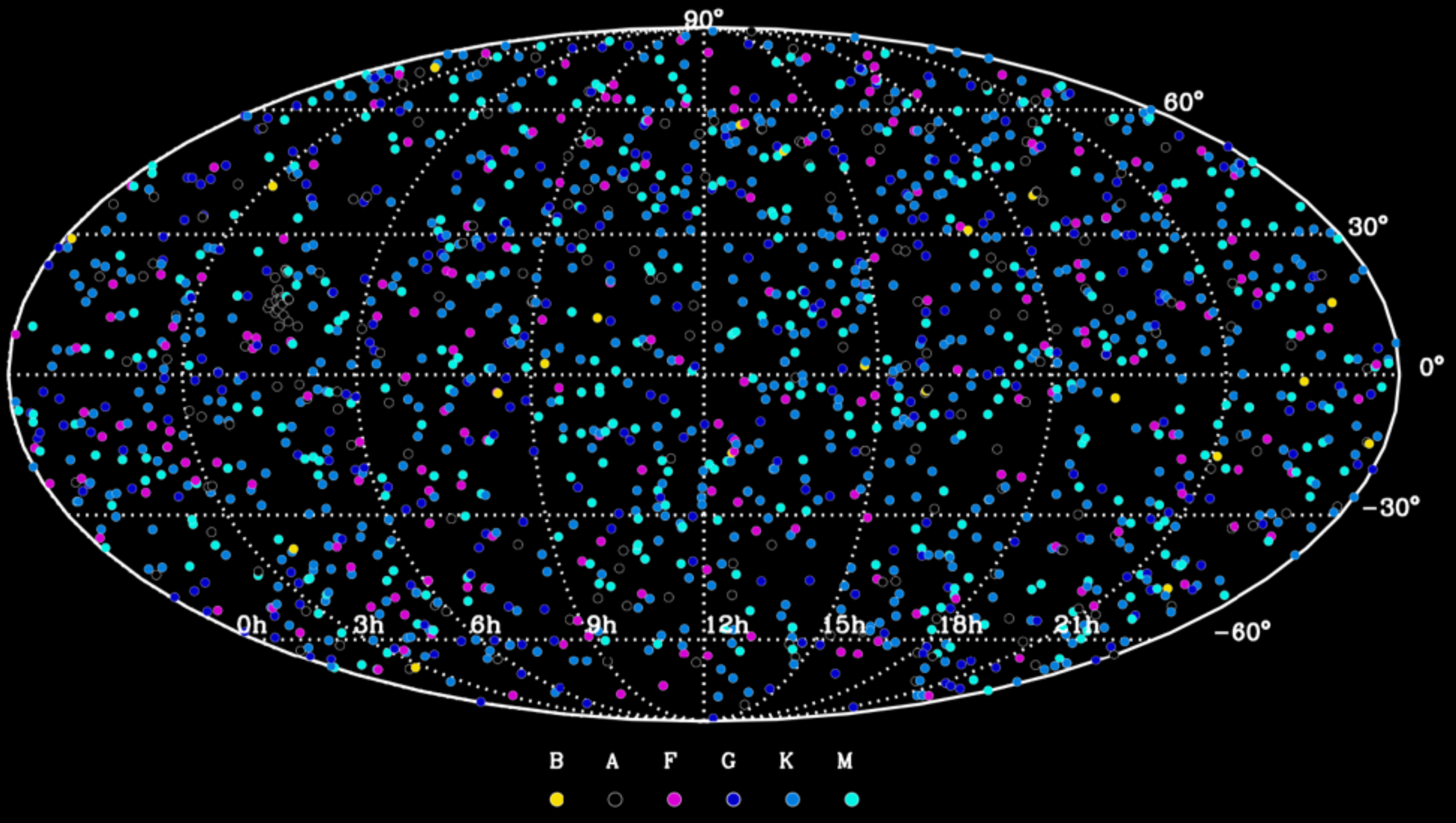




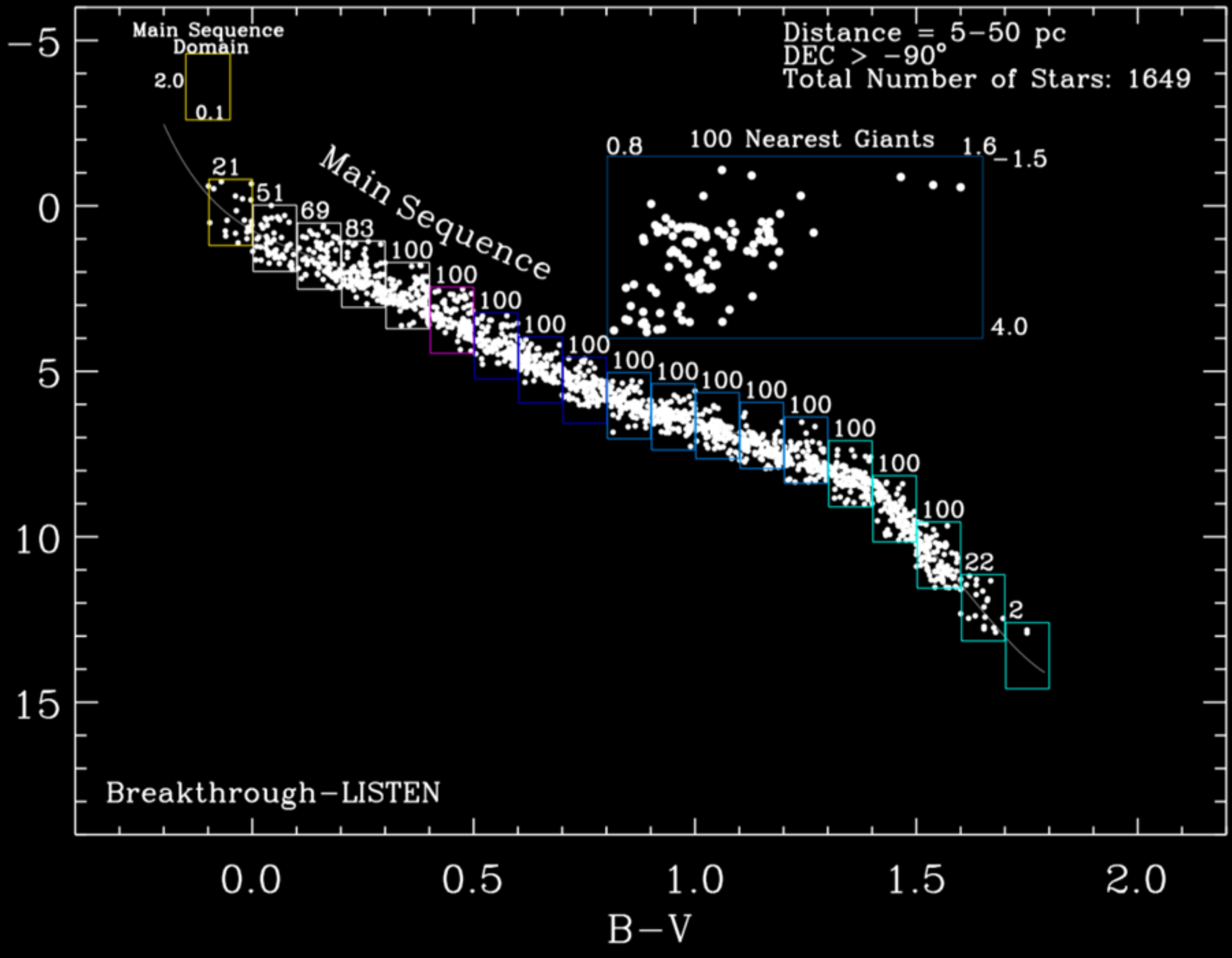
1709 Nearby Target Stars

for

Breakthrough *LISTEN*

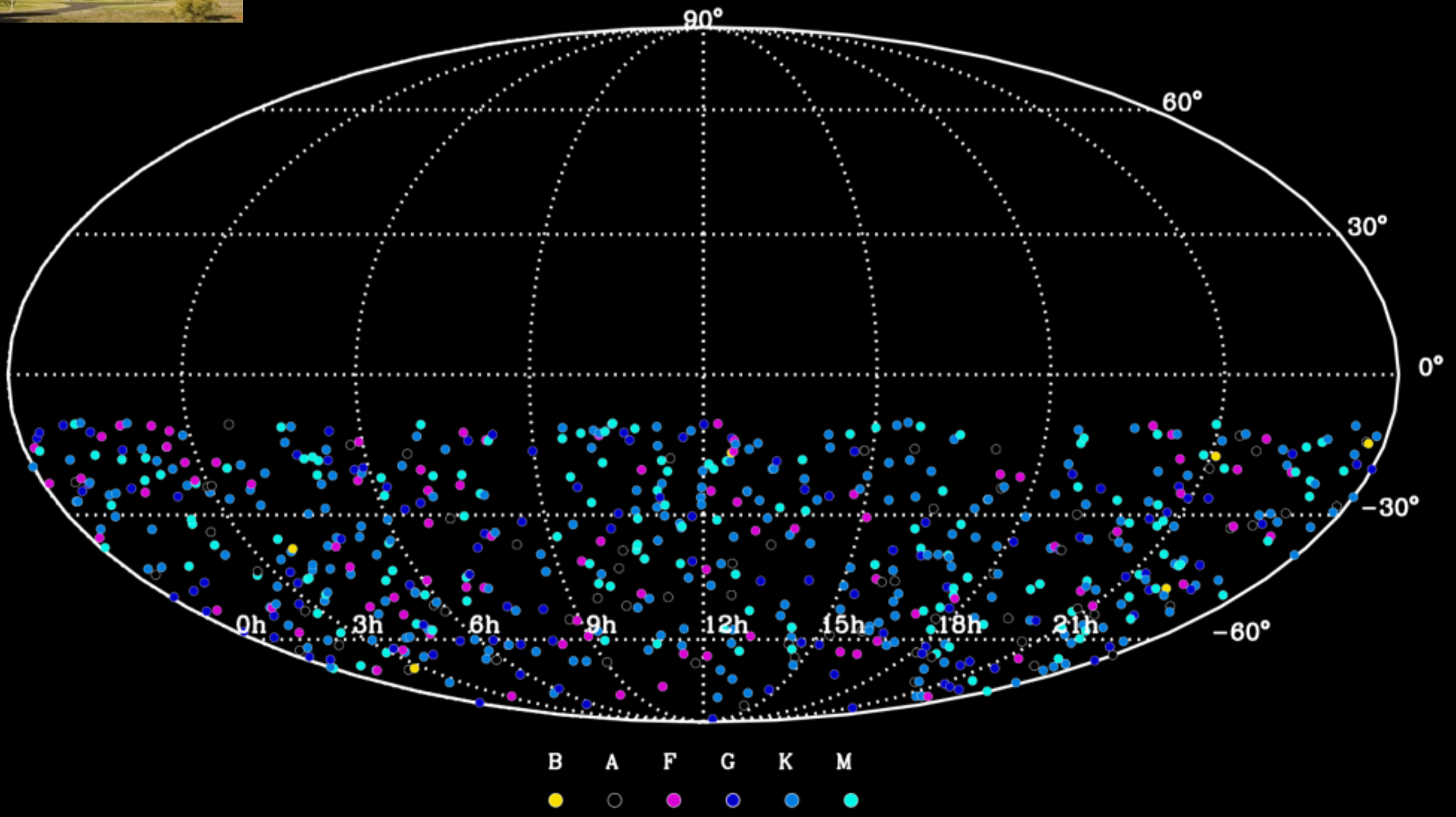


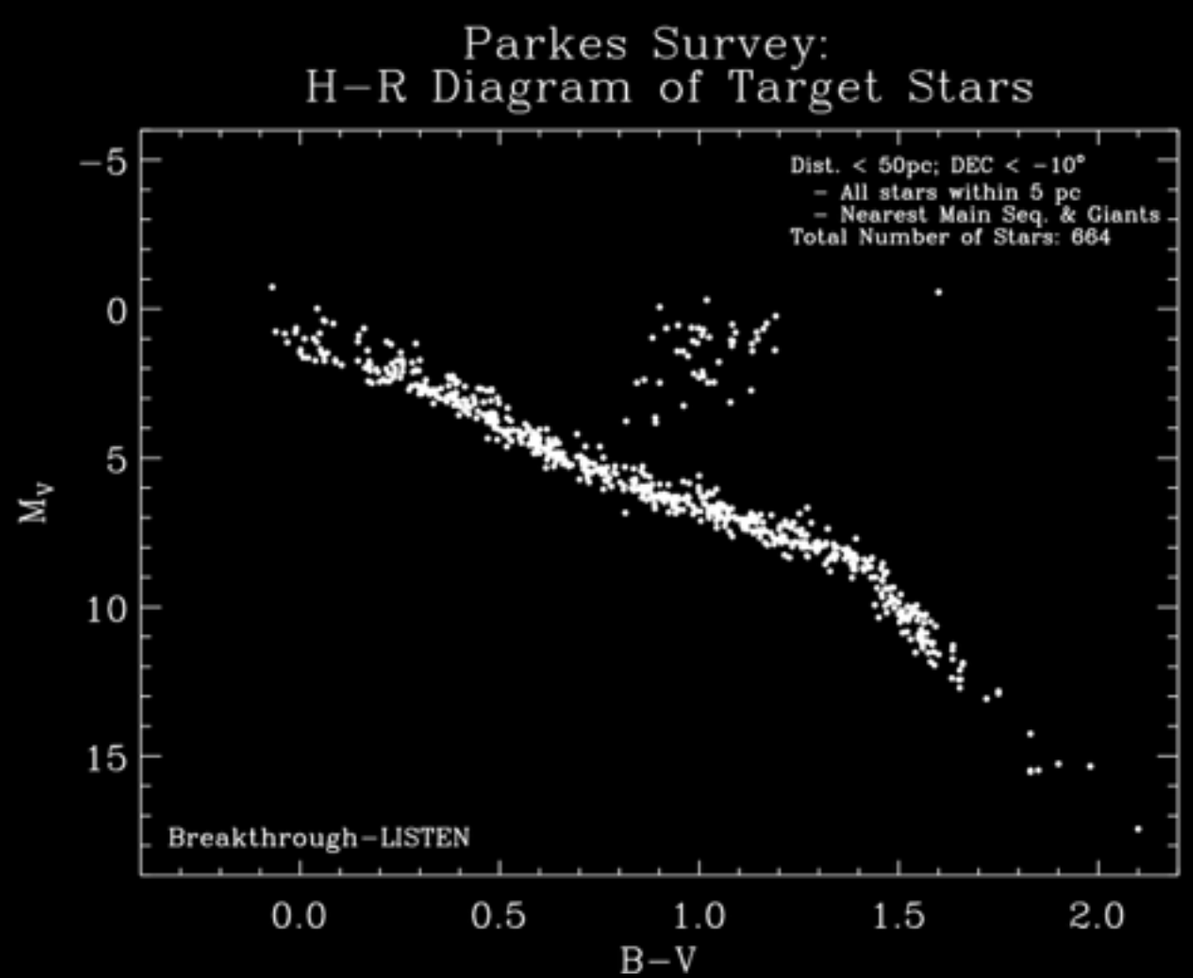
Main Sequence and Giant Stars (in Domains)

