Green Bank Instrumentation circa 2030

Dan Werthimer and 800 CASPER Collaborators

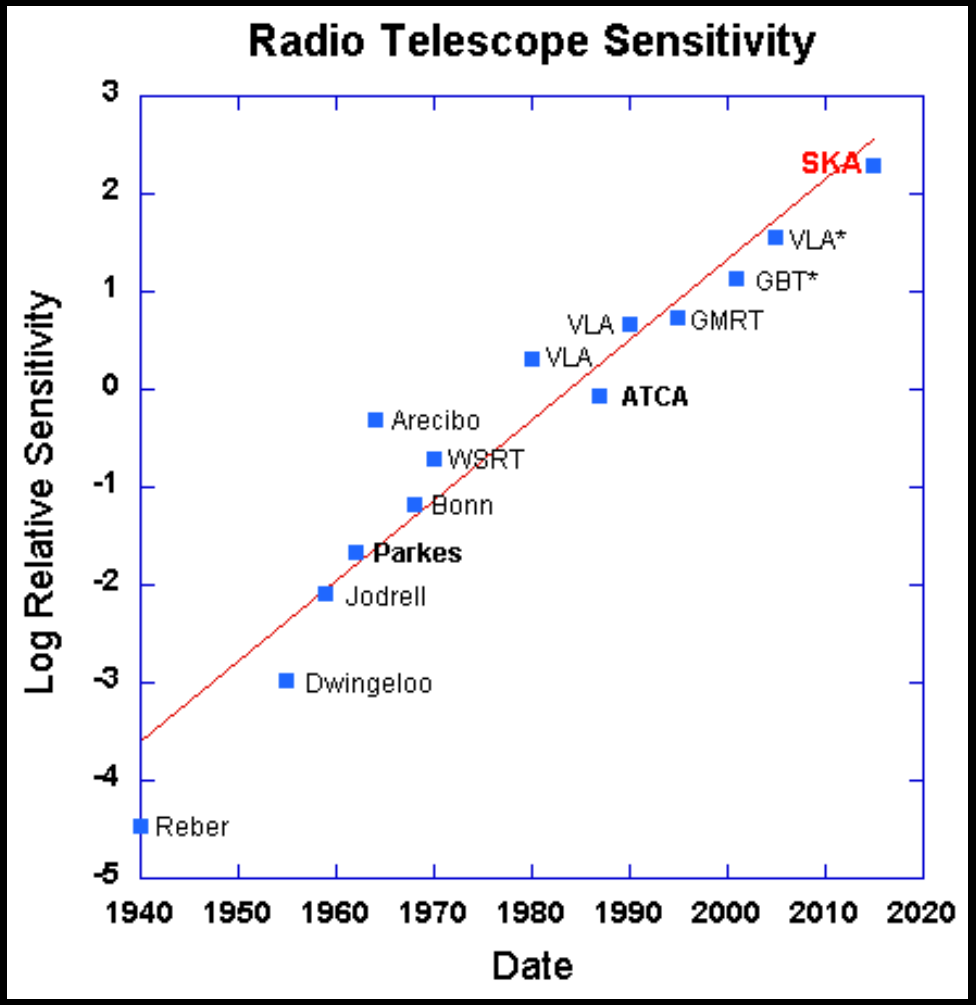
http://casper.berkeley.edu

Upcoming **Nobel Prizes** with Radio Instrumentation

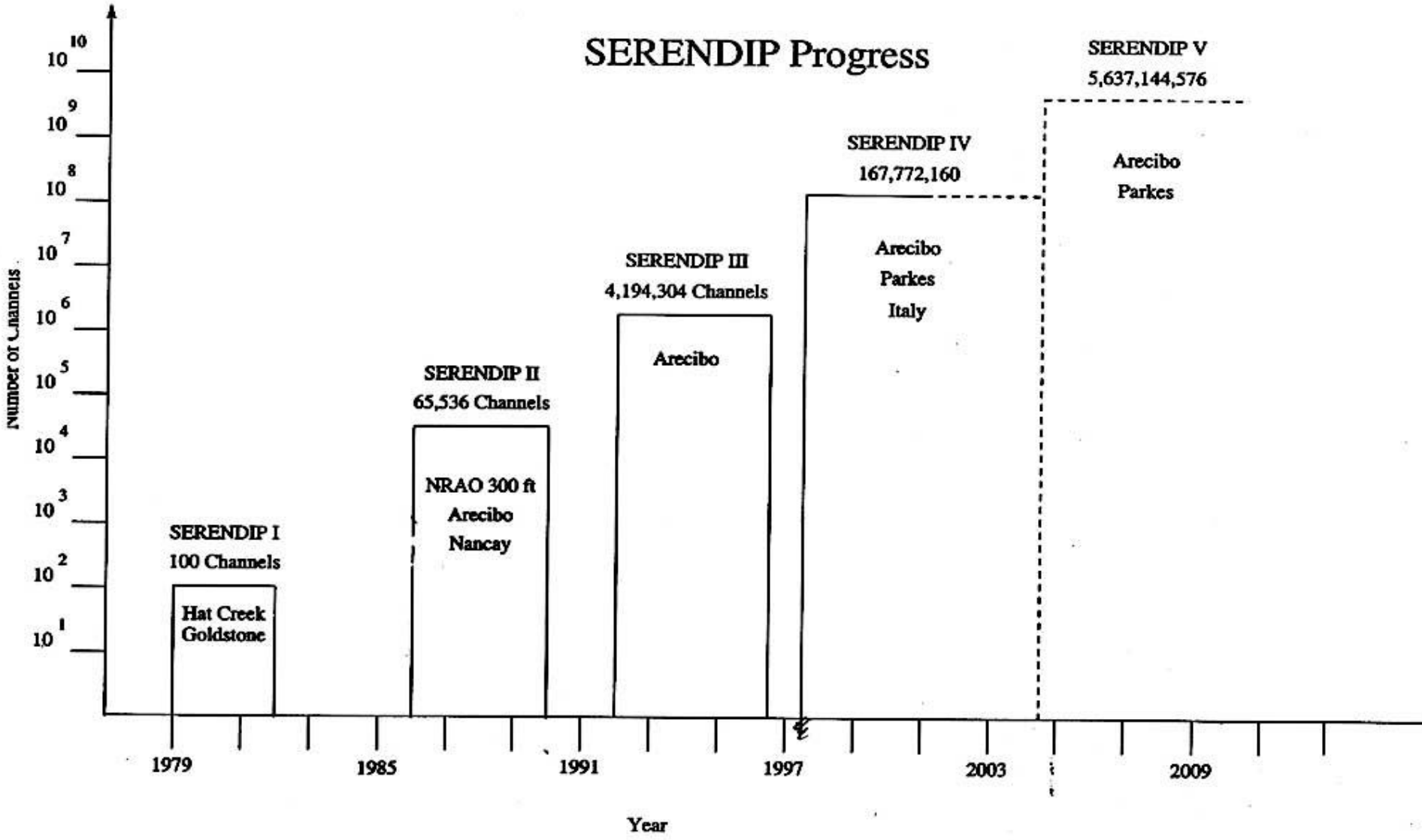
- Gravitational Wave Detection (pulsar timing)

  (eg: this morning's LIGO announcement)
- Black Hole Physics (Event Horizon Telescope…)
- How did the First Stars and Galaxies Form ? (EOR)
- What causes FRB's ?
- Measure baryon density of universe using FRB's
- B mode polarization CMB
- Discover ET

