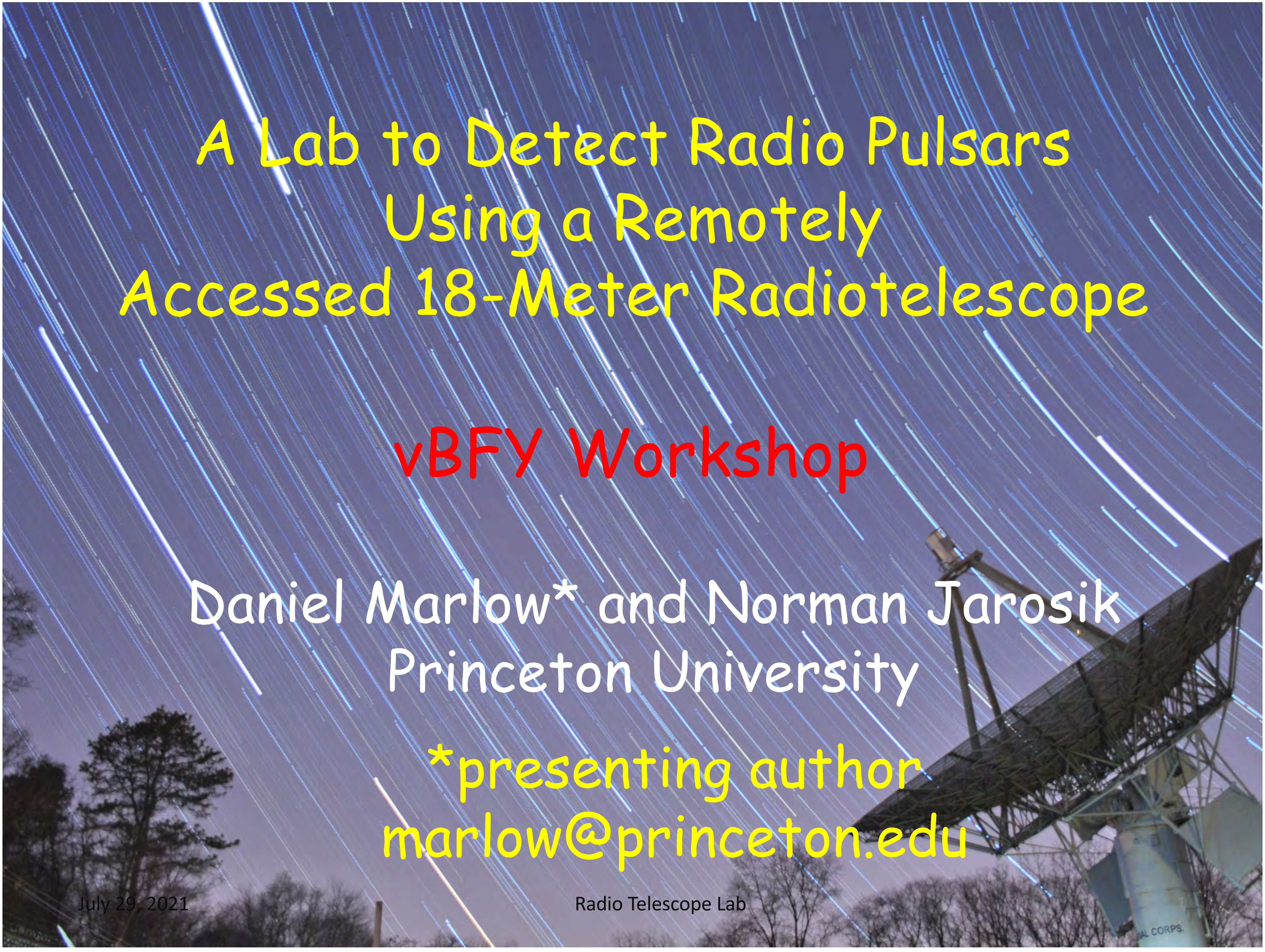


A Lab to Detect Radio Pulsars Using a Remotely Accessed 18-Meter Radiotelescope

vBFY Workshop

Daniel Marlow* and Norman Jarosik
Princeton University

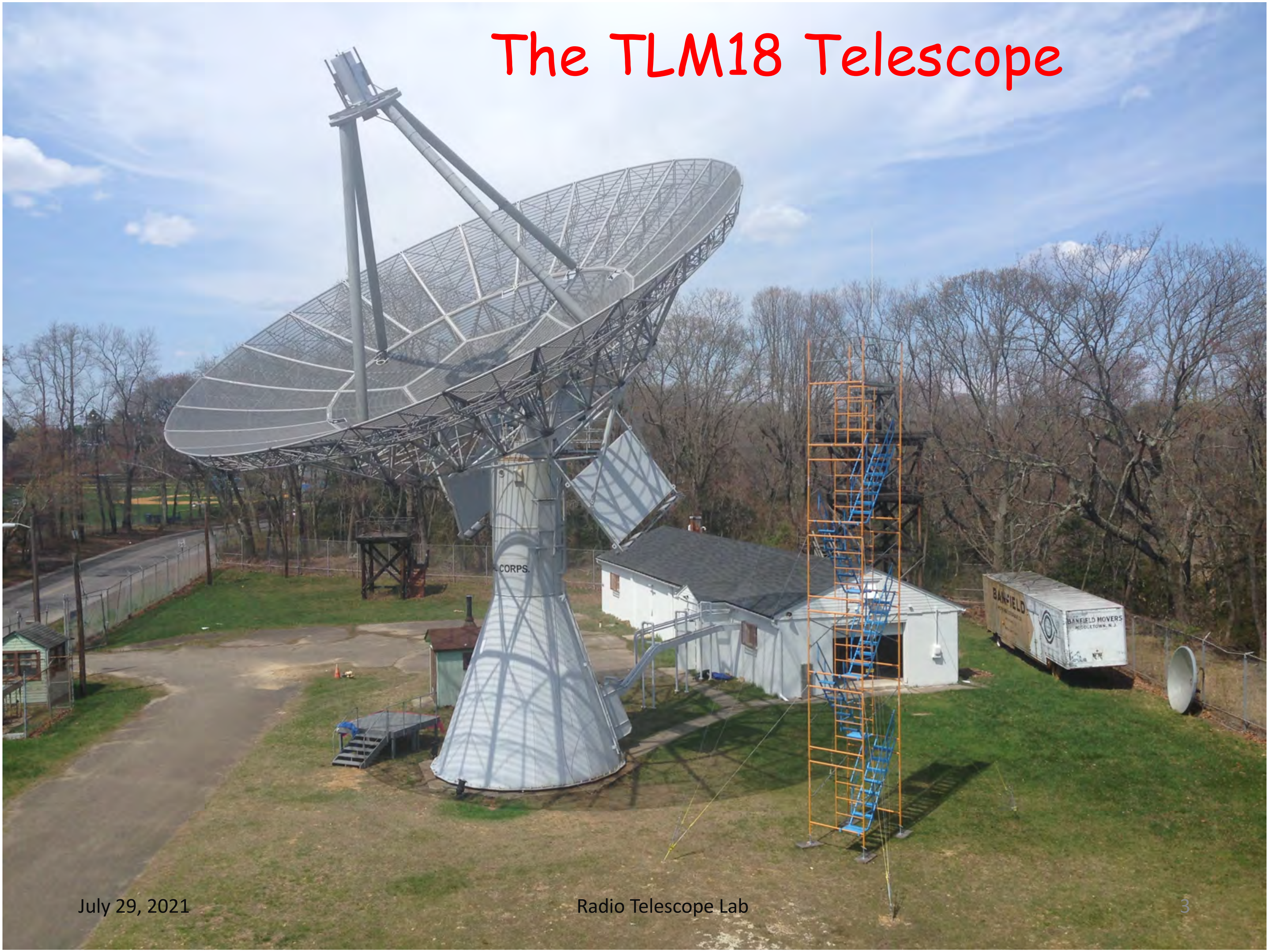
*presenting author
marlow@princeton.edu

Outline

- Apparatus
- Point Sources
- The 21 cm line
  - Origin and Doppler Shift
  - Spectra
- Pulsars

Note: there is more material than there is time to present. I will therefore go quickly over some slides. Moreover, there are several slides in the backup material.

The TLM18 Telescope



The TLM18 Telescope

- The 60' dish used for these results is a cold-war relic.
- Location
  - Belmar, NJ, a few miles from Jersey shore
  - Former site of Camp Evans, a U.S. Army R&D site
- History
  - Site was used for first "moonbounce" experiment in 1947
  - In 1960 the TLM18 dish received the first weather satellite images from space (TIROS)
  - The TLM18 was used in classified research until ~1980 or so.
  - Refurbished by Princeton team in 2012~2015