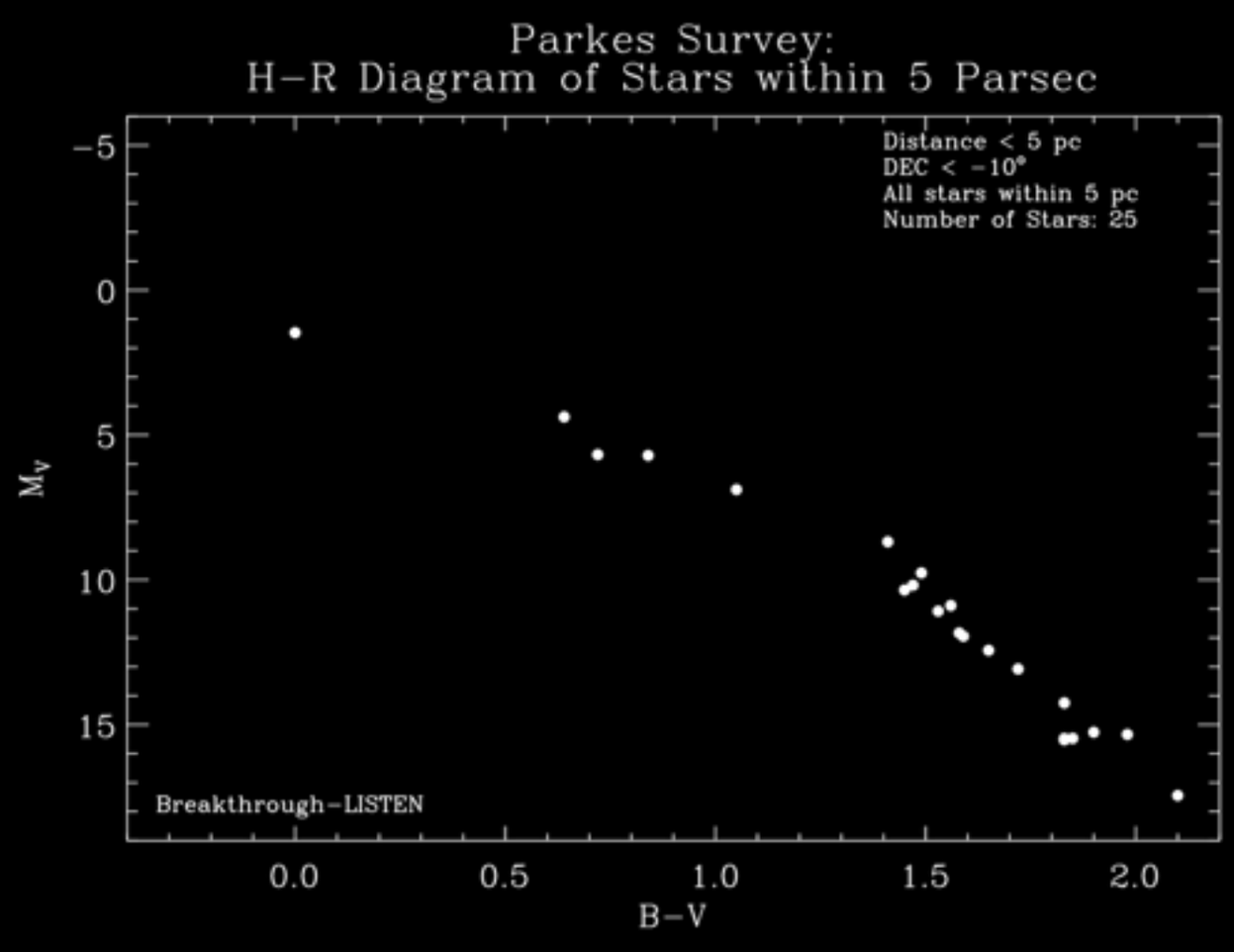


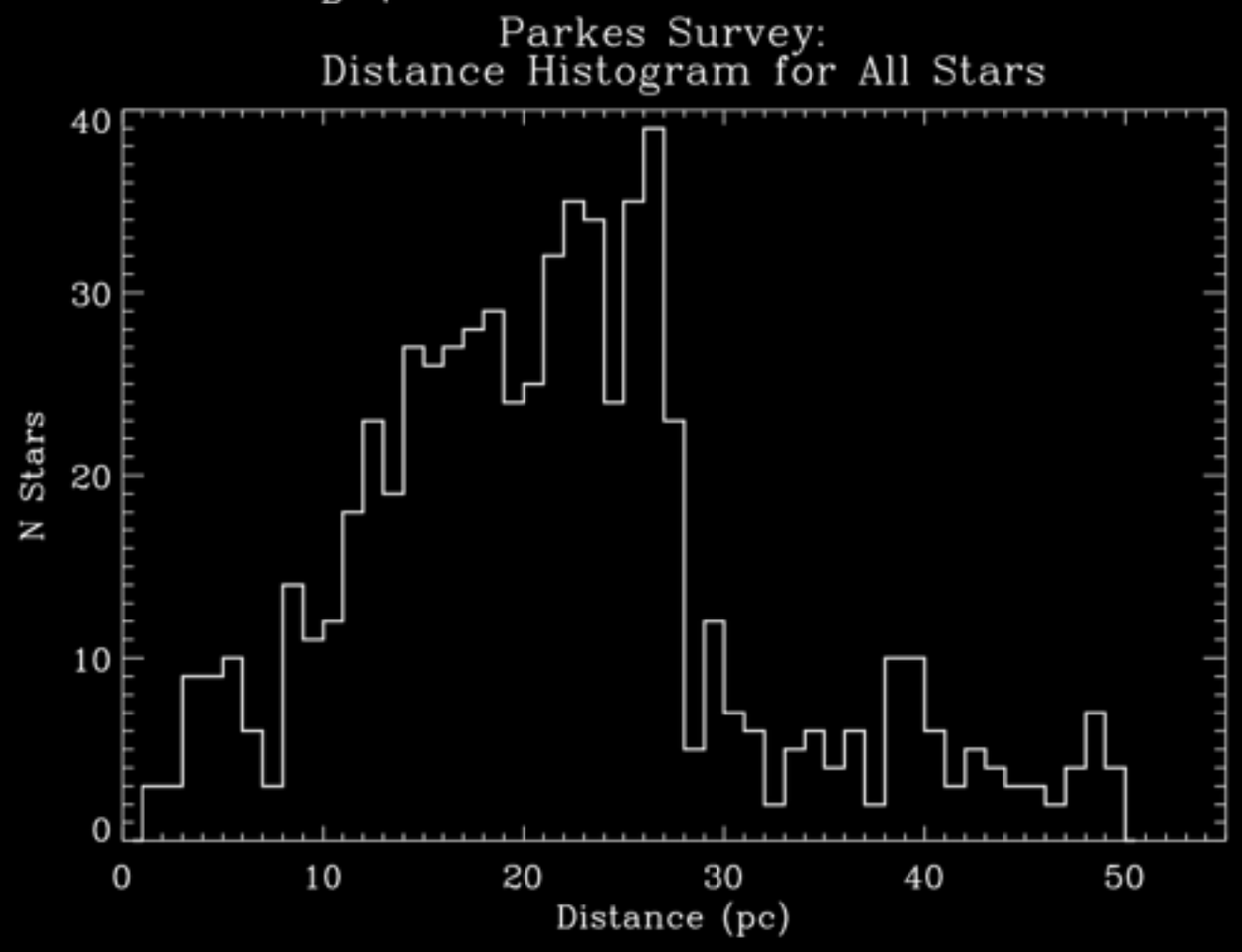
664 Nearby Target Stars
for
Breakthrough *LISTEN*

Parkes

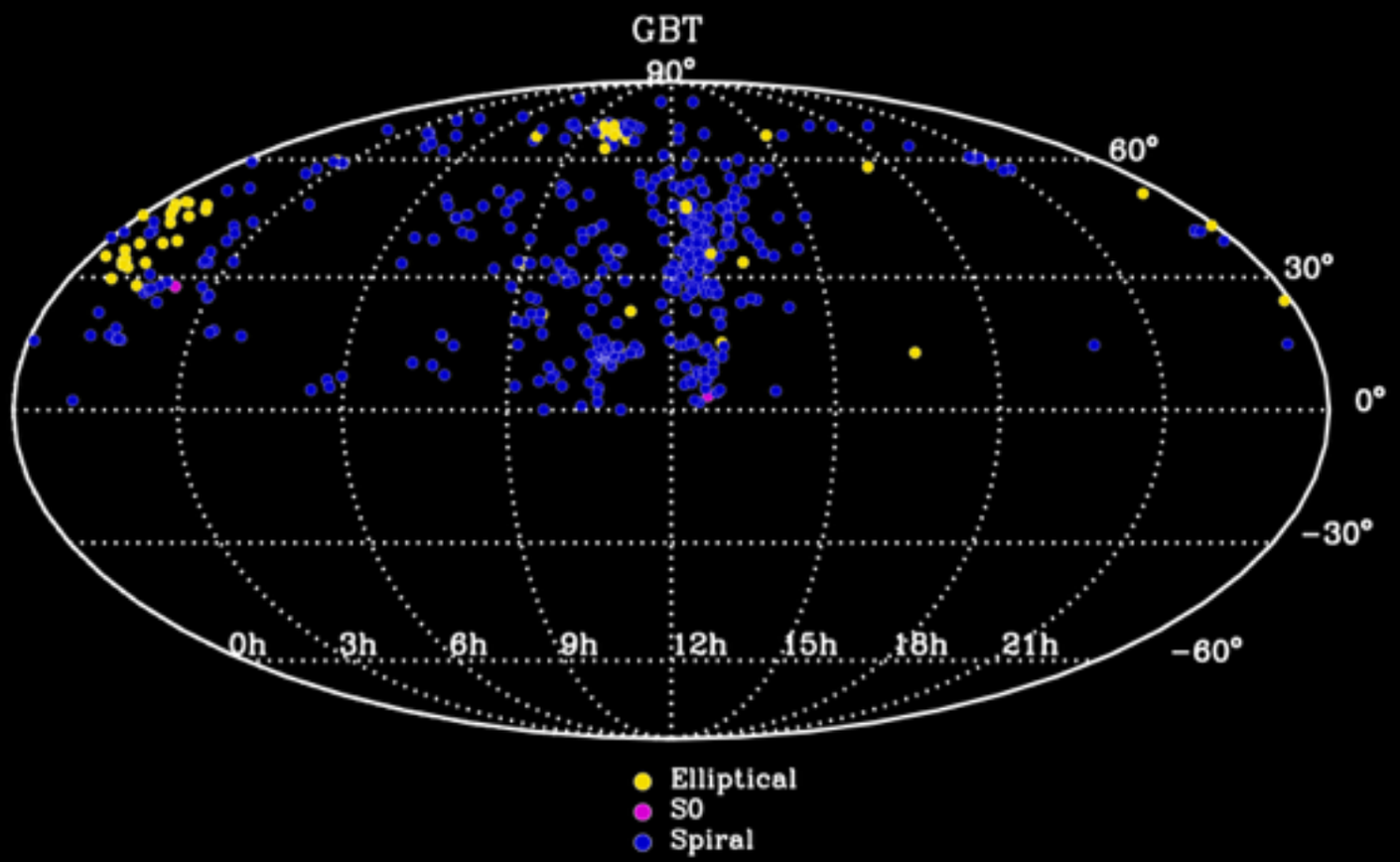



Parkes Survey:
H−R Diagram of Target Stars
Dist. < 50pc; DEC < −10°
– All stars within 5 pc
– Nearest Main Seq. & Giants
Total Number of Stars: 664
Breakthrough−LISTEN
M_V
B−V

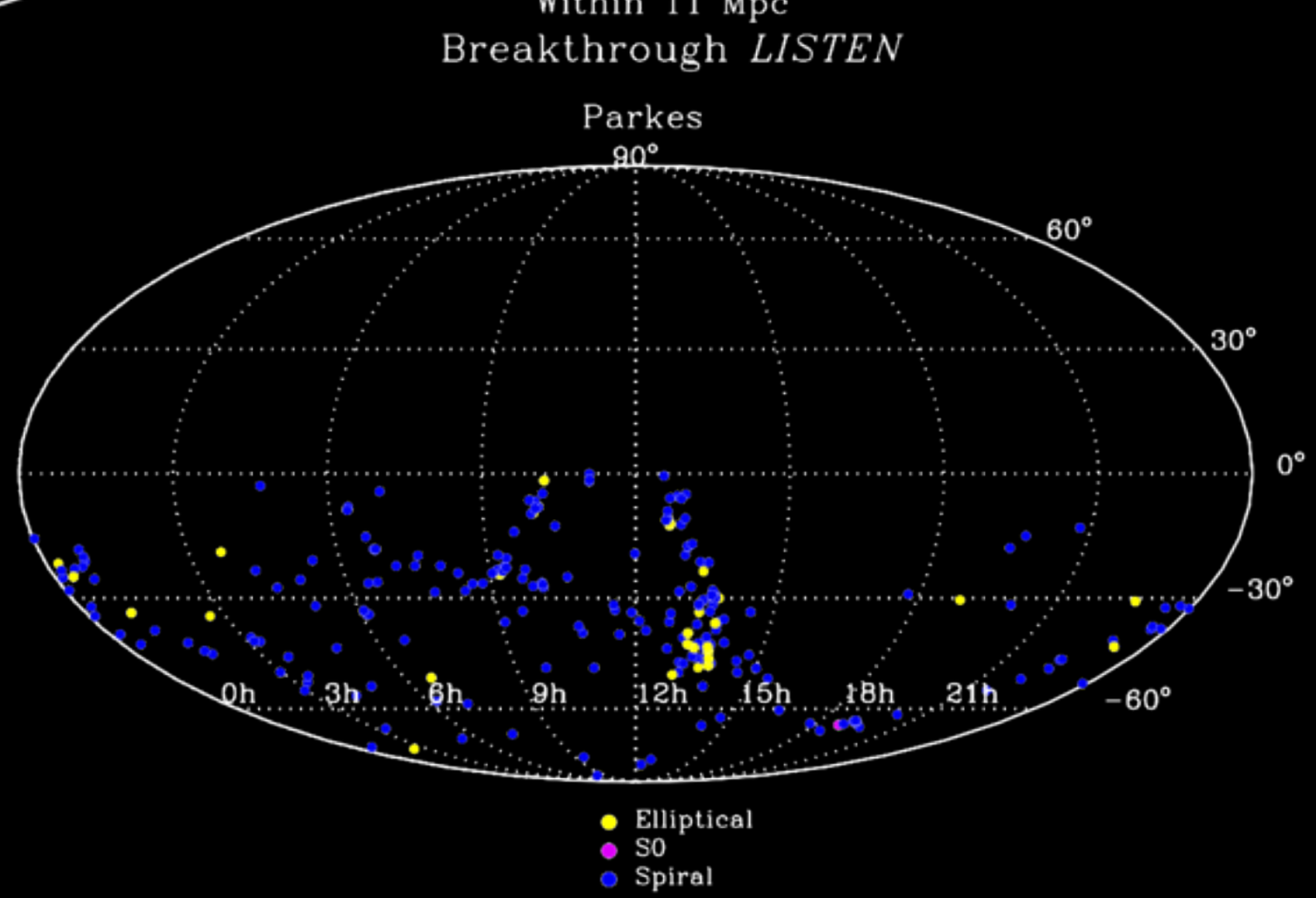

Parkes Survey:
H−R Diagram of Stars within 5 Parsec
Distance < 5 pc
DEC < −10°
All stars within 5 pc
Number of Stars: 25
Breakthrough−LISTEN
M_V
B−V


Parkes Survey:
Distance Histogram for All Stars
N Stars
Distance (pc)

551 Nearby Target Galaxies
Within 11 Mpc
Breakthrough *LISTEN*

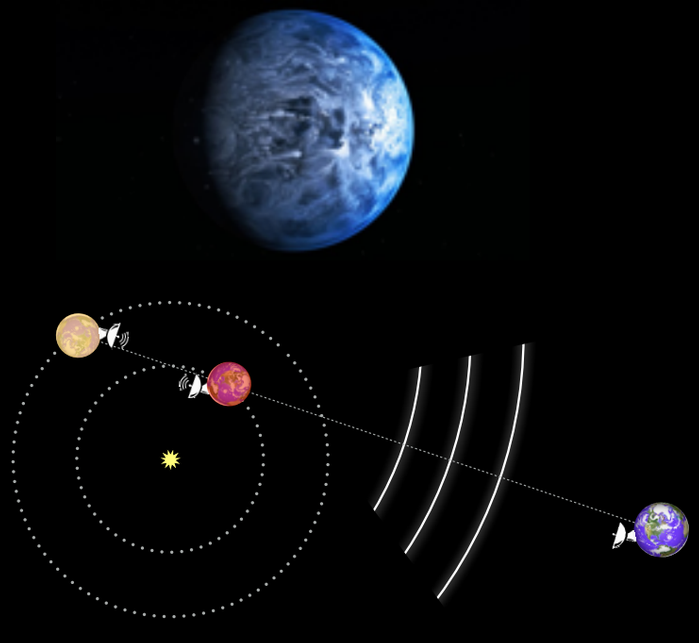


247 Nearby Target Galaxies
Within 11 Mpc
Breakthrough *LISTEN*



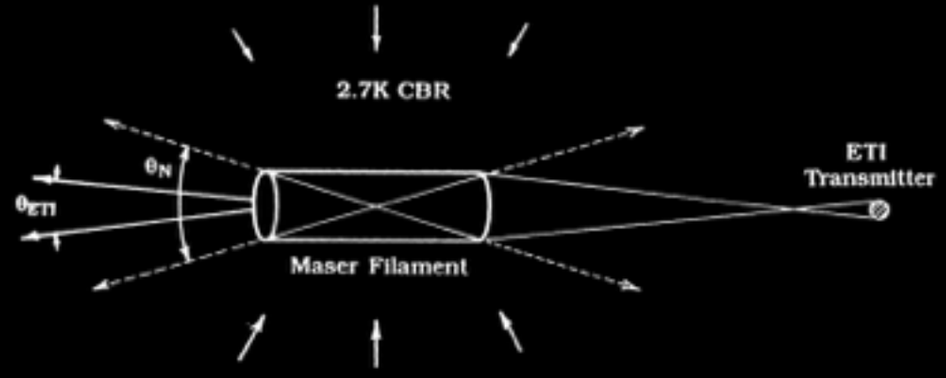
NEARGALCAT
(Karachentsev, Makarov, Kaisina, AJ, 2013)

Other Targets…



Known Earth-like Exoplanets or Solar System-like Exoplanet Systems

Serendipitous Alignments, e.g. multiple exoplanets in a single system along a line of sight to the Earth, “eavesdropping SETI”

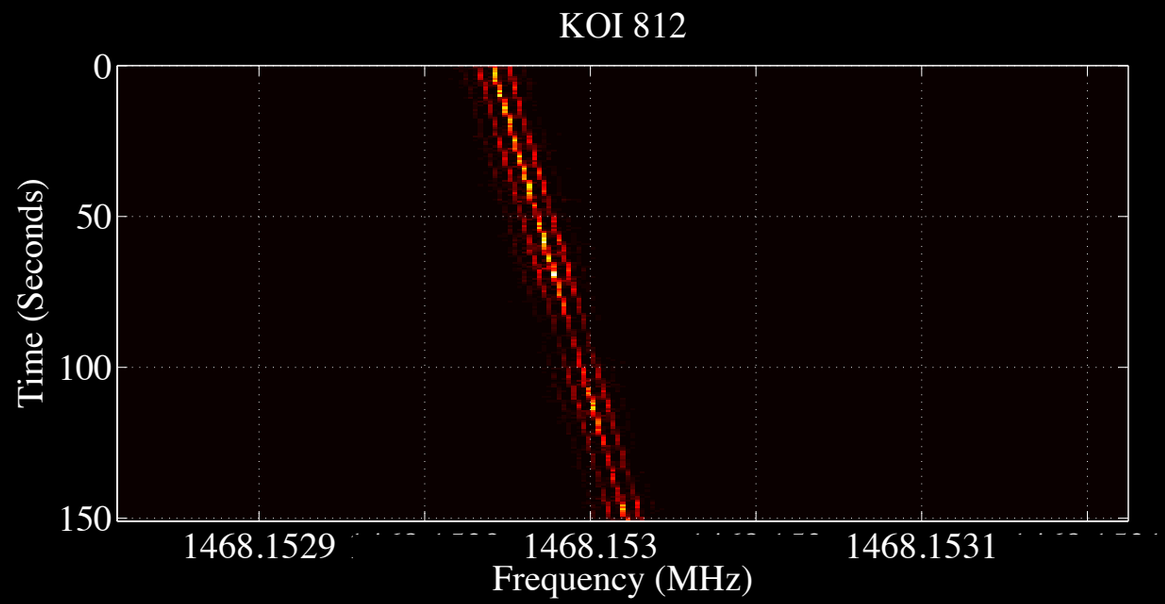


Exotica, e.g. natural amplifiers, astrophysical masers, a la Cordes, 1993

Globular Clusters (Rosanne DiStefano et al)

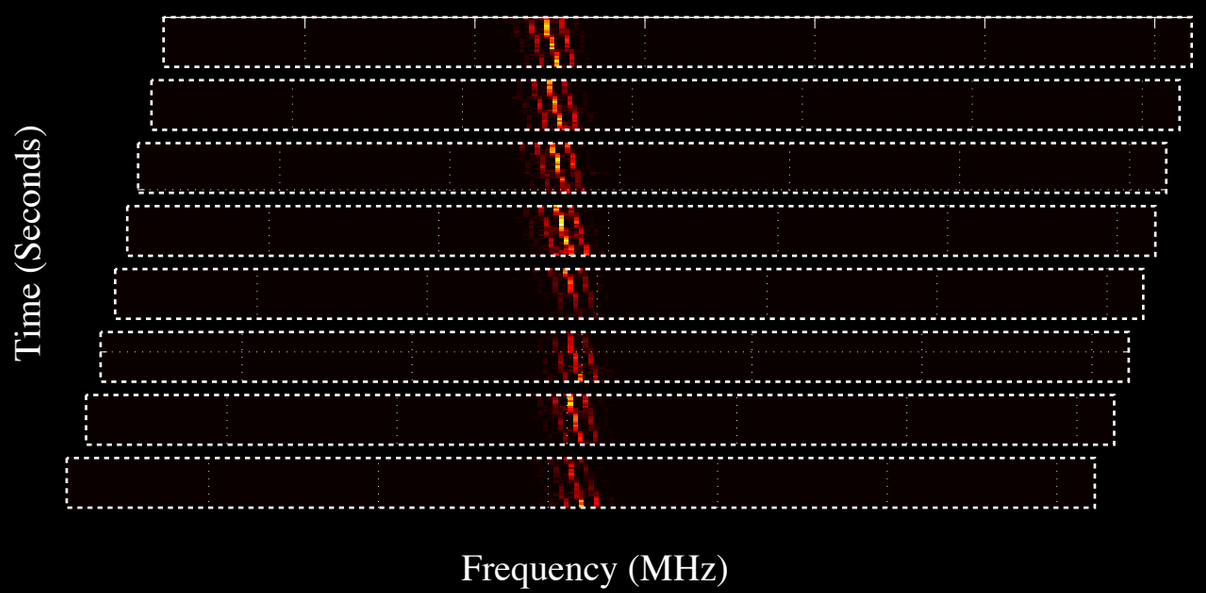
Narrow-band Signals

- Low energy - Radio photons are cheap
- Easy to generate, easy to receive - Earth technology makes photons look attractive



