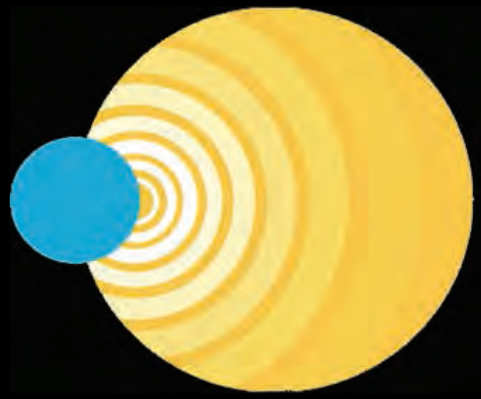
Berkeley SETI Group

Zuhra Abdurashidova, David Anderson, Jeff Cobb, Steve Croft, David DeBoer, Matt Dexter, Emilio Enriquez, Walt Fitelson, Griffin Foster, Vishal Gajjar, Greg Hellbourg, Jack Hickish, Howard Isaacson, Eric Korpela, Matt Lebofsky, Dave MacMahon, Danny Price, Chris Schodt, Isaac Shivvers, Andrew Siemion, Nate Tellis, Ed Wishnow, Dan Werthimer

Breakthrough Foundation, NSF , NASA, Donors
Keysight, Intel, Seagate, Xilinx

BERKELEY SETI RESEARCH CENTER



BERKELEY **SETI**

SSL
UNIVERSITY OF CALIFORNIA
Berkeley

CASPER

BWRC

BERKELEY
ASTRONOMY
DEPARTMENT

BERKELEY LAB

THE UNIVERSITY OF CALIFORNIA
LET THERE BE LIGHT
1868

AMERICAN MUSEUM OF NATURAL HISTORY

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COLUMBIA UNIVERSITY

NRAO

NATIONAL ASTRONOMY AND IONOSPHERE CENTER
ARECIBO OBSERVATORY

UNIVERSITY OF TORONTO

SETI INSTITUTE

ASTRON

UNIVERSITY OF HAWAI'I

LOFAR

CORNELL UNIVERSITY
FOUNDED A.D. 1865

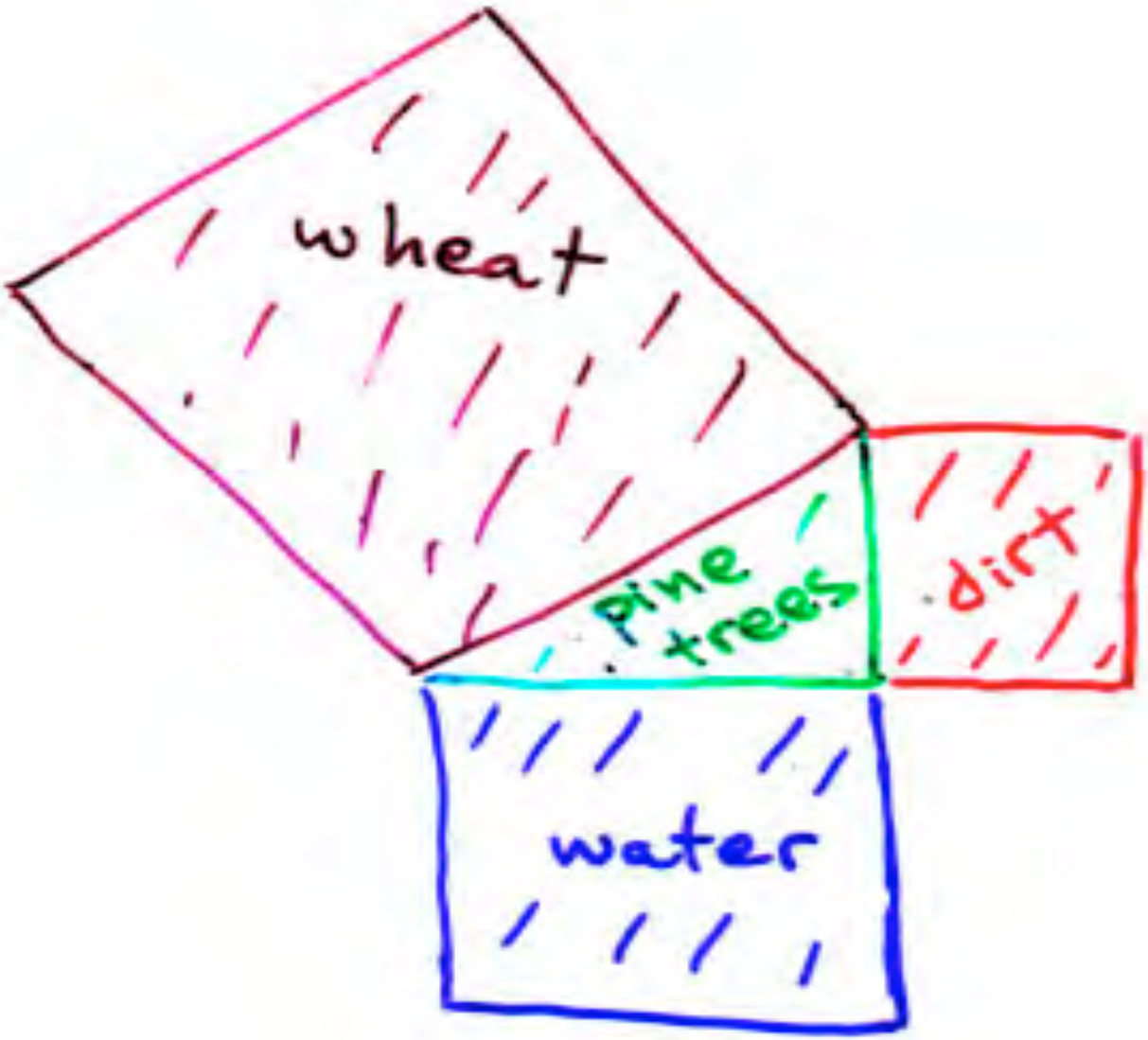
It's naïve to think we know how best to search today, given our history of changing SETI fashion.

- Multiple strategy is best

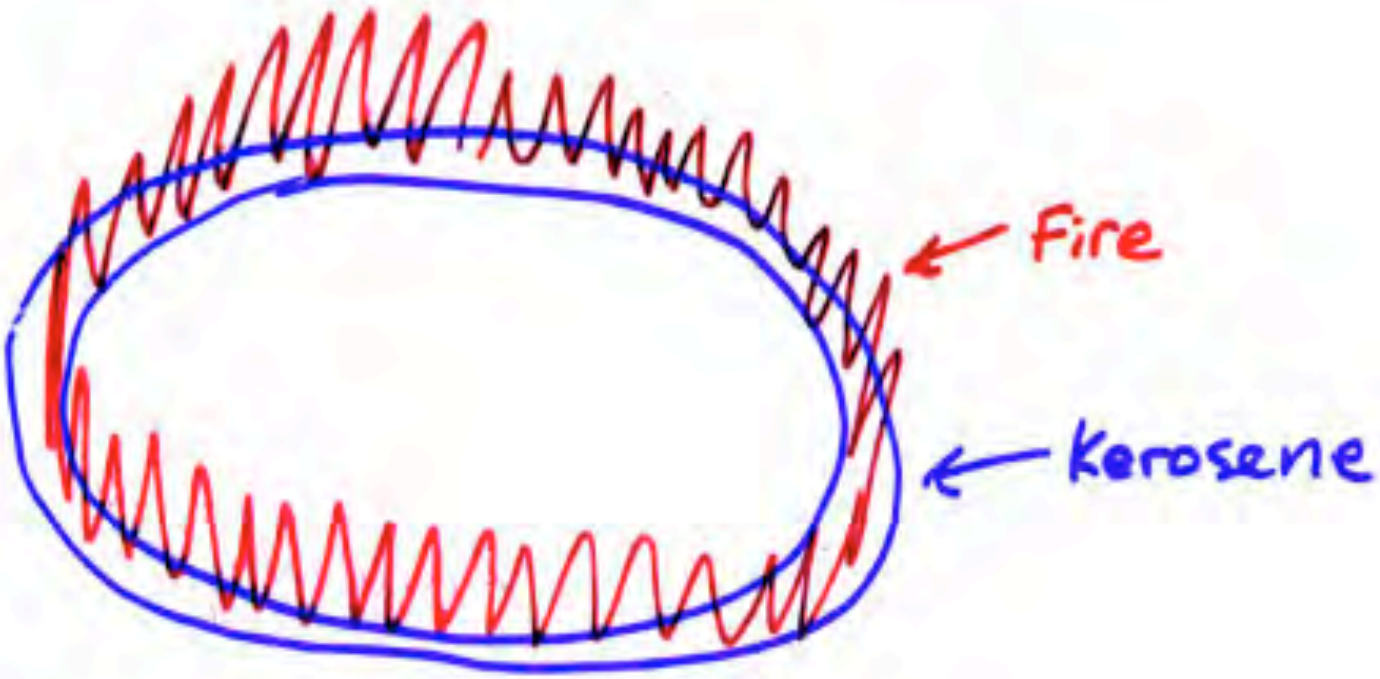
  (IR, Vis, Radio, pulse, continuous, targetted sky survey…)
- Half of astronomy discoveries are serendipitous
- Examine glitches in data
- Data Mining Experiments (Virtual Observatory)

SETI ideas morphing over 200 years

Karl Gauss 1820



Joseph Von Littron ~1840



Last Century – Mostly Radio SETI

- Nikola Tesla (1899)
  - Announces "coherent signals from Mars"
- Guglielmo Marconi (1920) strange signals
- Navy observes Mars on closest approach (1924)
- Frank Drake (1960)
  - Project Ozma
  - one channel, 1420-1420.4 MHz

1924 navy search for martian radio

Is Mars Signaling to Us by Radio?

On August 22d the planet Mars will be at its nearest point to the earth—closer than it has been for more than 100 years! All over the world scientists are preparing to communicate with our distant neighbor by radio. Read about it in POPULAR RADIO for August, now on the newsstands.

A Remarkable 3-Dry Cell Tube Receiver

How to Get Good Reception

Secret Pictures by Radio

A "How to Build" Article for Beginners

Helpful Hints for the "HCL"

Popular Radio

627 West 43d Street New York City

Form 125L

7241

S[illegible]IAL CORPS, UNITED STATES ARM[illegible]

WASHINGTON-ALASKA MILITARY CABLE AND TELEGRAPH SYSTEM

TELEGRAM

RECEIVED AT 1308 1ST AVENUE, SEATTLE, WASH.

18RD B 78 GOVT DUPE

RD PUGETSOUND WN AUG 22 1924

GOVT COMDT 13 NAV DIST 158

SEATTLE WN

7021 ALNAVSTA EIGHT NAVY DESIRES COOPERATE ASTRONOMERS WHO BELIEVE POSSIBLE THAT MARS MAY ATTEMPT COMMUNICATION BY RADIO WAVES WITH THIS PLANET WHILE THEY ARE NEAR TOGETHER THIS END ALL SHORE RADIO STATIONS WILL ESPECIALLY NOTE AND REPORT ANY ELECTRICAL PHENOMENON UNUSUAL CHARACTER AND WILL COVER AS WIDE BAND FREQUENCIES AS POSSIBLE FROM 2400 AUGUST TWENTY FIRST TO 2400 AUGUST TWENTY FOURTH WITHOUT INTERFERRING WITH TRAFFIC 1800

SECNAV WASHN DC

257P

OPTICAL SETI -
Example of anthropomorphic SETI

1961 Charlie Townes Paper

largely ingored until 1999

1971 Cyclops report calculates radio >> optical

Today's lasers can communicate across galaxy

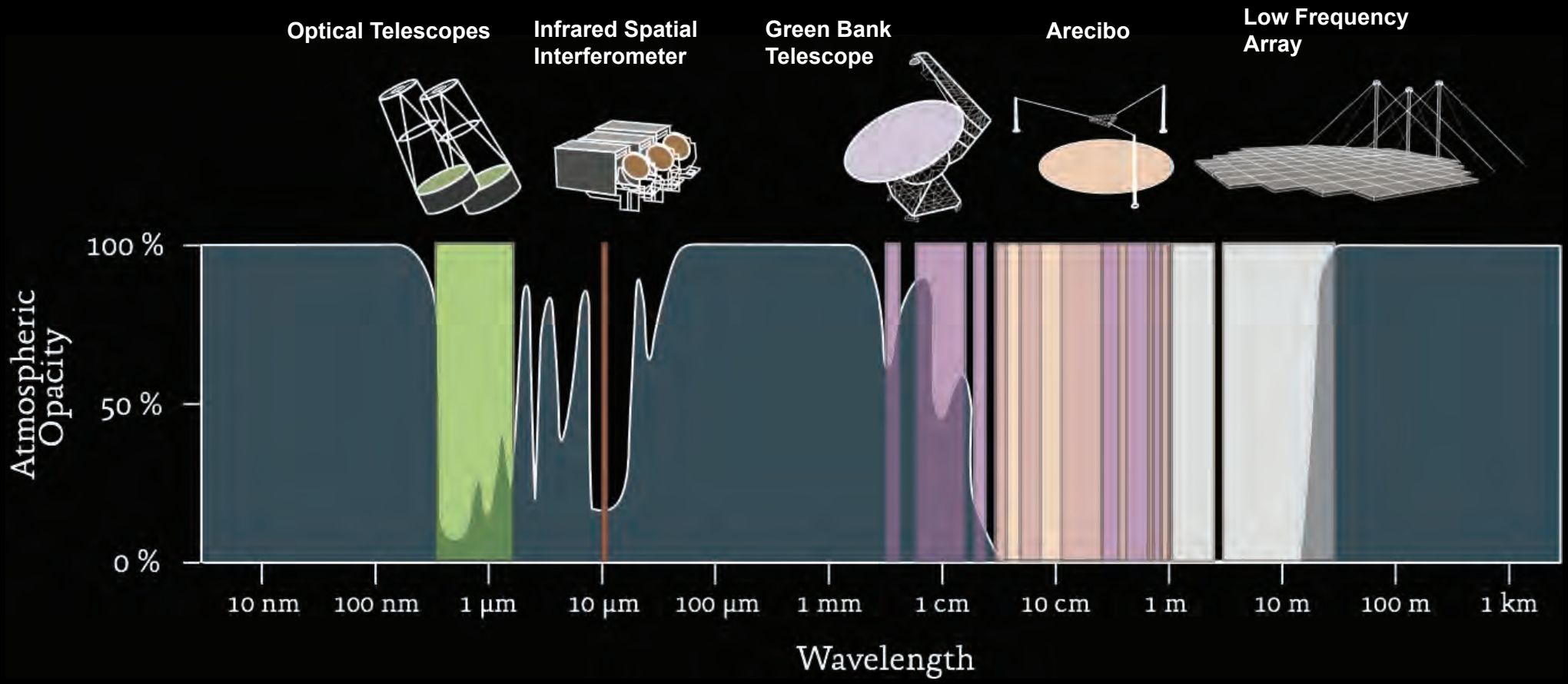
Habitable planets and stars – Example of anthropomorphic SETI

Habitable Zone → other ways to heat

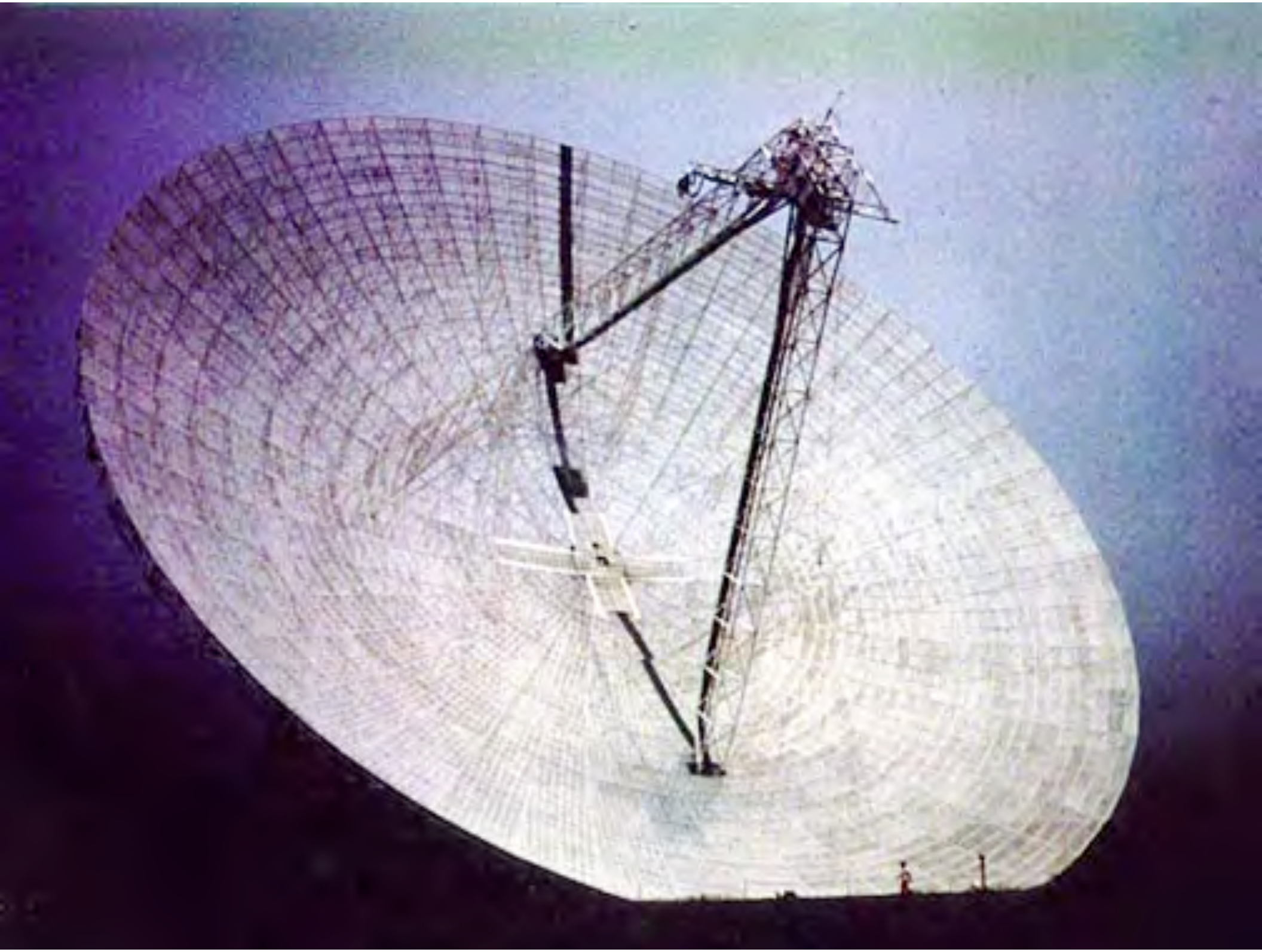
F and G stars only → many stellar types

no binary stars -→ stable planetary orbits

Searching Across the Electromagnetic Spectrum



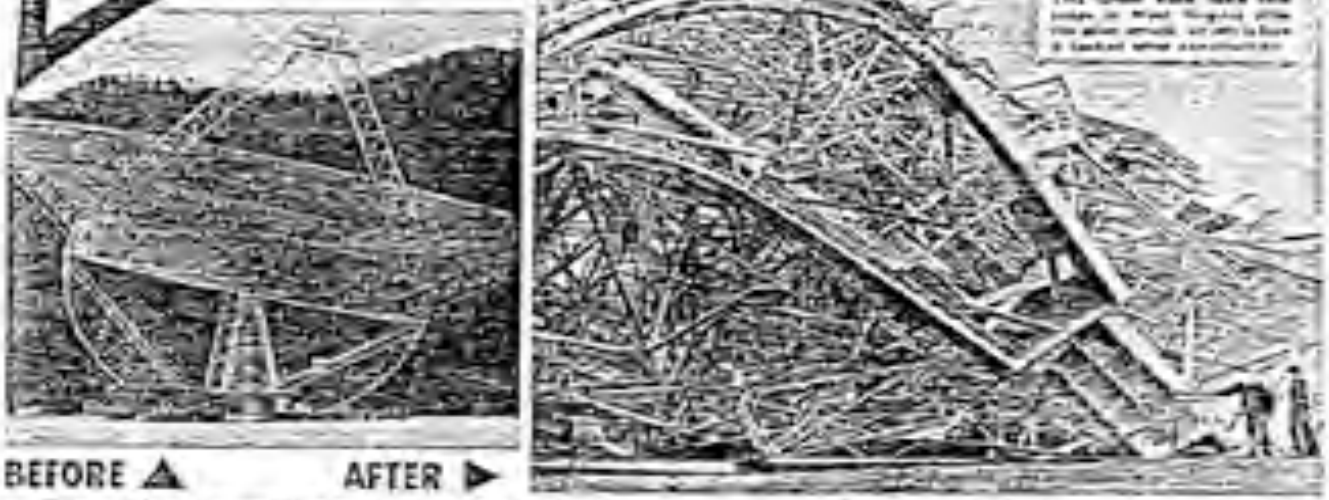
Using multiple telescopes, we can search across the electromagnetic spectrum for indicators of advanced technology.



America's most powerful radio telescope IS . . .

ZAPPED!

. . . by hostile space aliens!