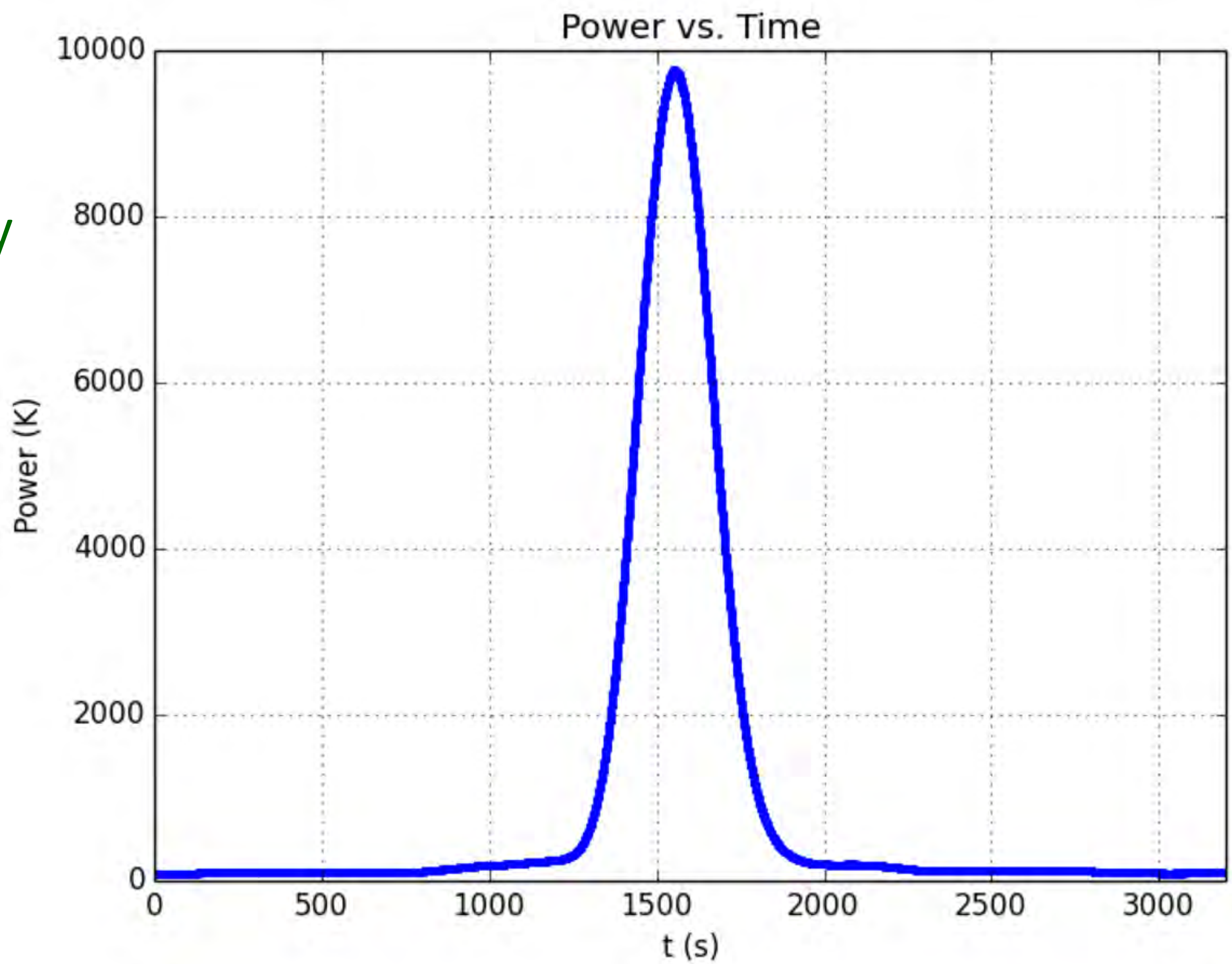
Technical Details

- Low noise amplifiers in feedhorn
- Software defined radio (SDR) readout in control building
- Remote access
  – Both the control computer and the computer on which the SDR runs are accessible over the internet.
  – The dish is an hour's drive from Princeton, too far to drive to do the lab: essentially all students do the lab remotely.
  – We are open to students from other institutions using the dish in a similar fashion.