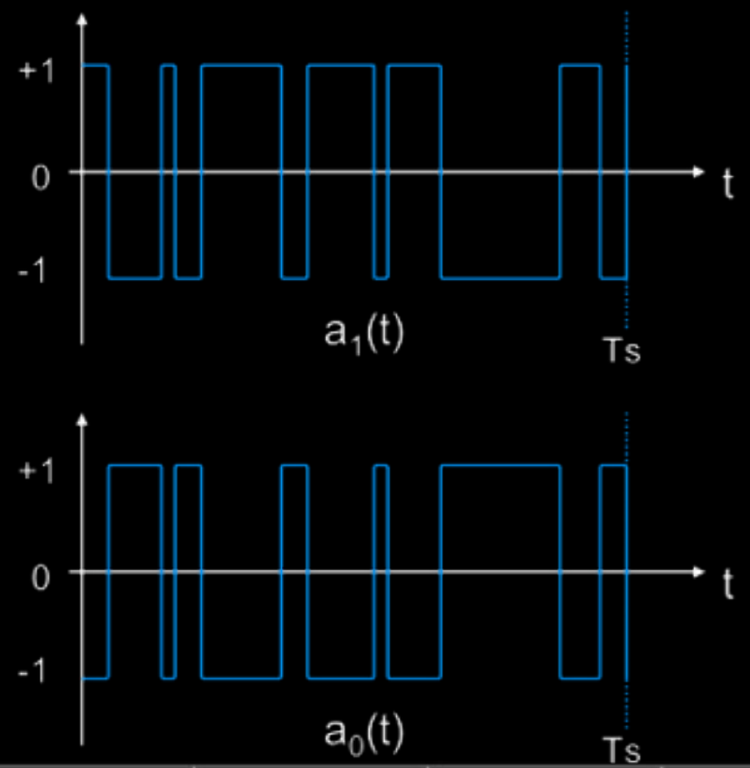
- As fast as possible - c
- Easily distinguished from natural sources - narrowest astrophysical sources 100s of Hz wide (masers) - very few astrophysical sources with nanosecond structure.
- Robust to the interstellar medium

Doppler "drift" correction

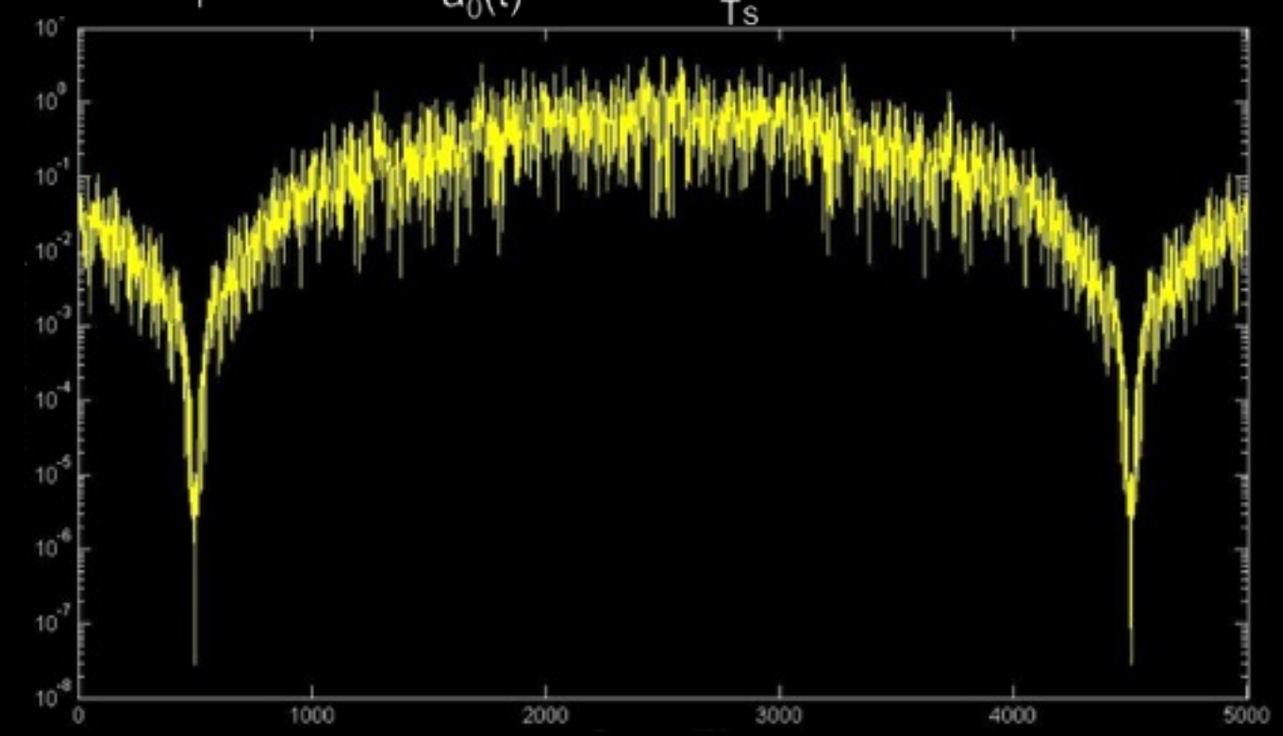


Broadband Emission

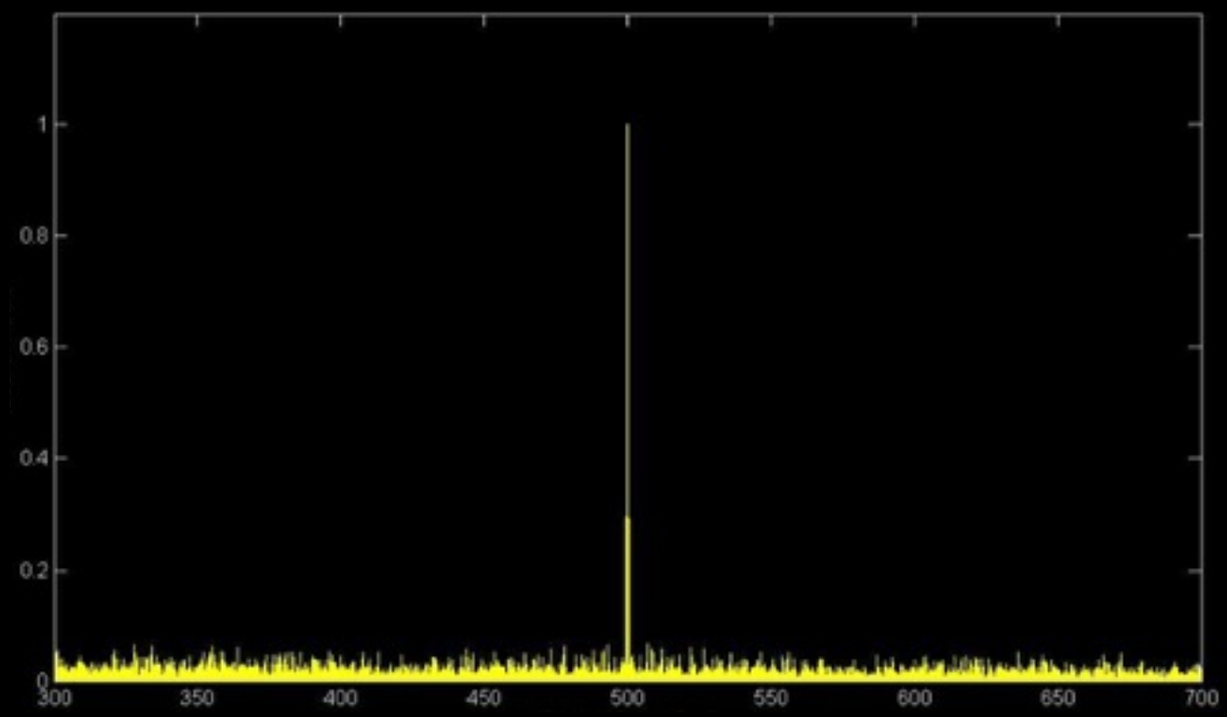
An example… Binary Phase Shift Keying (BPSK)



- Modern radio communication largely broadband
- Preferable for interference robustness
- Wide bandwidths permit rich information content



Power Spectrum

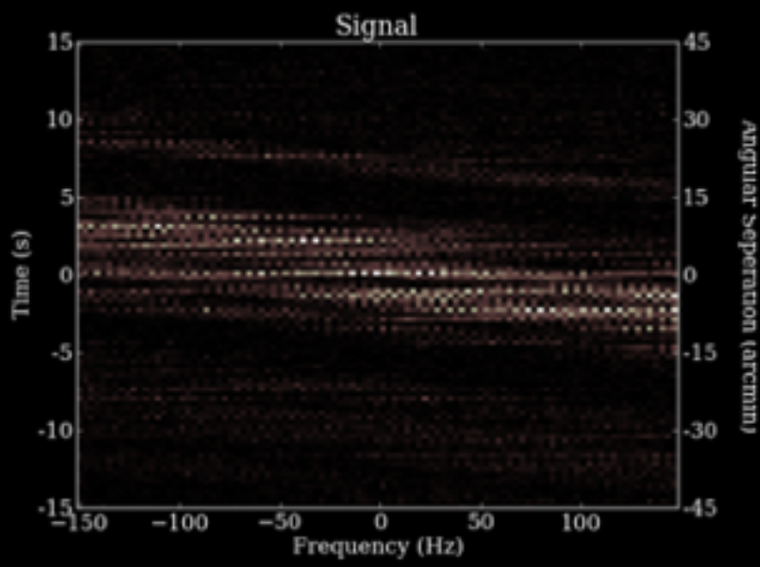


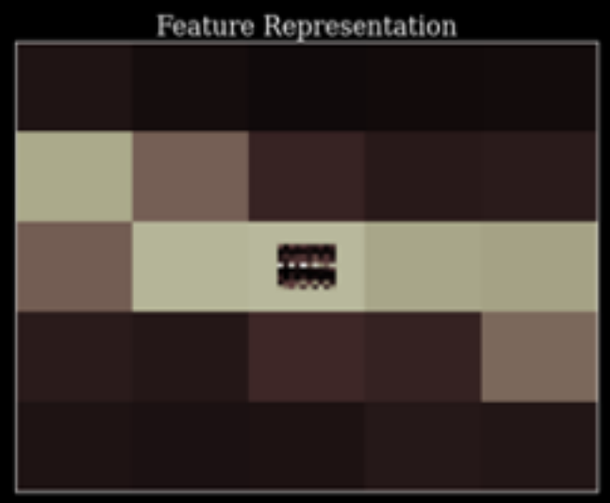
Auto Correlation

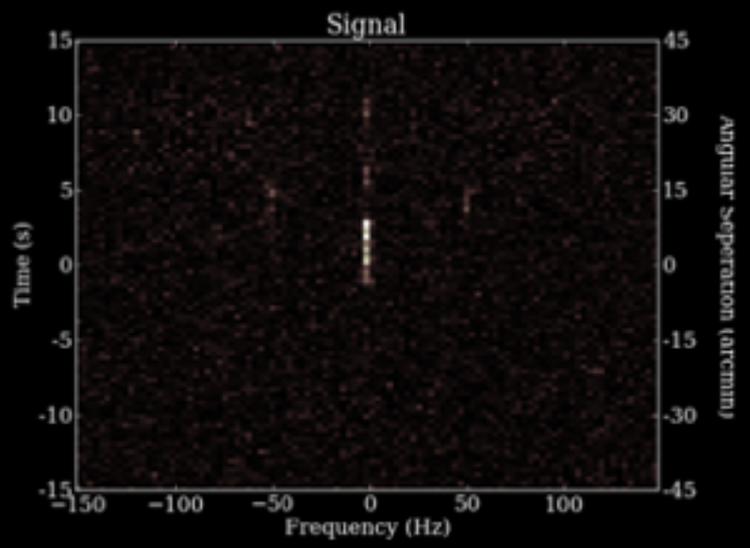
Machine Learning-based Searches

- Local Outlier Factor (LOF) ranking approach
  - Find those signals that are most isolated in 150-dimensional feature space.

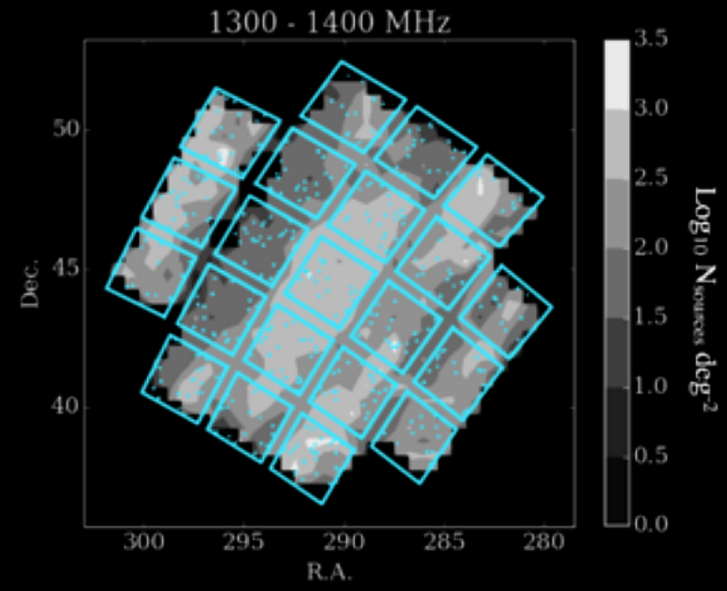
Breunig et al. 2000

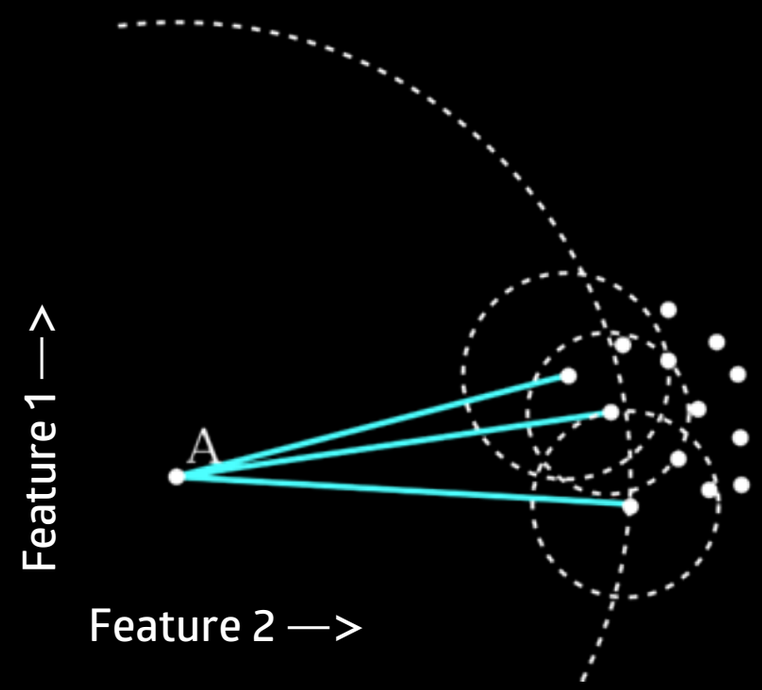






Issac Shivvers et al.