BEFORE ▲ AFTER ▶

Brave dog

NAIC Arecibo Observatory, Puerto Rico


The Robert C. Byrd
Green Bank
Telescope

Breakthough Foundation "LISTEN" SETI Project

- $100M over 10 years
- Starting with Green Bank and Parkes Radio Telescopes
- Lick Observatory (optical SETI)
- 1,000,000 stars; 1000 galaxies; galactic plane; all sky
- New instrumentation: 10 GHz bandwidth (20 billion channels)
- SETI@home participants will analyze interesting parts of data
- Open source data, hardware, software, gpuware, gateware

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, $\lambda/\Delta\lambda = 10^5$

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

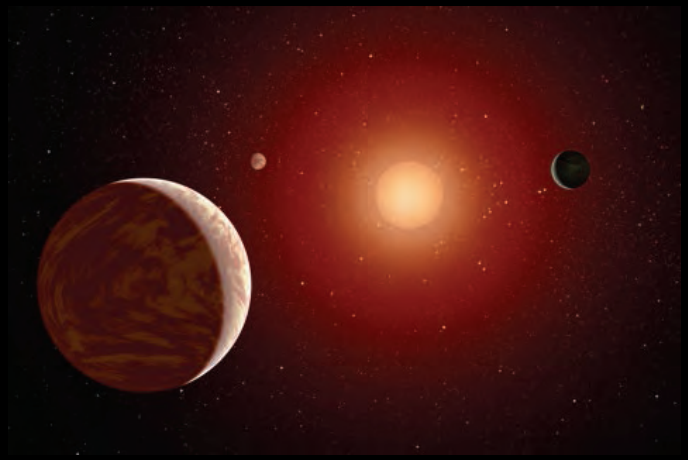
Parkes Telescope (New South Wales, Australia)

- 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) sky surveys

MeerKAT

The Breakthrough Listen Initiative:

10 years - 10^8 dollars



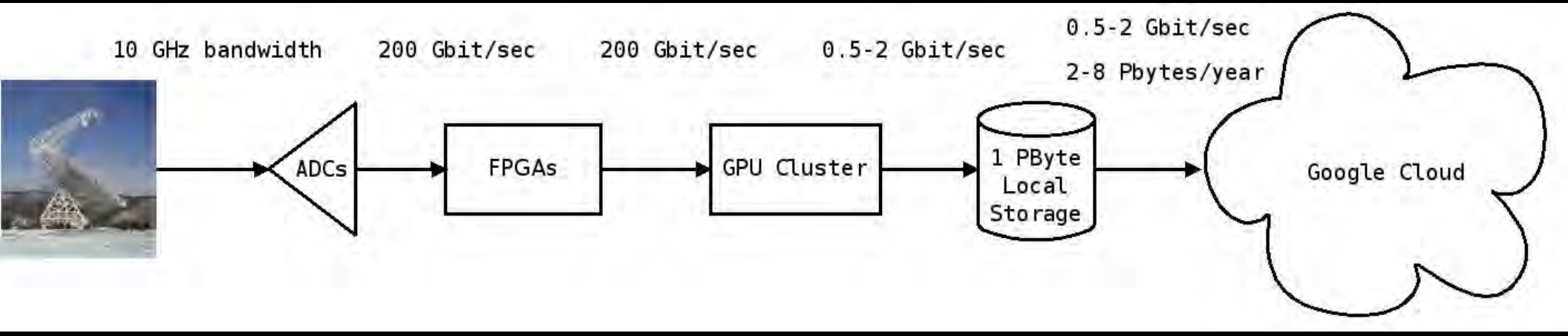
1 Million Stars

1000 Galaxies

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

http://breakthroughinitiatives.org

LISTEN SETI Data Rates



Data Products (all data is Open)

- Candidate Signals: raw data [voltage(t)]
- Voltage Surveys (all sky? Galactic Plane)
- SETI@home raw data (mostly Southern Sky Survey)
- High Spectral Resolution Data

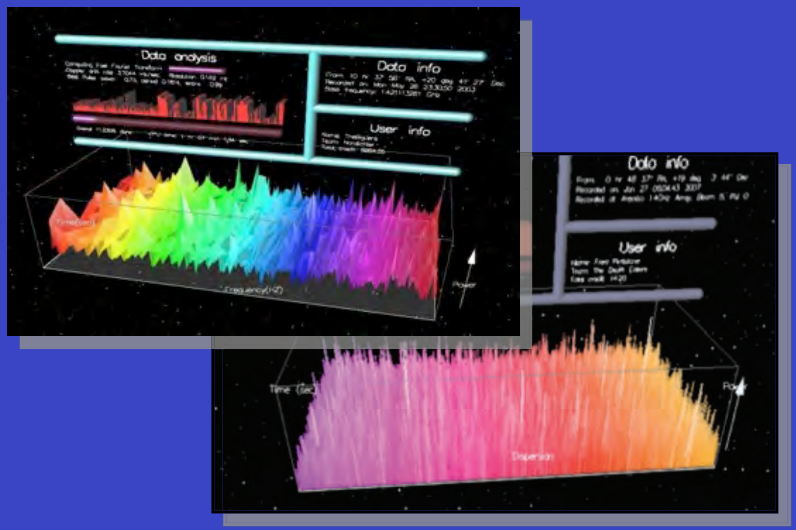
  (SETI, Galactic Structure and Evolution)
- High Time Cadence Spectral Data

  (SETI, Fast Radio Bursts, Primordial Black Holes, Transients)

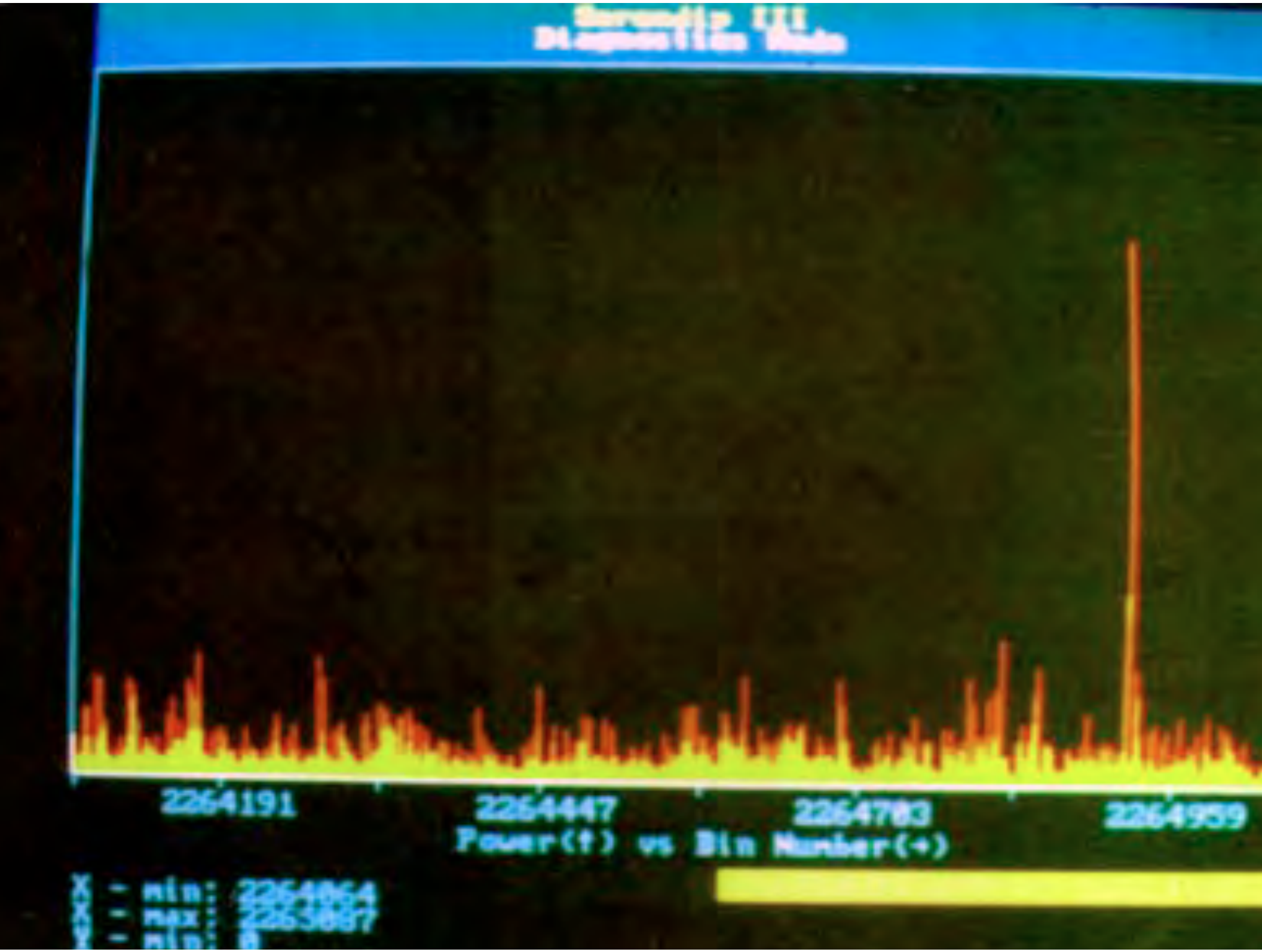
Arecibo Observatory

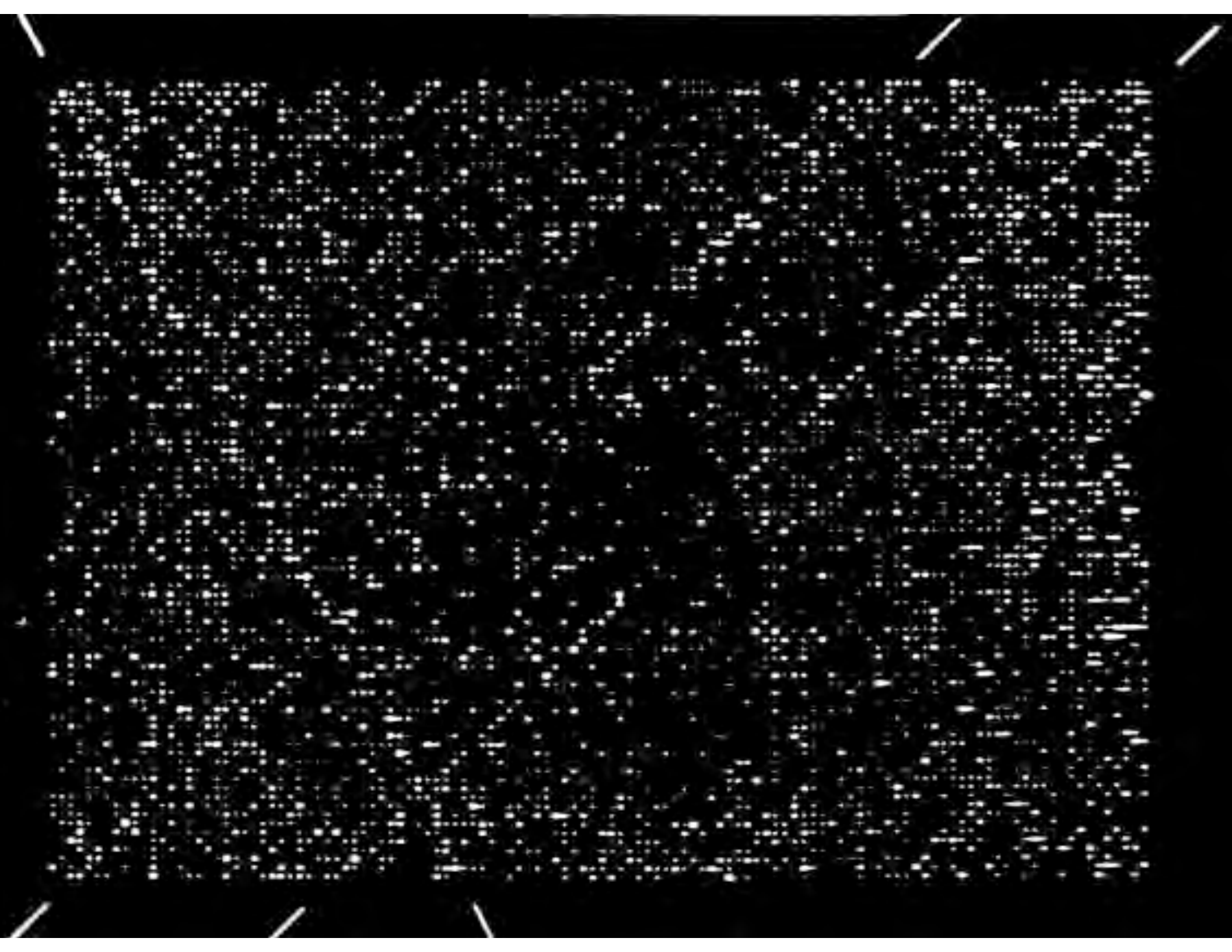
High performance data storage silo

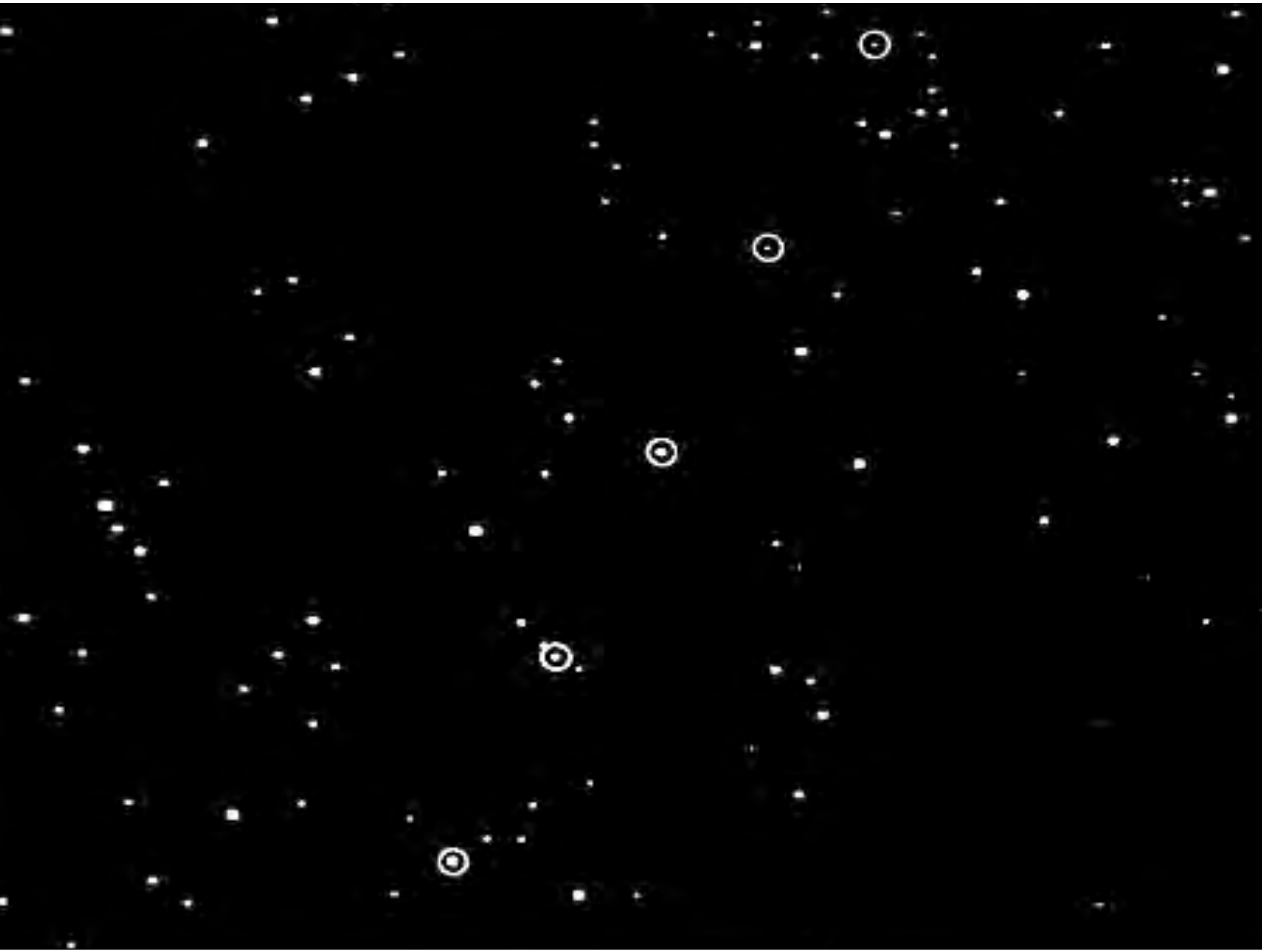
UC Berkeley Space Sciences Lab



Public Volunteers


2264191
2264447
2264703
2264959
Power(↑) vs Bin Number(→)

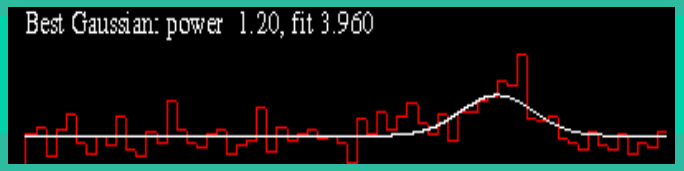




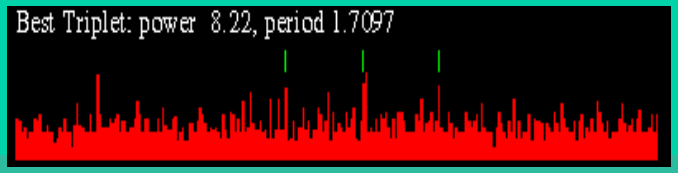
Signal Types

Spike – A single frequency bin at a specific time above a threshold

Gaussian – A power profile over time that matches the telescope beam width.



Triplet – Three spikes evenly spaced in time separated by 3.5 ms to 53 seconds.

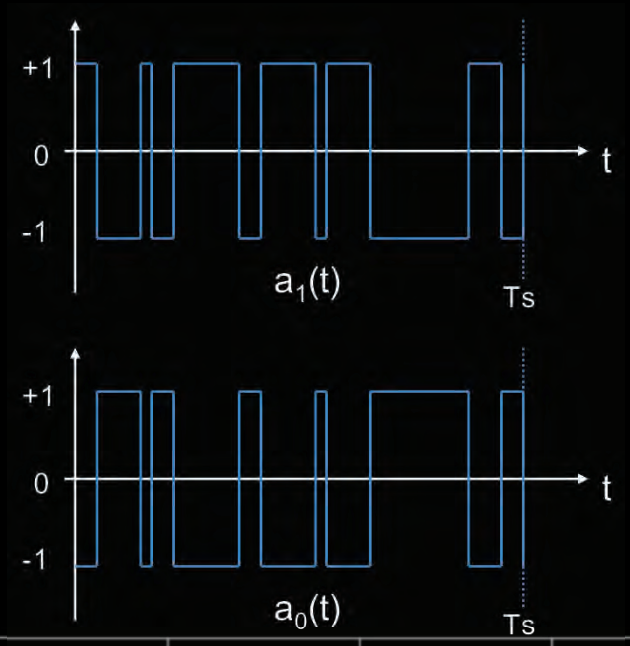


Pulse – Repeated pulsation on scales from 1 ms to 53 seconds.

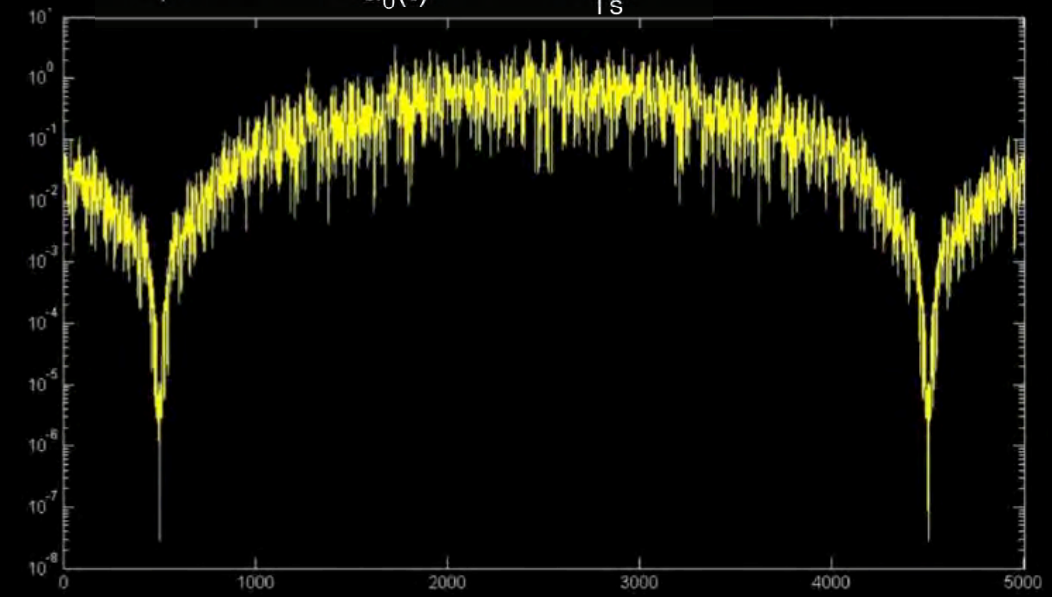
Autocorrelation – Any waveform that is repeated one or more times with a characteristic delay (0.1 ms to 6.7s).