Point Sources

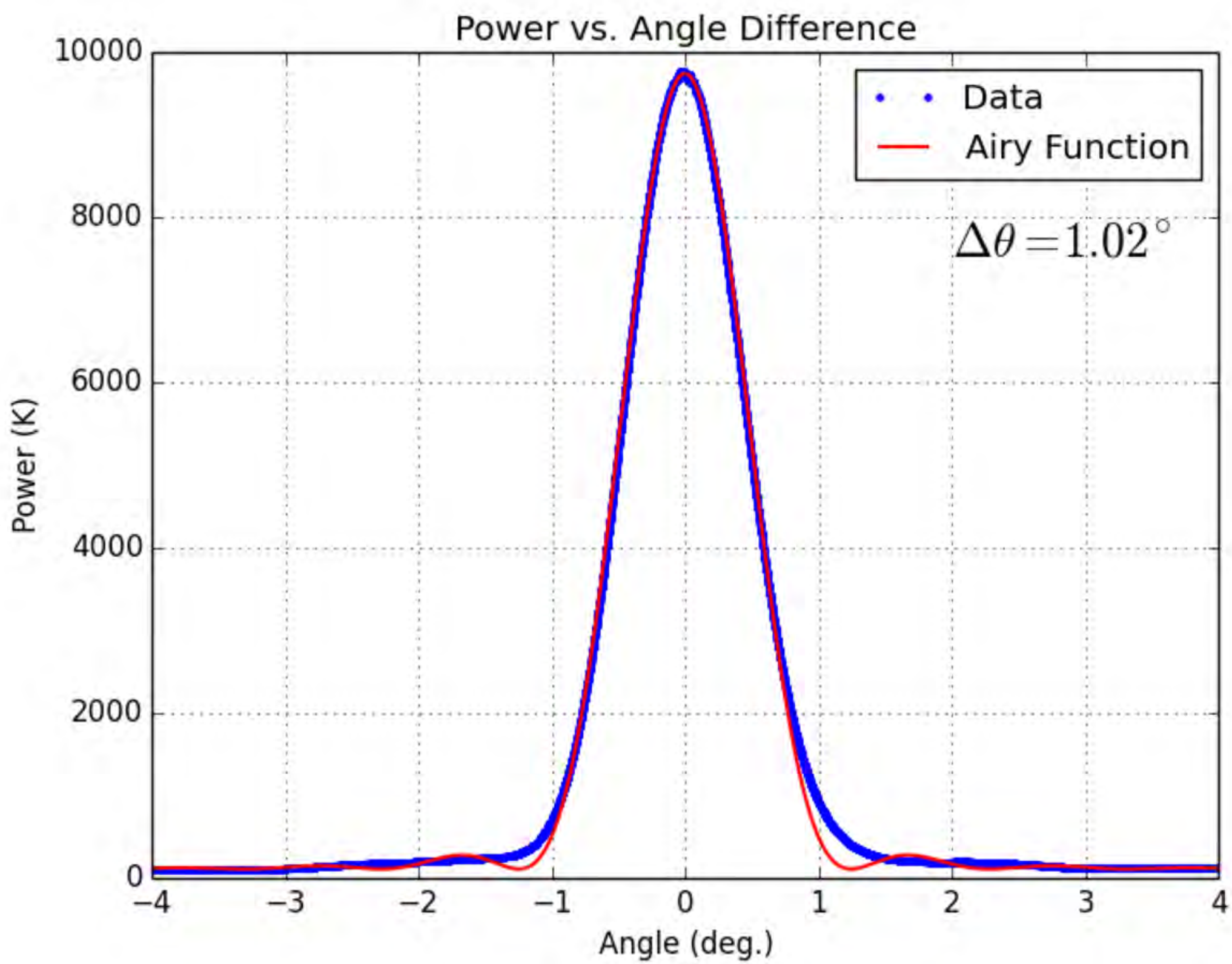
Angular Resolution: Sun Scan

We measure the angular resolution of the telescope by fixing the dish pointing south at an altitude corresponding to the Sun's highest altitude for the day. The Sun then "drifts" through the beam.



Angular Resolution

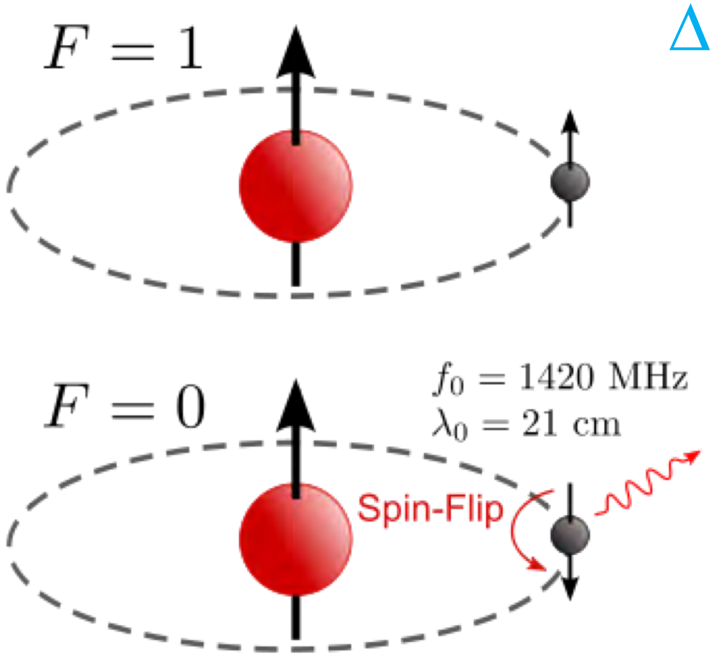
The time axis can be converted to an angular difference axis using the known rate of the Earth's rotation (corrected for the declination of the Sun).