Radio Telescope Sensitivity doubles every 3.6 years



Moores Law – Instruments using FPGA's: 2X per year (1,000,000 over 20 years)

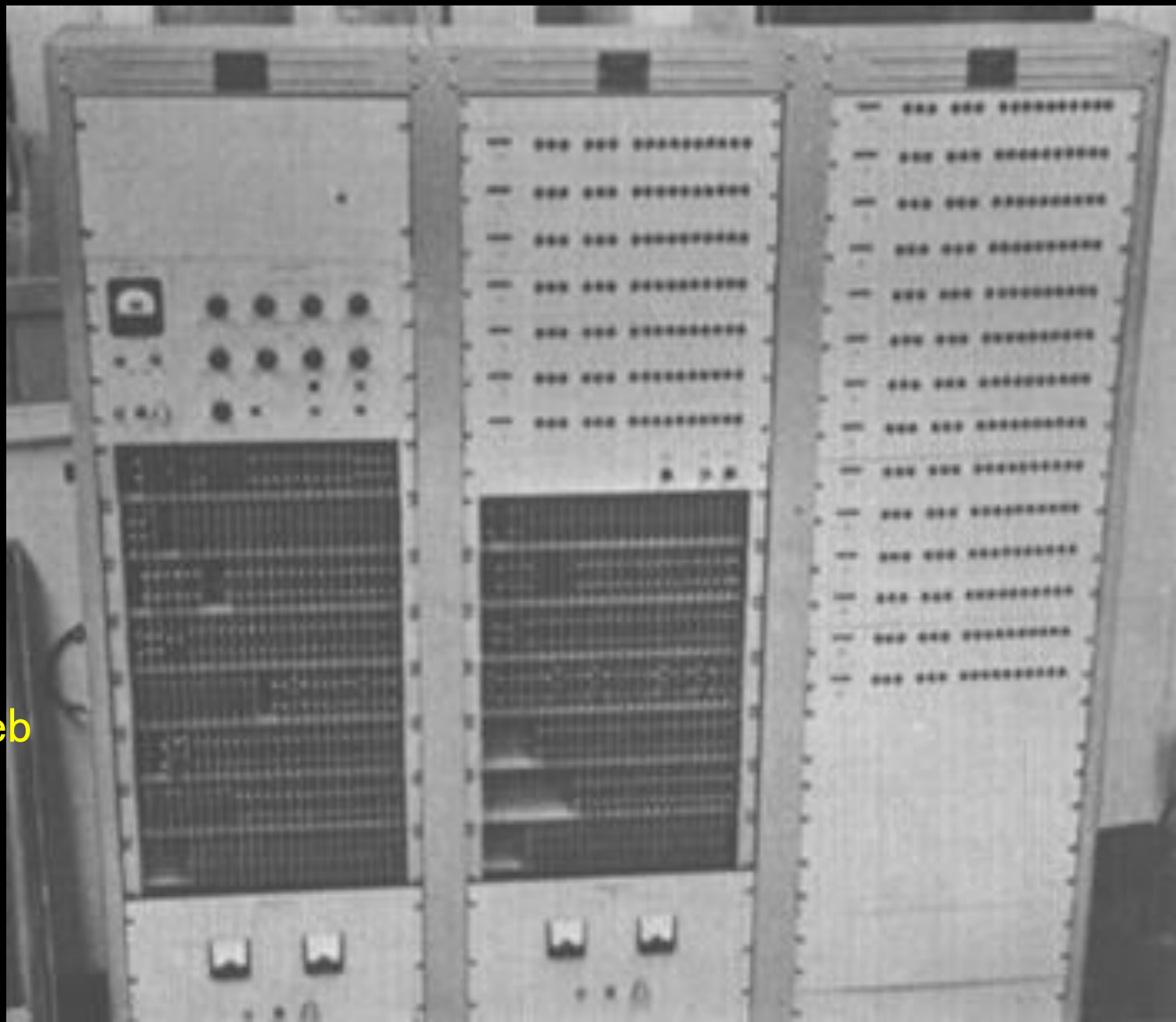


1960 – First Radio Astronomy Digital Correlator

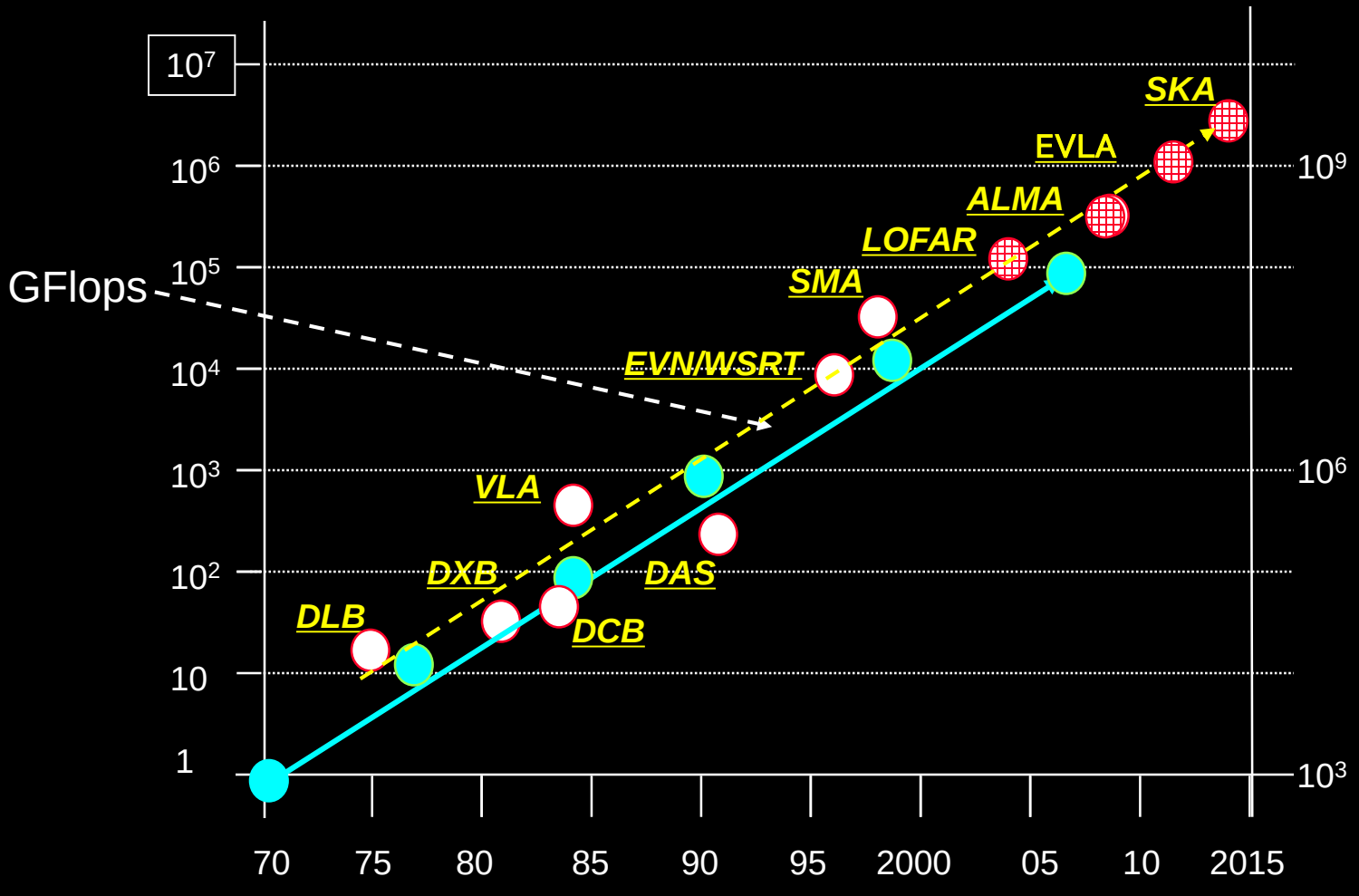
21 lags
300kHz clock
discrete transistors