Broadband Emission

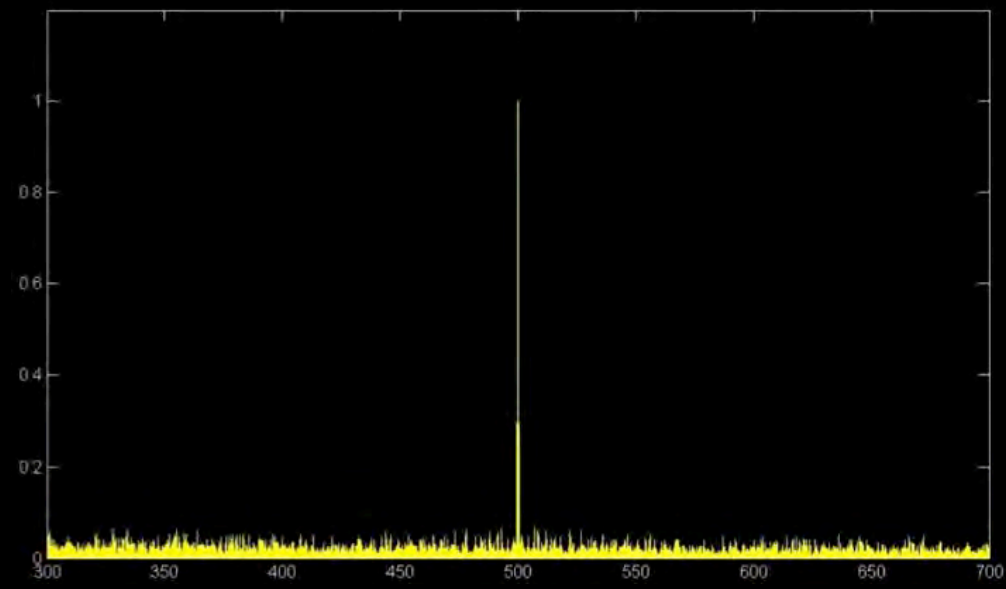
An example… Binary Phase Shift Keying (BPSK)



- Modern radio communication largely broadband
- Wide bandwidths permit rich information content

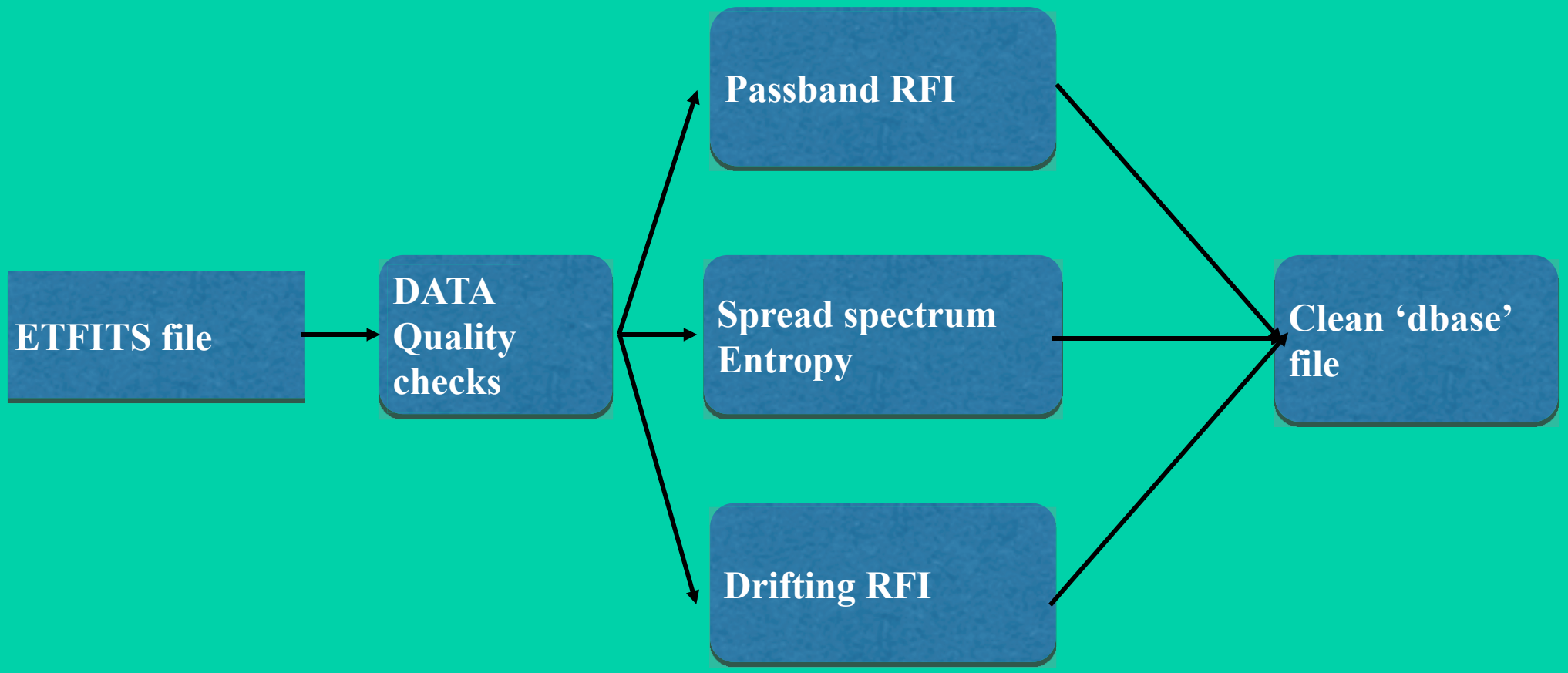


Power Spectrum

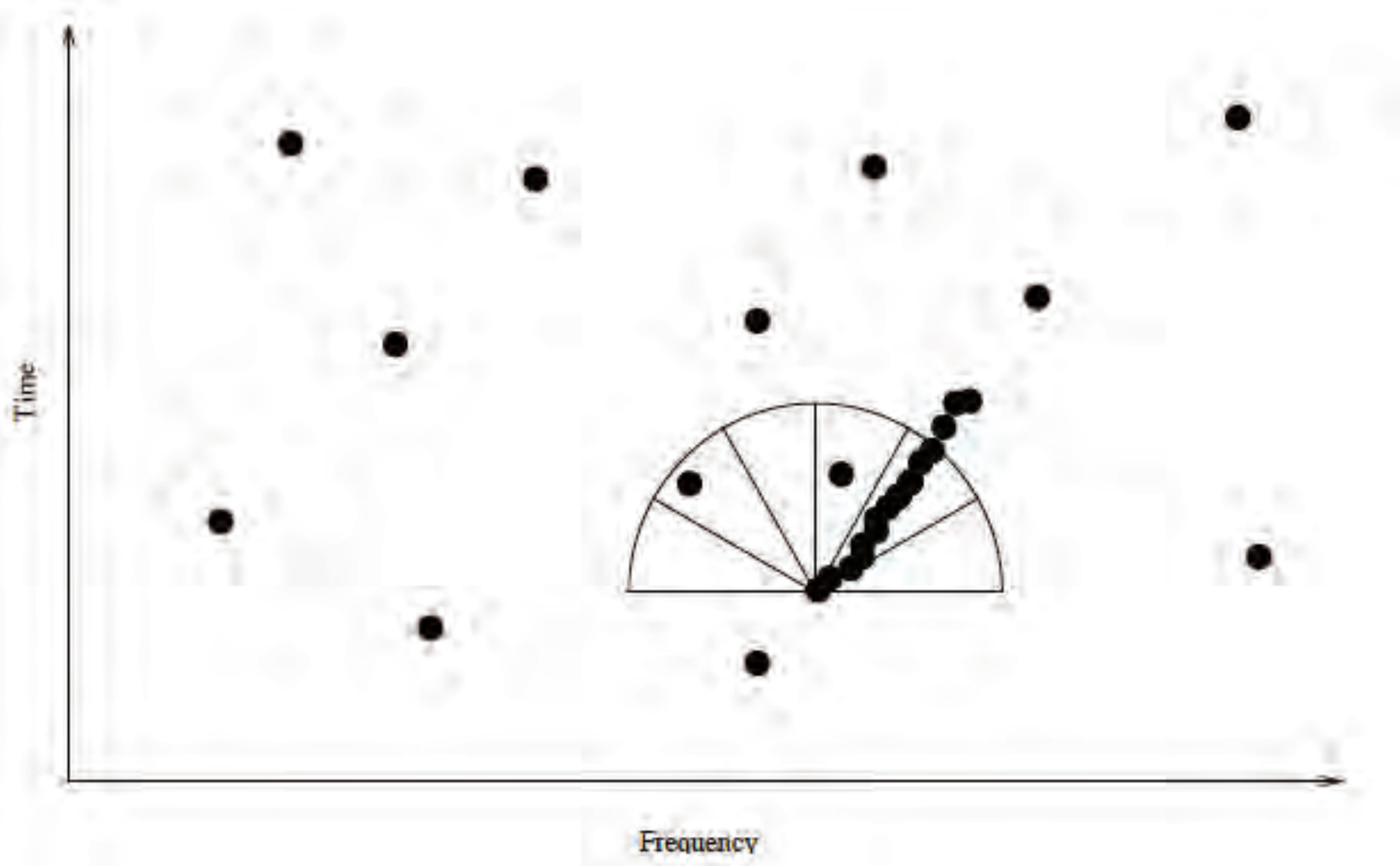


Auto Correlation

RFI rejection pipeline



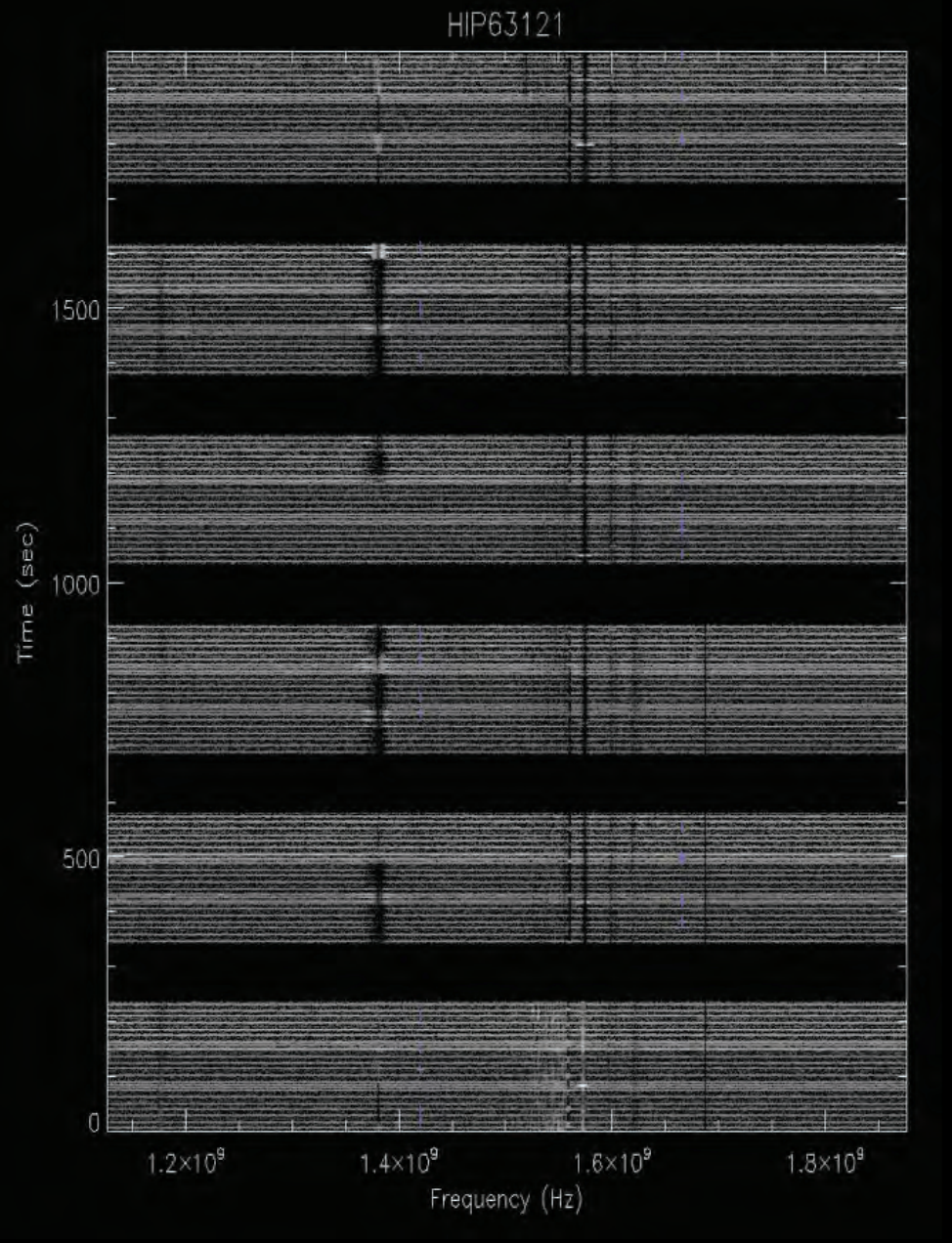
Drifting RFI mitigation



SETI@home Breakthrough Pipeline

Barycentric cluster identification

- Require event be in every on and no off observation at P_{rand}



SETI@home Statistics

TOTAL	RATE
8,464,550 participants (in 226 countries)	2,000 per day
3 million years computer time	1,000 years per day
$3*10^{23}$ operations	1,000 Tera-flops

- Primary Schools
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4
- Secondary Schools
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4
- Junior Colleges
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4
- Universities and Departments
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4
- Small Companies (<= 50 employees)
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4
- Medium Companies (50-1000 employees)
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4
- Large Companies (> 1000 employees)
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4
- Clubs
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4
- Government Agencies
  - Top 200
  - A B C D E F G H I J K L M N O P Q R S T U V W X Y Z 0 1 2 3 4

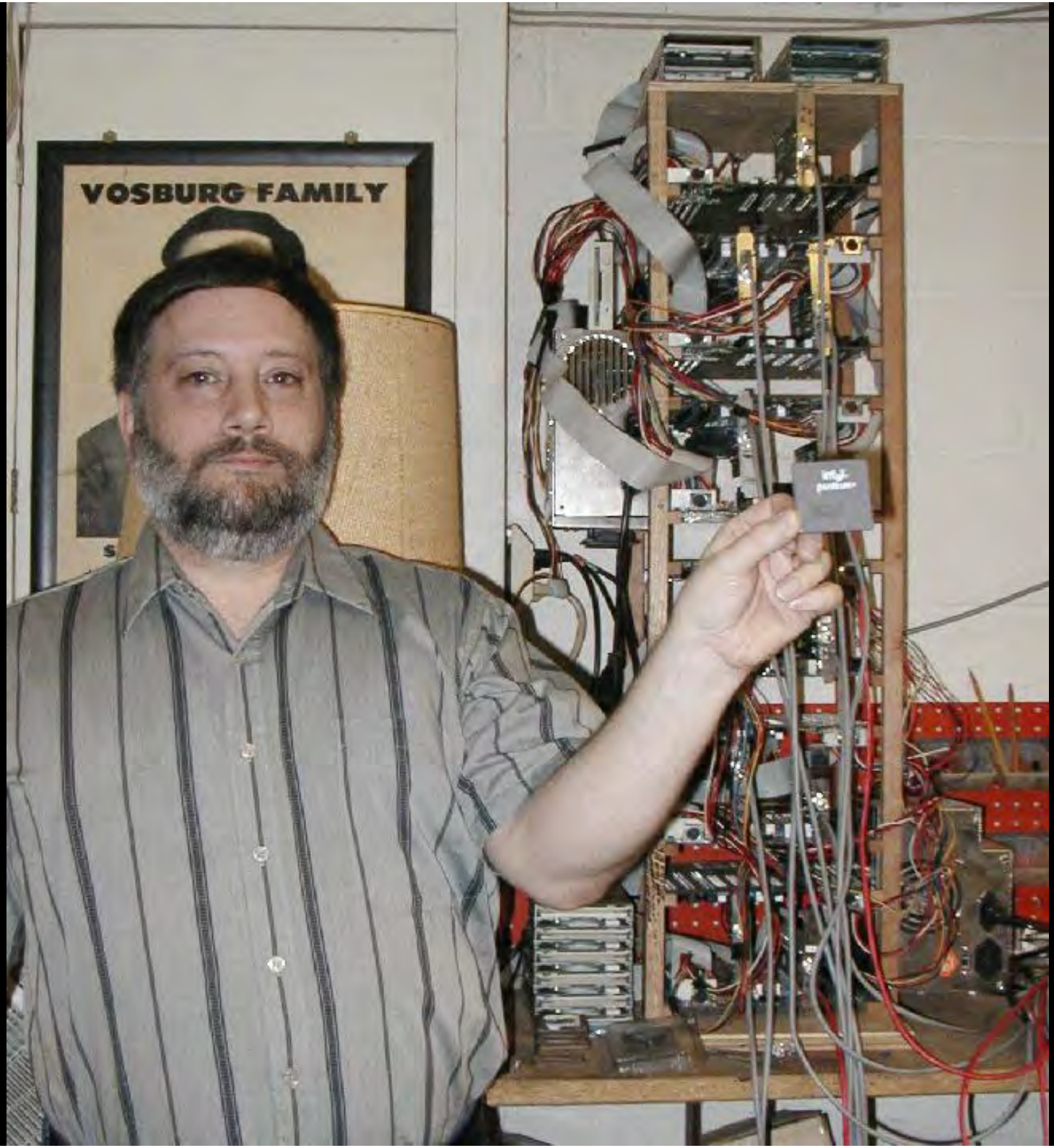
SETI@home

The Search for Extraterrestrial Intelligence

Large Company Teams

Last updated: Mon Apr 29 13:43:25 2002 UTC

Name	Members	Results received	Total CPU time	Average per wo
1) Compaq Computer Corporation	790	3558699	3186.750 years	7 hr 50 m
2) Sun Microsystems	476	3332359	3466.458 years	9 hr 06 m
3) SGI SETI	390	3093165	2162.647 years	6 hr 07 m
4) IBM	1078	1675466	2844.529 years	14 hr 52 r
5) Microsoft	1208	1605938	2037.371 years	11 hr 06 r
6) Intel® Corporation	475	1595846	1388.653 years	7 hr 37 m
7) Hewlett-Packard	610	1265982	1764.556 years	12 hr 12 r
8) Apple Computer, Inc.	714	841045	1381.364 years	14 hr 23 r


VOSBURG FAMILY

Web site: 2 million hits/day
200,000 visitors/day

(stats & games popular; science less popular)

100,000 children, families

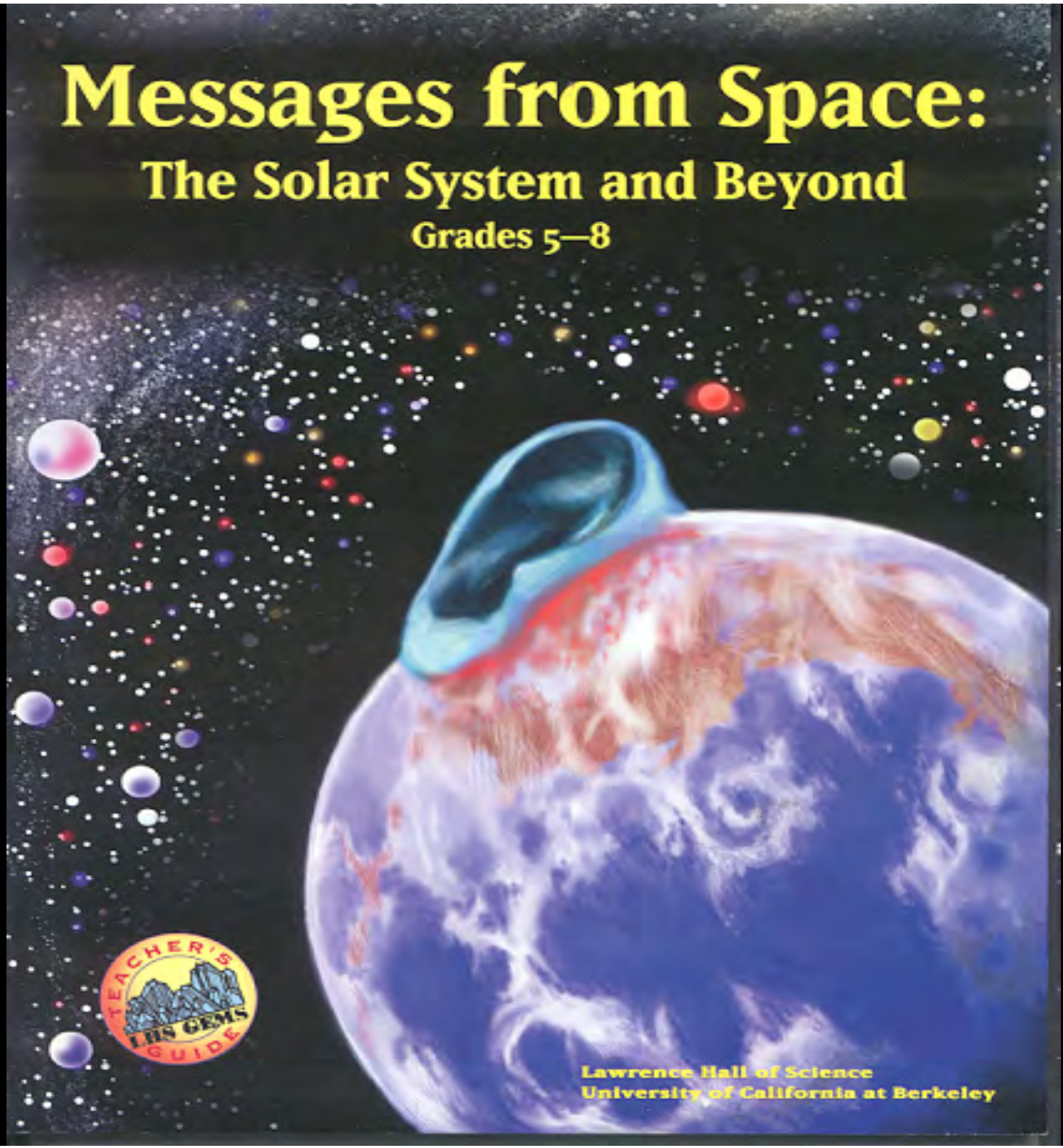
(including congress members and their kids)

> 7,000 schools

Messages from Space:

The Solar System and Beyond

Grades 5—8



Lawrence Hall of Science
University of California at Berkeley

Public Participation Scientific Supercomputing

aka “Distributed Computing”

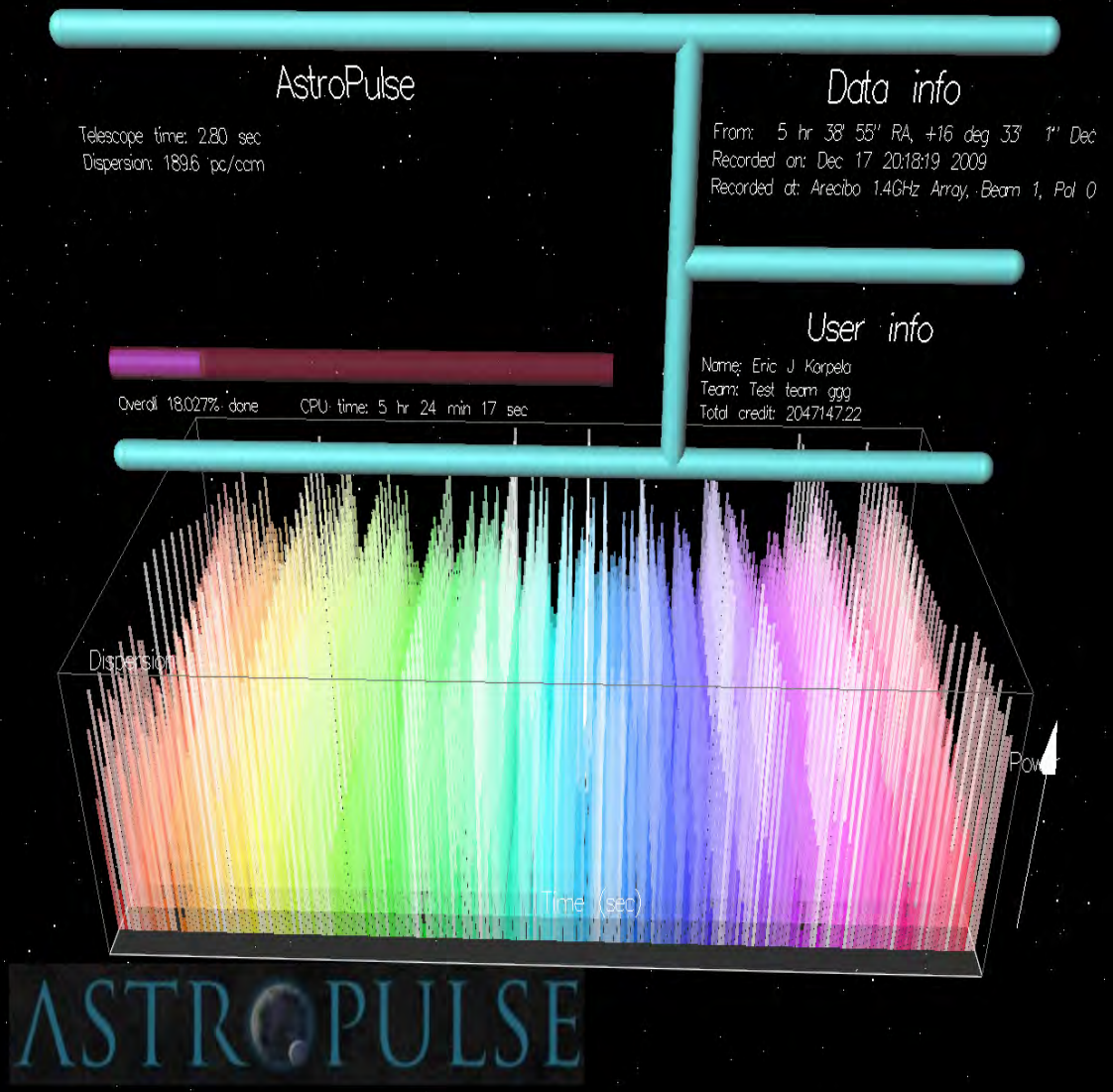
aka “edge resource aggregation”