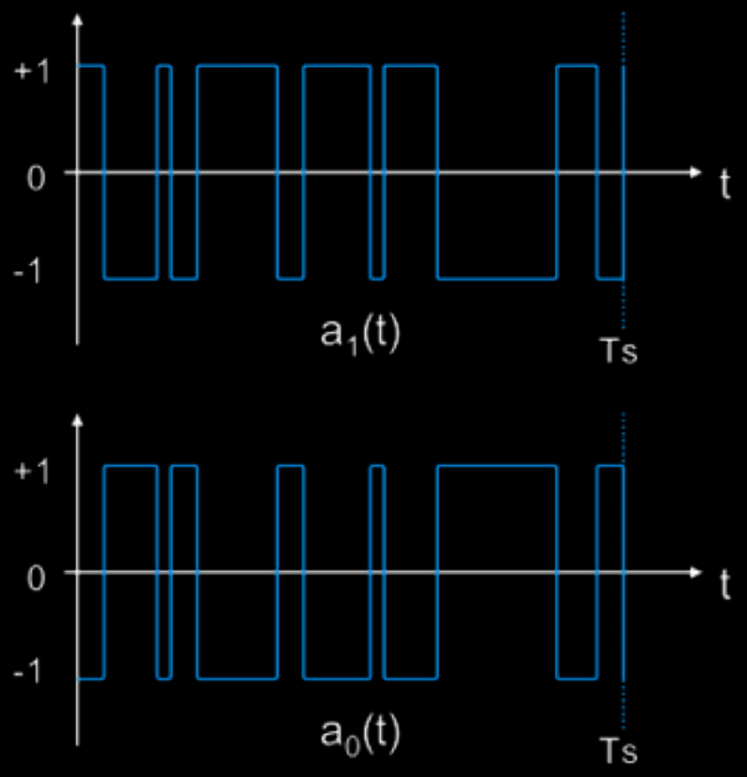


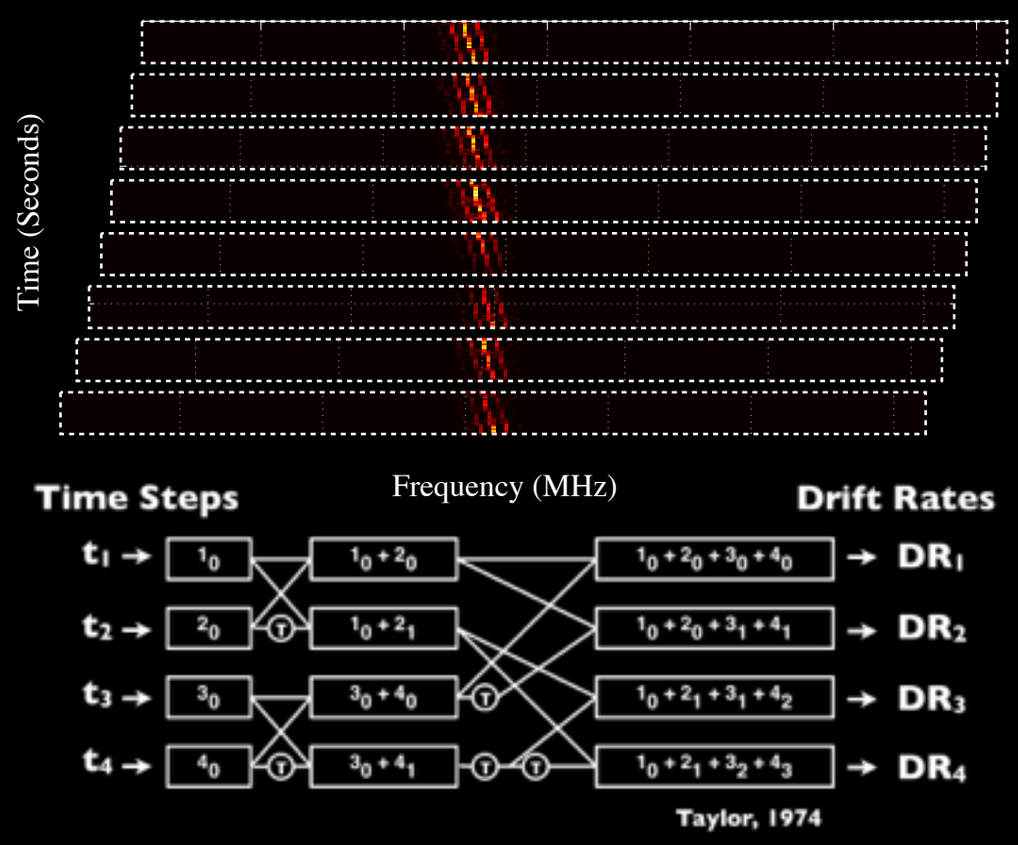


Illustrating LOF using a neighborhood of k=3

Wikimedia

An “Open Source SETI Analysis Toolkit”





jupyter

docker

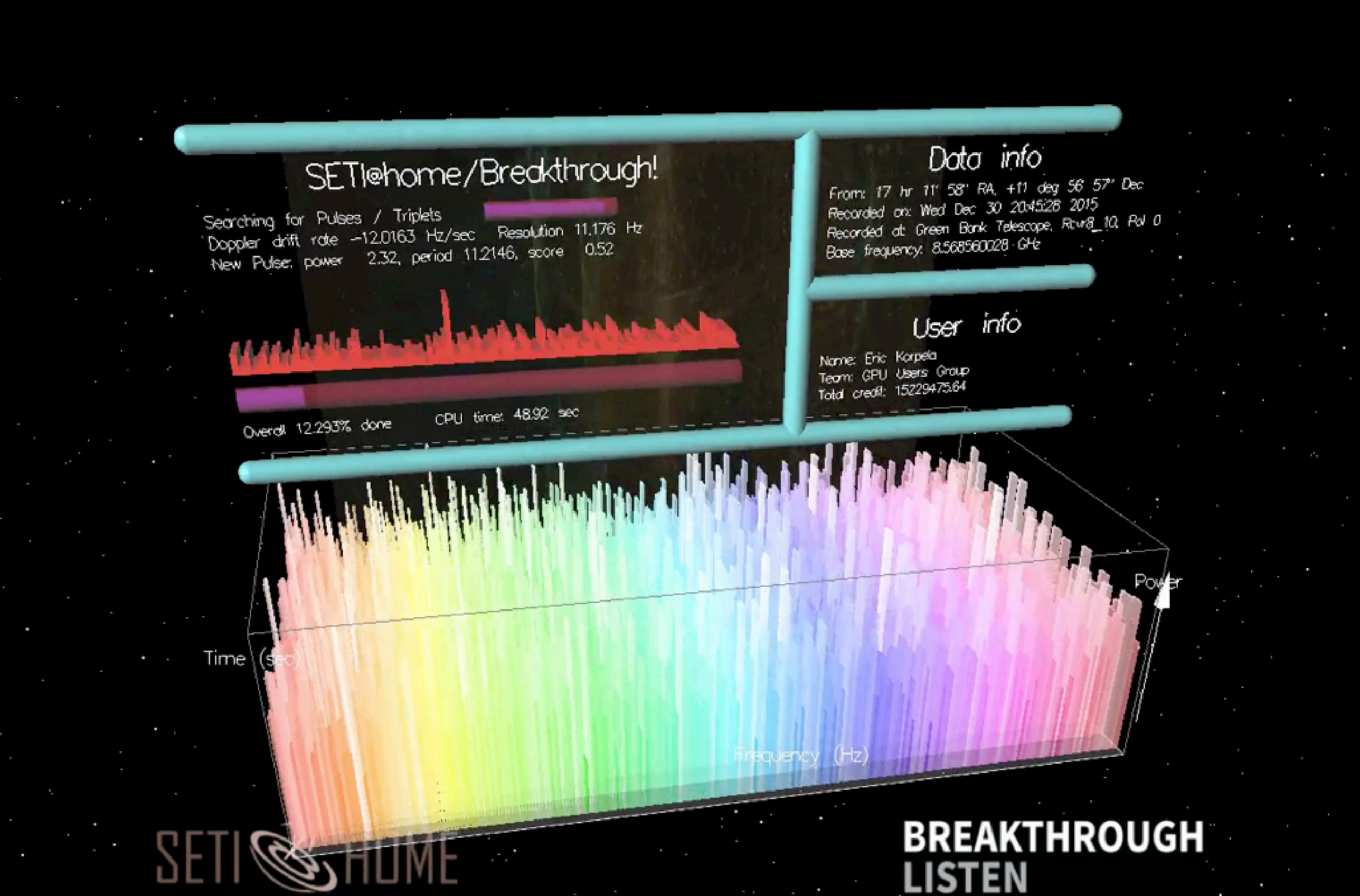
GitHub

amazon web services

Google Cloud Platform

COLLABORATORS WANTED!

siemion@berkeley.edu


SETI@home/Breakthrough!
Searching for Pulses / Triplets
Doppler drift rate -12.0163 Hz/sec Resolution 11.176 Hz
New Pulse: power 2.32, period 11.2146, score 0.52
Overall 12.293% done
CPU time: 48.92 sec
Data info
From: 17 hr 11' 58" RA, +11 deg 56 57" Dec
Recorded on: Wed Dec 30 20:45:28 2015
Recorded at: Green Bank Telescope, Rcvr8_10, Pol 0
Base frequency: 8.568560028 GHz
User info
Name: Eric Korpela
Team: GPU Users Group
Total credit: 1522947.64
Time (sec)
Frequency (Hz)
Power
SETI HOME
BREAKTHROUGH
LISTEN

BERKELEY SETI RESEARCH CENTER

SETI@HOME

BREAKTHROUGH LISTEN

Work Units Sent
41.6/sec

Work Units Received
41.6/sec

This map shows SETI@home transmissions during a period of five minutes collected within the past 24 hours, and includes IP2Location LITE data available from ip2location.com.

Berkeley

Green Bank

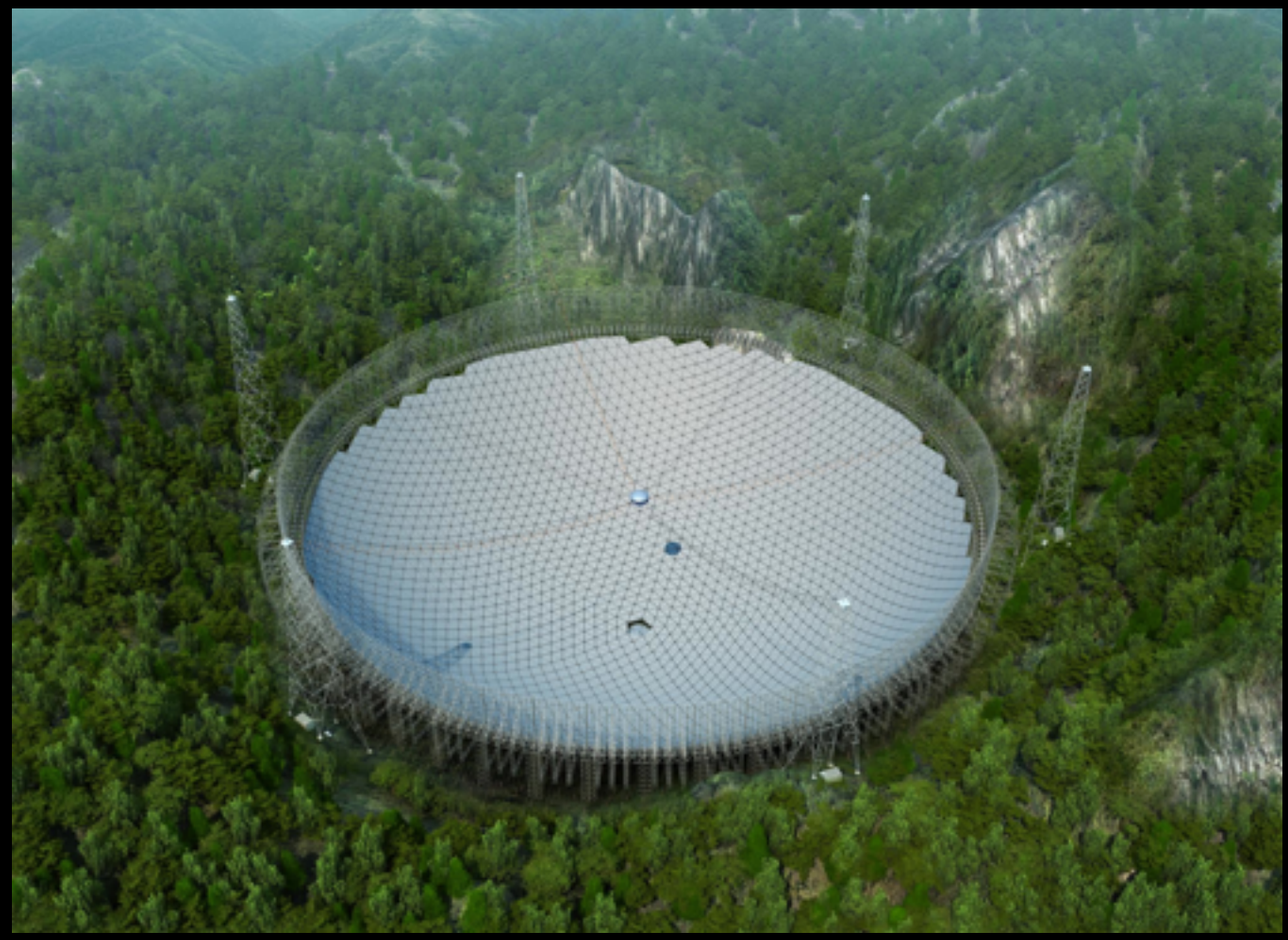
Parkes

SETI@home is a scientific experiment that uses Internet-connected computers in the Search for Extraterrestrial Intelligence (SETI).

Future Opportunities…

MeerKAT - South Africa
64 15m dishes - a ‘Southern JVLA’

MWA - Australia
2048 dipole antennas - 80-300 MHz



FAST - China
500m single dish - a ‘Super Arecibo’

SEARCHING FOR EXTRATERRESTRIAL INTELLIGENCE WITH THE

SKA

SQUARE KILOMETRE ARRAY

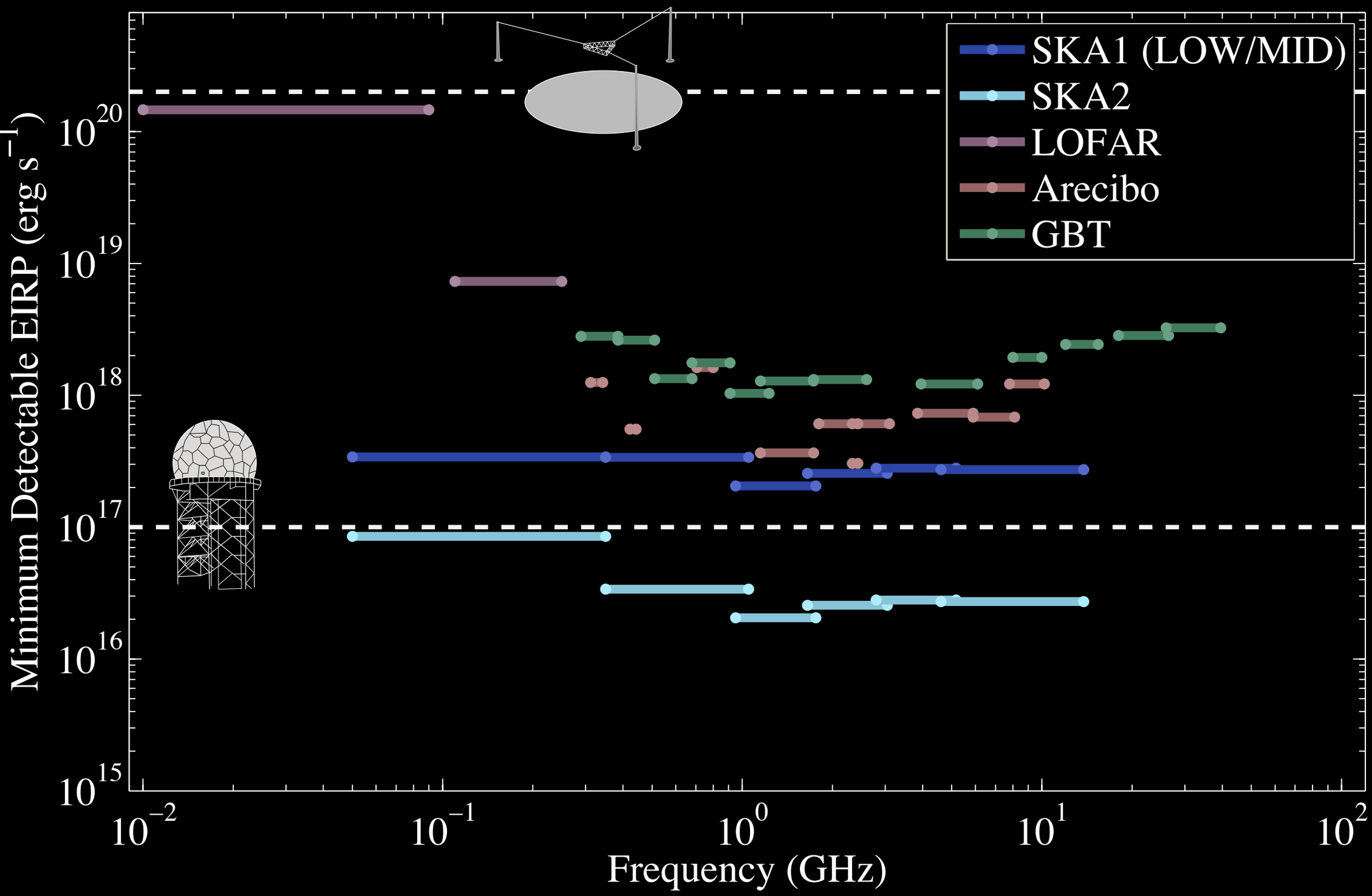
WITH… JAMES BENFORD, JIN CHENGJIN, JAYANTH CHENNAMANGALAM, JIM CORDES, FRANK DRAKE, HEINO FALCKE, DUNCAN FORGAN, MIKE GARRETT, SIMON GARRINGTON, LEONID GURVITS, MELVIN HOARE, ERIC KORPELA, JOSEPH LAZIO, DAVID MESSERSCHMITT, IAN S. MORRISON, TIM O'BRIEN, ZSOLT PARAGI, ALAN PENNY, LAURA SPITLER, JILL TARTER, DAN WERTHIMER