$19,000

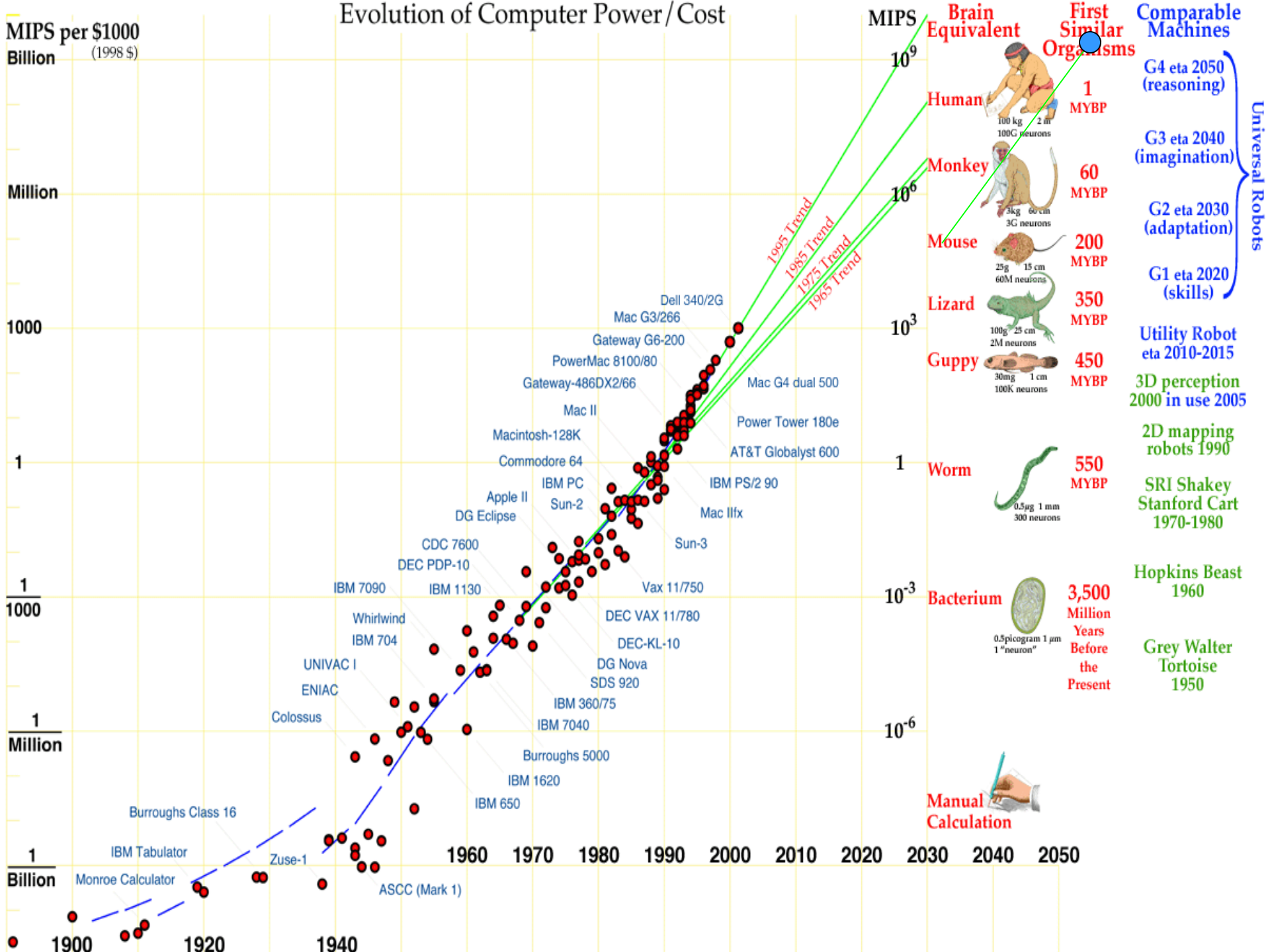
Sandy Weinreb



Correlator processing power



source: Arnold van Ardenne


Evolution of Computer Power/Cost
MIPS per $1000
(1998 $)
Billion
Million
1000
1
1/1000
1/Million
1/Billion
1900
1920
1940
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Monroe Calculator
IBM Tabulator
Burroughs Class 16
Zuse-1
ASCC (Mark 1)
IBM 650
IBM 1620
Burroughs 5000
IBM 360/75
IBM 7040
SDS 920
DG Nova
DEC-KL-10
DEC VAX 11/780
Vax 11/750
Sun-3
IBM PS/2 90
Mac IIfx
Sun-2
IBM PC
Apple II
DG Eclipse
CDC 7600
DEC PDP-10
IBM 7090
IBM 1130
Whirlwind
IBM 704
UNIVAC I
ENIAC
Colossus
Commodore 64
Macintosh-128K
Mac II
Gateway-486DX2/66
PowerMac 8100/80
Gateway G6-200
Mac G3/266
Dell 340/2G
Mac G4 dual 500
Power Tower 180e
AT&T Globalyst 600
1995 Trend
1985 Trend
1975 Trend
1965 Trend
MIPS
10^9
10^6
10^3
1
10^{-3}
10^{-6}
Brain Equivalent
First Similar Organisms
Comparable Machines
Human
1 MYBP
100 kg 2 m
100G neurons
Monkey
60 MYBP
3kg 60 cm
3G neurons
Mouse
200 MYBP
25g 15 cm
60M neurons
Lizard
350 MYBP
100g 25 cm
2M neurons
Guppy
450 MYBP
30mg 1 cm
100K neurons
Worm
550 MYBP
0.5µg 1 mm
300 neurons
Bacterium
3,500 Million Years Before the Present
0.5picogram 1 µm
1 "neuron"
Manual Calculation
G4 eta 2050 (reasoning)
G3 eta 2040 (imagination)
G2 eta 2030 (adaptation)
G1 eta 2020 (skills)
Universal Robots
Utility Robot eta 2010-2015
3D perception 2000 in use 2005
2D mapping robots 1990
SRI Shakey Stanford Cart 1970-1980
Hopkins Beast 1960
Grey Walter Tortoise 1950

CASPER Philosophy and Religion

Design Observatories with Plan for Exponential Growth in Digital Processing

- Digital Backend should be replaced every 5 years (keep software, toss old - buy new hardware)
- DSP Part of Operating Costs, not construction costs

expect (plan for)