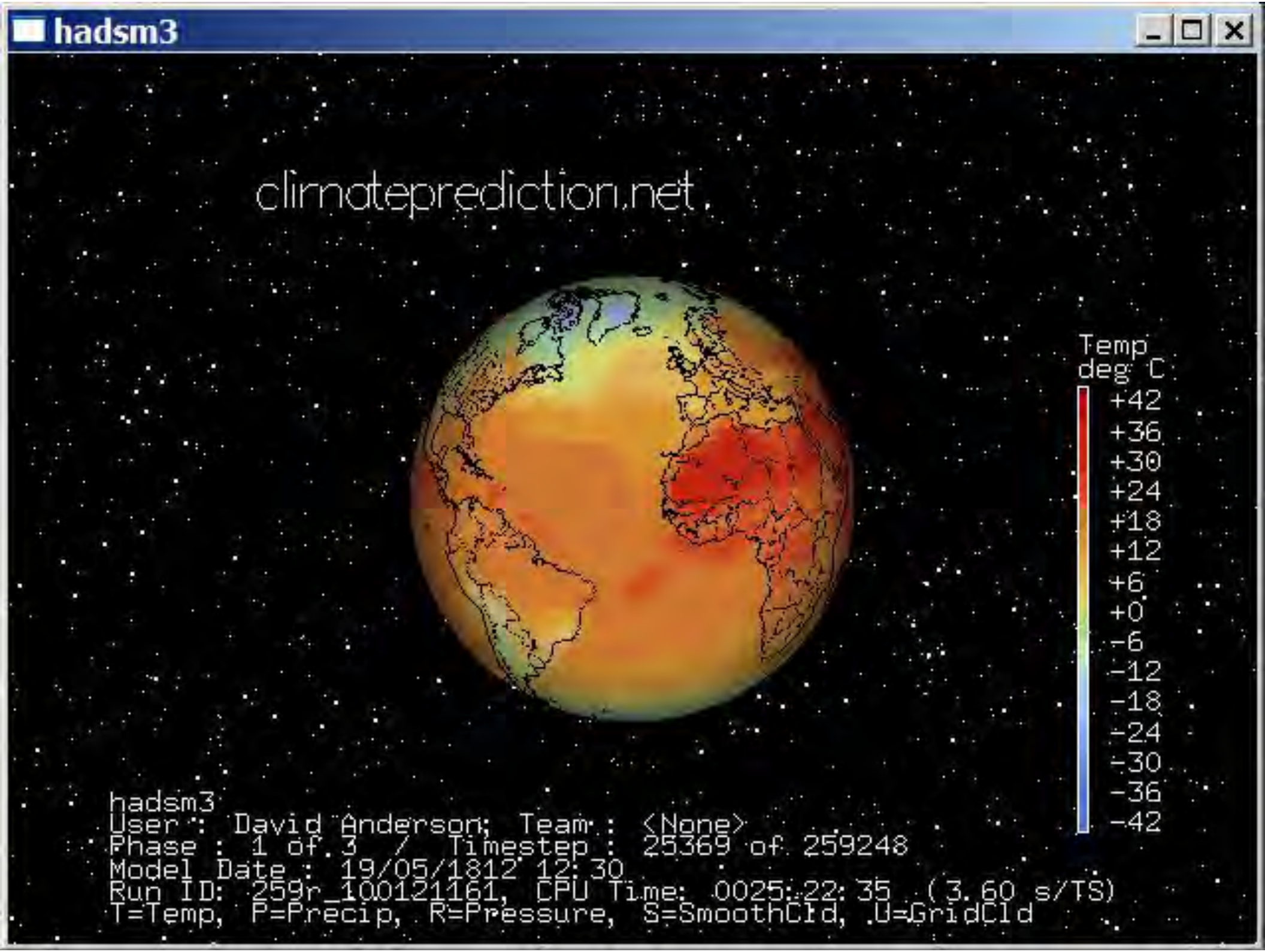
Projects

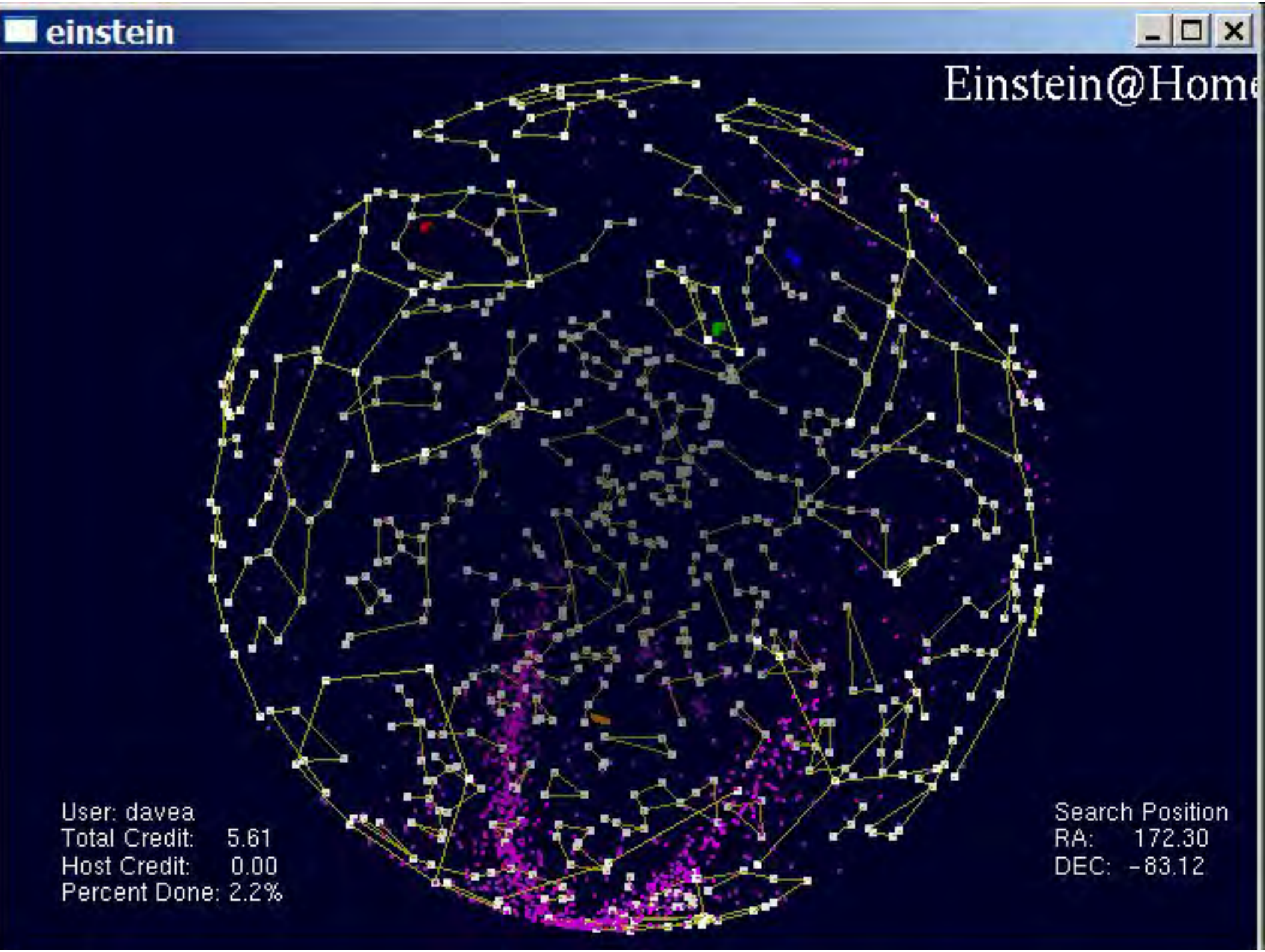
- Astronomy
  - SETI@home (Berkeley)
  - Astropulse (Berkeley)
  - Einstein@home: gravitational pulsar search (Caltech,…)
  - PlanetQuest (SETI Institute)
  - Stardust@home (Berkeley, Univ. Washinton,…)
- Earth science
  - Climateprediction.net (Oxford)
- Biology/Medicine
  - Folding@home, Predictor@home (Stanford, Scripts)
  - FightAIDSathome: virtual drug discovery
- Physics
  - LHC@home (Cern)
- Other
  - Web indexing/search
  - Internet Resource mapping (UC Berkeley)

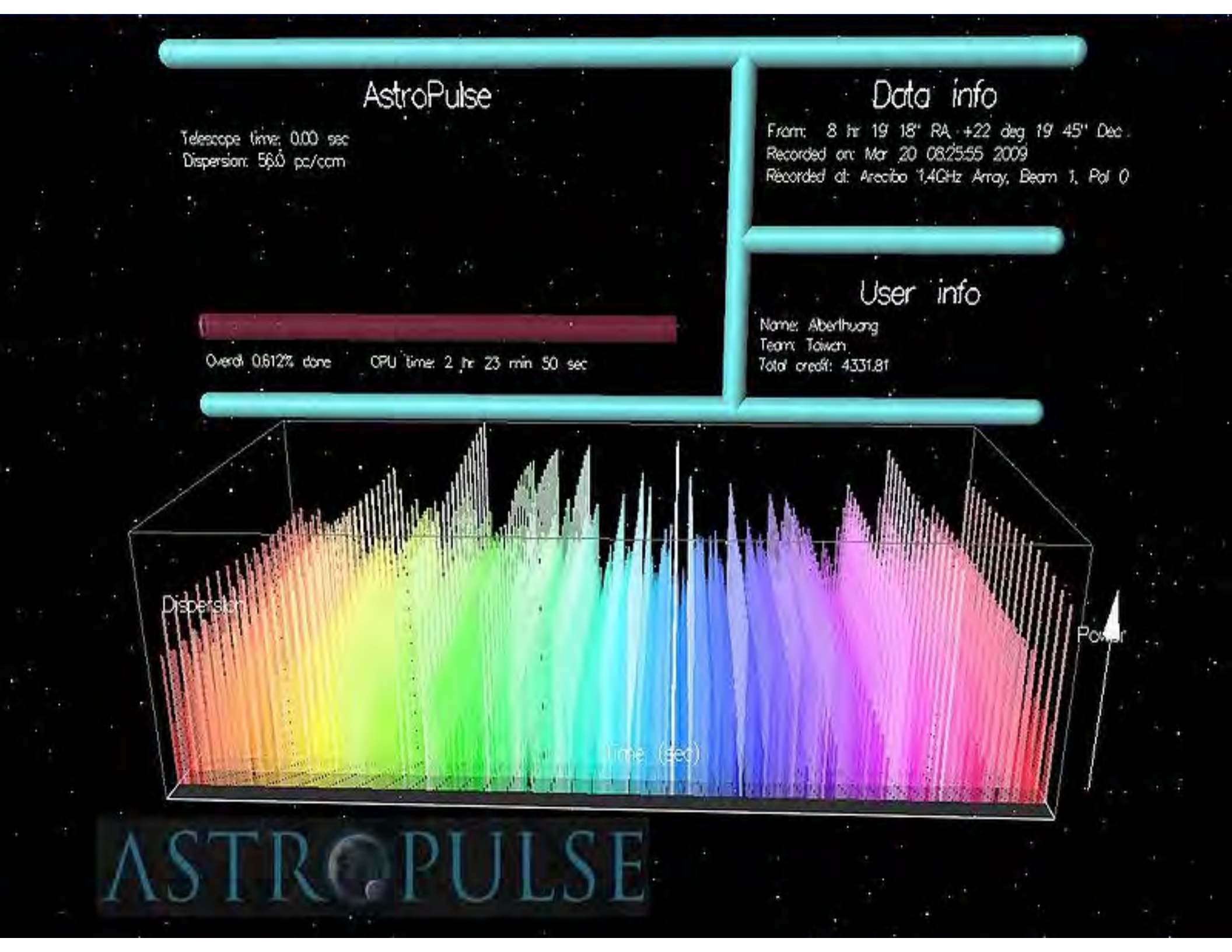
Astropulse

- "SETI@home for pulses"
- Coherent Dedispersion
- 2.5 MHz Bandwidth
  (0.4 μs samples)
- 28416 DMs
  54 cm^{-3} pc < | DM | < 1200 cm
- Sensitivity ~ 54 Jy μs
- Repeating and single pulse s
  - 10 octaves pulse duratic
    (0.4 – 409.6 μs)
- 394,144,520 pulses in databa
- 50% single, 50% repeating

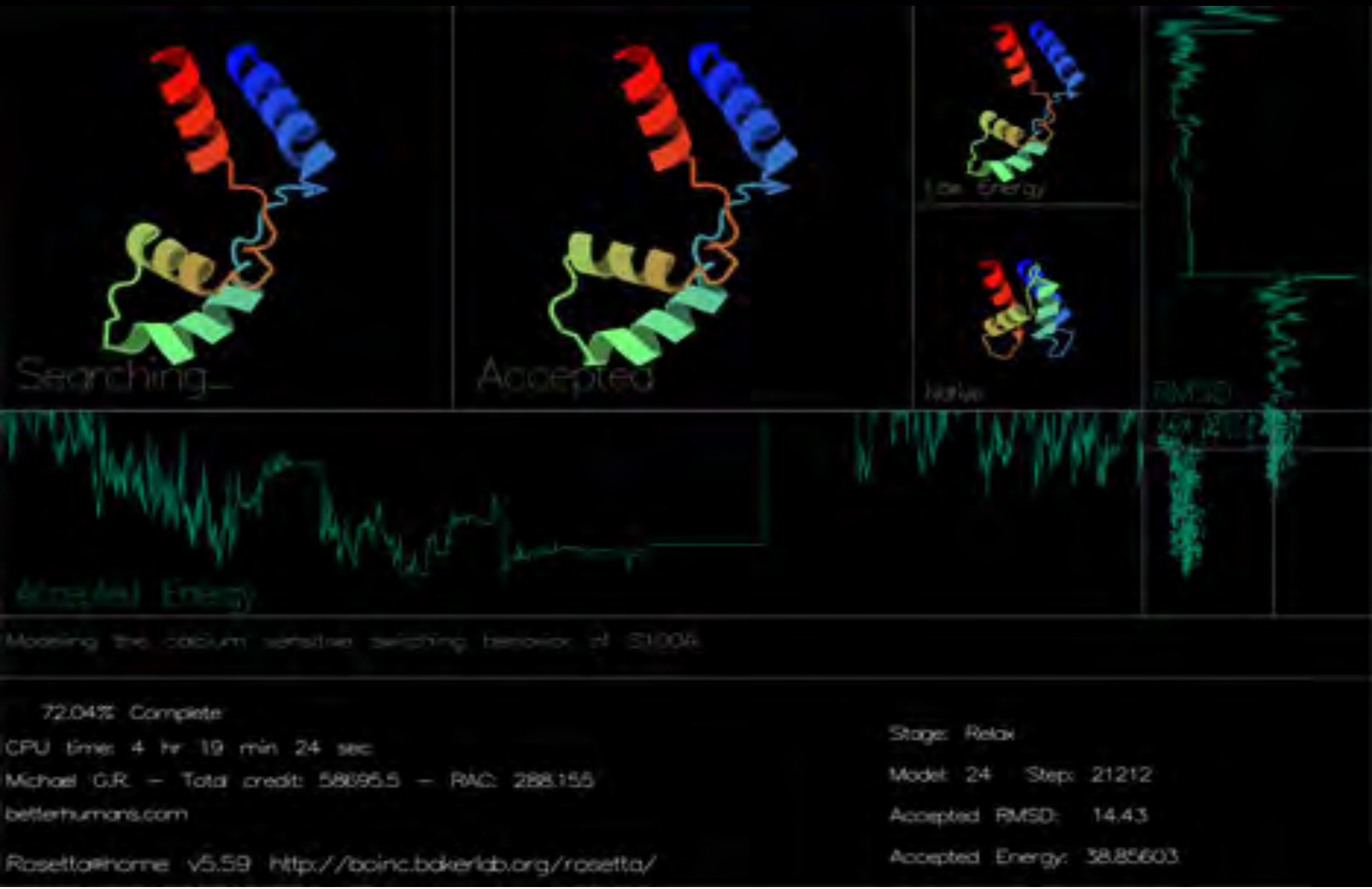



hadsm3
climateprediction.net
Temp
deg C
+42
+36
+30
+24
+18
+12
+6
+0
-6
-12
-18
-24
-30
-36
-42
hadsm3
User : David Anderson; Team : <None>
Phase : 1 of 3 / Timestep : 25369 of 259248
Model Date : 19/05/1812 12:30
Run ID: 259r_100121161, CPU Time: 0025:22:35 (3.60 s/TS)
T=Temp, P=Precip, R=Pressure, S=SmoothCld, U=GridCld


einstein
Einstein@Home
User: davea
Total Credit: 5.61
Host Credit: 0.00
Percent Done: 2.2%
Search Position
RA: 172.30
DEC: -83.12


AstroPulse
Telescope time: 0.00 sec
Dispersion: 56.0 pc/cm
Overall 0.612% done
CPU time: 2 hr 23 min 50 sec
Data info
From: 8 hr 19 18" RA +22 deg 19 45" Dec
Recorded on: Mar 20 08:25:55 2009
Recorded at: Arecibo 1.4GHz Array, Beam 1, Pol 0
User info
Name: Alberthuang
Team: Taiwan
Total credit: 4331.81
Dispersion
Time (sec)
Power
ASTROPULSE

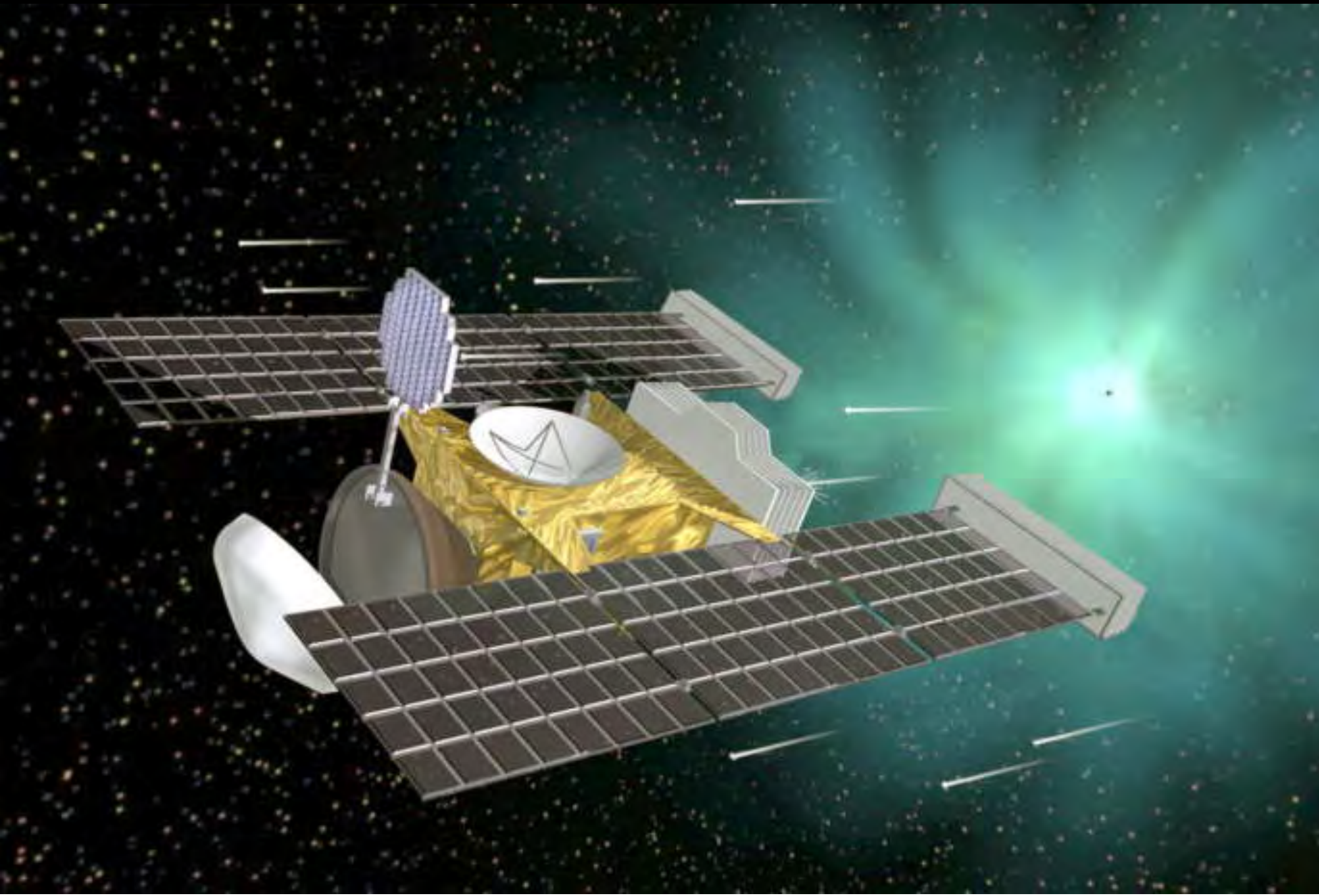
Rosetta Screensaver



Thinking@Home

Stardust@home...