SETI ON THE SKA

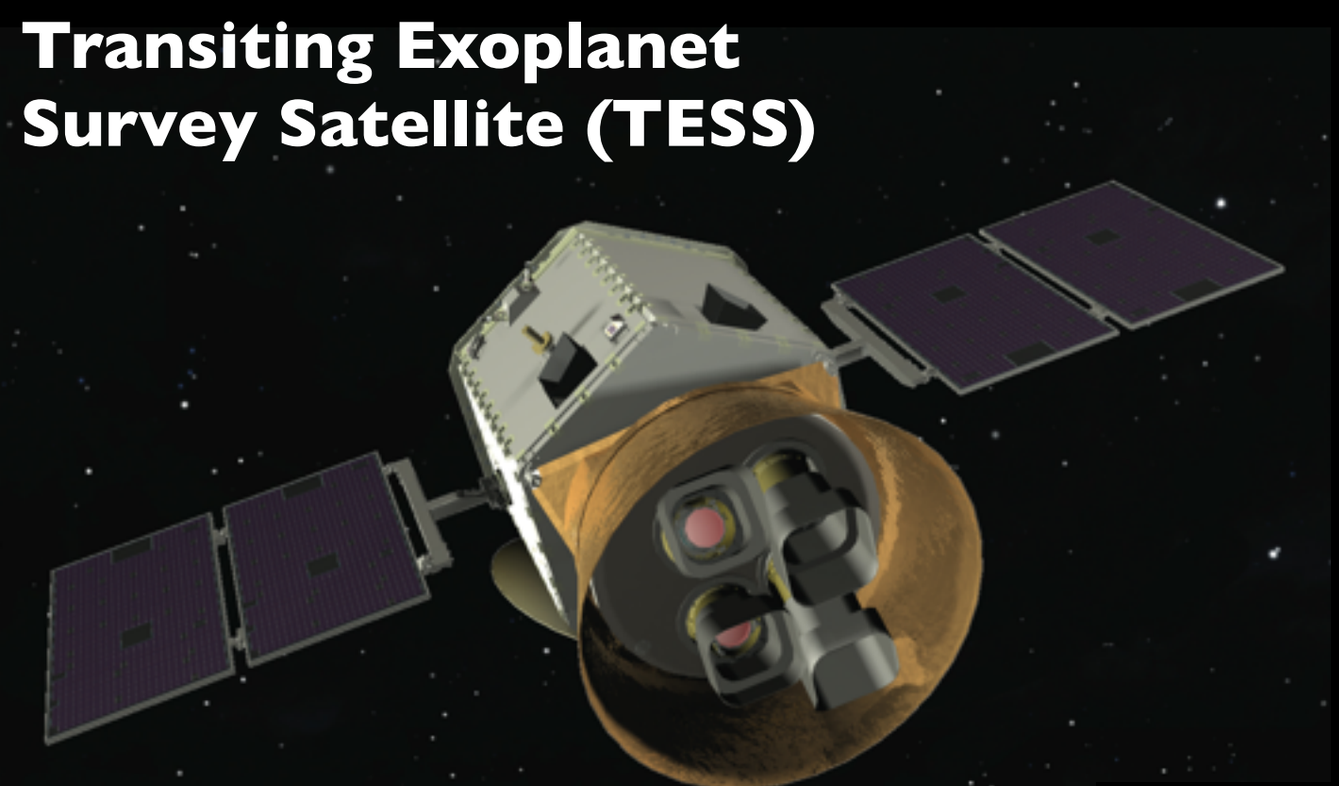
SQUARE KILOMETRE ARRAY

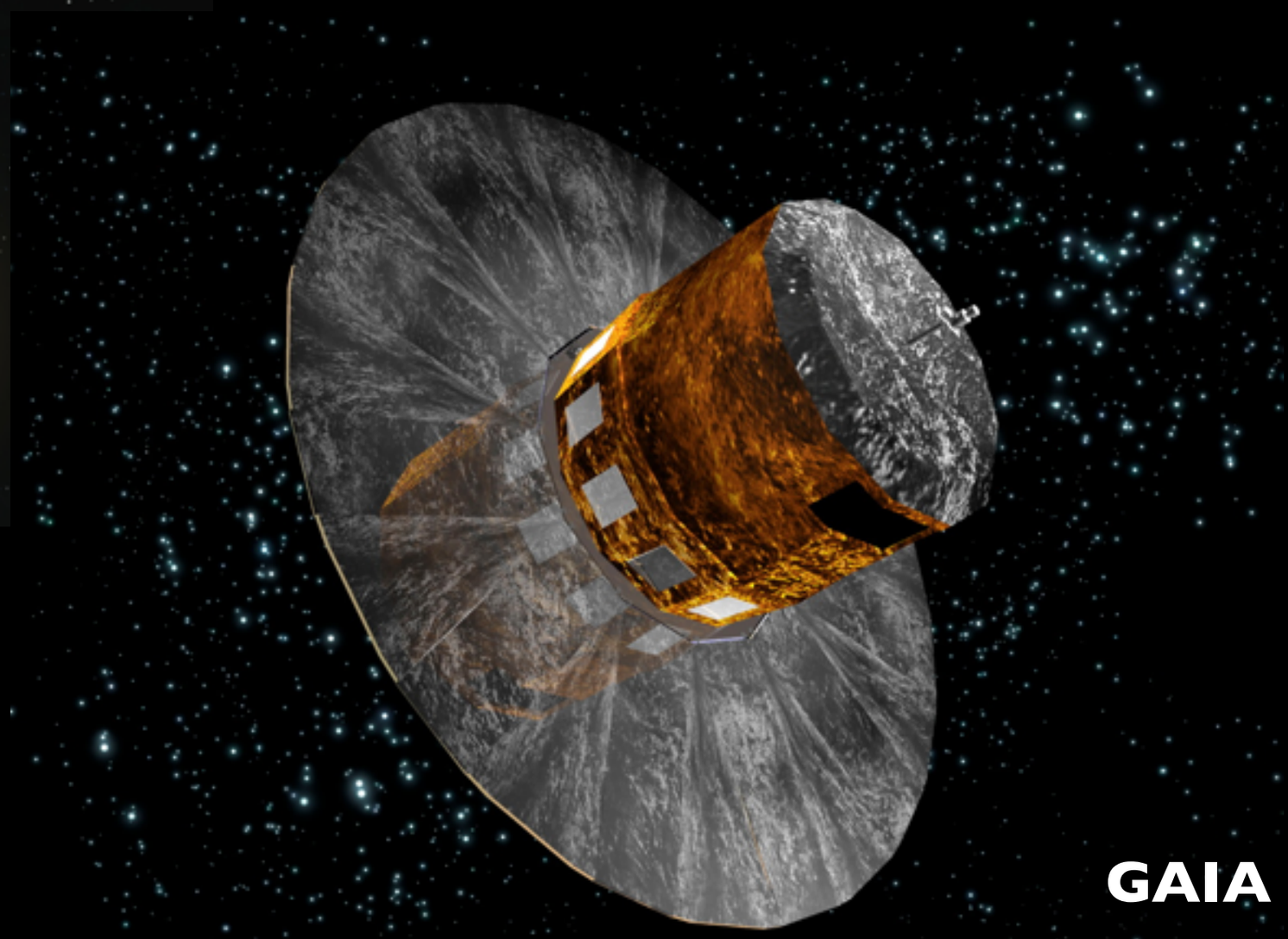
FOR AN EXTRATERRESTRIAL TRANSMITTER @ 50 LY

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



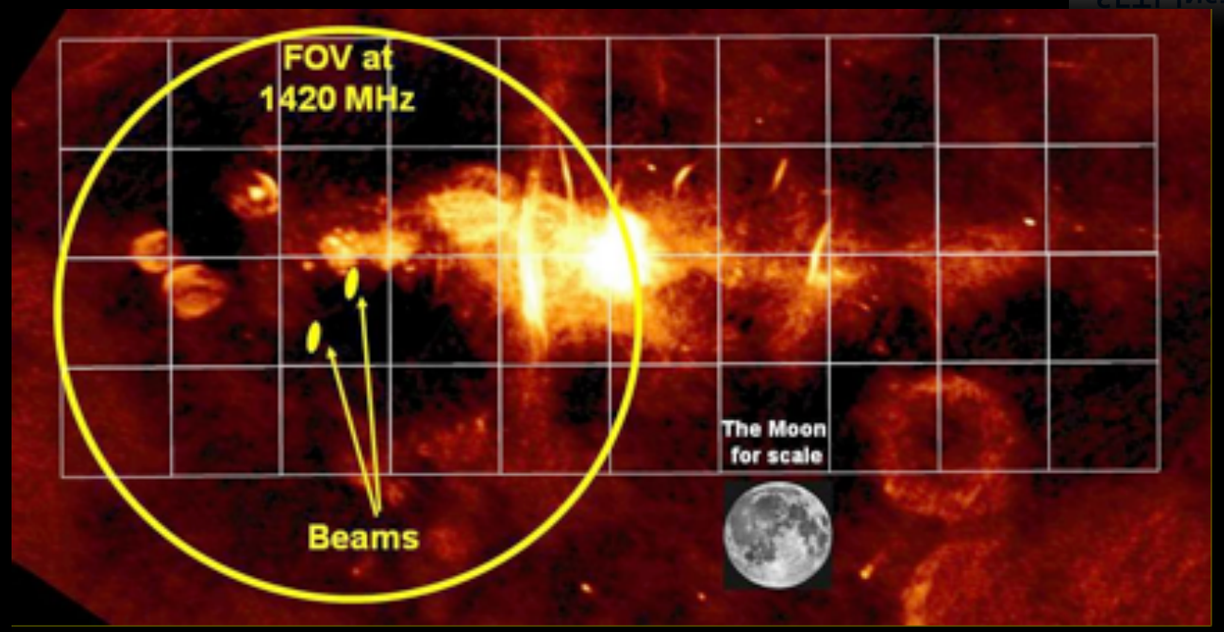
Transiting Exoplanet Survey Satellite (TESS)





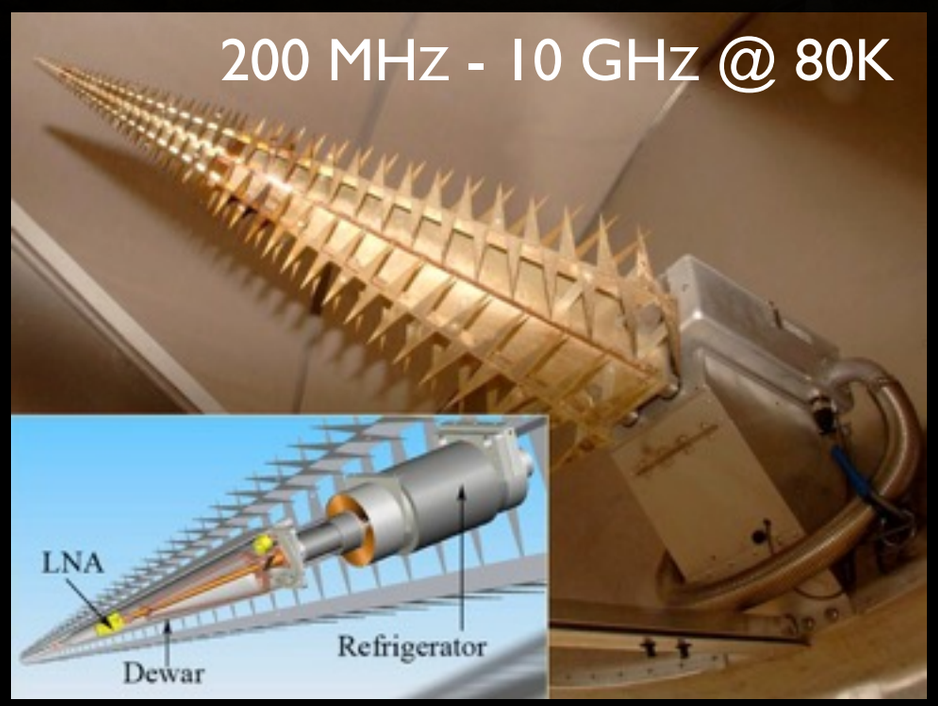
GAIA

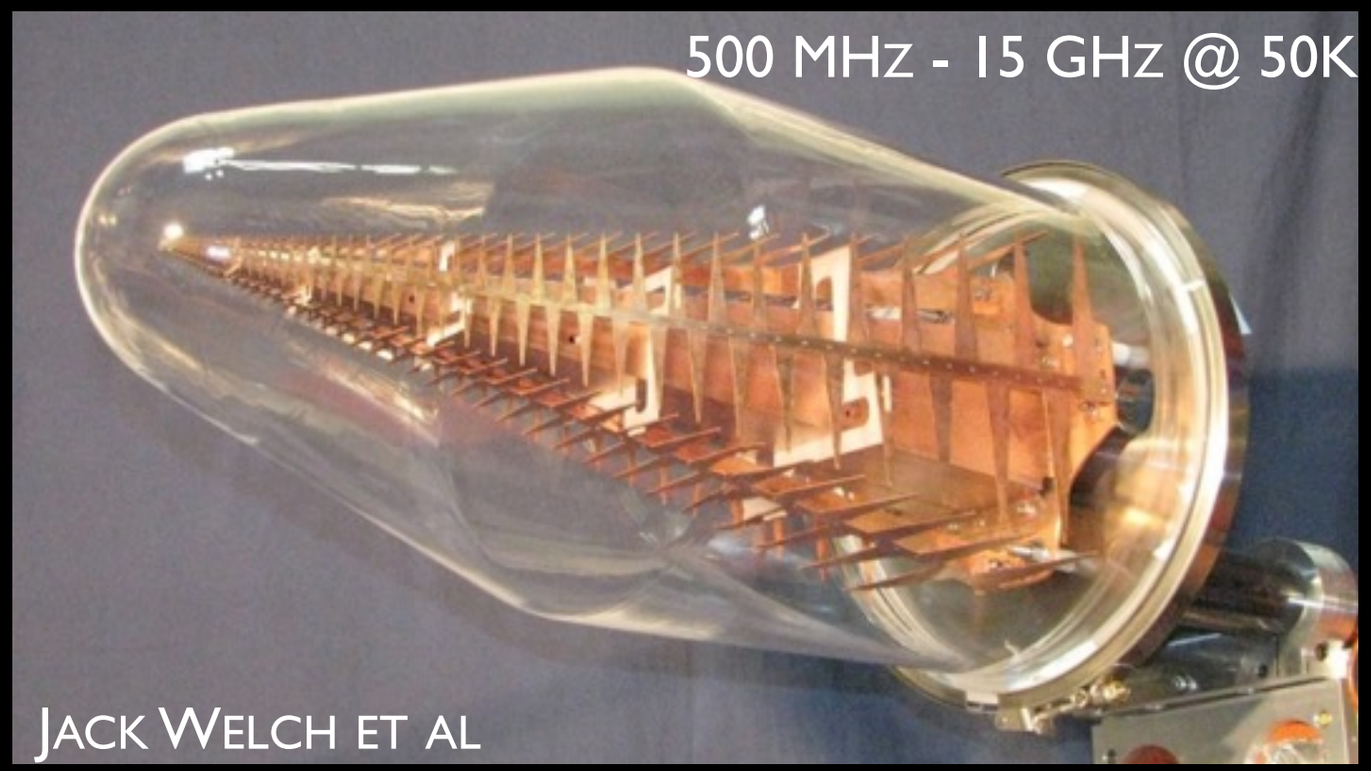
Allen Telescope Array



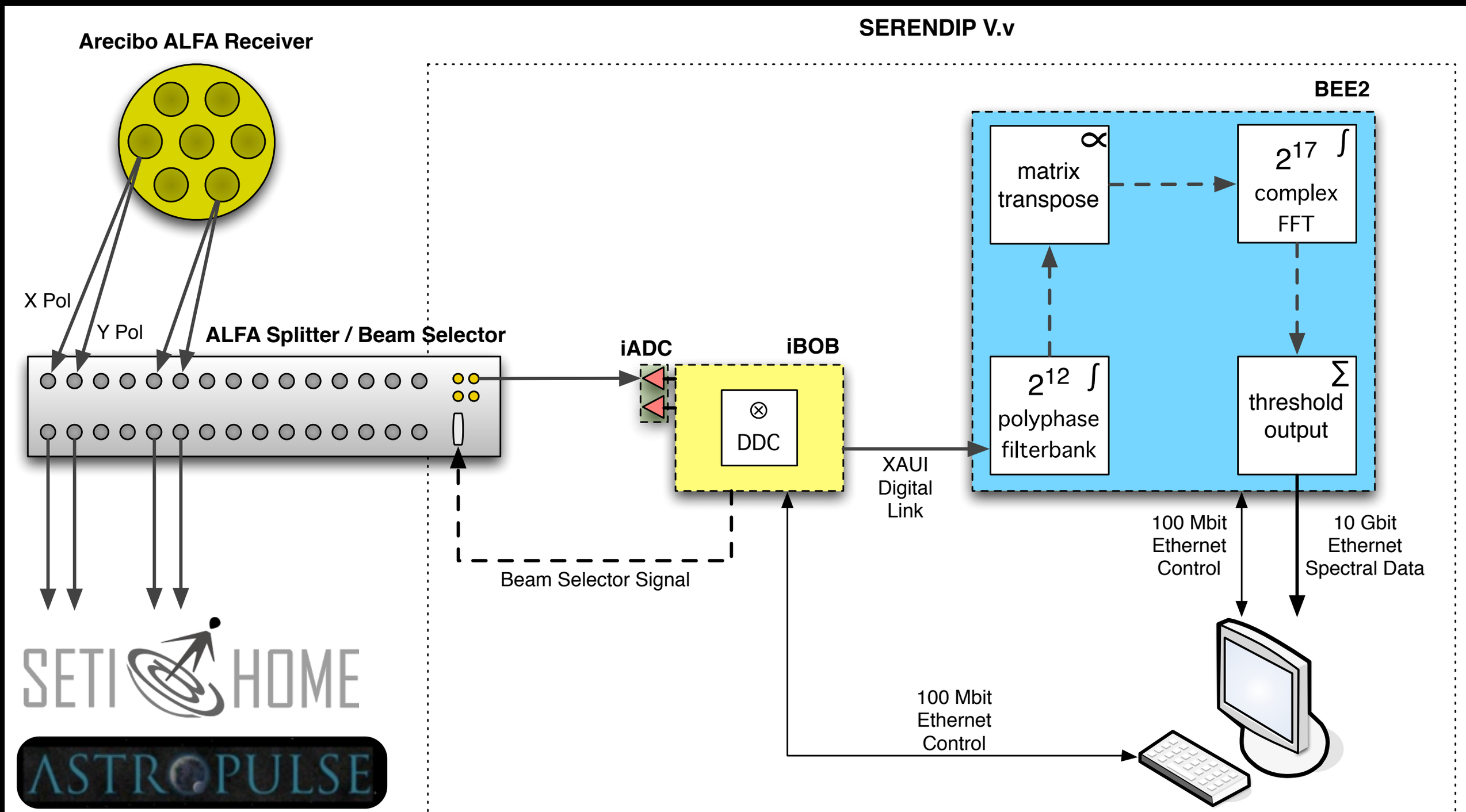
SETI Institute

"Antonio" Feed

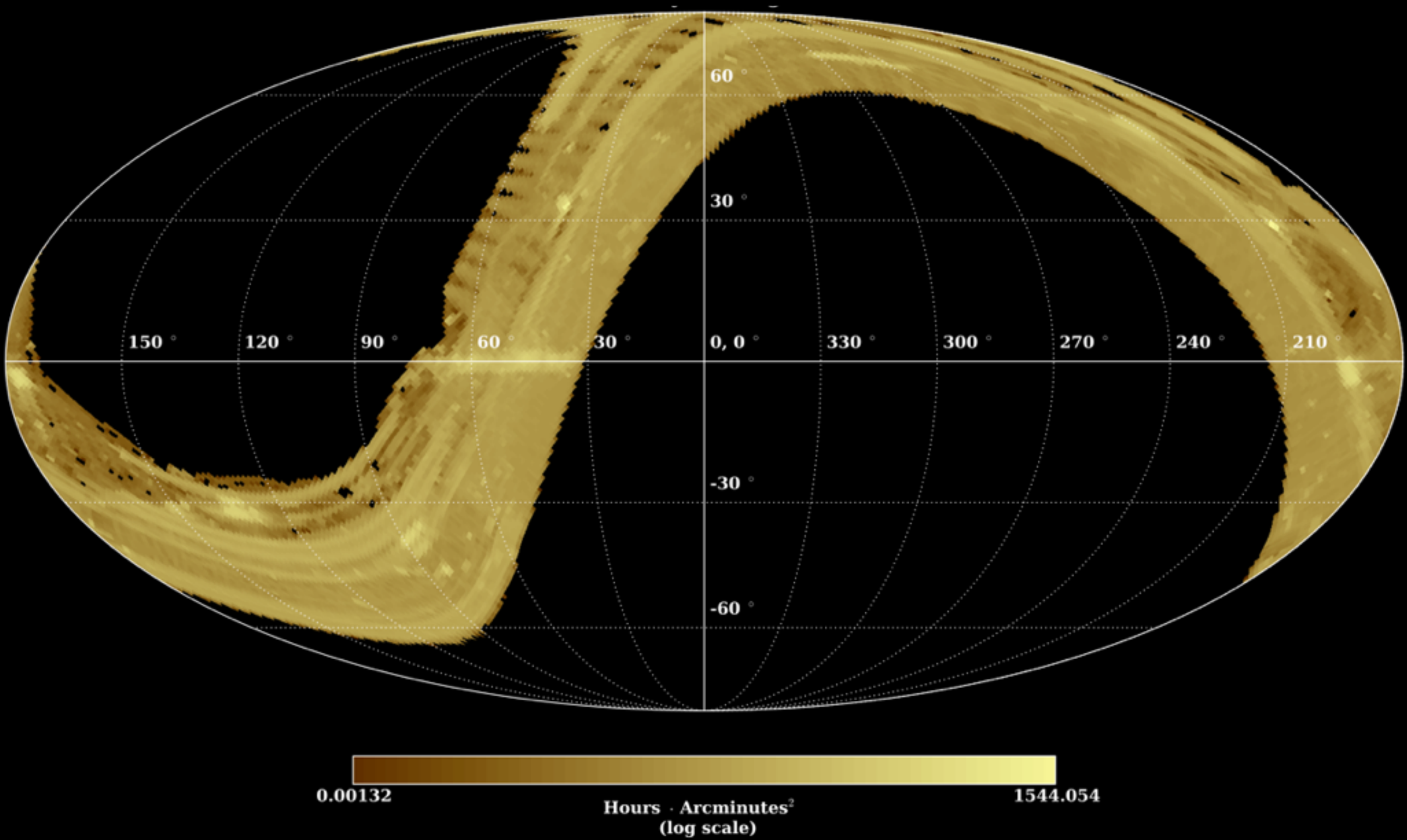




SERENDIP V.v (2012)