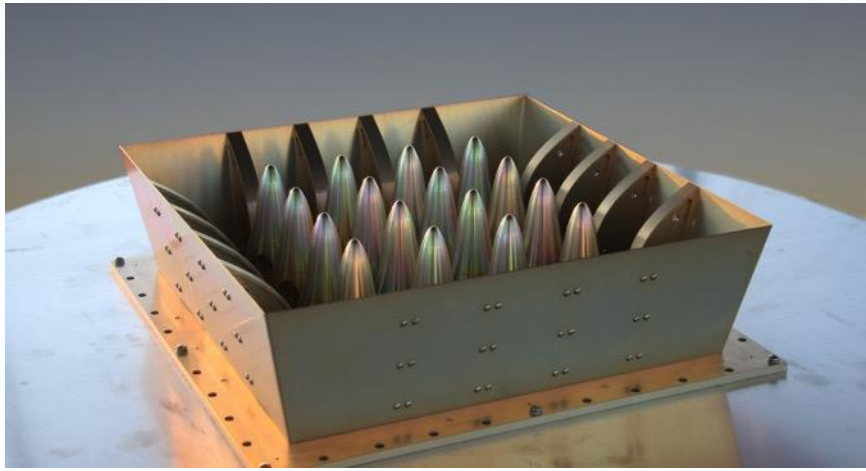
- 100 GHz bandwidth
- 1000 to 1M antenna arrays
- 1000 to 1M beams (commensal experiments)
- 6:1 or 20:1 ? Feeds and receivers
- phased array feeds with low Tsys ?
- Observatory removes RFI (part of instrument)

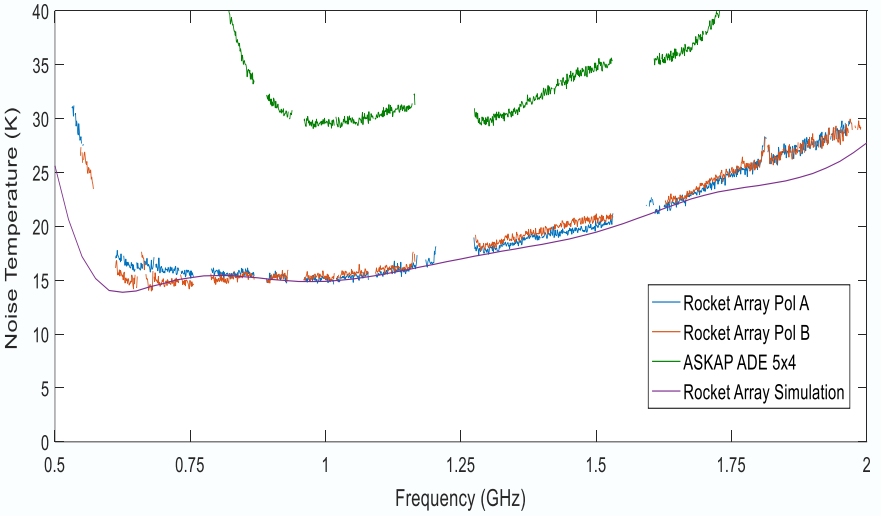
GBO Receivers circa 2025

- 0.6 to 4 GHz 6:1 22K single beam
- 4 to 24 GHz 6:1 22K single beam
- 20 to 120 GHz 6:1 single beam
- 0.6 to 2 GHz Phased Array Feed 20K 1,000 beams
- 75 – 115 GHz 800 beam horn array (ultra-argus)

“Rocket” PAF

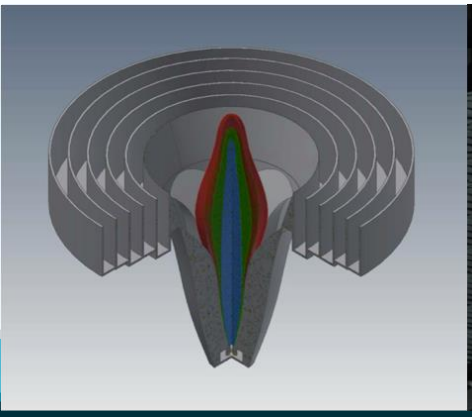
- Next generation PAF
  - “rocket” elements; “edge” elements
- Superb matching with LNA
  - Key to improved performance
  - Noise Temp due to uncooled LNAs
- 4x5 prototype constructed
  - tested as aperture array
  - ~15K better than equivalent ASKAP tests
  - Tested on Parkes
    - Measurements affected by RFI
- Design better suited to cooling
  - → **CryoPAF funding proposal**
    - Full 94 dual-pol array + ASKAP back-end
    - Expected Tsys <20K !?

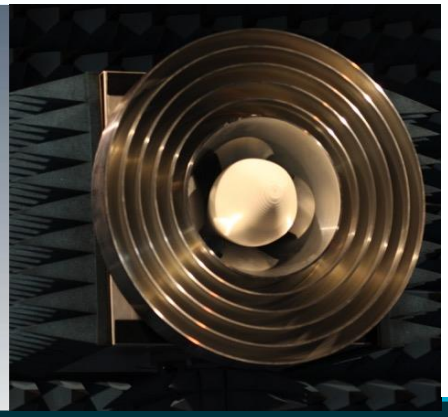


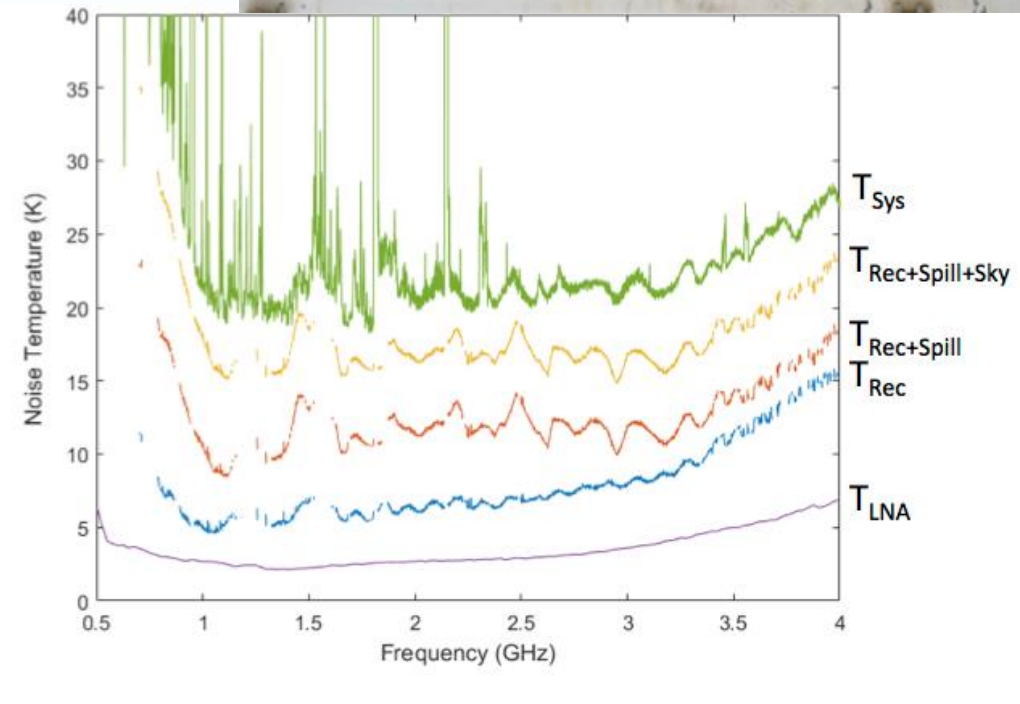


Parkes UltaWideBand system

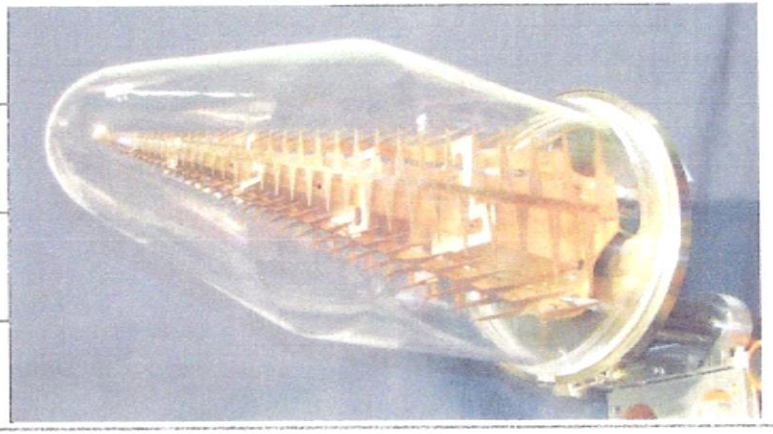
- Quadridge structure with dielectric spear
- 0.7—4.0 GHz, Tsys ~22K, SEFD ~35 Jy
- First light Aug 2017, commission late 2017
- Sampler/digitiser and timing (Back-end)
  - 4 Gsps (2 GHz bands)
- Ethernet switch and GPU cluster
  - Installed 2016 & used PAF@Parkes
  - Software - collaborators
- RFI mitigation built-in – reference antenna