Stardust (NASA)

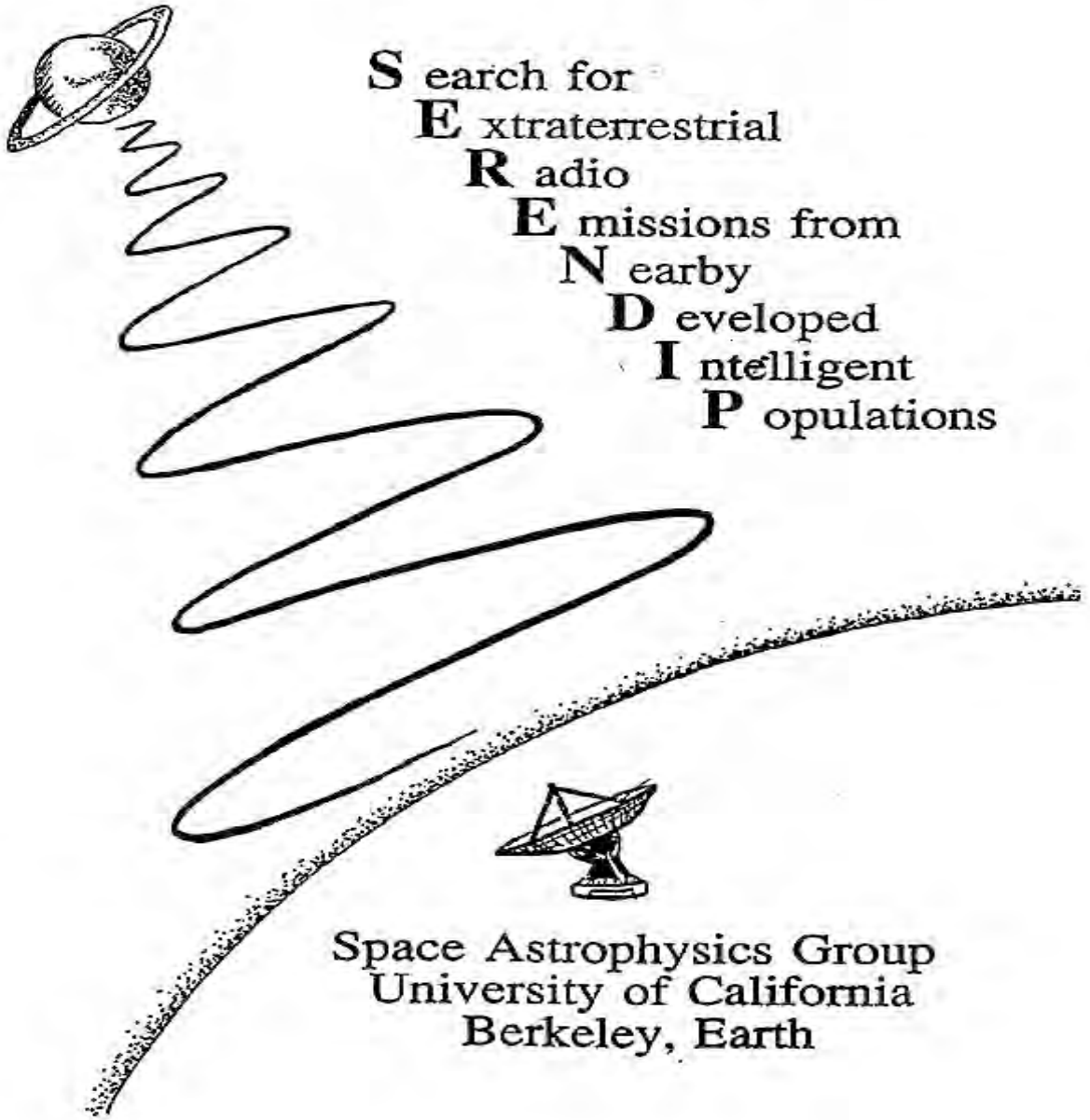


Citizen Science Projects

- SETI@home and Astropulse (UC Berkeley)
- Stardust@home (UC Berkeley)
- SetiQuest (Seti Institute)
- Galaxy Zoo (Galaxy Classification)
- Audubon Society's Christmas Bird Count (1900)
- Community Collaborative Rain, Hail & Snow Monitor Network
- Clickworkers (mars crater identficiation - NASA)
- Ebird, NestWatch, FeederWatch, Urban Birds (Cornell Univ.)
- ParkScan (monitor San Francisco Parks)
- ScienceForCitizens.net

- ENERGY@home

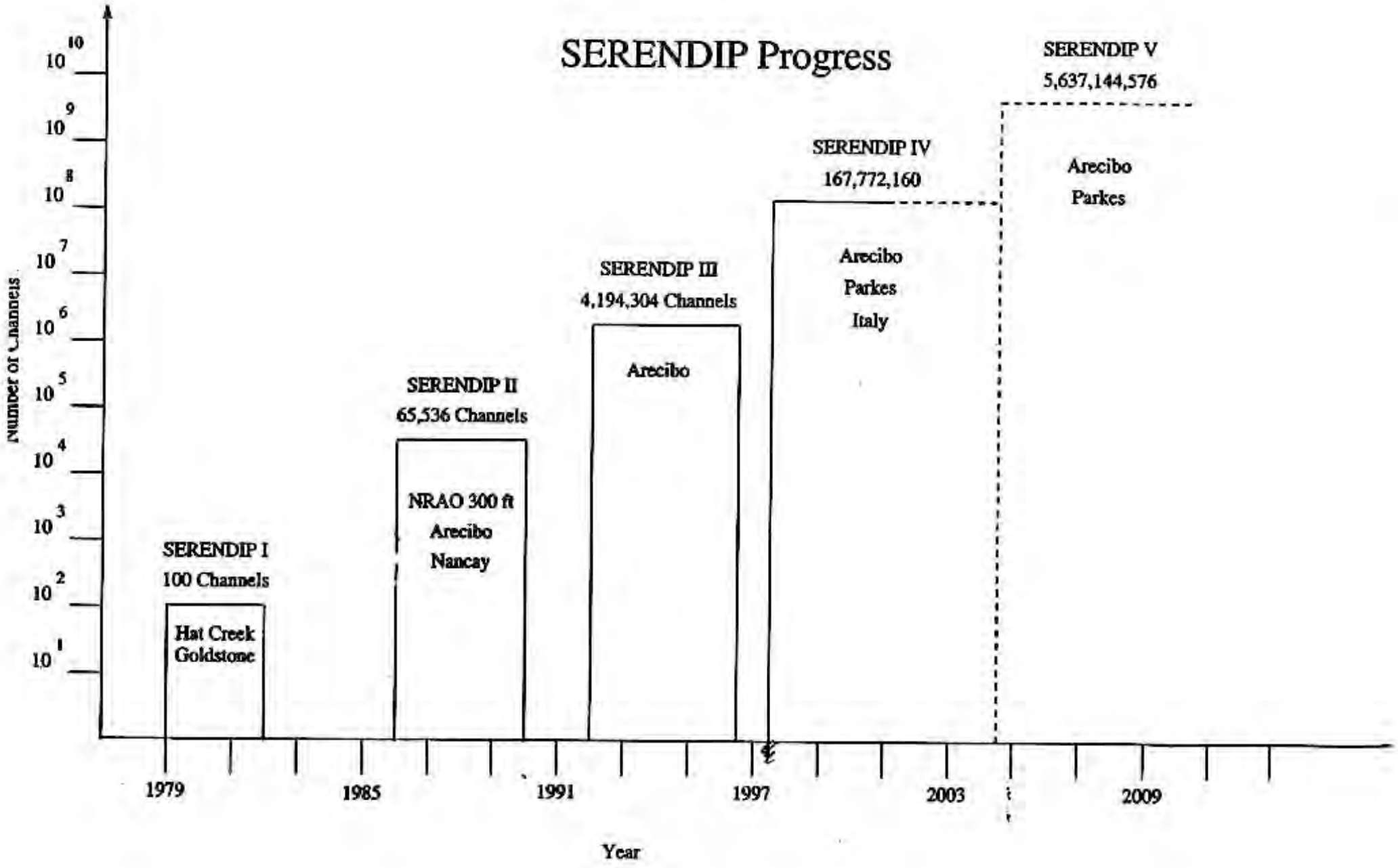
SERENDIP



S earch for
E xtraterrestrial
R adio
E missions from
N earby
D eveloped
I ntelligent
P opulations

Space Astrophysics Group
University of California
Berkeley, Earth

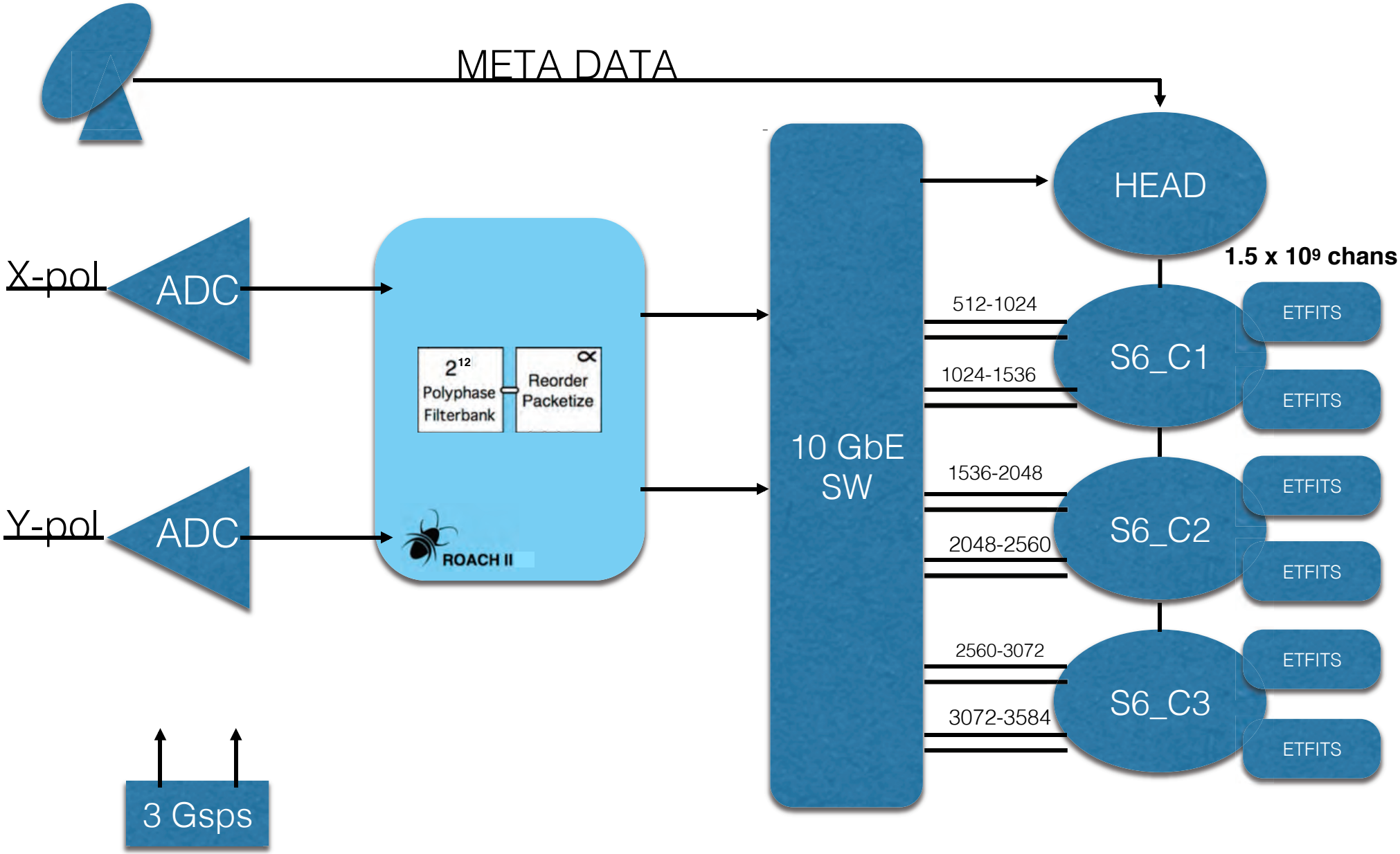
SERENDIP Instruments using 2X per year (1,000,000 over 20 years)



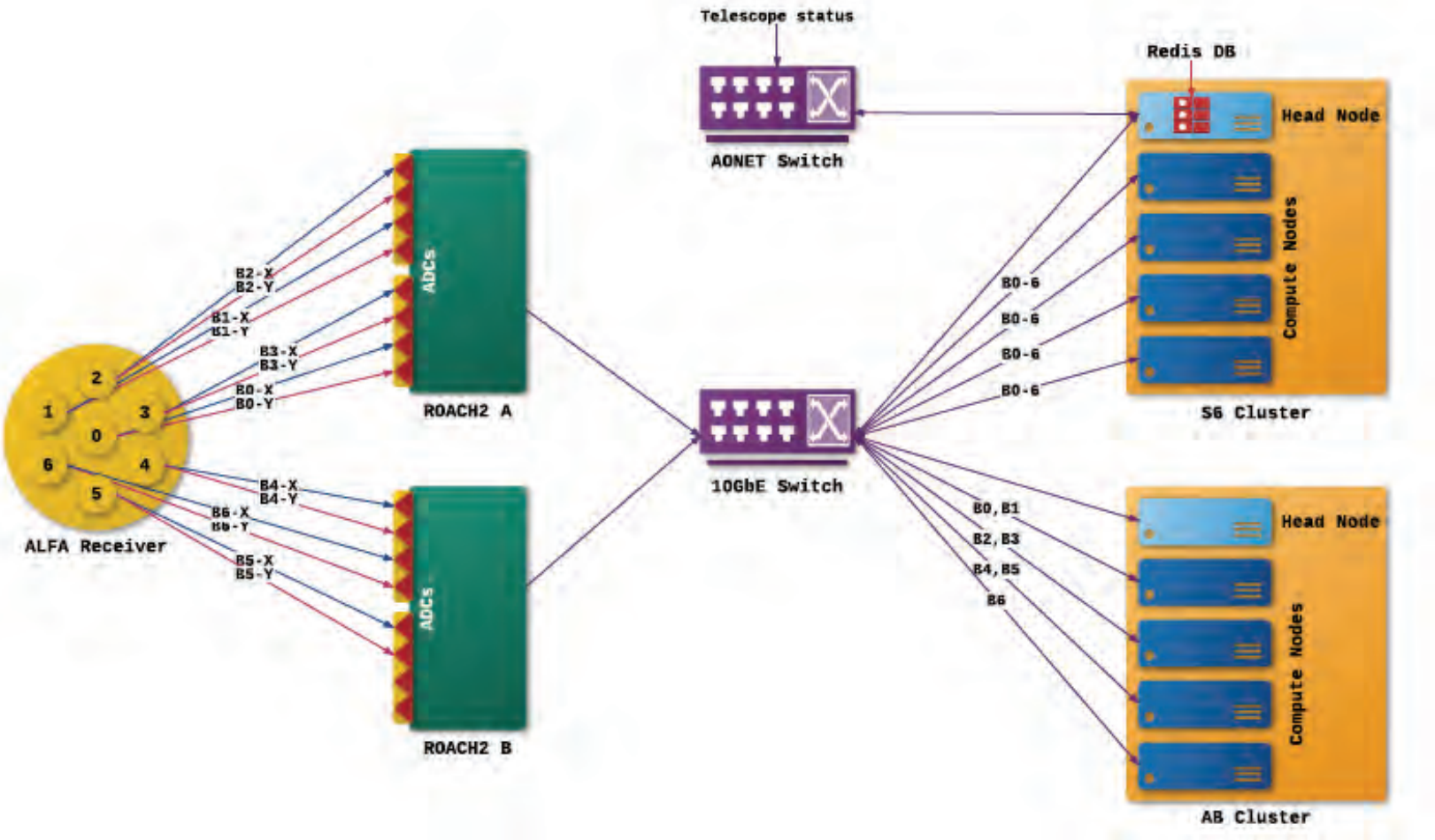
SERENDIP 6

	GBT	Arecibo
Bandwidth (MHz)	1125	280
Beams	1	7
Frequencies	Q, Ku, K, X C, L, 90cm	L, 90cm
Coarse Channels	3072	2560
Fine channels/CC	512k	131k
Resolution (Hz)	0.6	0.8

SERENDIP 6 at the Green Bank telescope



SERENDIP 6 at the Arecibo telescope



Chennamangalam et al. 2016

High Speed Data Transport - Hashpipe

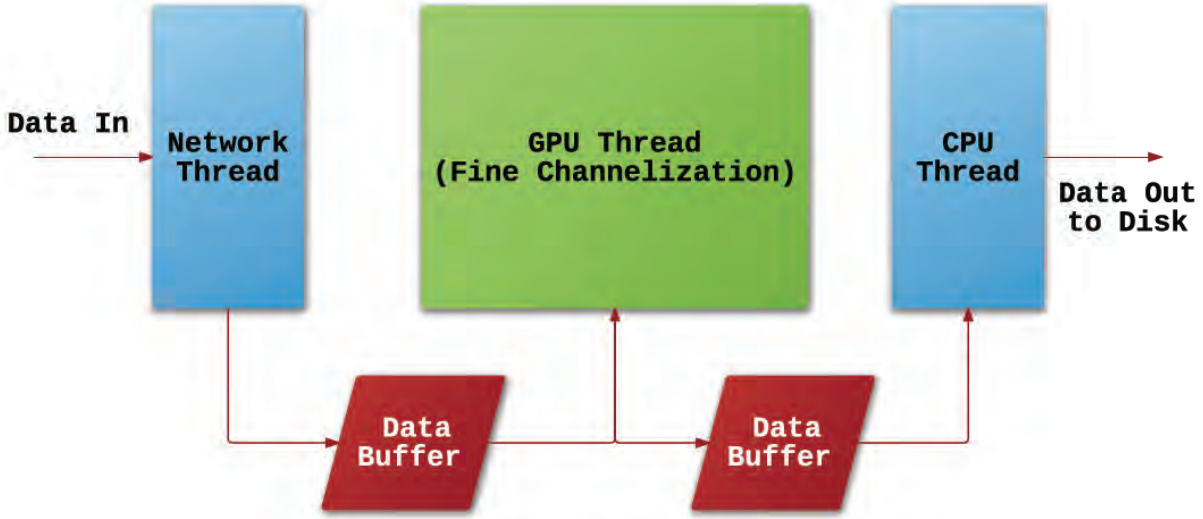
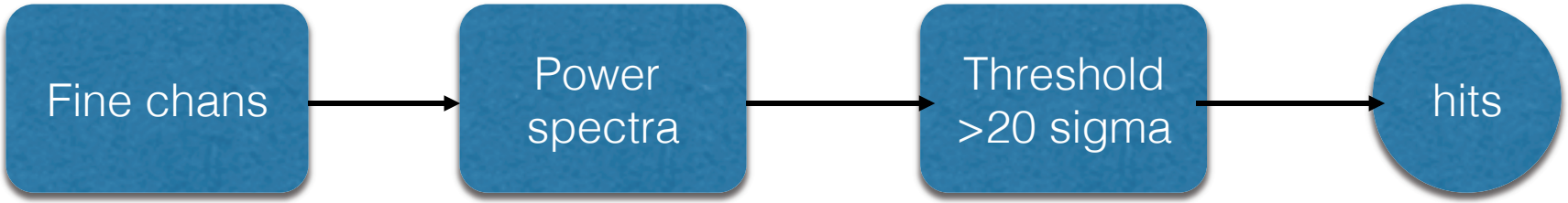
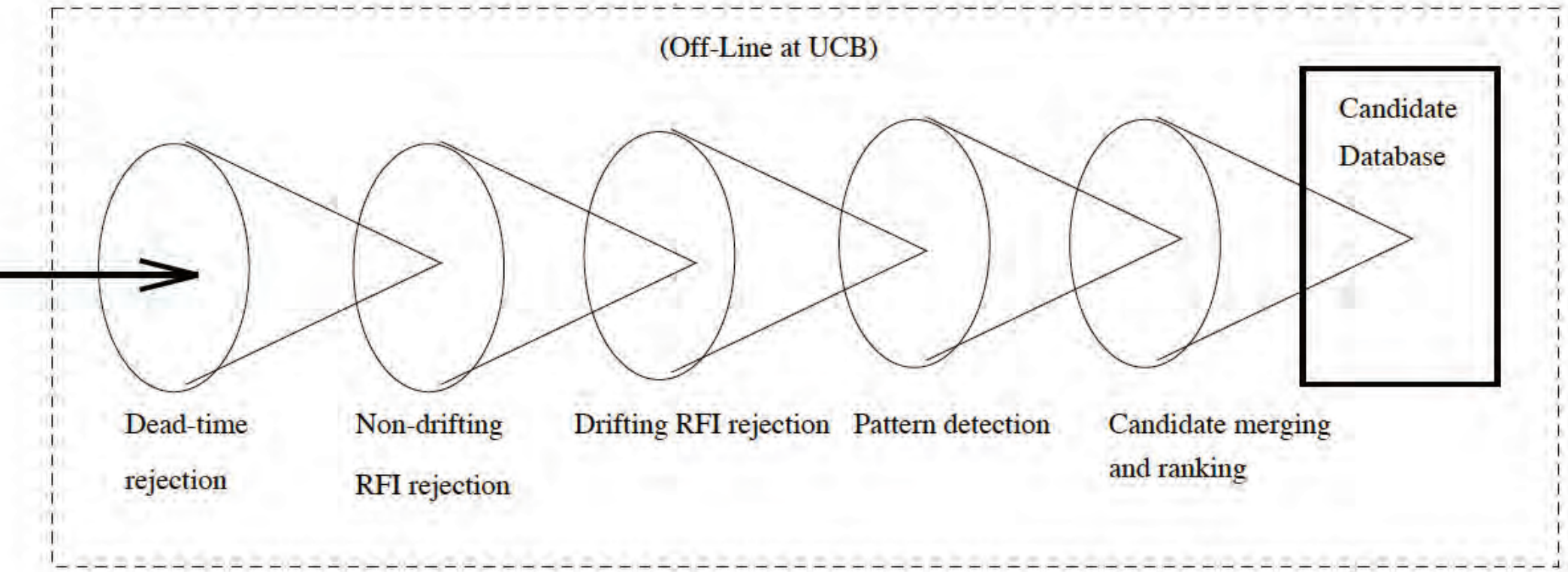


Fig. 3.— Schematic of the HASHPIPE data processing pipeline used in SERENDIP VI. The red blocks and lines depict the data storage and transport provided by the framework, while the blue and green blocks are user-supplied plug-in modules that implement certain functionalities, as described in §2.2.