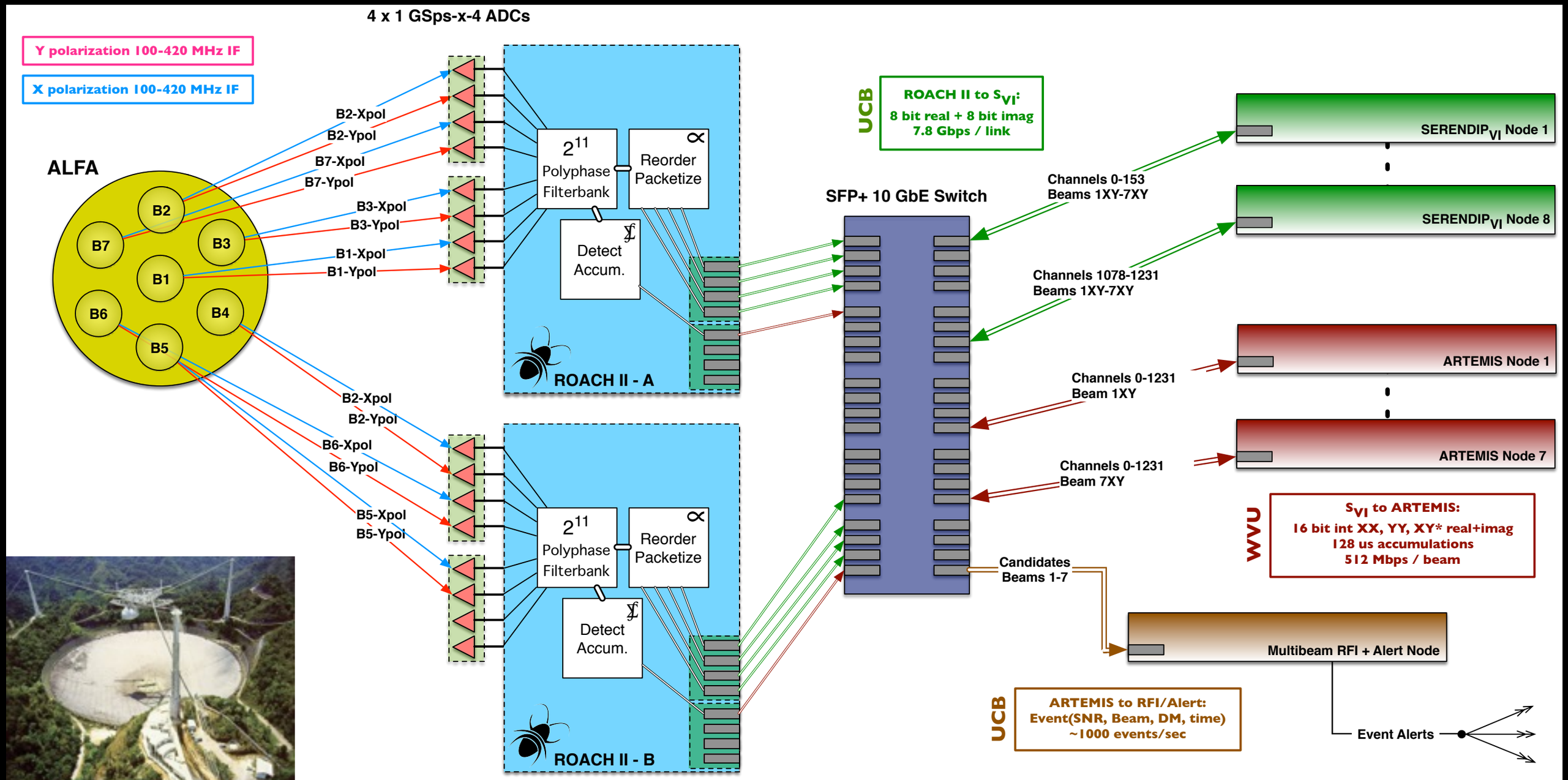


SERENDIP V.v
Sky Coverage 2009-2012: 6000 hours observed

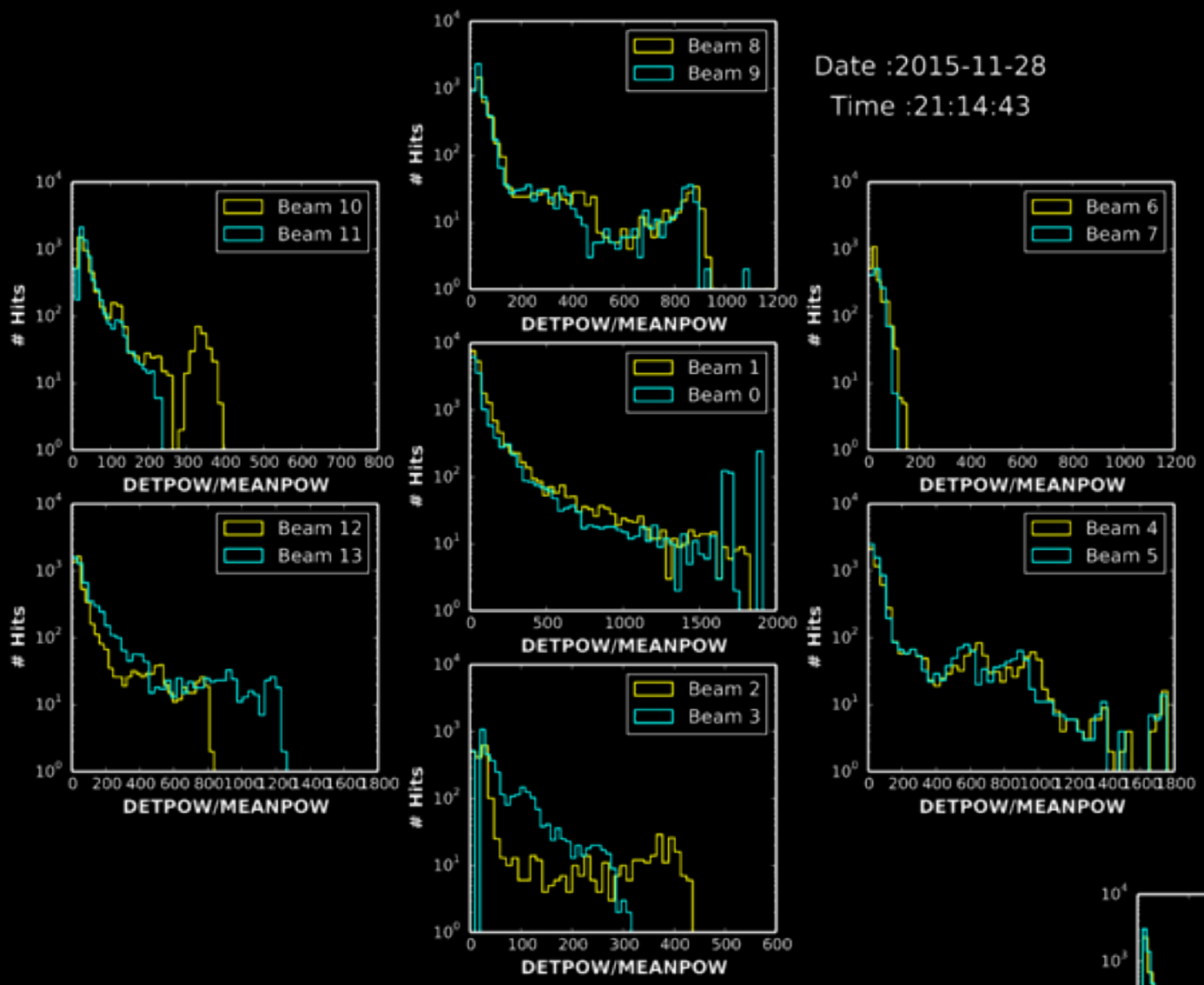


Siemion et al. (in prep)

SERENDIP VI / ALFABURST @ ARECIBO

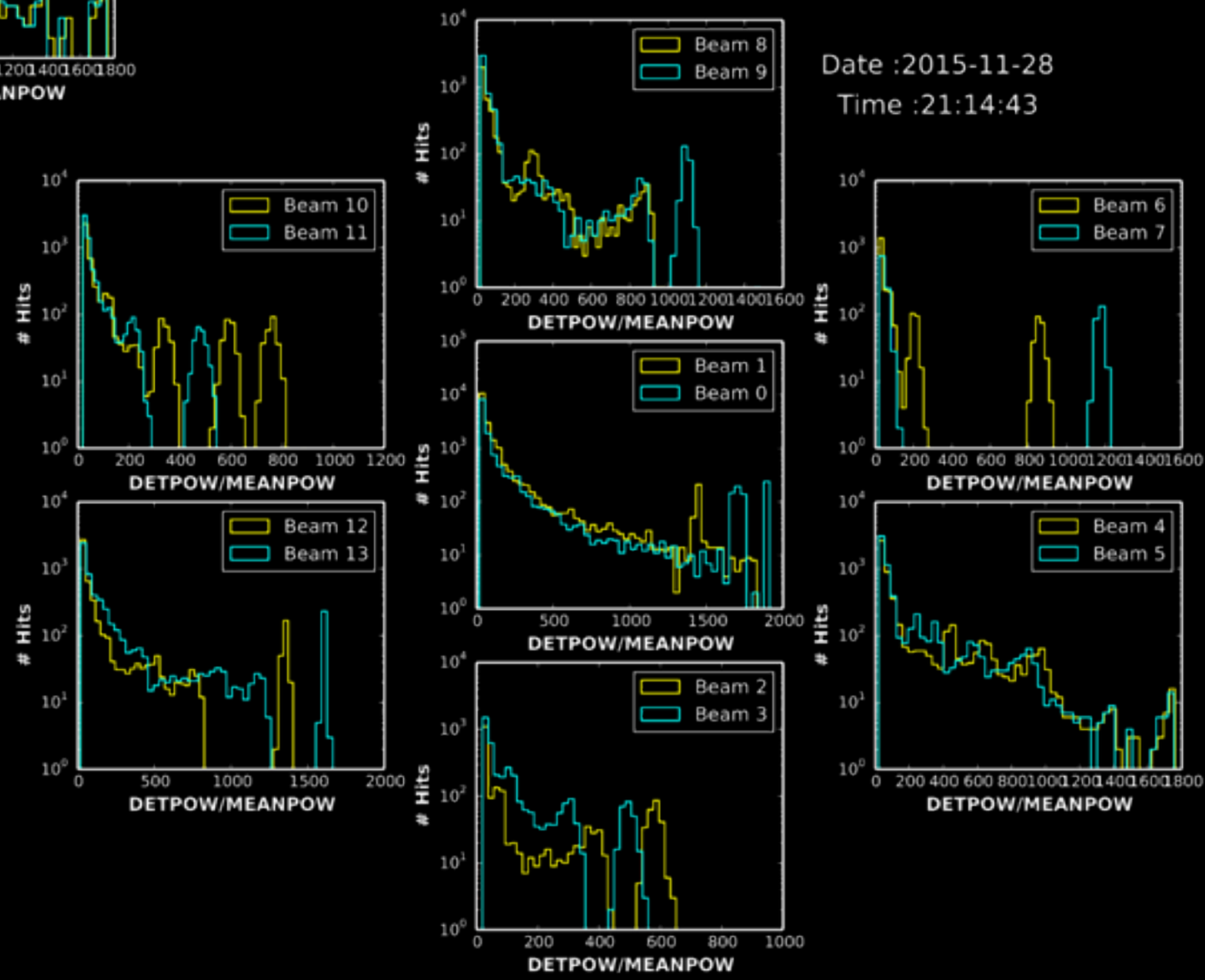


- 500 MHz - 2 GHz Bandwidth (dual polarization), sub-Hz spectroscopy, Doppler-drift searching, incoherent dedispersion pulse searching, interference rejection, all in real time.
- All open source hardware and software.
- Development Funded by NASA ASTID



Date :2015-11-28
Time :21:14:43

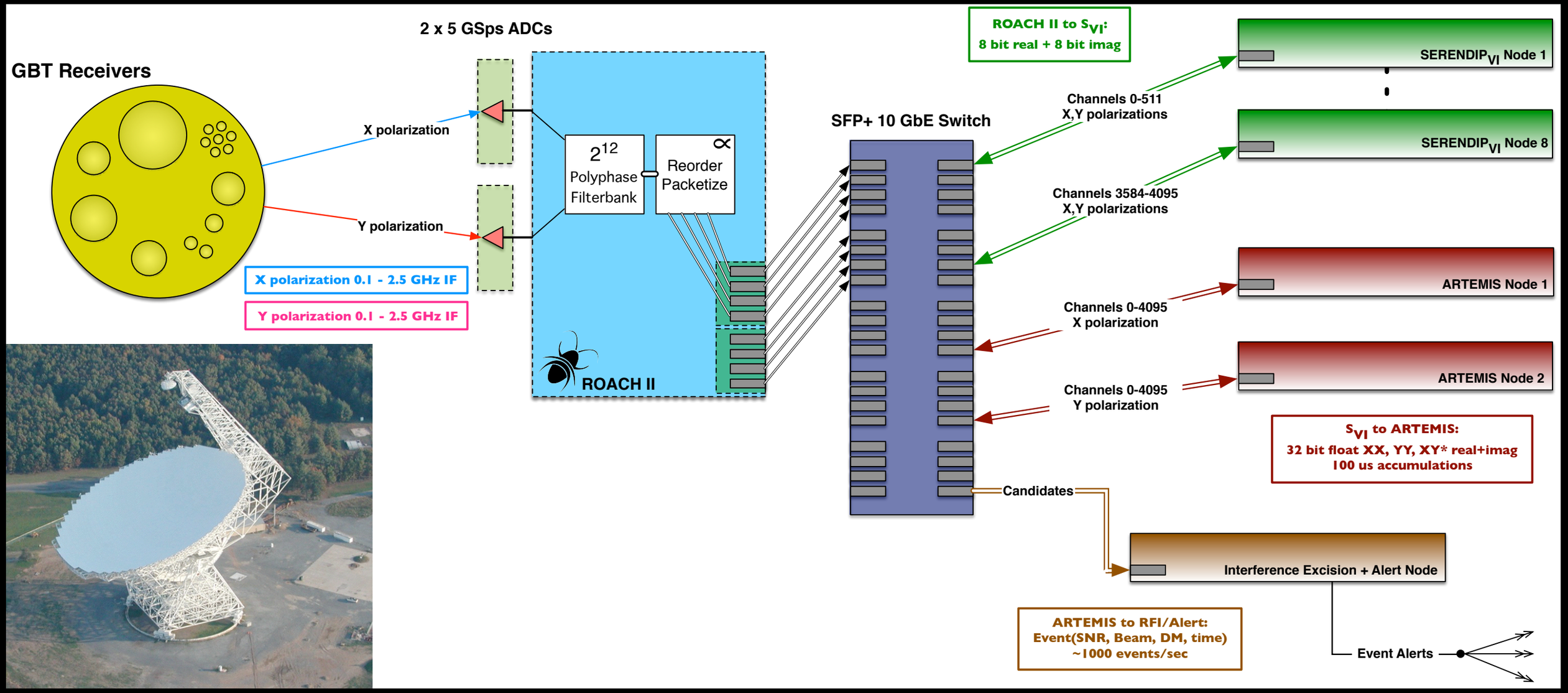
Before (top left) and after (bottom right)
Multibeam RFI Excision



Date :2015-11-28
Time :21:14:43

Vishal Gajjar (new UCB Postdoc)

Commensal Observations @ the Green Bank Telescope



- 2.5 GHz Bandwidth (dual polarization)
- Installation March 2015
- Will operate commensally with *all* receivers.