Measured Receiver Temperature & Tsys at Zenith
Cooled ATA Feed



Jack Welch, Matt Fleming, Dave DeBoer,
Sandy Weinreb, Rob Spencer

Temperature in K

80
70
60
50
40
30
20
10
0

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

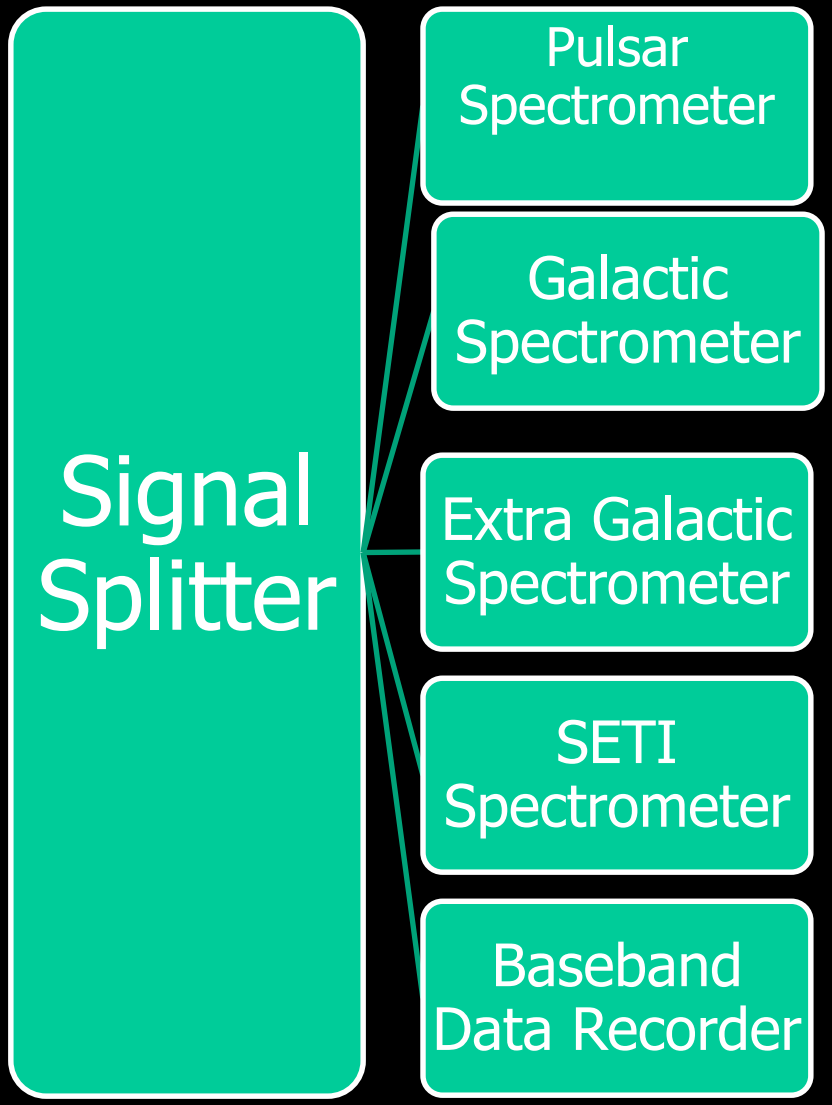
Frequency in GHz

AVG TRx (sky,Tradome=7)
AVG TRx (lab)
Tsys at zenith w. galaxy