Chennamangalam et al. 2016

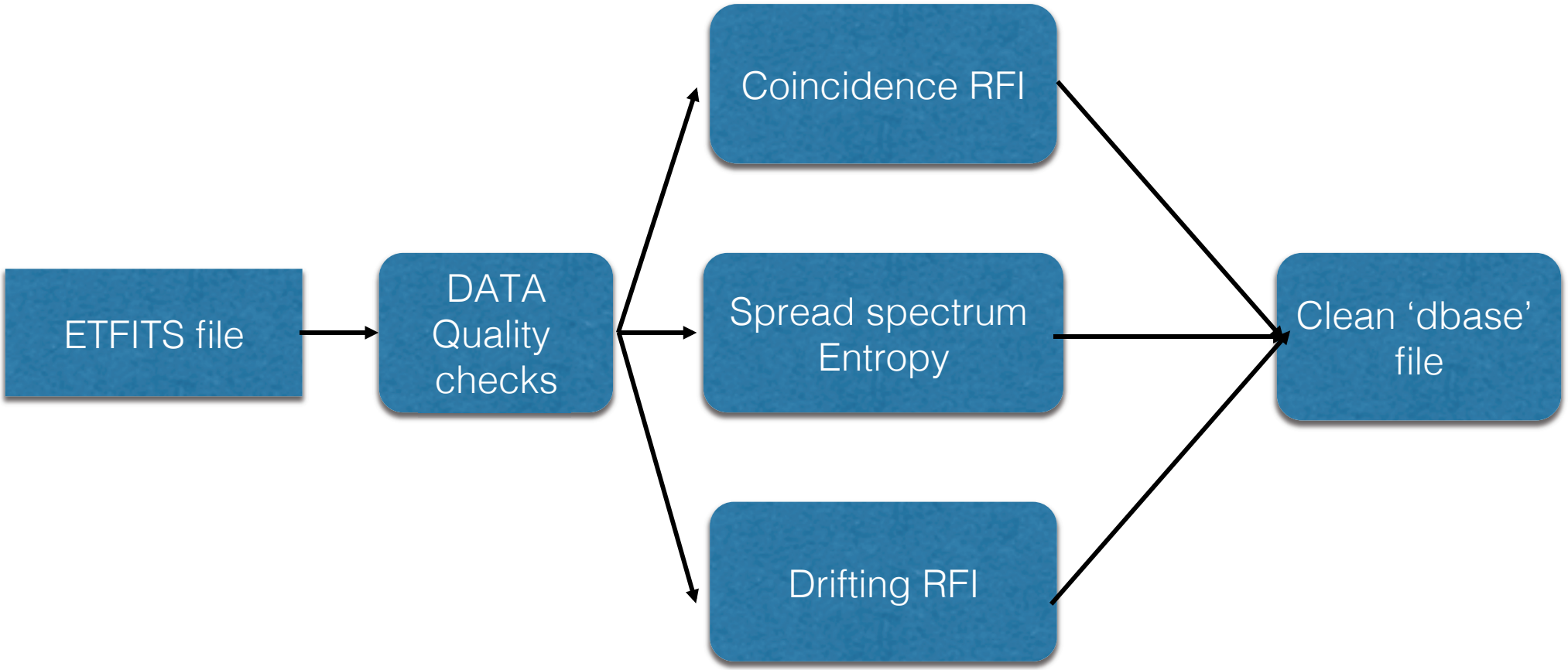


Data analysis pipeline

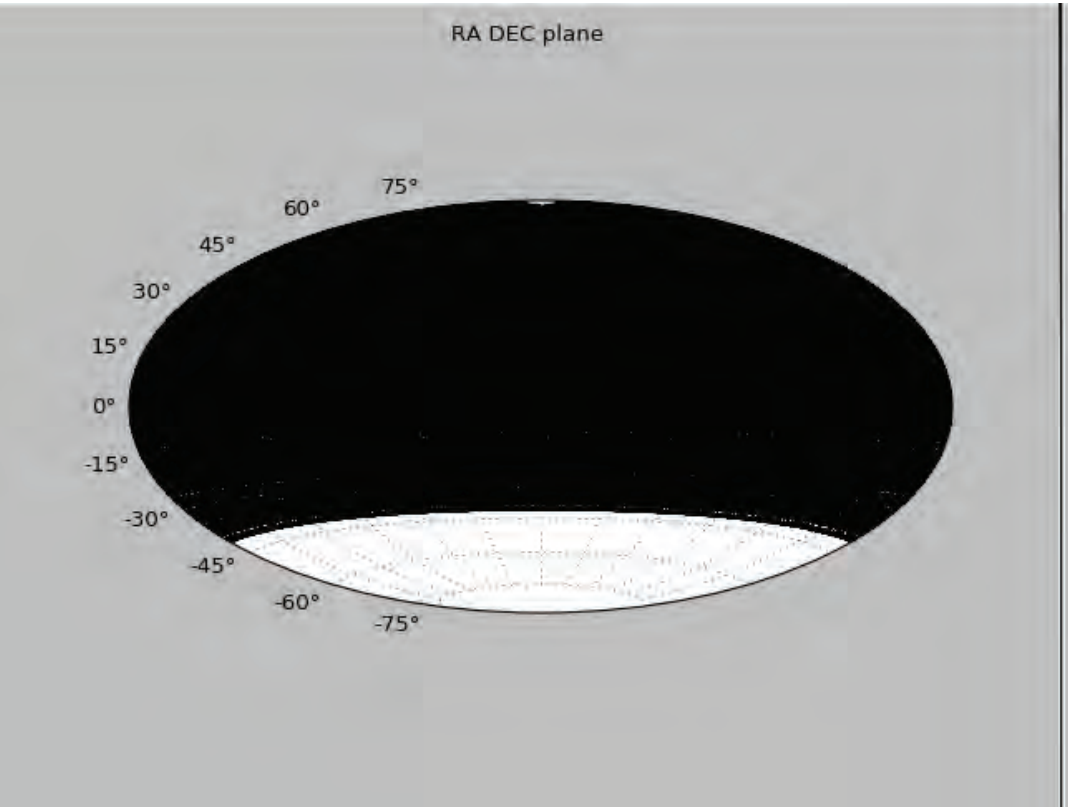


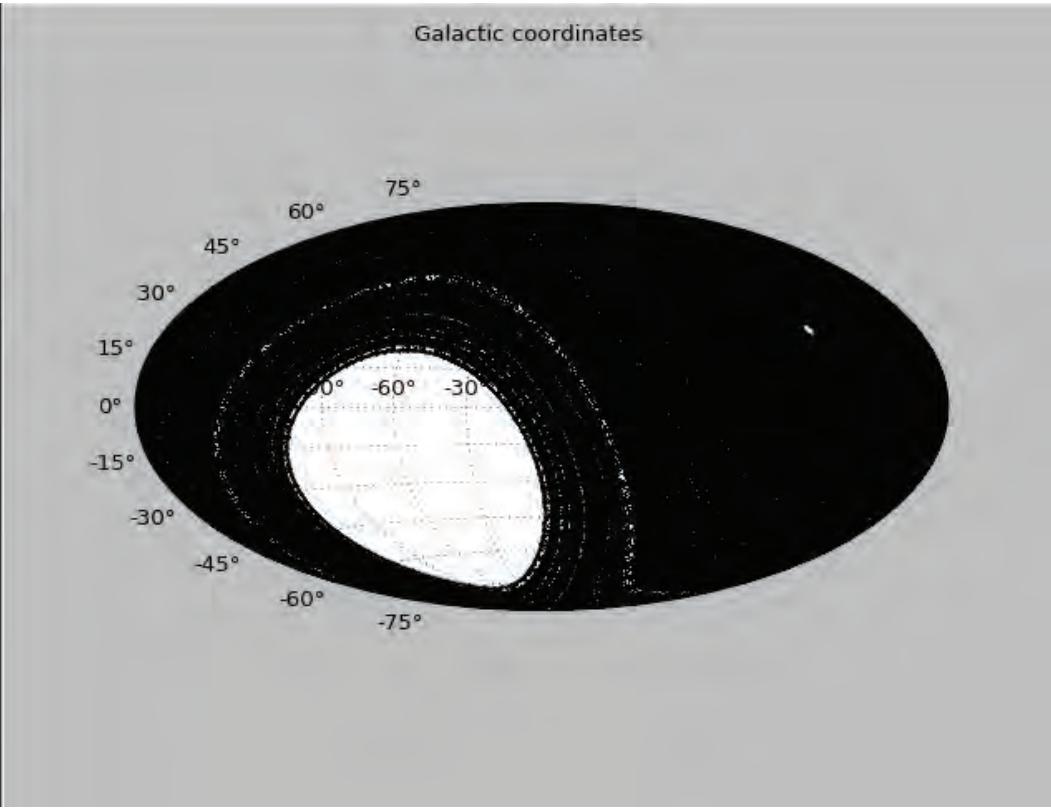
Bowyer et al. 2016

RFI rejection pipeline

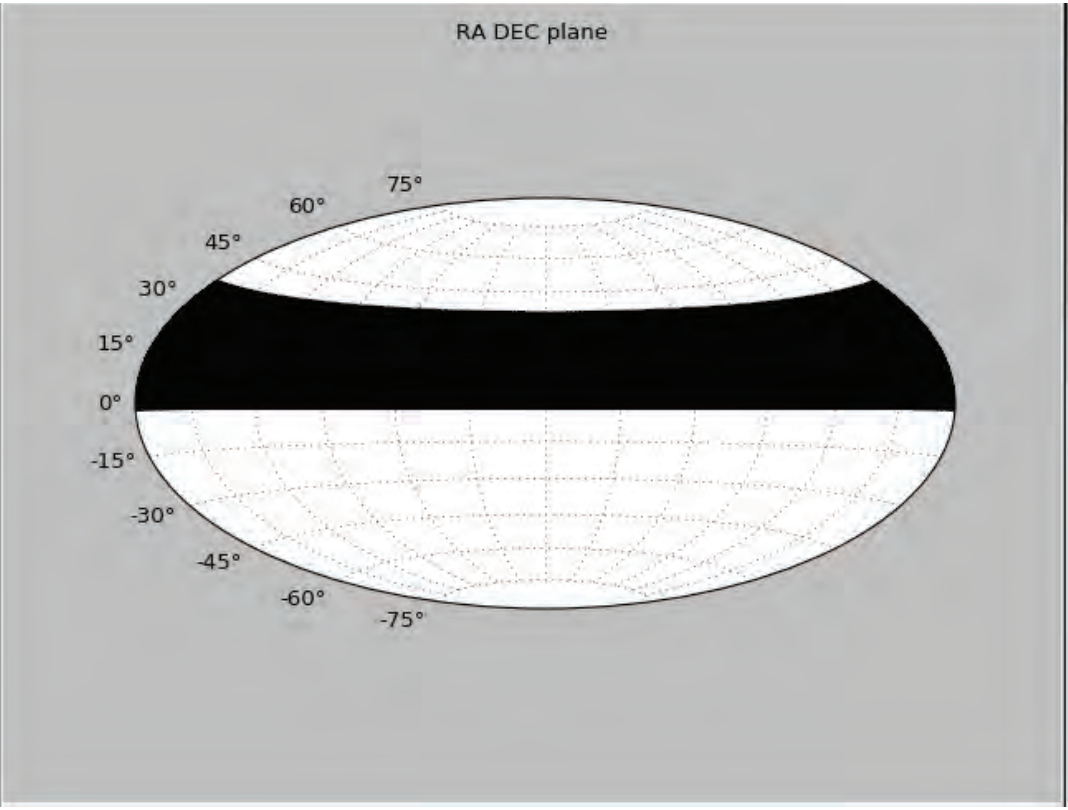


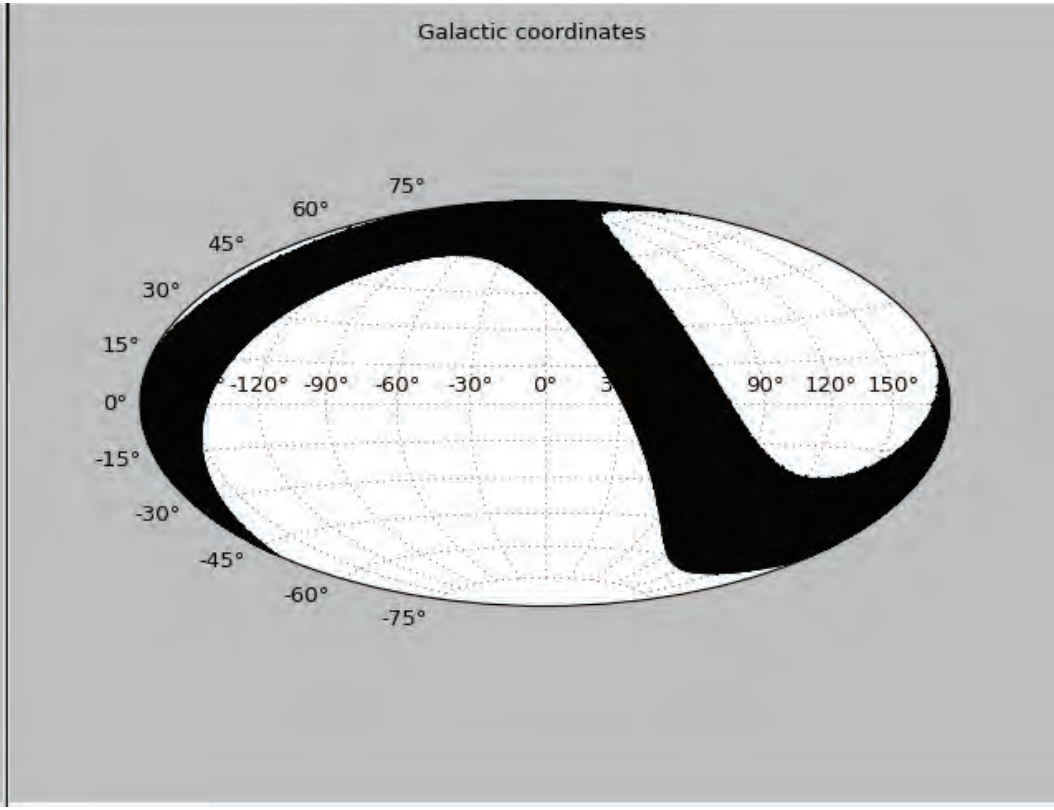
Sky coverage of SERENDIP 6 data from the GBT



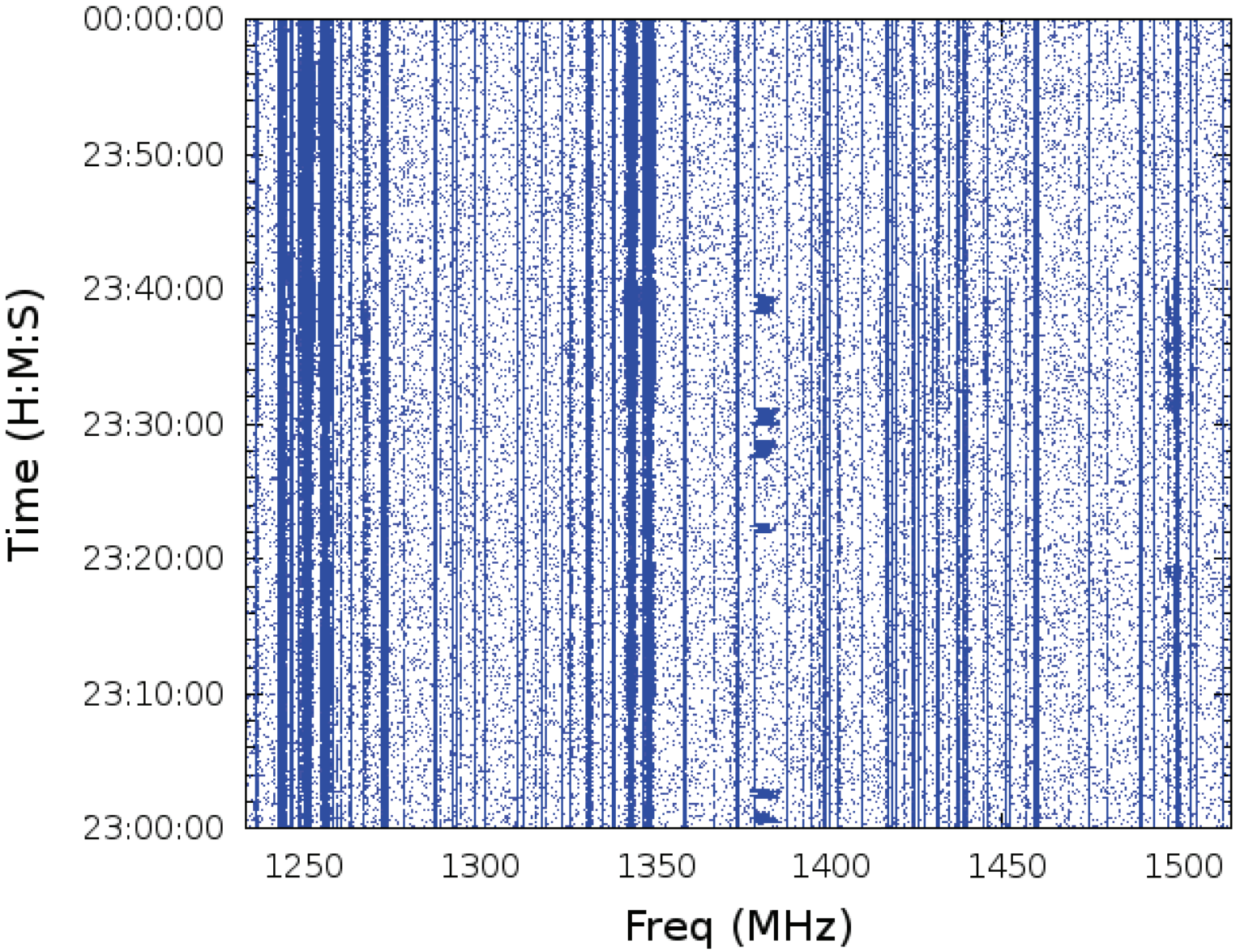


Sky coverage of SERENDIP 6 data from the Arecibo

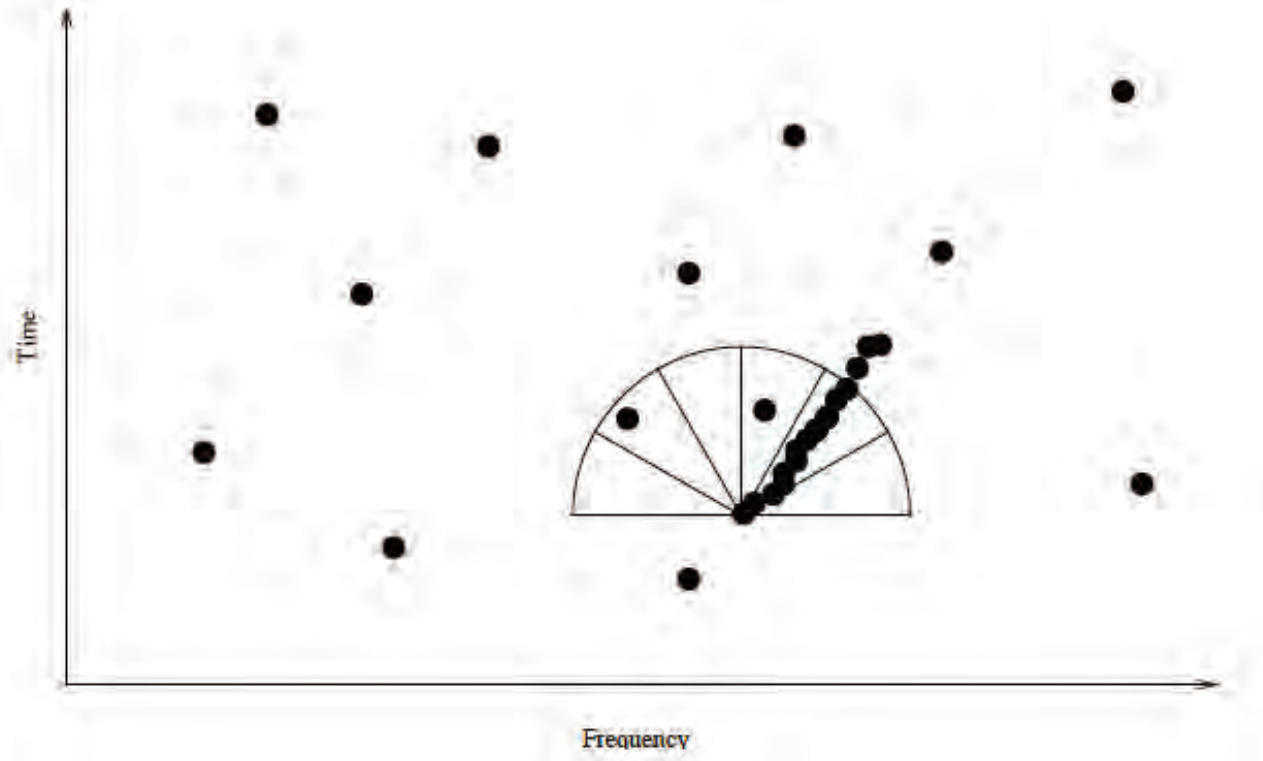


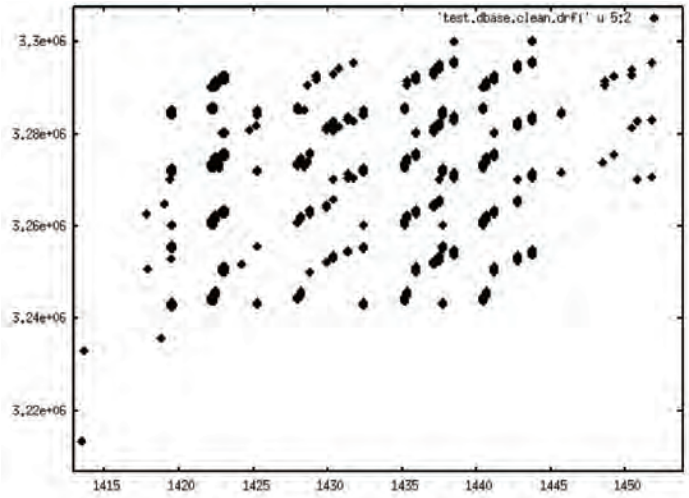


L band (20th September 2016)