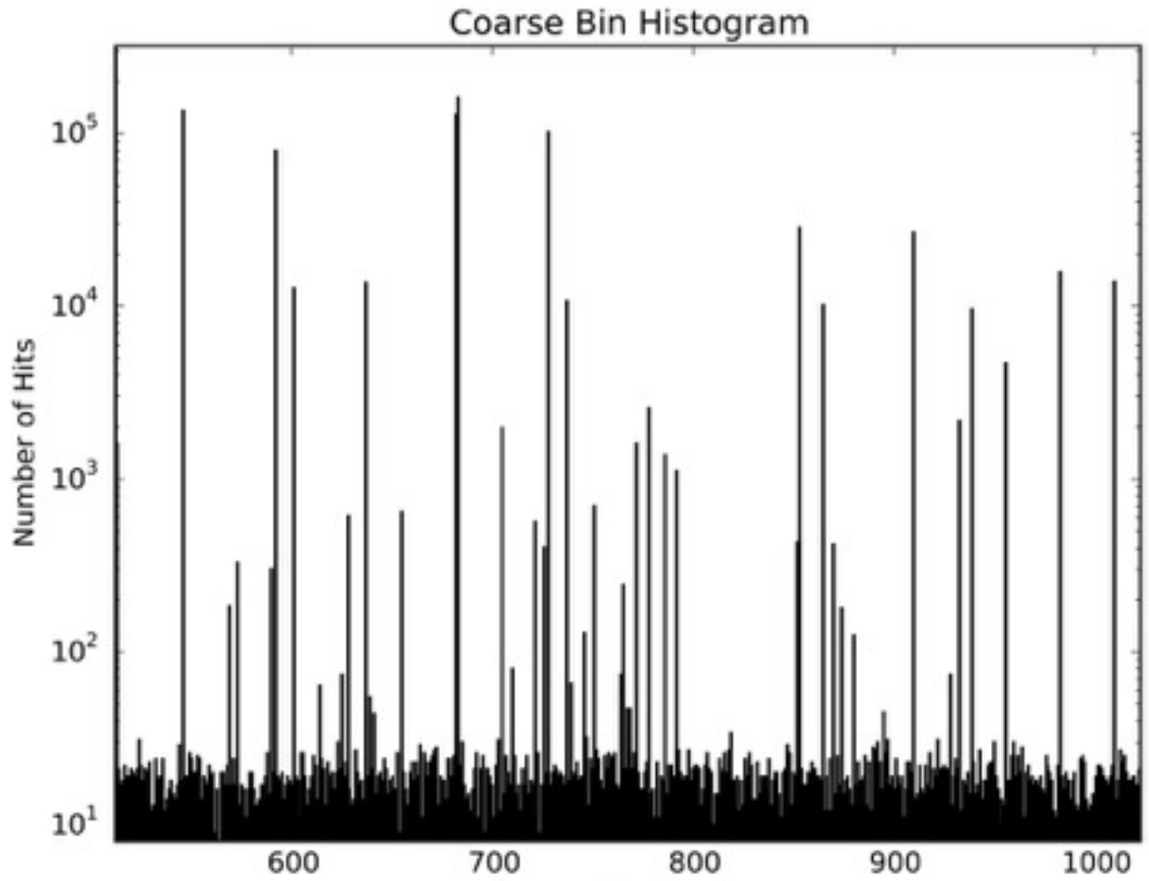
Data from GBT L-band

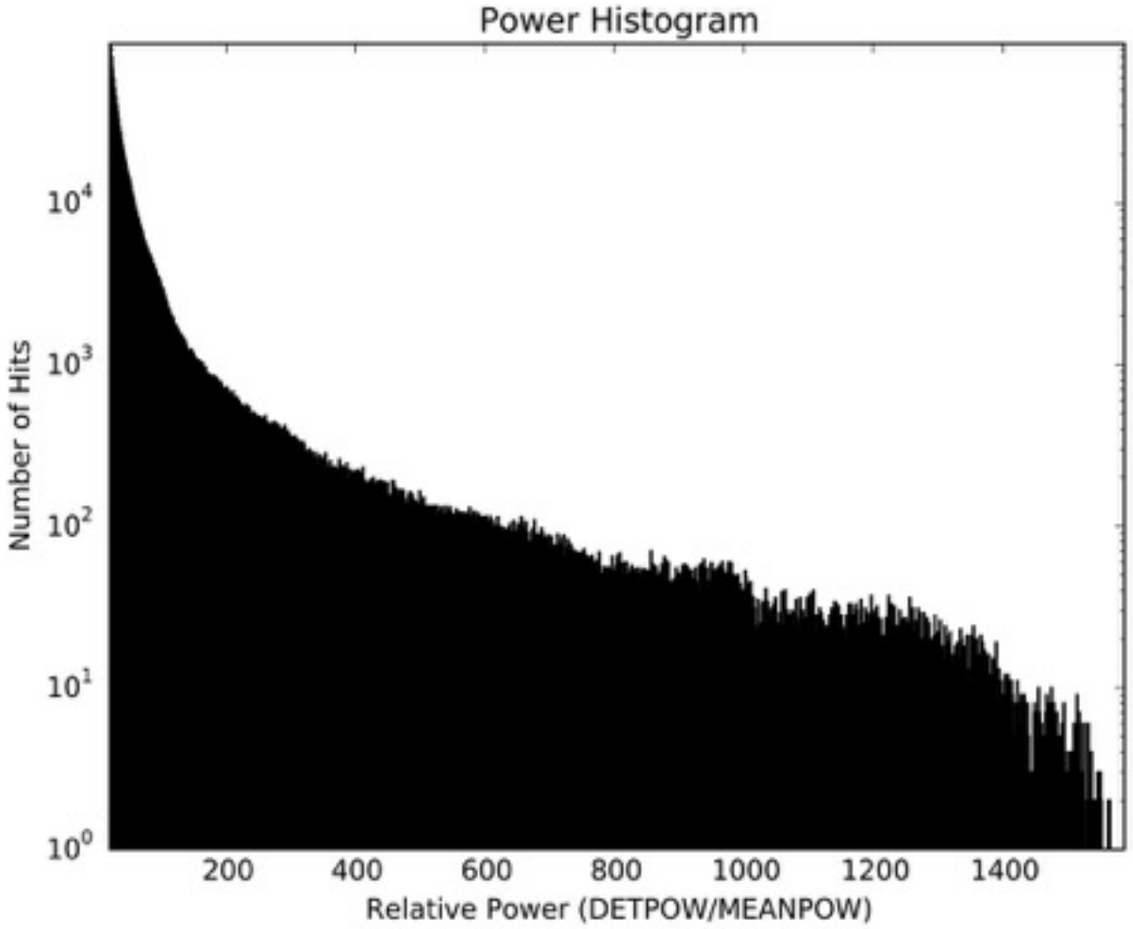
Date: 2015-11-29

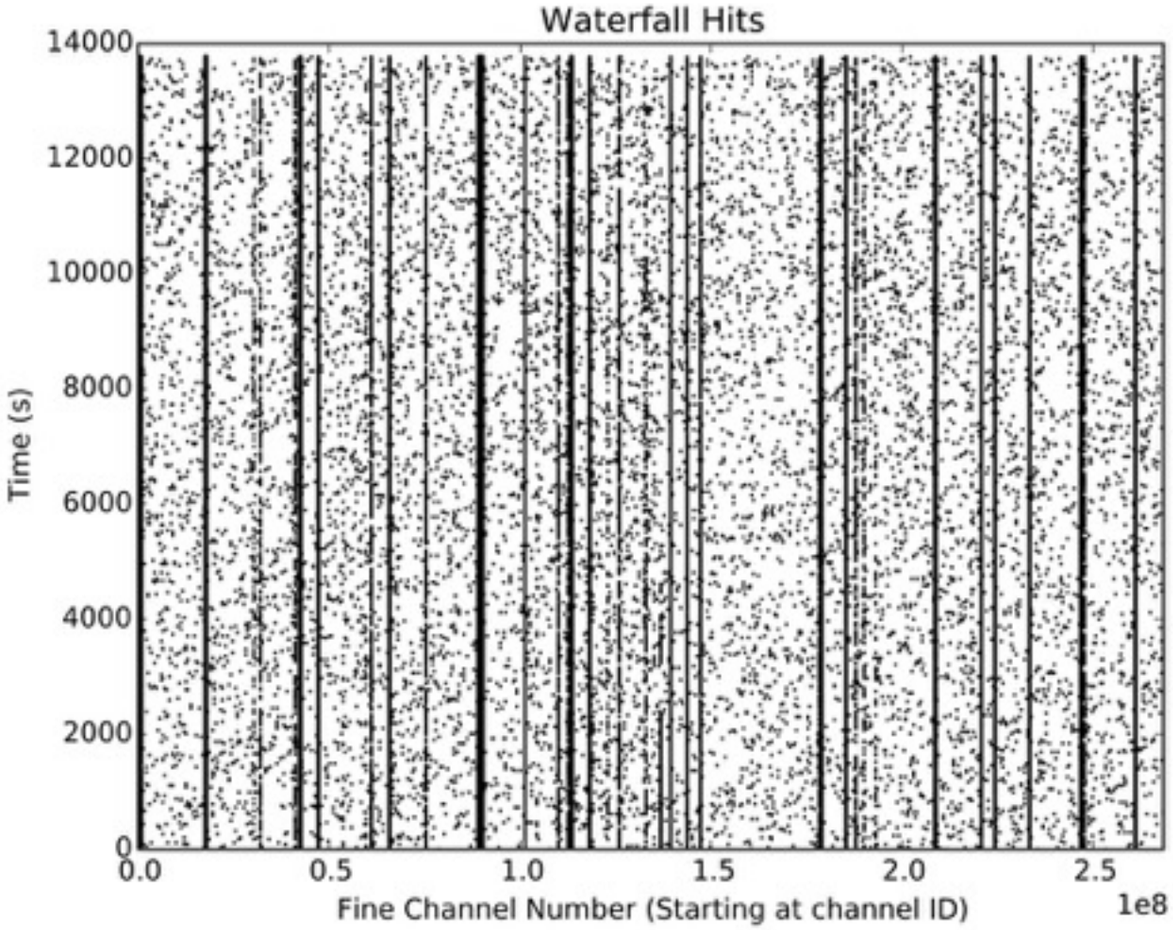
NHITS: 1101877

Duration: 229.42 Min

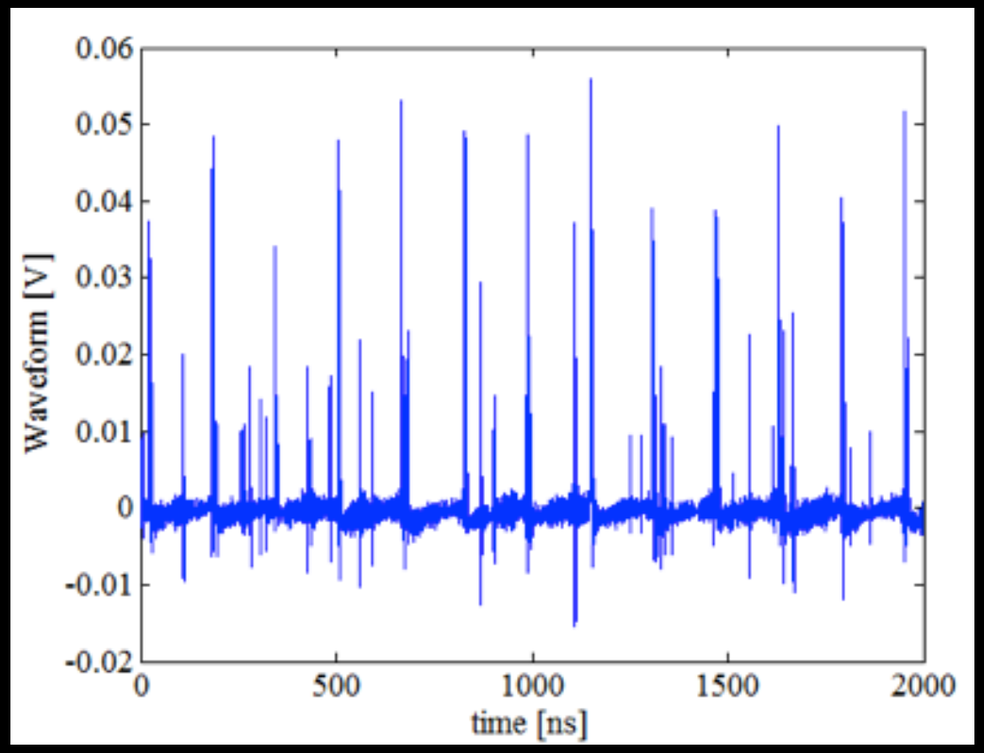
Kyle Archer, UCB UG







Pulsed Near-IR SETI at Lick Observatory, California



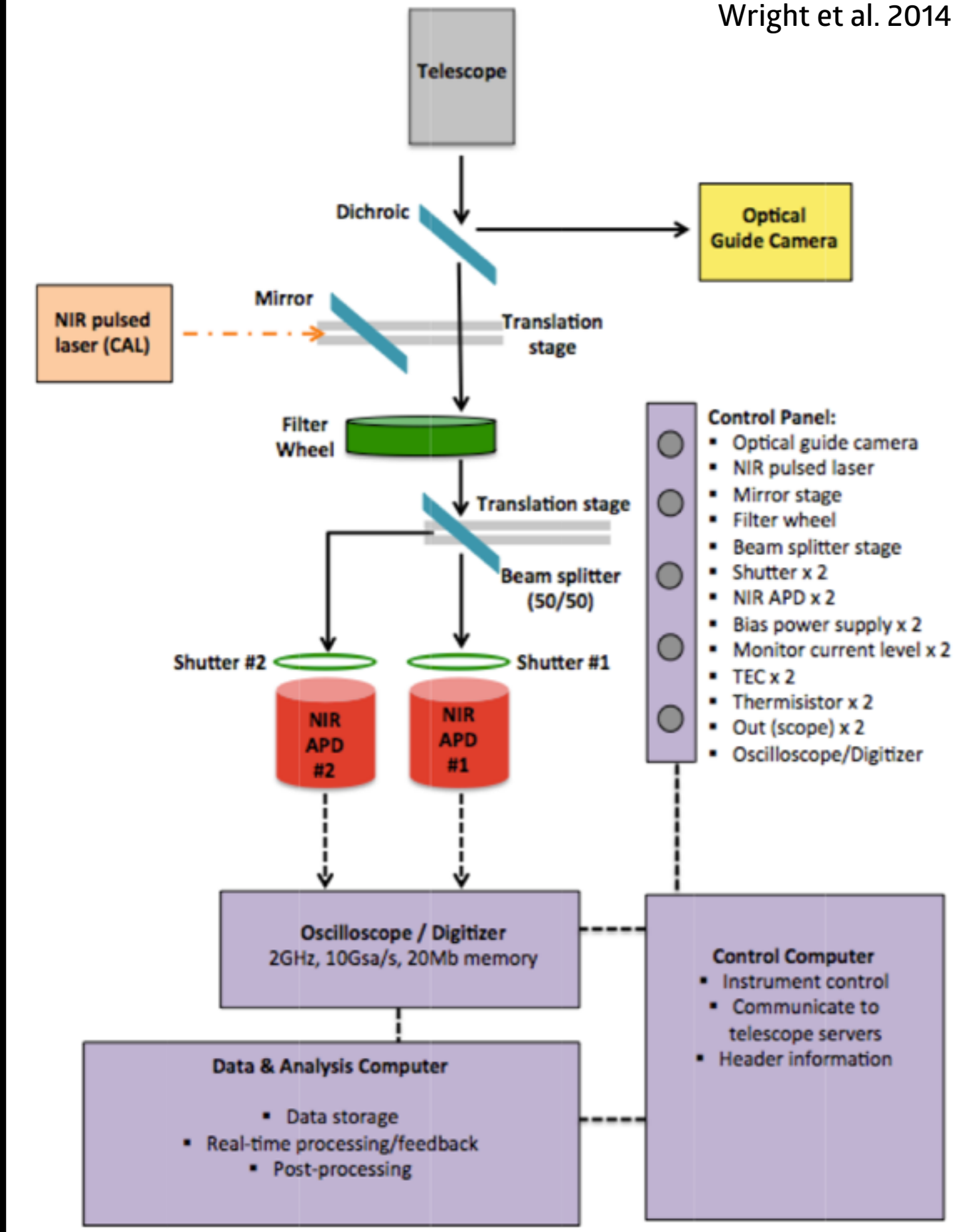
Maire et al 2014

0.5 ns resolution

720-1700 nm

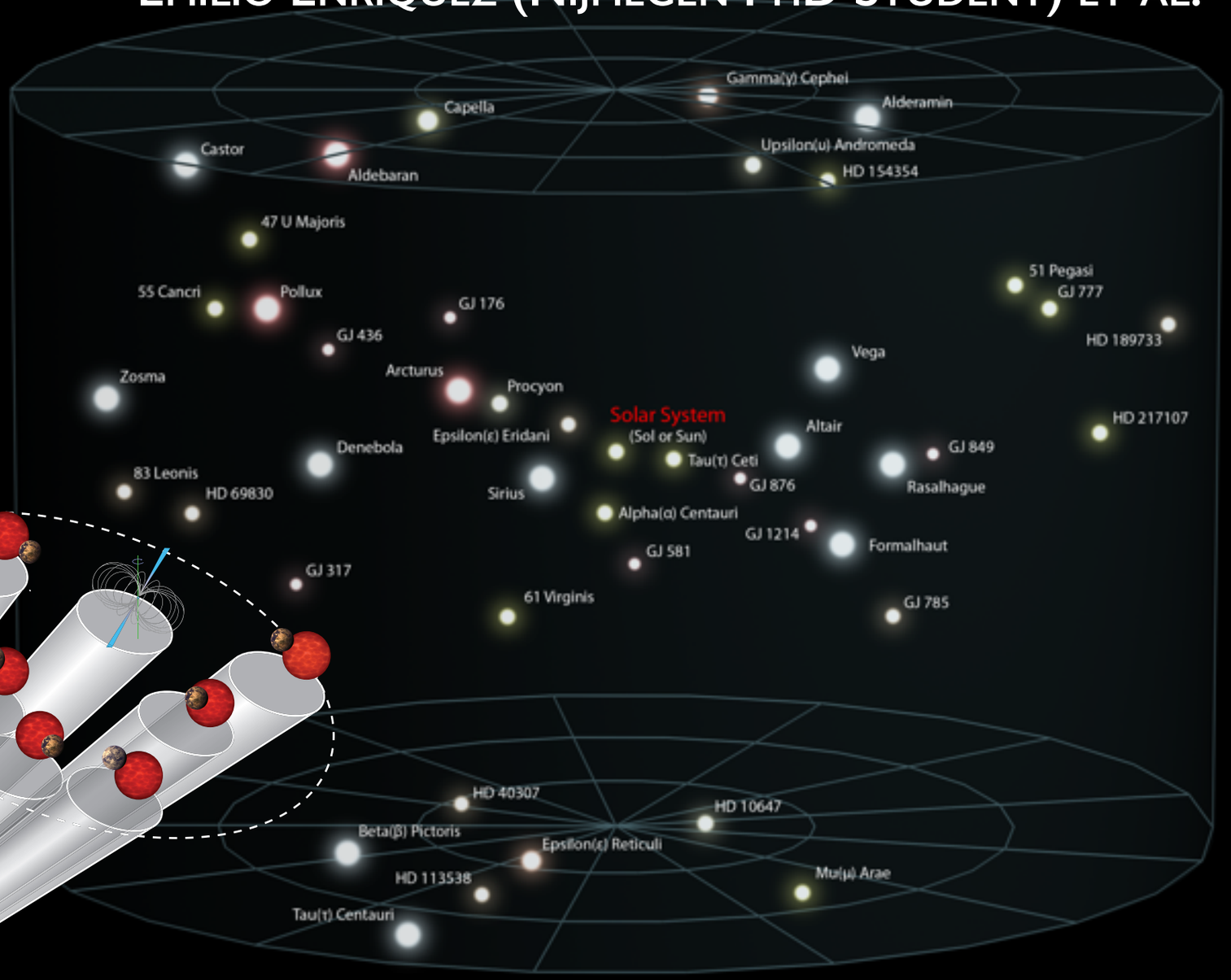
First light March 2015

Wright et al. 2014



SETI on Nearby Stars with LOFAR

Emilio Enriquez (Nijmegen PhD Student) et al.