Instrument Architectures

- Scalable
- Upgradeable
- Flexible
- General and Multi-Purpose
- Fault Tolerant

Simultaneous Digital Backends Piggyback, Commensal, Sky Surveys



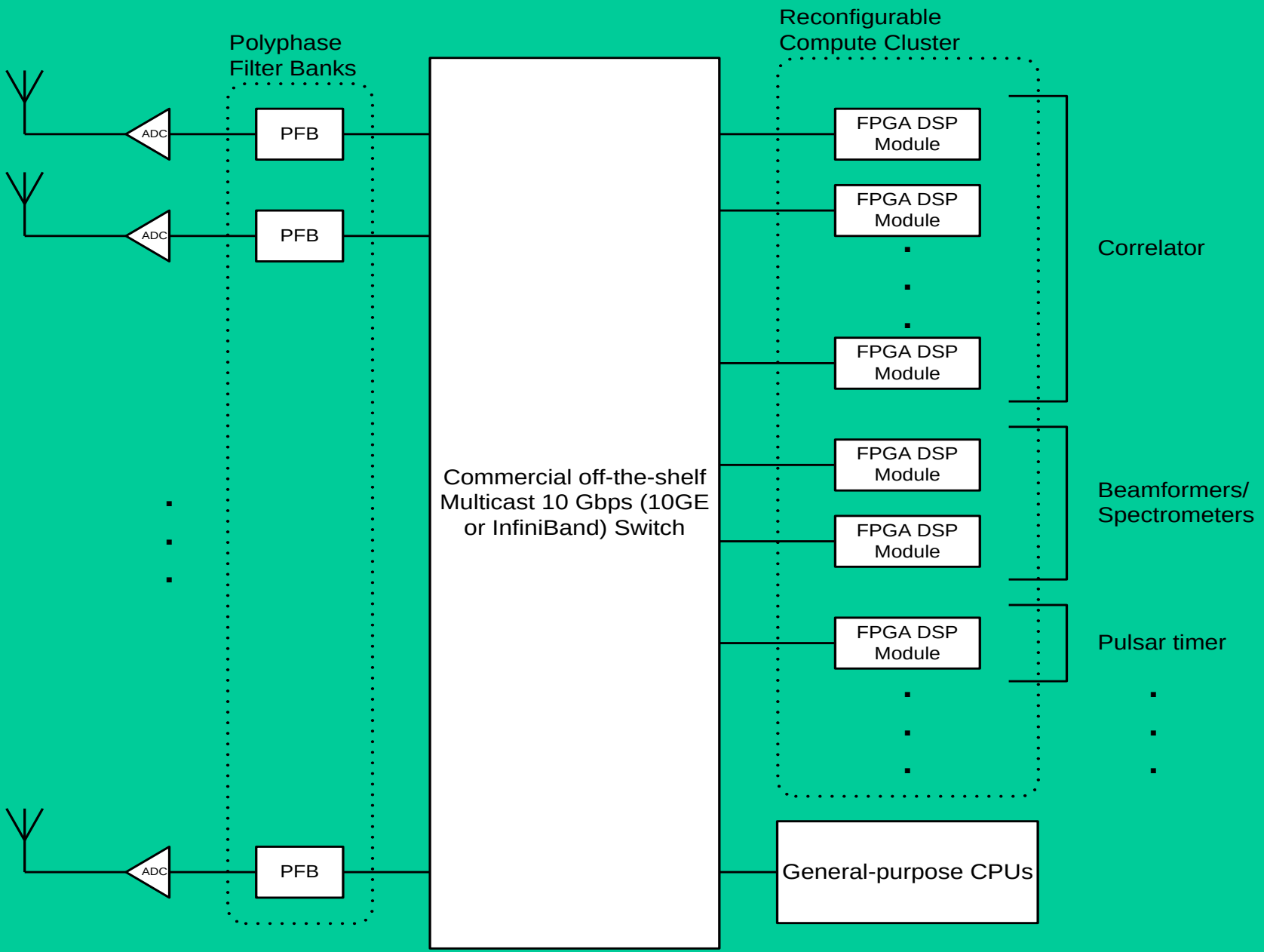
Analog Power Splitters

or

Digital Data Splitter

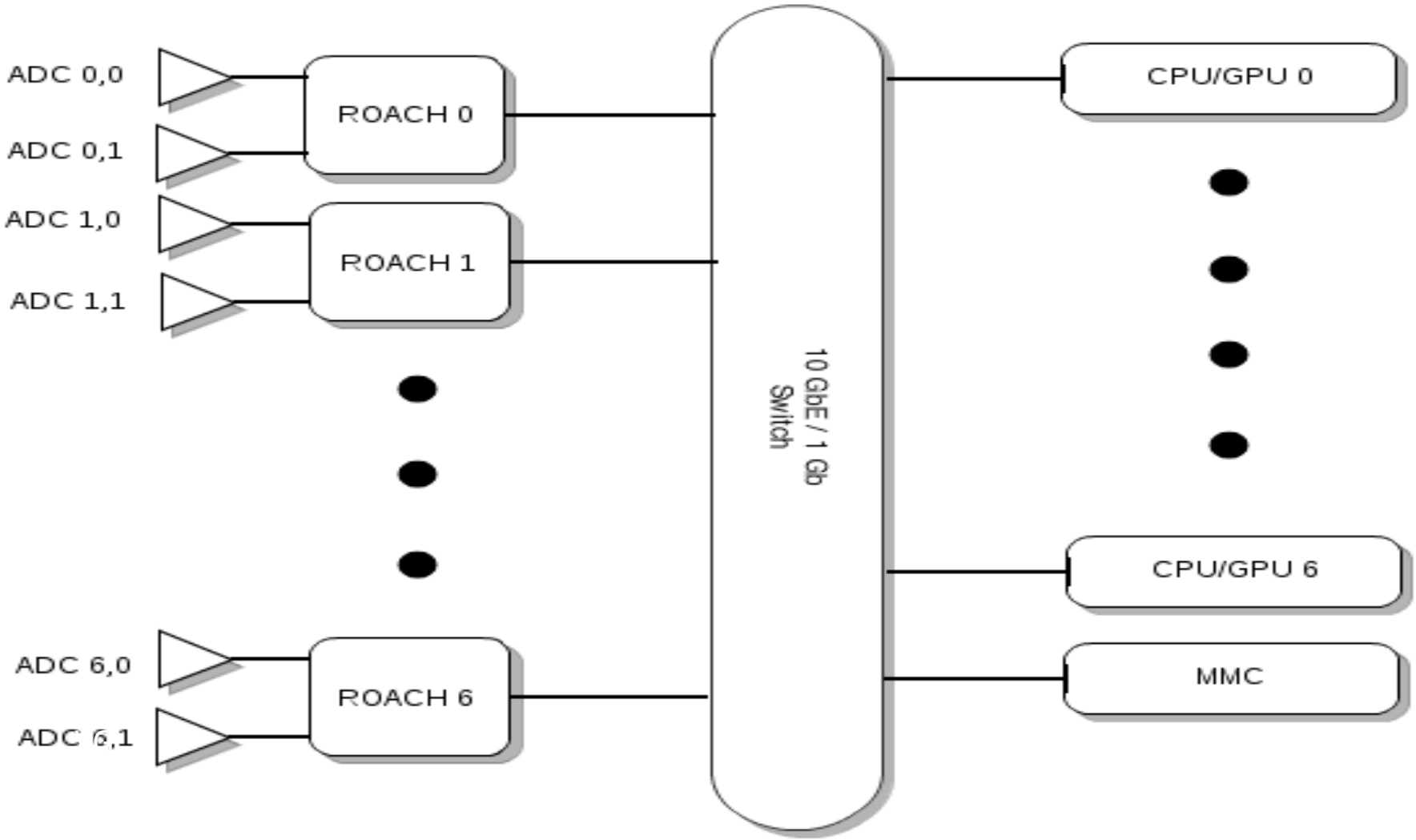
CASPER General Purpose Architechture