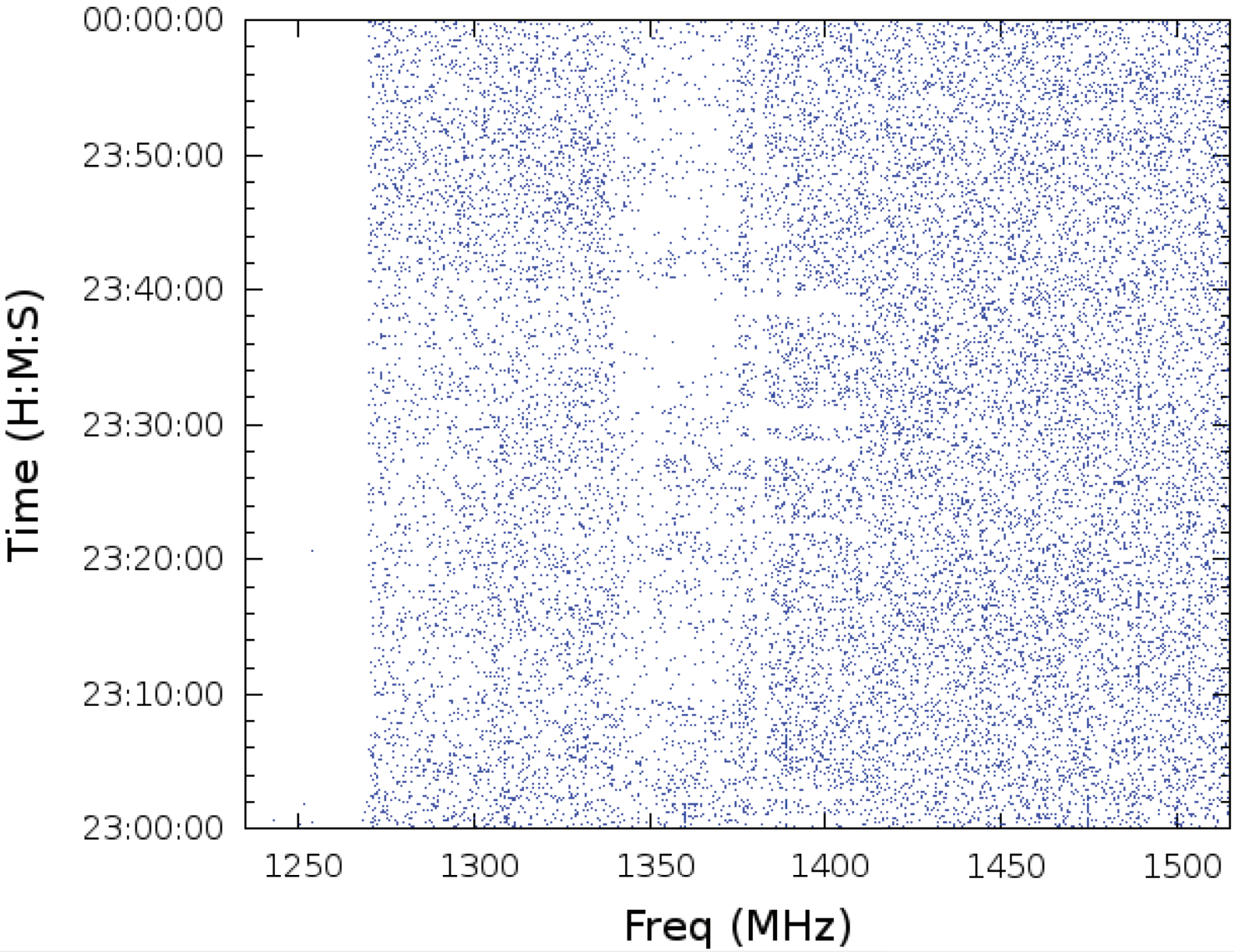
Drifting RFI mitigation

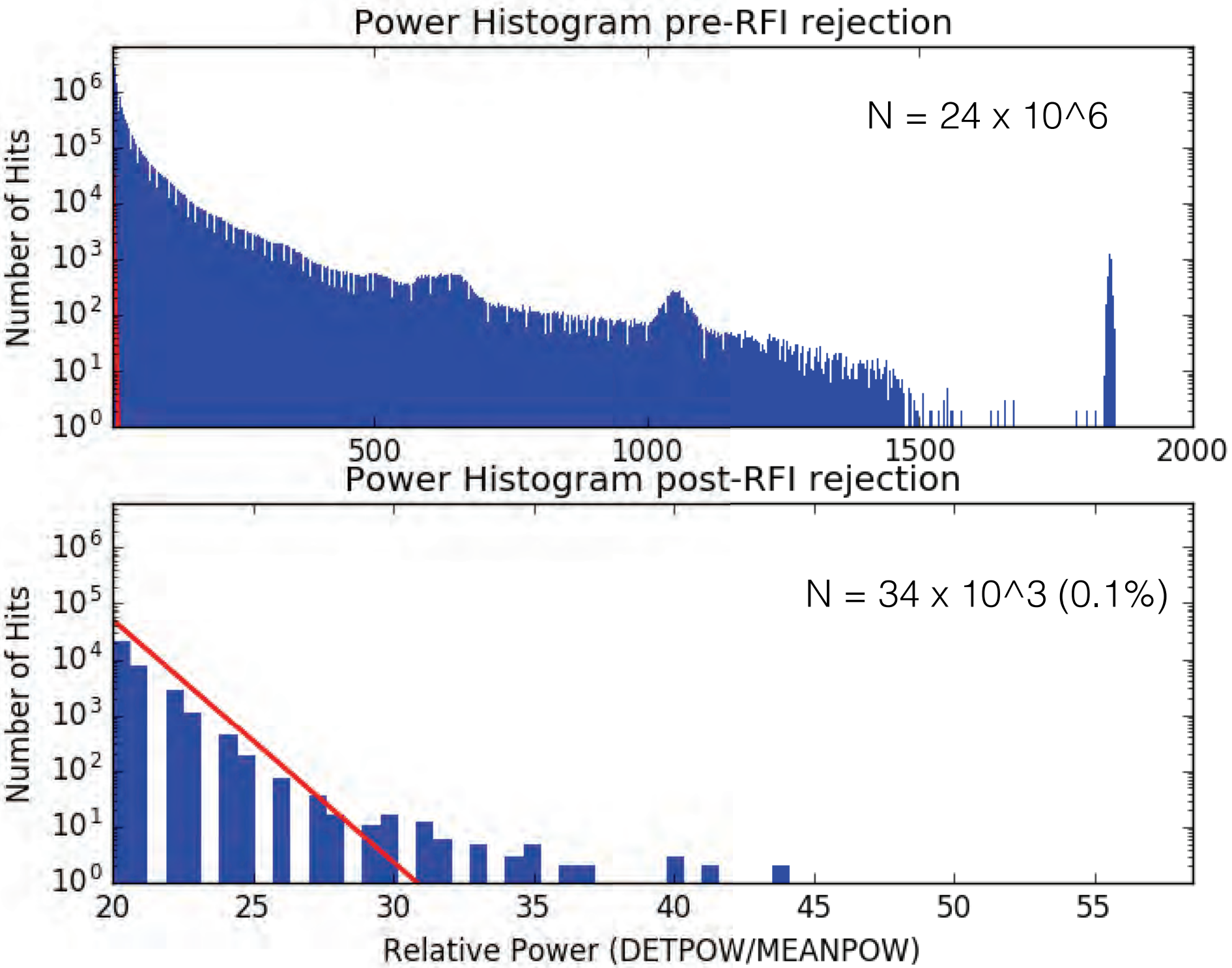




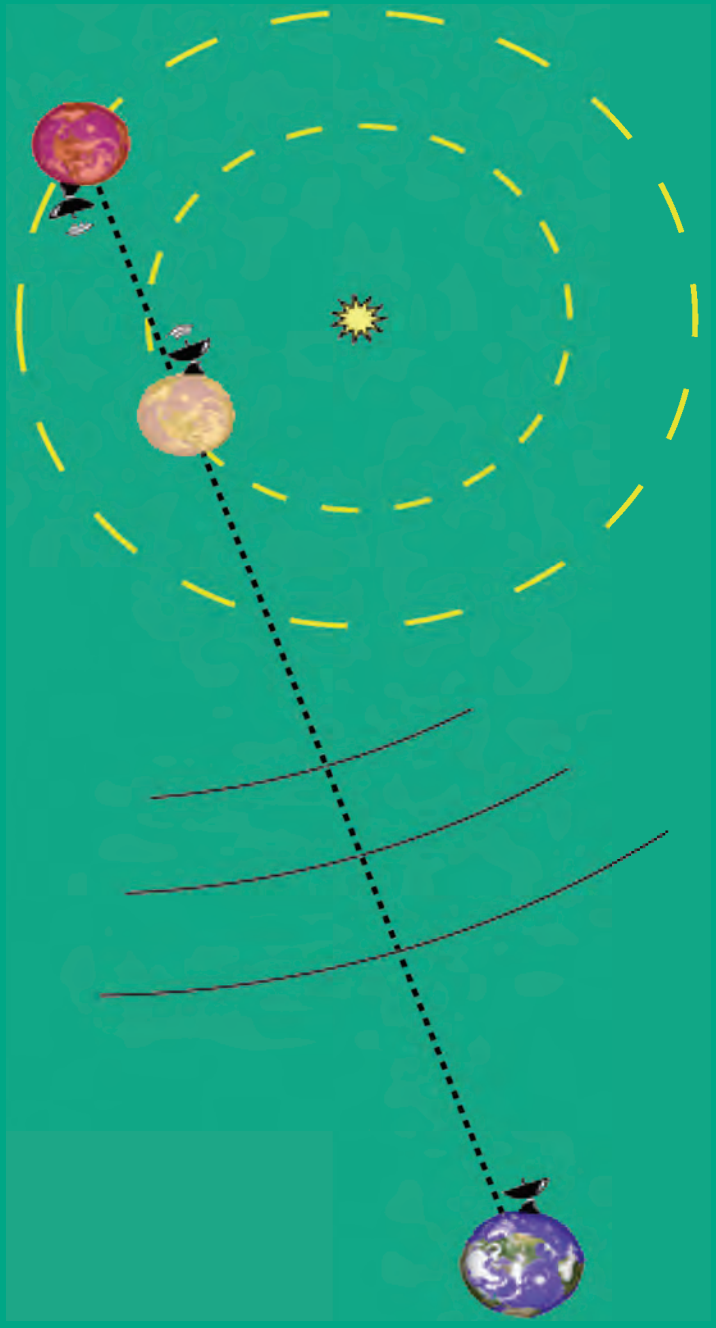
Bowyer et al. 2016

Post-RFI rejection




Power Histogram pre-RFI rejection
N = 24 x 10^6
Number of Hits
10^0
10^1
10^2
10^3
10^4
10^5
10^6
500
1000
1500
2000
Power Histogram post-RFI rejection
N = 34 x 10^3 (0.1%)
Number of Hits
20
25
30
35
40
45
50
55
Relative Power (DETPOW/MEANPOW)

Interplanetary eavesdropping



- Kepler has found numerous multiple planet systems
- When planets are in conjunction with Earth the more distant planet is beaming its signals at us, giving us an opportunity to catch spillover.
- Given the number of exoplanet systems, these conjunctions are frequent
- 5-10 minute obs (per band)
  - 1.1-1.9 GHz
  - 1.8-3.0 GHz
  - 7.8-11.0 GHz
- total of about 30 hours thus far

Future SETI Experiments

New wavelengths? Signal Types? Instruments? Algorithms? Machine Learning? Data Mining? Commensal?

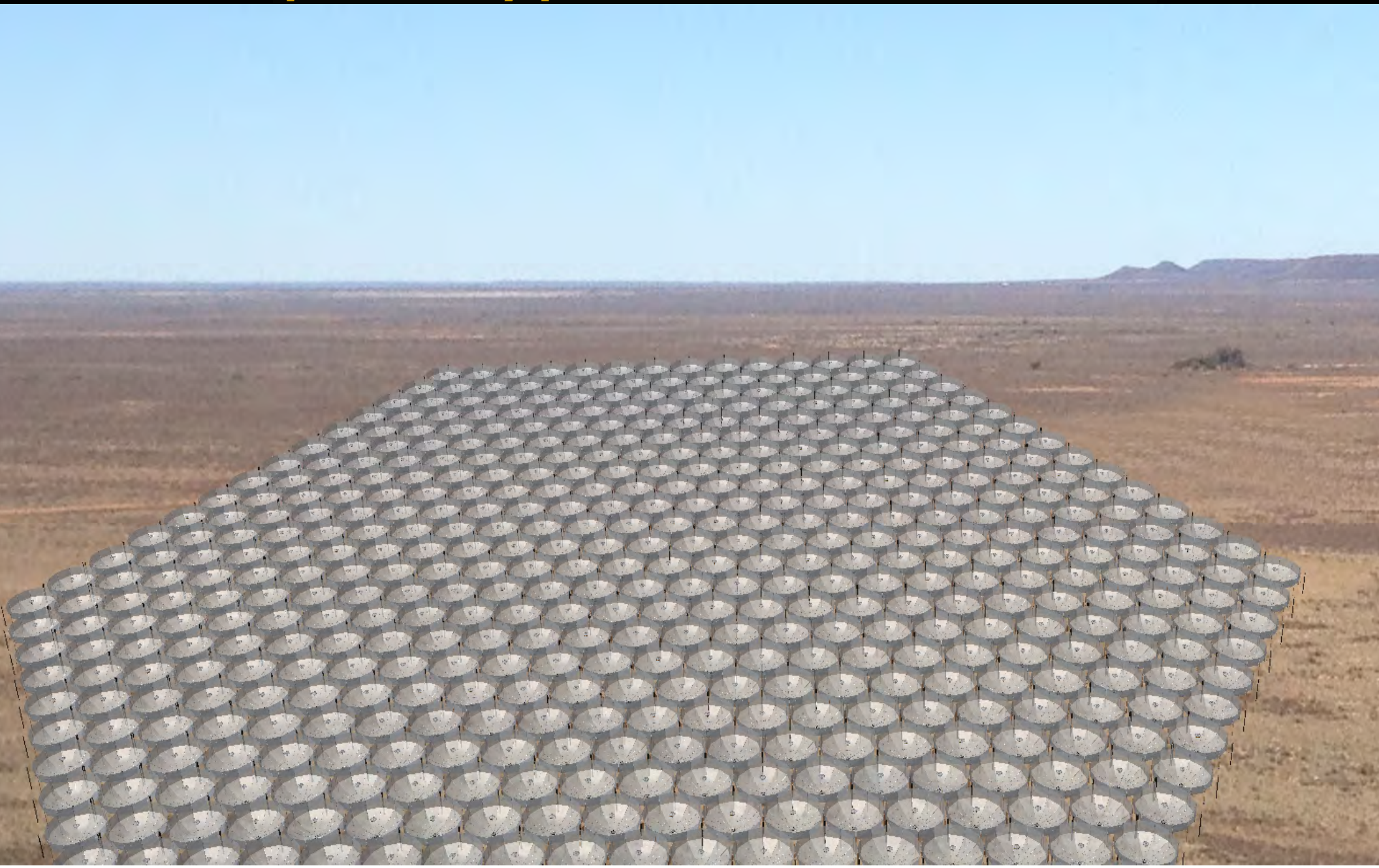
Encouraging new SETI Experiments and Groups
Student and Postdoc Training

OSETI Data Mining

VERITAS, Panoramic Survey Telescope and Rapid Response (Pan-STARRS), Catalina Sky Survey (CSS), Palomar Transient Factory (PTF), Zwicky Transient Factory (ZTF), Advanced Technology Large Aperture Space Telescope (ATLAS), Dark Energy Spectroscopic Instrument (DESI), Kepler, the Large Synoptic Survey Telescope (LSST), and the James Webb Space Telescope (JWST)


FAST

HERA Array 352 x 14 meter dishes prototype tested at GBO



All Sky All the Time (low duty cycle search)

- 1973 Troitsky et al, Sporadic Radiation Resulting from Technological Activity of Extraterrestrial Civilization (Baku, USSR) (cross correlation of several dipoles)
- Phase Array Feeds (Ron Ekers et al)
- Paul Horowitz, All Sky Optical Working Group

  "Synoptic All-sky Pulsed Optical SETI"
- Eliot Gillum and Gerry Harp: Wide Field Camera
- Shelley Wright – SETI WideField IR Survey (SWIS)

Paul Horowitz - All Sky All the Time Optical Pulse Search

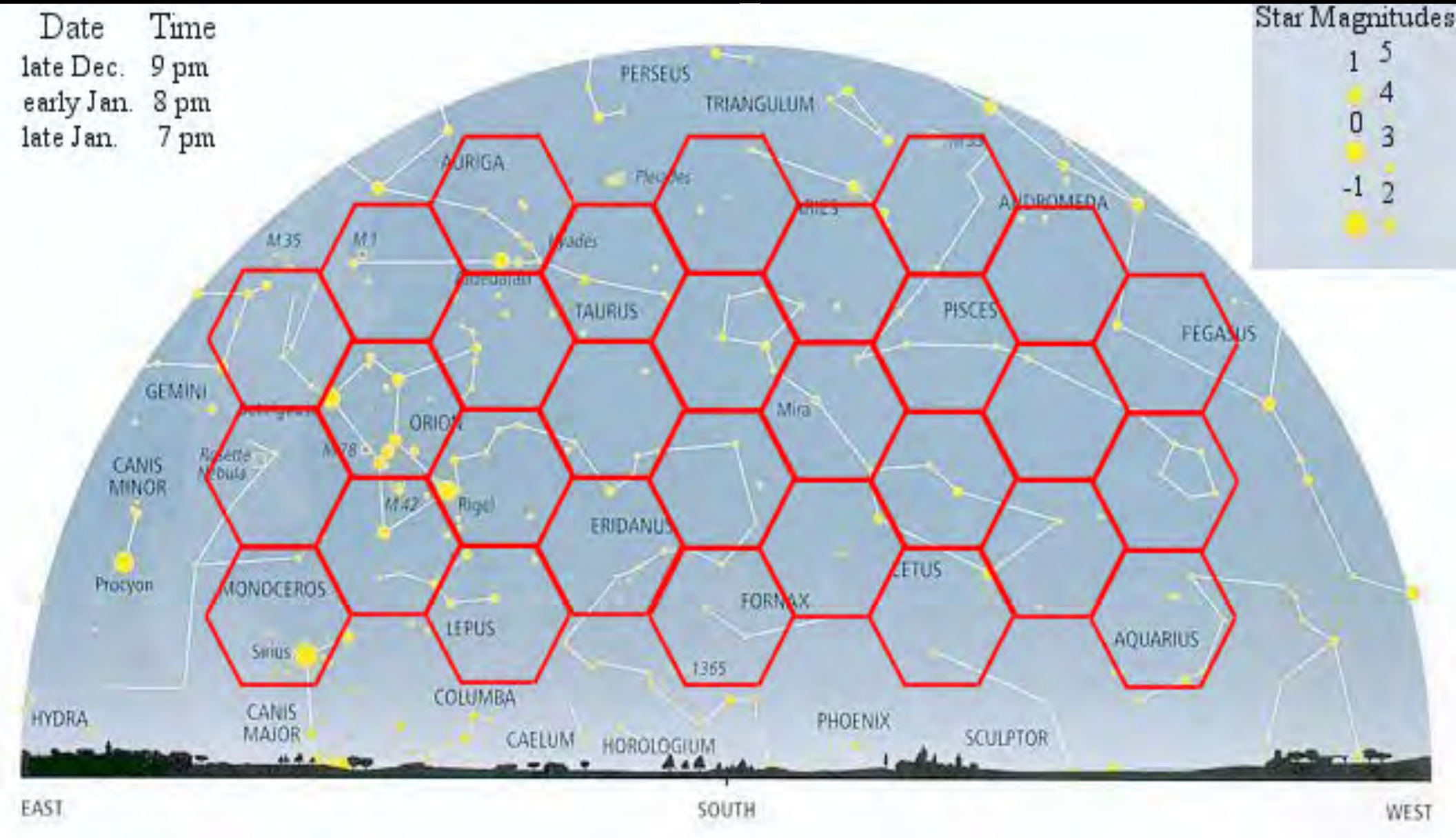
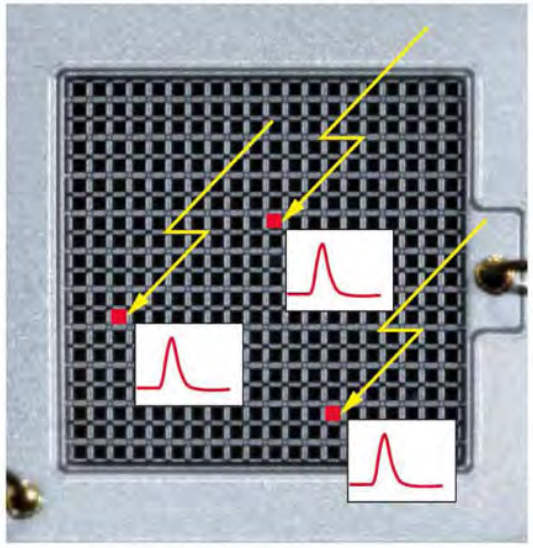
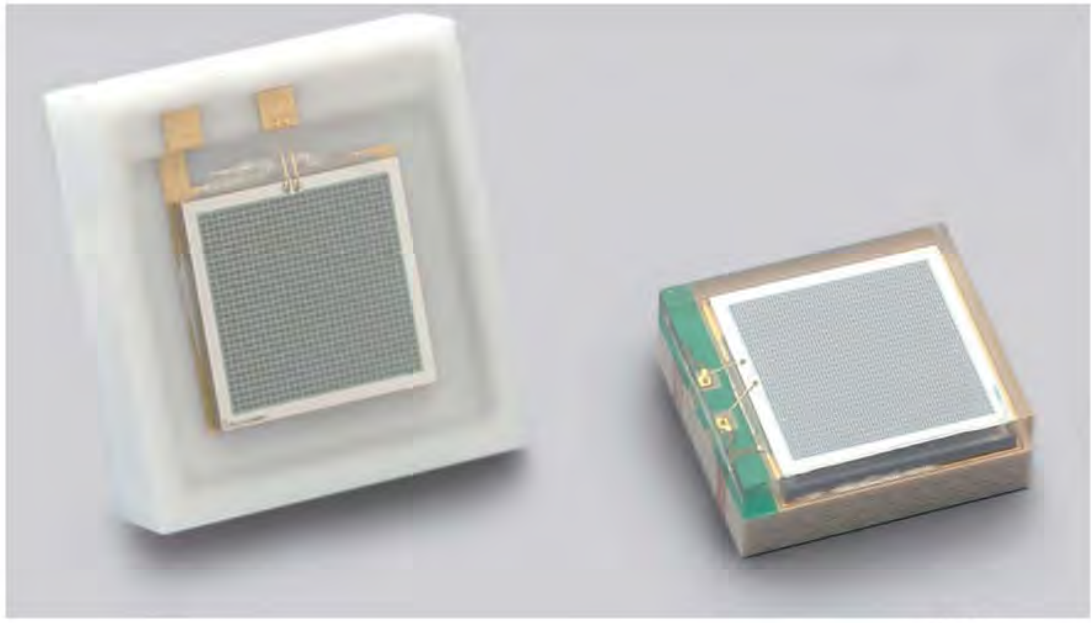


Image of MPPC's photon counting



(A)

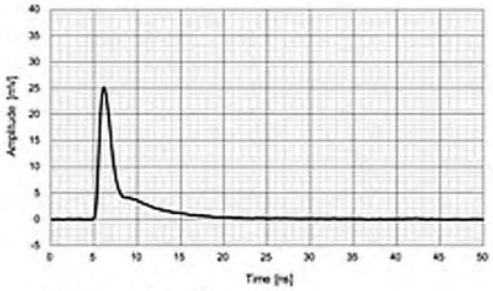


(B)

Wave form

- S1257x Series (10, 15, 25 μm)

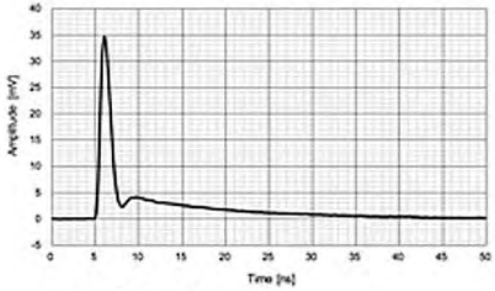
S12571-010C



Gain : 1.3×10^5

Rise time : 1.0 [ns]
Fall time : 10 [ns]