Observations of the 30 nearest stars to the Earth at the frequencies of our own TV and radio - September 2014

Could detect brightest terrestrial transmitters at ~100 MHz

Megastructures and Mega Energy

THE Ĝ INFRARED SEARCH FOR EXTRATERRESTRIAL CIVILIZATIONS WITH LARGE ENERGY SUPPLIES. I. BACKGROUND AND JUSTIFICATION

J. T. Wright[1,2], B. Mullan[1,3,4], S. Sigurđsson[1,2], and M. S. Povich[5]

Accepted for publication in The Astrophysical Journal *on 23 June 2014.*

THE Ĝ INFRARED SEARCH FOR EXTRATERRESTRIAL CIVILIZATIONS WITH LARGE ENERGY SUPPLIES. II. FRAMEWORK, STRATEGY, AND FIRST RESULT

J. T. Wright[1,2], R. Griffith[1,2], S. Sigurđsson[1,2], M. S. Povich[3], and B. Mullan[4,5]

Accepted for publication in The Astrophysical Journal *on 23 June 2014.*

The application of the Mid-IR radio correlation to the $\hat{G}$ sample and the search for advanced extraterrestrial civilisations

M. A. Garrett[1,2]

MODELING INDICATIONS OF TECHNOLOGY IN PLANETARY TRANSIT LIGHT CURVES – DARK-SIDE ILLUMINATION.

Eric J. Korpela
Space Sciences Laboratory, University of California at Berkeley, Berkeley, CA, 94720

Shauna M. Sallmen, Diana Leystra Greene
University of Wisconsin - La Crosse, La Crosse, WI 54601

Submitted to The Astrophysical Journal

EXTRAGALACTIC SETI: THE TULLY-FISHER RELATION AS A PROBE OF DYSONIAN ASTROENGINEERING IN DISK GALAXIES

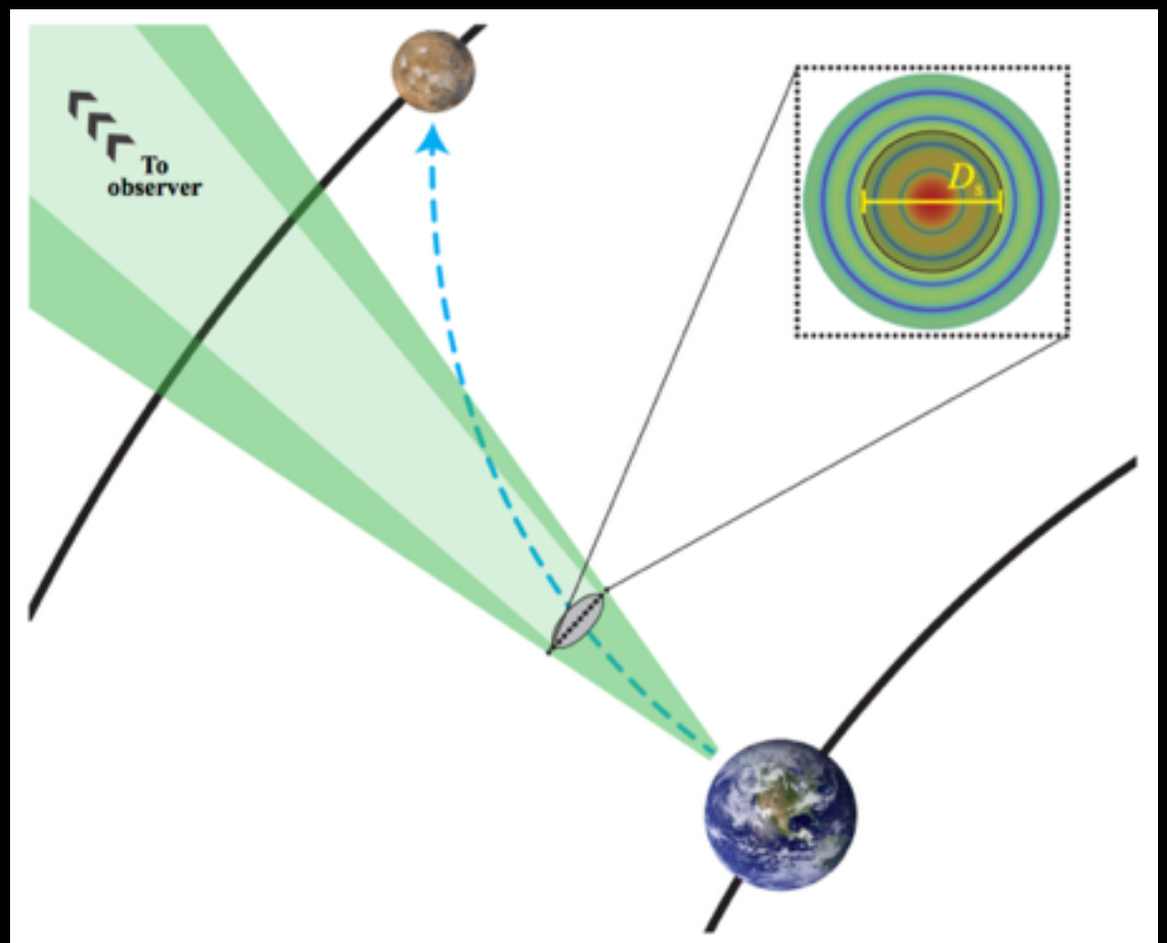
Erik Zackrisson[1,2*], Per Calissendorff[2], Saghar Asadi[2] & Anders Nyholm[2]

Target Theory

SETI VIA LEAKAGE FROM LIGHT SAILS IN EXOPLANETARY SYSTEMS

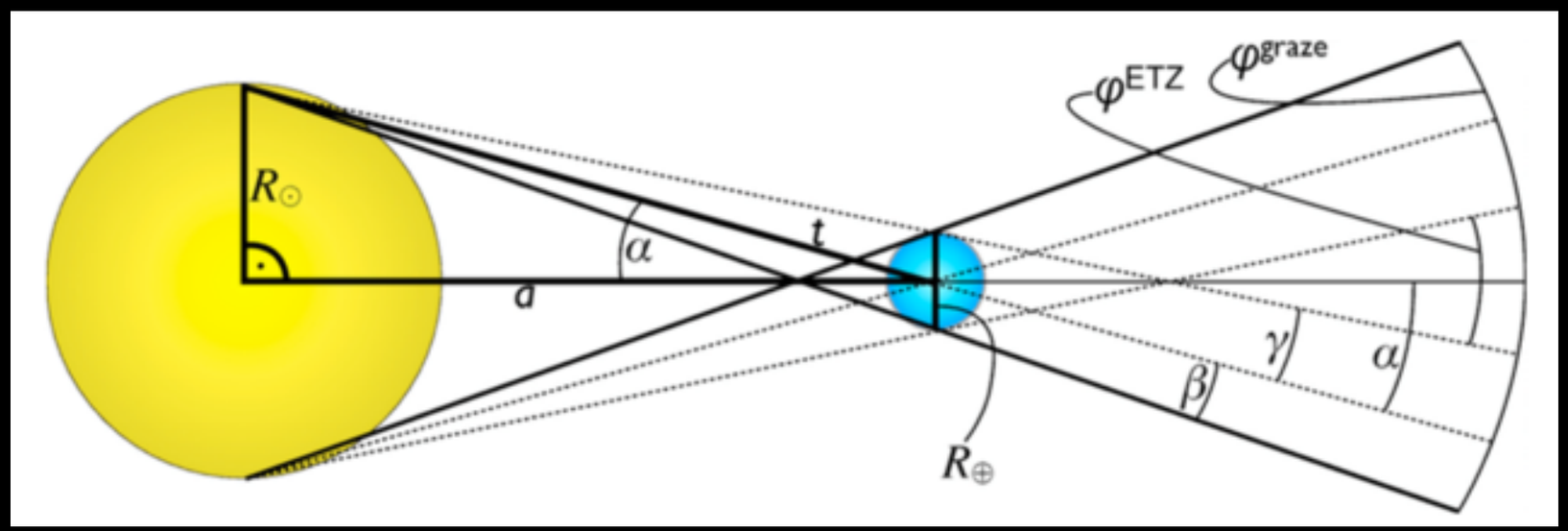
James Guillochon[1,2] and Abraham Loeb[1]

Draft version September 4, 2015



The Search for Extraterrestrial Intelligence in the Earth's Solar Transit Zone

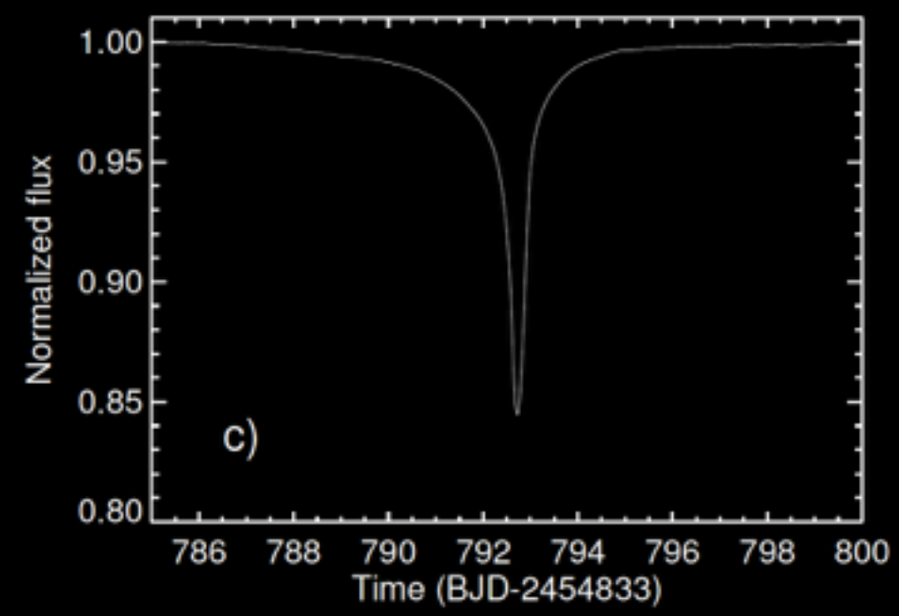
René Heller[1,2,3] and Ralph E. Pudritz[1,2]

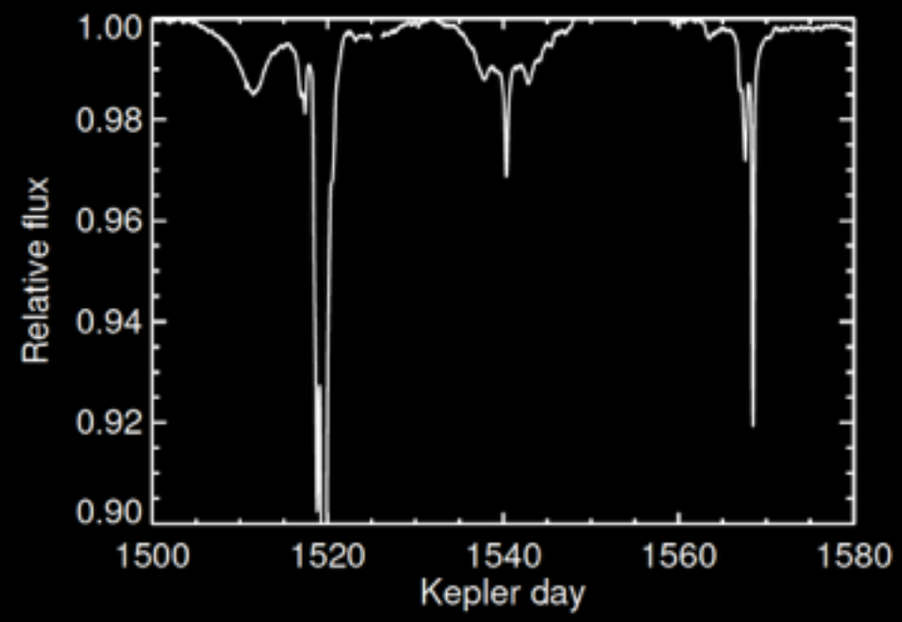


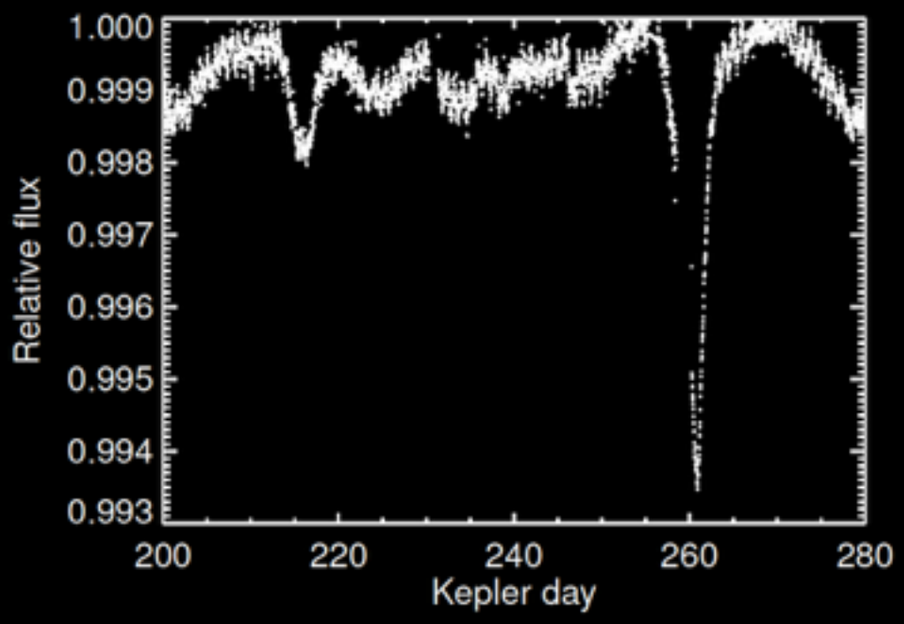
The Curious Case of KIC 8462852 (WTF 001)

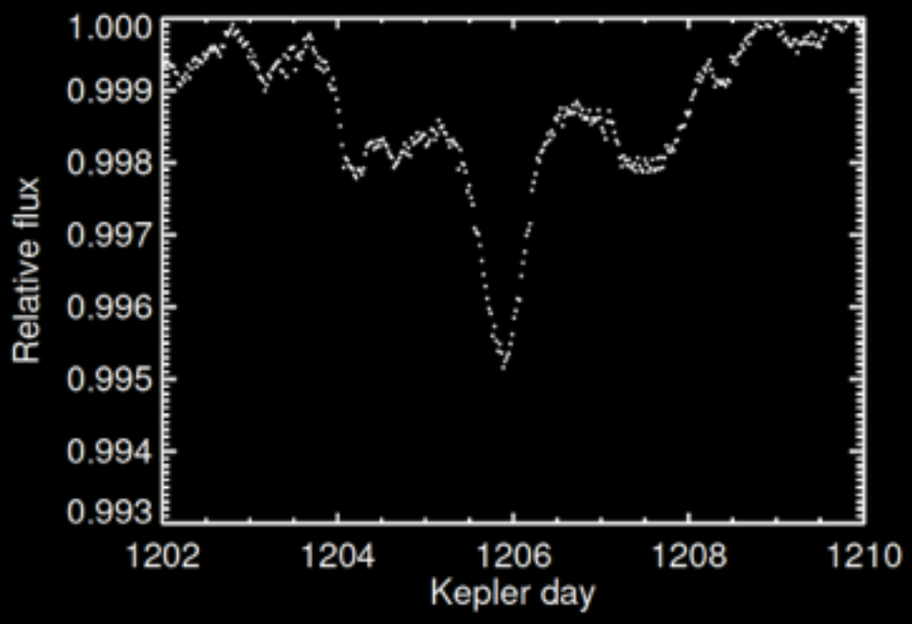
Planet Hunters X.
KIC 8462852 – Where's the flux? *†

T. S. Boyajian[1], D. M. LaCourse[2], S. A. Rappaport[3],









The Curious Case of KIC 8462852 (WTF 001)

Boyajian, Wright, et al

THE Ĝ SEARCH FOR EXTRATERRESTRIAL CIVILIZATIONS WITH LARGE ENERGY SUPPLIES. IV. THE SIGNATURES AND INFORMATION CONTENT OF TRANSITING MEGASTRUCTURES

Jason T. Wright[1], Kimberly M. S. Cartier, Ming Zhao[1], Daniel Jontof-Hutter, Eric B. Ford[1]
Department of Astronomy & Astrophysics, and Center for Exoplanets and Habitable Worlds, 525 Davey Lab, The Pennsylvania State University, University Park, PA, 16802
Accepted to ApJ

A Search for Brief Optical Flashes Associated with the SETI Target KIC 8462852

A. U. Abeysekara[1], S. Archambault[2], A. Archer[3], W. Benbow[4], R. Bird[5], M. Buchovecky[6], J. H. Buckley[3], K. Byrum[7], J. V Cardenzana[8], M. Cerruti[4], X. Chen[9,10], J. L. Christiansen[11], L. Ciupik[12], W. Cui[13], H. J. Dickinson[8,B], J. D. Eisch[8], M. Errando[14], A. Falcone[15], D. J. Fegan[5], Q. Feng[13], J. P. Finley[13], H. Fleischhack[10], P. Fortin[4], L. Fortson[16], A. Furniss[17], G. H. Gillanders[18], S. Griffin[2], J. Grube[12], G. Gyuk[12], M. Hütten[10], N. Håkansson[9], D. Hanna[2], J. Holder[19,28,A], T. B. Humensky[20], C. A. Johnson[21], P. Kaaret[22], P. Kar[1], N. Kelley-Hoskins[10], M. Kertzman[23], D. Kieda[1], M. Krause[10], F. Krennrich[8], S. Kumar[19], M. J. Lang[18], T. T.Y. Lin[2], G. Maier[10], S. McArthur[13], A. McCann[2], K. Meagher[24], P. Moriarty[18], R. Mukherjee[14], D. Nieto[20], S. O'Brien[5], A. O'Faoláin de Bhróithe[10], R. A. Ong[6], A. N. Otte[24], N. Park[25], J. S. Perkins[26], A. Petrashyk[20], M. Pohl[9,10], A. Popkow[6], E. Pueschel[5], J. Quinn[5], K. Ragan[2], G. Ratliff[12], P. T. Reynolds[27], G. T. Richards[24], E. Roache[4], M. Santander[14], G. H. Sembroski[13], K. Shahinyan[16], D. Staszak[2], I. Telezhinsky[9,10], J. V. Tucci[13], J. Tyler[2], S. Vincent[10], S. P. Wakely[25], O. M. Weiner[20], A. Weinstein[8], D. A. Williams[21], B. Zitzer[7]

OPTICAL SETI OBSERVATIONS OF THE ANOMALOUS STAR KIC 8462852

[SHORT TITLE: OPTICAL SETI OBSERVATIONS OF KIC 8462852]

Marlin Schuetz[1,2], Douglas A. Vakoch[1*], Seth Shostak[3], Jon Richards[3]

[1]SETI International, 100 Pine St., Ste. 1250, San Francisco, CA 94111-5235, USA
[2]Boquete Optical SETI Observatory, Volcancito Road, Boquete, Chiriquí 0413, Panama
[3]Center for SETI Research, SETI Institute, 189 Bernardo Ave., Mountain View, CA 94043, USA

RADIO SETI OBSERVATIONS OF THE ANOMALOUS STAR KIC 8462852

G. R. Harp[1], Jon Richards[1], Seth Shostak[1], J. C. Tarter[1], Douglas A. Vakoch[1,2], Chris Munson[1]