Dynamic Allocation of Resources, need not be FPGA based

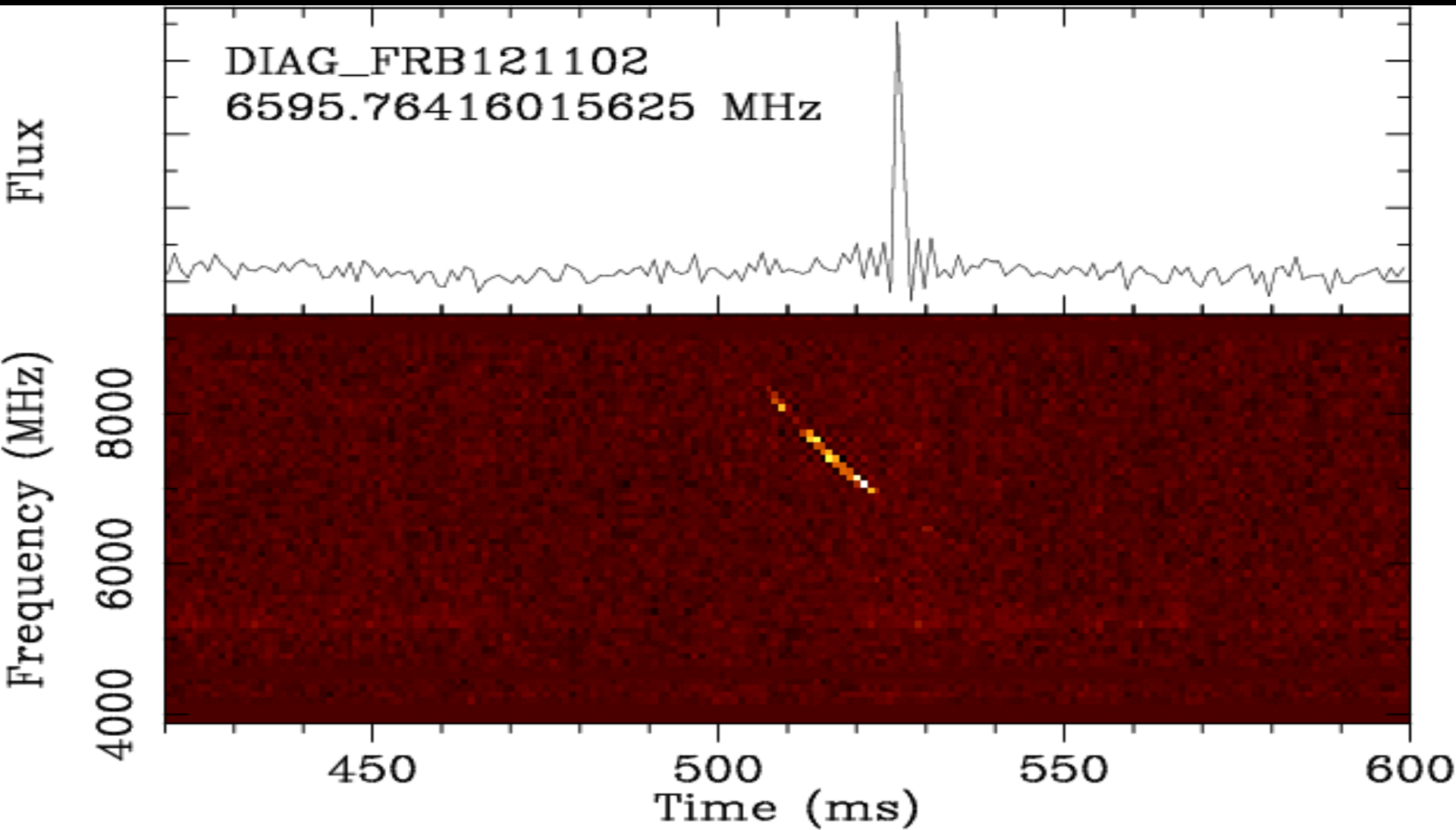


VEGAS/DIBAS Multi-beam Spectrometer + Pulsar Timing/Searching

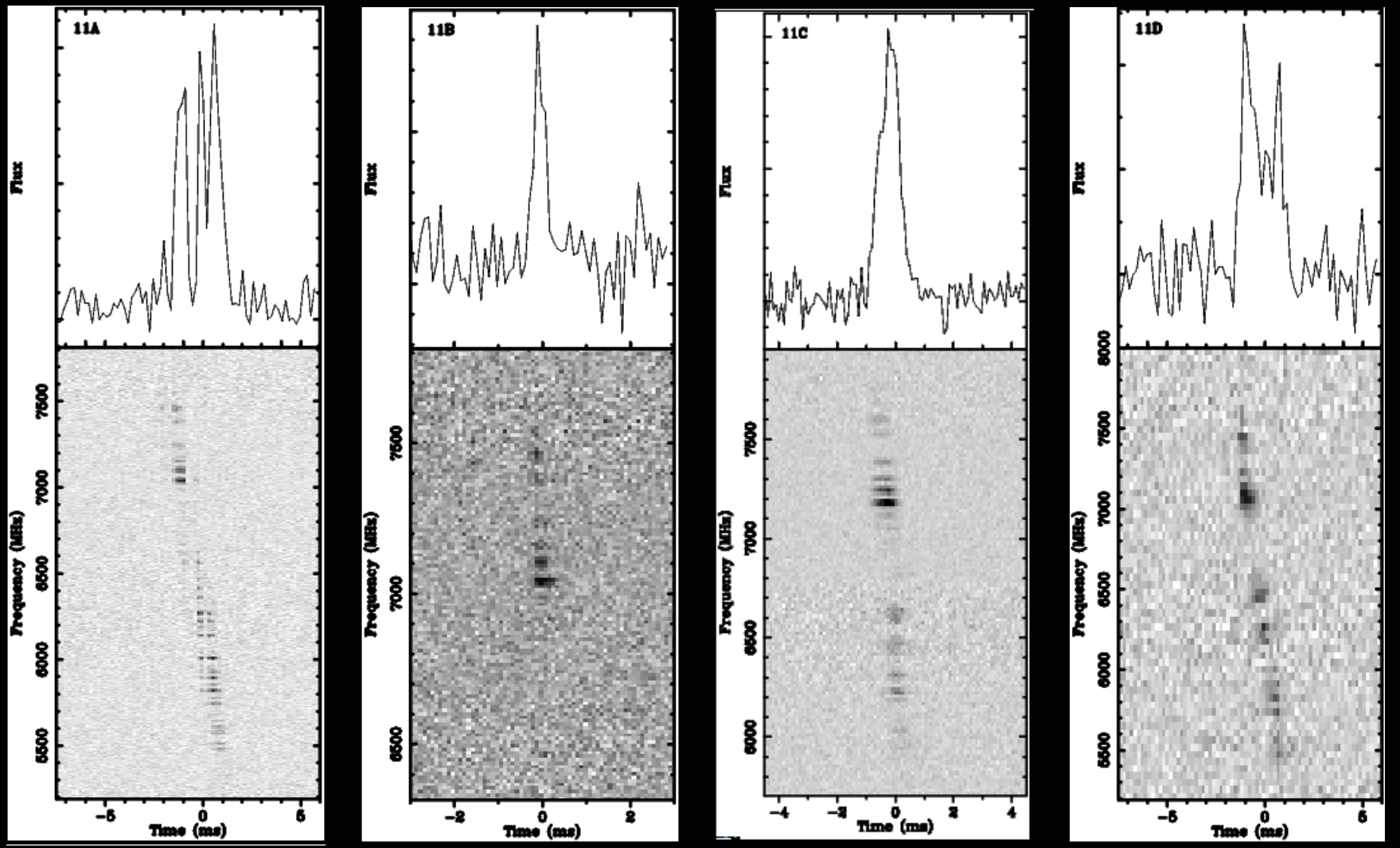
John Ford, Dan Werthimer, David MacMahon, Richard Prestage



FRB121102 (repeater)
Highest Frequency detection (4 – 9 GHz)
widest bandwidth (5.4 GHz)