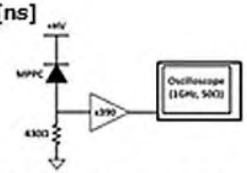
S12571-015C



Gain : 2.3×10^5

Rise time : 1.0 [ns]
Fall time : 25 [ns]

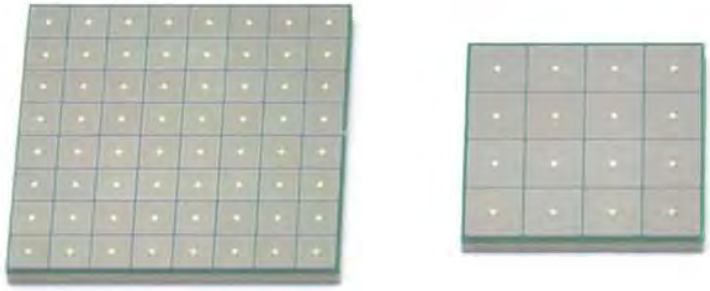
Rise time and fall time are defined by 10-90% pulse height to peak.
This data was taken by using 1GHz oscilloscope averaging 1,000 1pe pulse shape



Waveform measurement setup

- Rise time is very fast
- Fall time depends on micro cell size and active area size

(C)



(D)

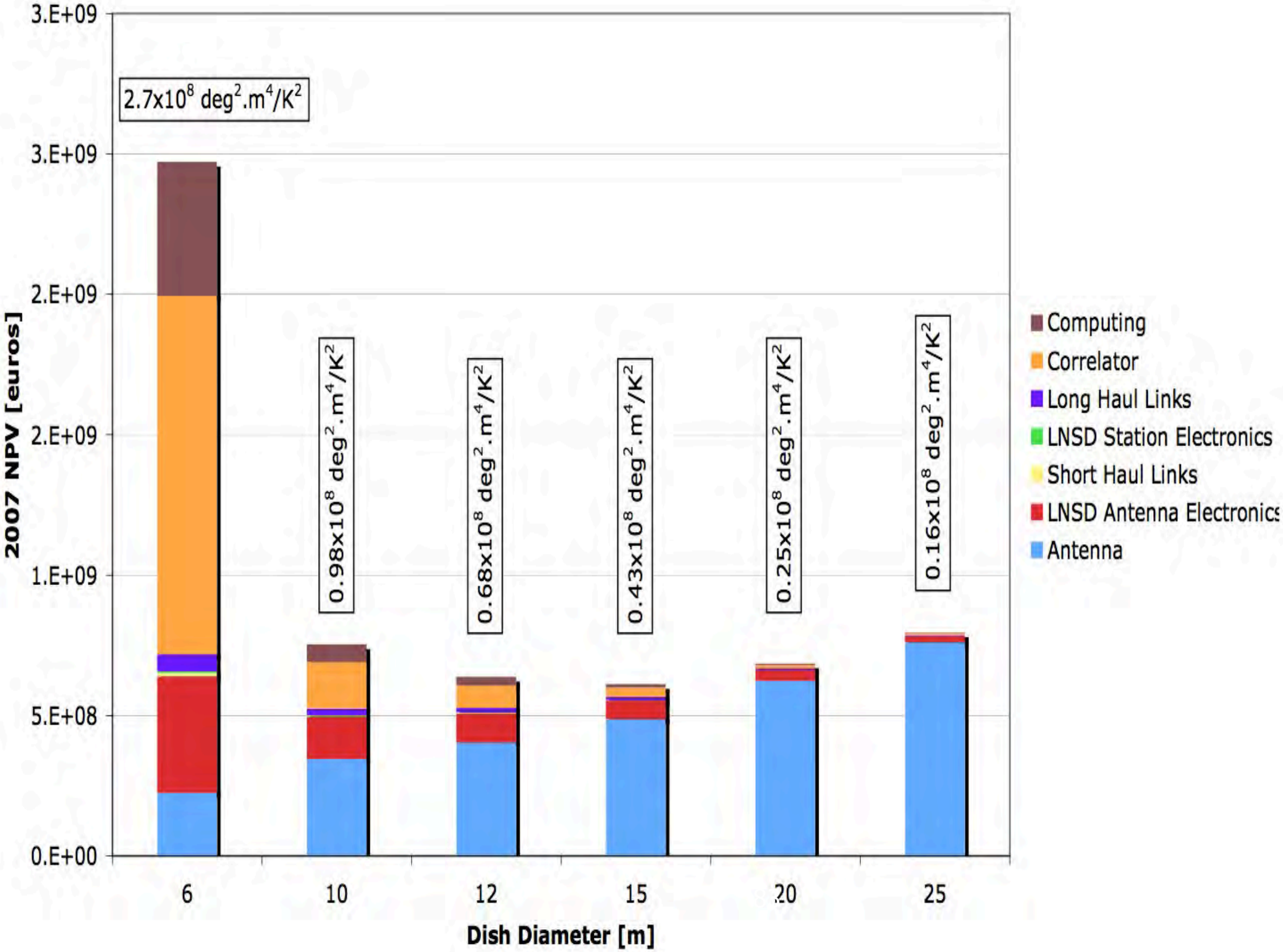
Embrace: 20K/10K elements, 160m^2, 500-1500 MHz

expect (plan for)

- 100 GHz bandwidth
- 1000 to 1M antenna arrays
- 1000 to 1M beams (commensal experiments)
- 6:1 or 20:1 ? Feeds and receivers
- phased array feeds with low Tsys ?
- Observatory removes RFI (part of instrument)

ADC's

26 Gsps	3.5 bit	Hittite
55 Gsps	8 bit	Fujitsu
80 Gsps	8 bit	Berkeley
160 Gsps	8 bit	Keysight
240 Gsps	8 bit	Teledyne Lecroy


3.E+09
3.E+09
2.E+09
2.E+09
1.E+09
5.E+08
0.E+00
2007 NPV [euros]
2.7x10^8 deg^2.m^4/K^2
0.98x10^8 deg^2.m^4/K^2
0.68x10^8 deg^2.m^4/K^2
0.43x10^8 deg^2.m^4/K^2
0.25x10^8 deg^2.m^4/K^2
0.16x10^8 deg^2.m^4/K^2
6
10
12
15
20
25
Dish Diameter [m]
Computing
Correlator
Long Haul Links
LNSD Station Electronics
Short Haul Links
LNSD Antenna Electronics
Antenna

SETI SPIN OFFS

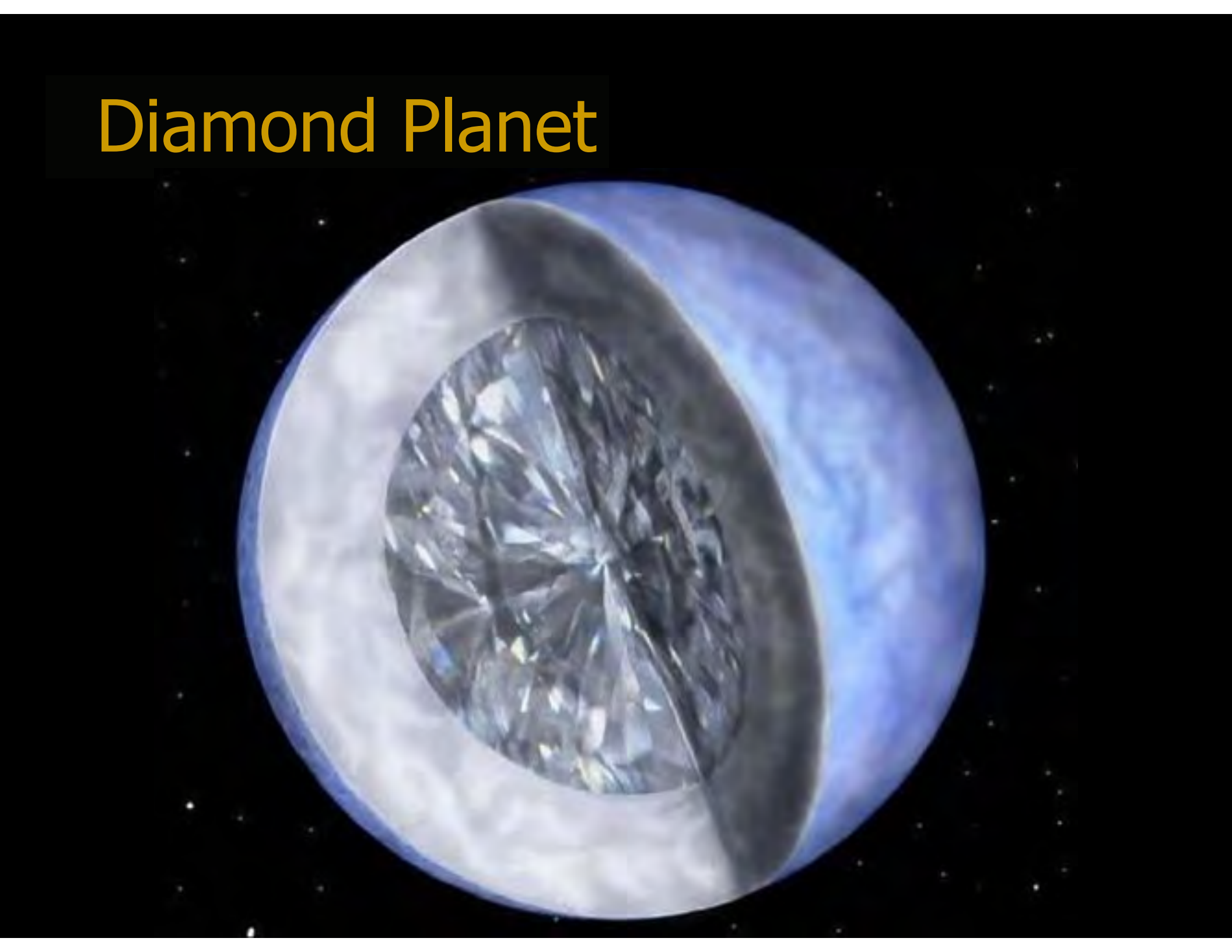
CASPER

Collaboration for Radio Astronomy Signal Processing and Electronics Research

Collaborators

Xilinx, Intel, Fujitsu, HP, Sun/Oracle, Nvidia, NSF, NASA, NRAO, NAIC, CFA (Havard/Smithsonian), Haystack (MIT), Caltech, Cornell, CSIRO/ATNF, JPL/DSN, South Africa KAT, Manchester/Jodrell Bank, GMRT (India), Oxford, Bologna, Metsahovi Observatory/Helsinki University, University of California, Berkeley; Swinburne University (Australia), Seti Institute, University of California, Santa Barbara; University of California, Los Angeles; CNRS (France), University of Maryland Nancay Observatory, Univerity of Cape Town (South Africa), ASTRON (Netherlands), Academica Sinica (Taiwan), Cambridge, Brigham Young University, Rhodes University (South Africa)

Diamond Planet



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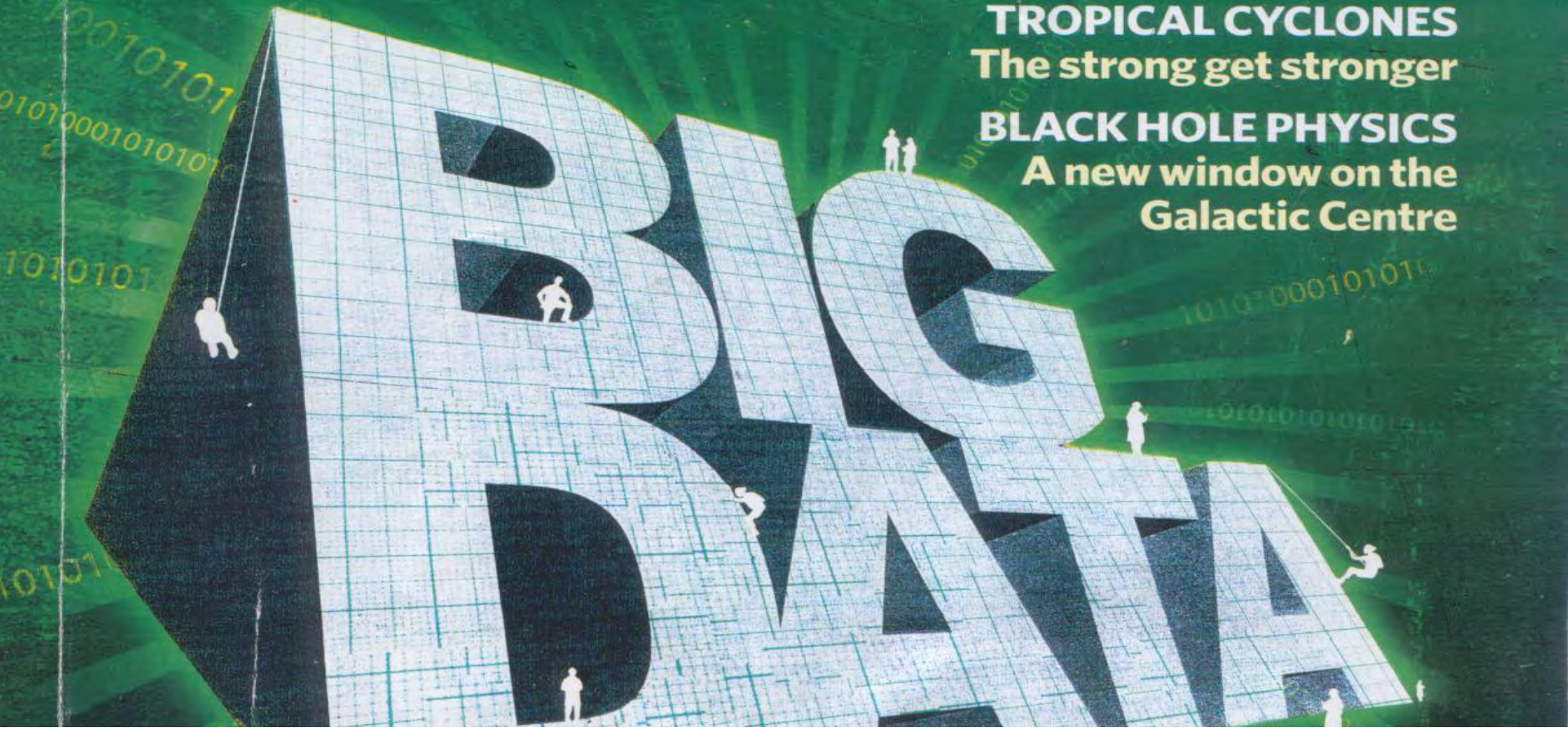
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

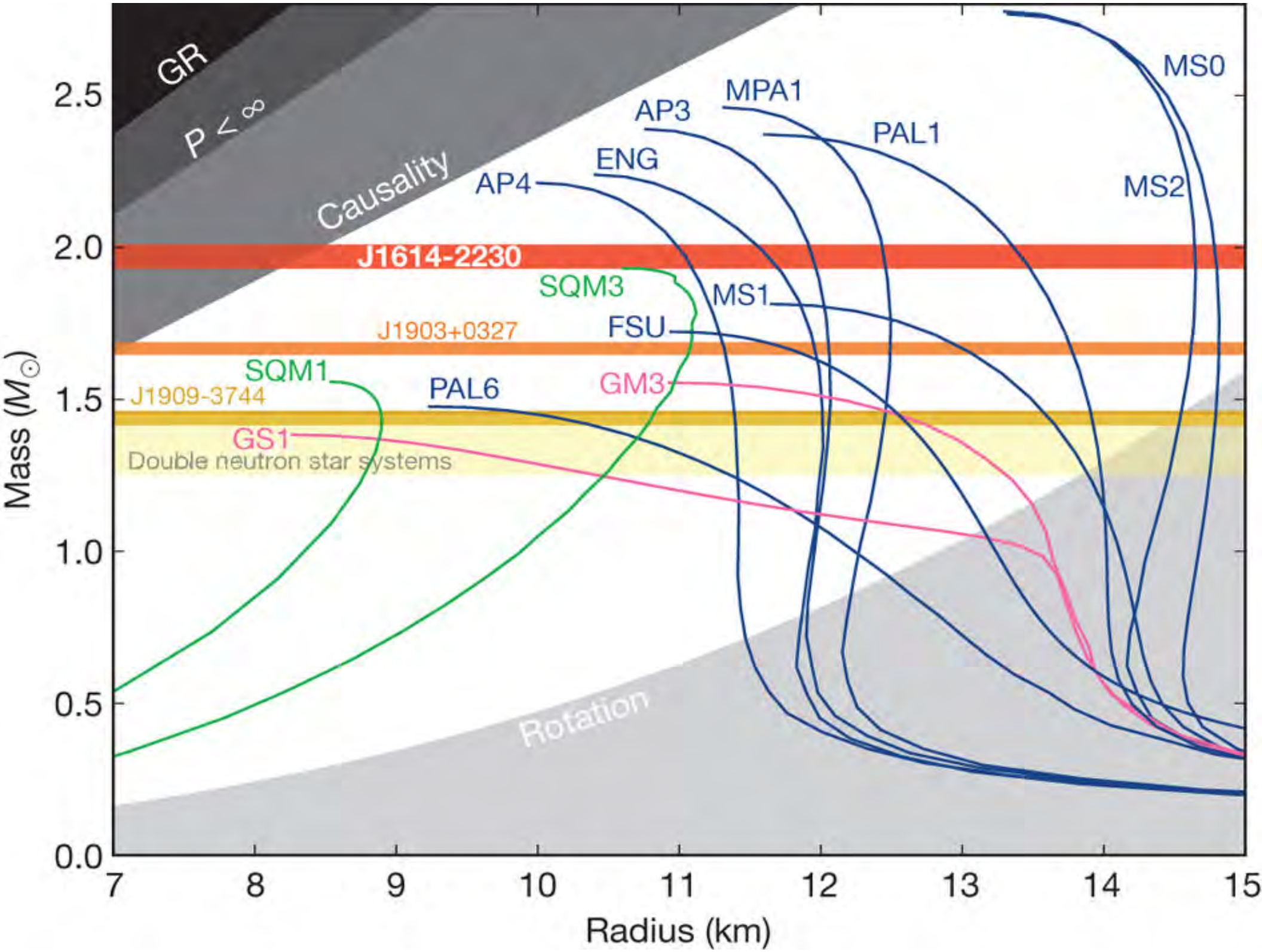
nature

THE BITER BIT
Viral infections for viruses

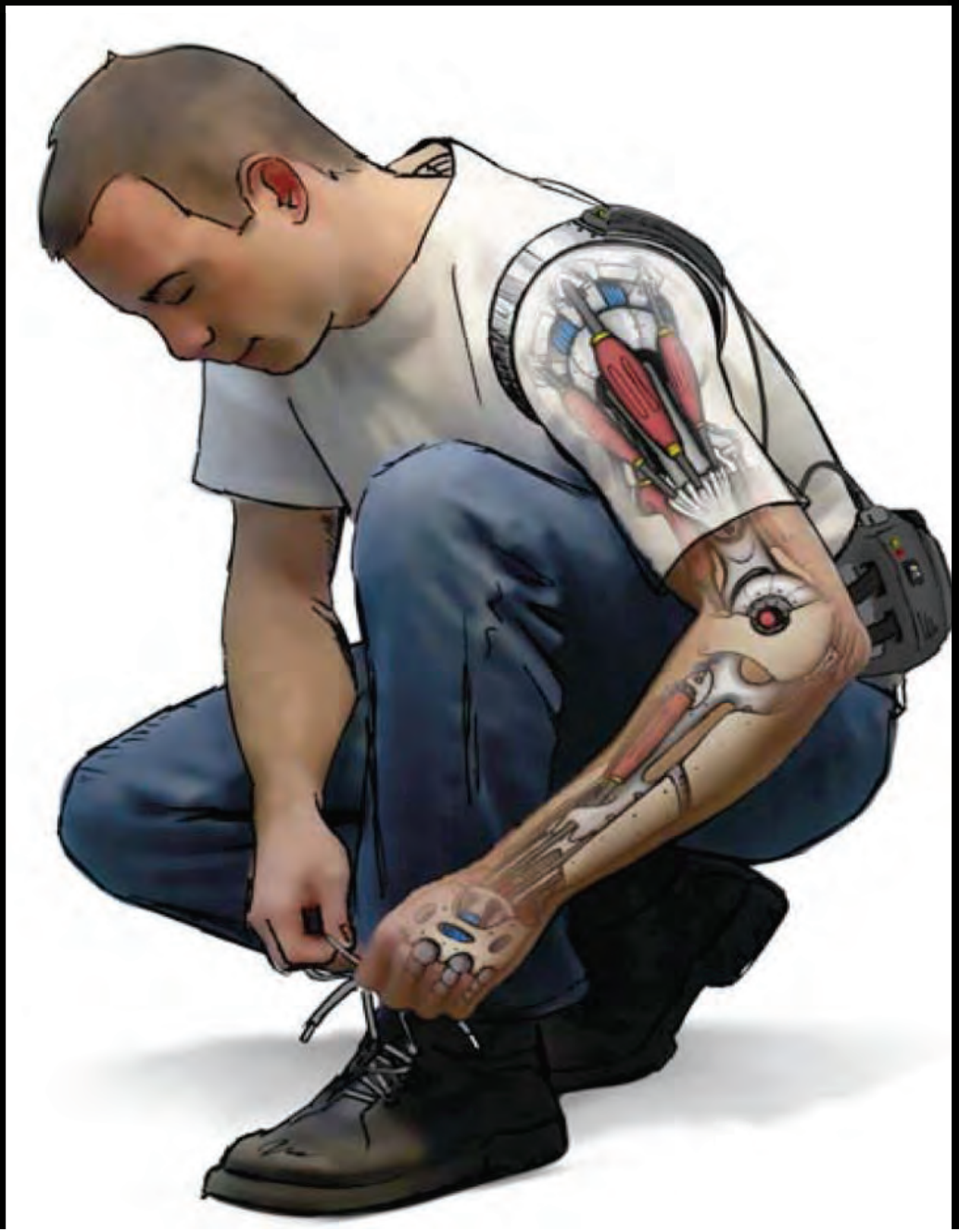
TROPICAL CYCLONES
The strong get stronger

BLACK HOLE PHYSICS
A new window on the Galactic Centre




GR
P < ∞
Causality
Rotation
J1614-2230
J1903+0327
J1909-3744
Double neutron star systems
MS0
MPA1
AP3
PAL1
ENG
AP4
MS2
SQM3
MS1
FSU
SQM1
PAL6
GM3
GS1
Mass ($M_\odot$)
Radius (km)
0.0
0.5
1.0
1.5
2.0
2.5
7
8
9
10
11
12
13
14
15

Prostheses Control



A.L.

Summary and Conclusion

No ET so far

Still working on it

SETI HAIKU

Searching for life
Answers are revealed
About ourselves

Paula Cook, Duke University

One million earthlings
Bounded by optimism
Leave their PC's on

Dan Seidner