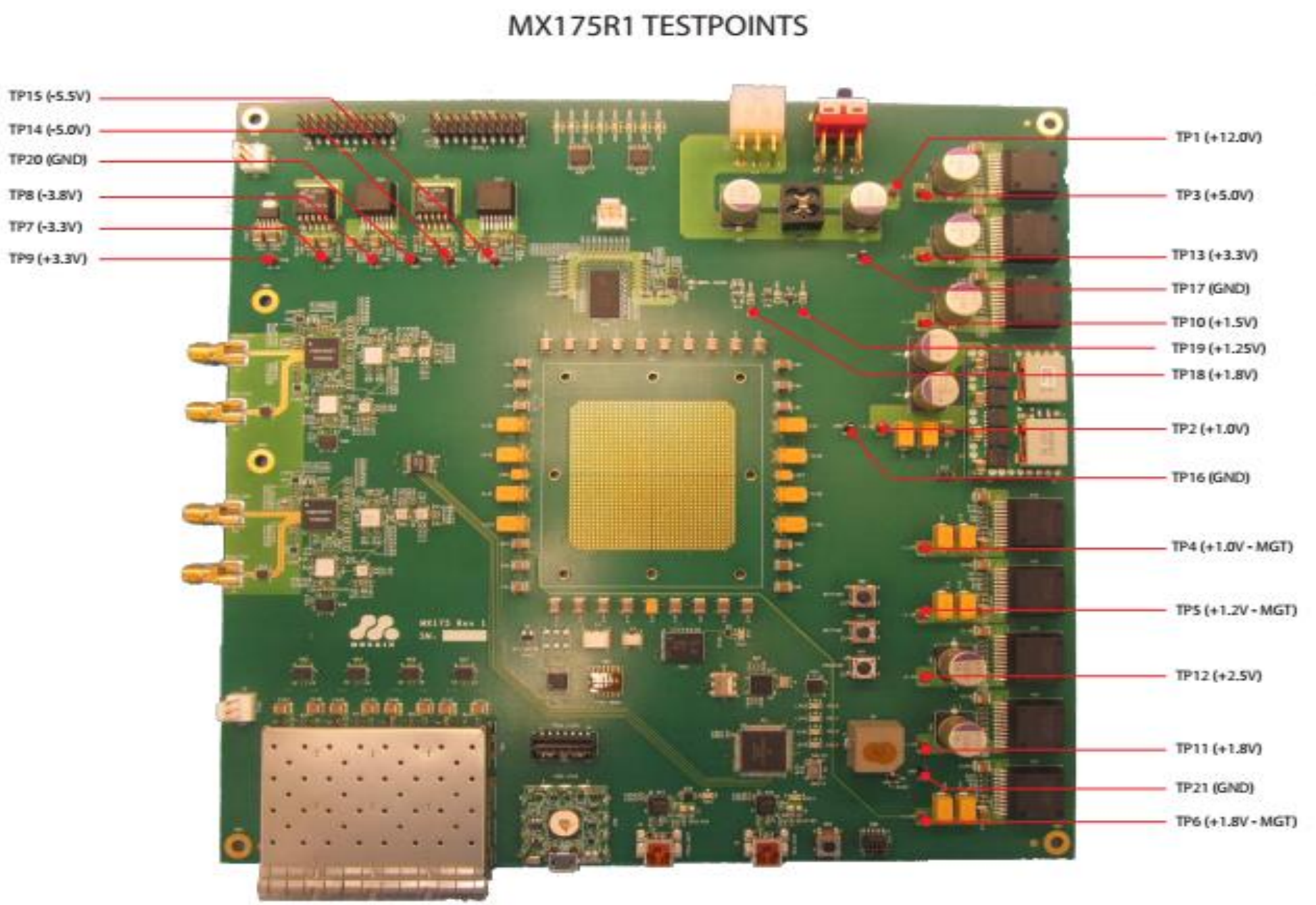
Coherently dedispersed pulses



Fast ADC's

15 Gsps	4 bit	Adsantec
26 Gsps	3.5 bit	Analog Devices
55 Gsps	8 bit	Fujitsu
80 Gsps	8 bit	Berkeley
160 Gsps	8 bit	Keysight
240 Gsps	8 bit	Teledyne Lecroy

Dual 26 Gsps 3.5 bit ADC and FPGA



Board Interconnect - Upgradable

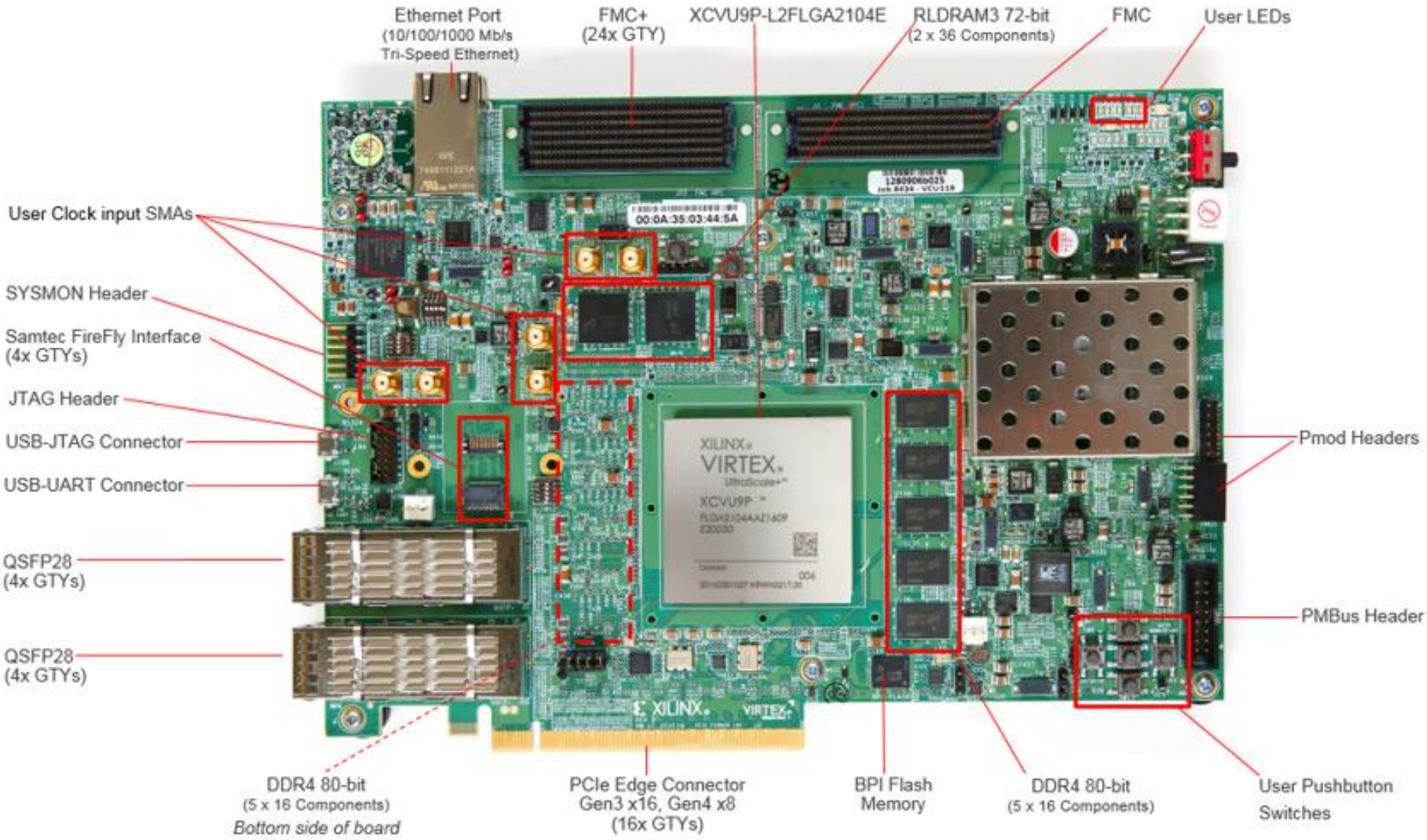
- Problem: Backplanes are short lived

  (S100, Multibus, VME, ISA, EISA, PCI, PCIx, PCIe, PCIe2.0, compactPCI, compactPCIe, ATCA…)

- Solution: Use 10, 40 or 100 Gbit/sec Ethernet

  Ethernet since 1973 – likely to stay around !

VCU118 5x100Gbit Ethernet ports



Casper Commandments

Thou Shalt Share thy Knowledge

Thou Shalt Help thy Neighbor Casperite

Thou Shalt Covet thy Ethernet to Connect Everything

Switches are Free

CASPER Real-time Signal Processing Instrumentation

- Rapid development
- Open-source, collaborative
- Reusable, platform-independent gateware
- Modular, upgradeable hardware
- Industry standard ethernet communication
- Use switches to interconnect FPGA/GPU/CPU
- Low Cost

Tutorials

- Introduction to Simulink and Roach (blink an LED)
- Using 10 Gbit Ethernet
- Spectrometer (400MHz, 2k channels)
- Correlator (4 input, 400MHz, 1k channels)
- Heterogeneous Computing ADC→ROACH→CPU/GPU
- Intro to embedding Verilog/VHDL in Simulink
- Yellow Block Creation

Annual CASPER Workshops

morning: talks

afternoon: lab training, tutorials, working groups,

get help designing an instrument….