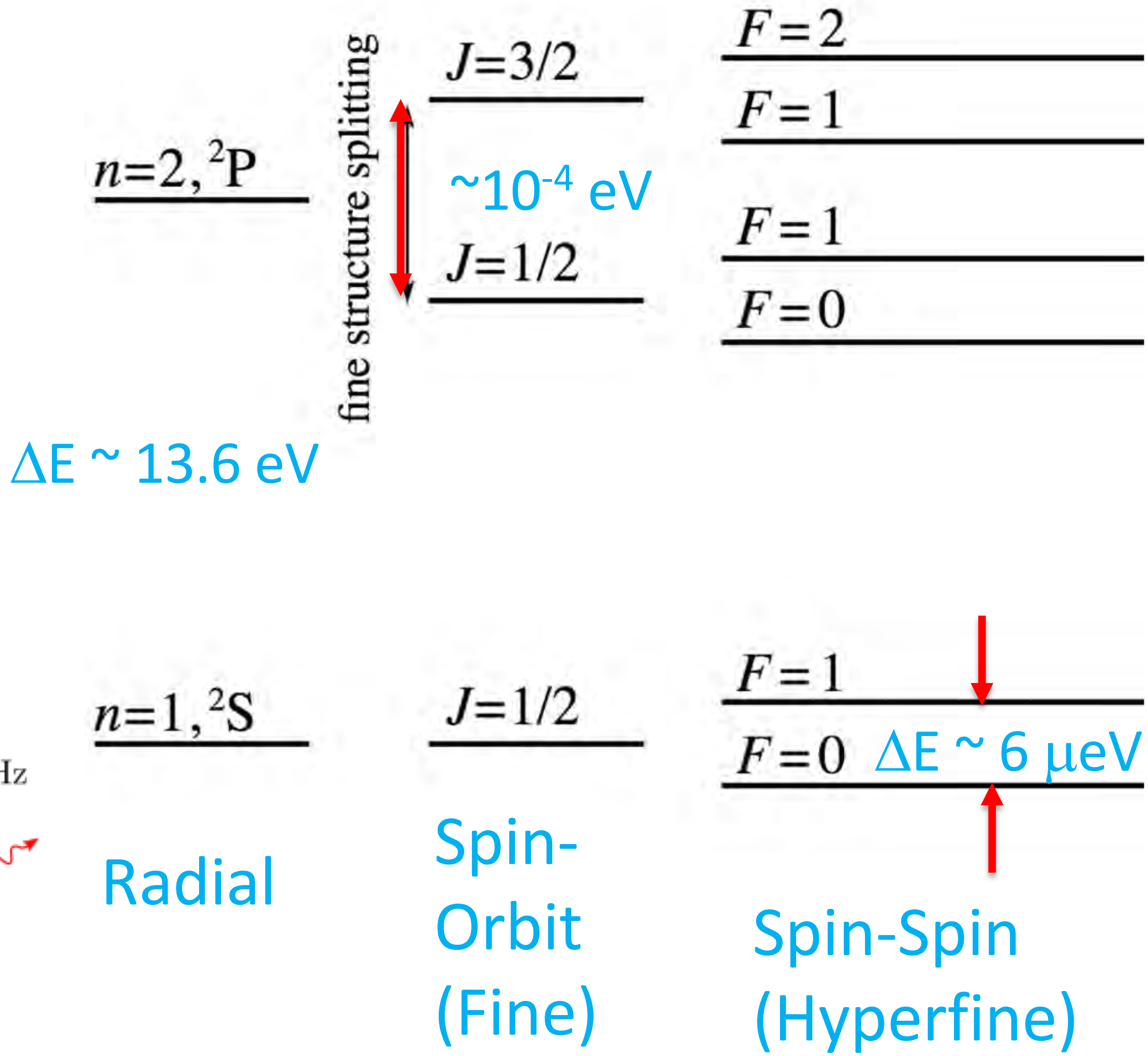


The 21 cm Line

The 21 cm Line

The 21 cm line results from the hyperfine splitting in atomic hydrogen.





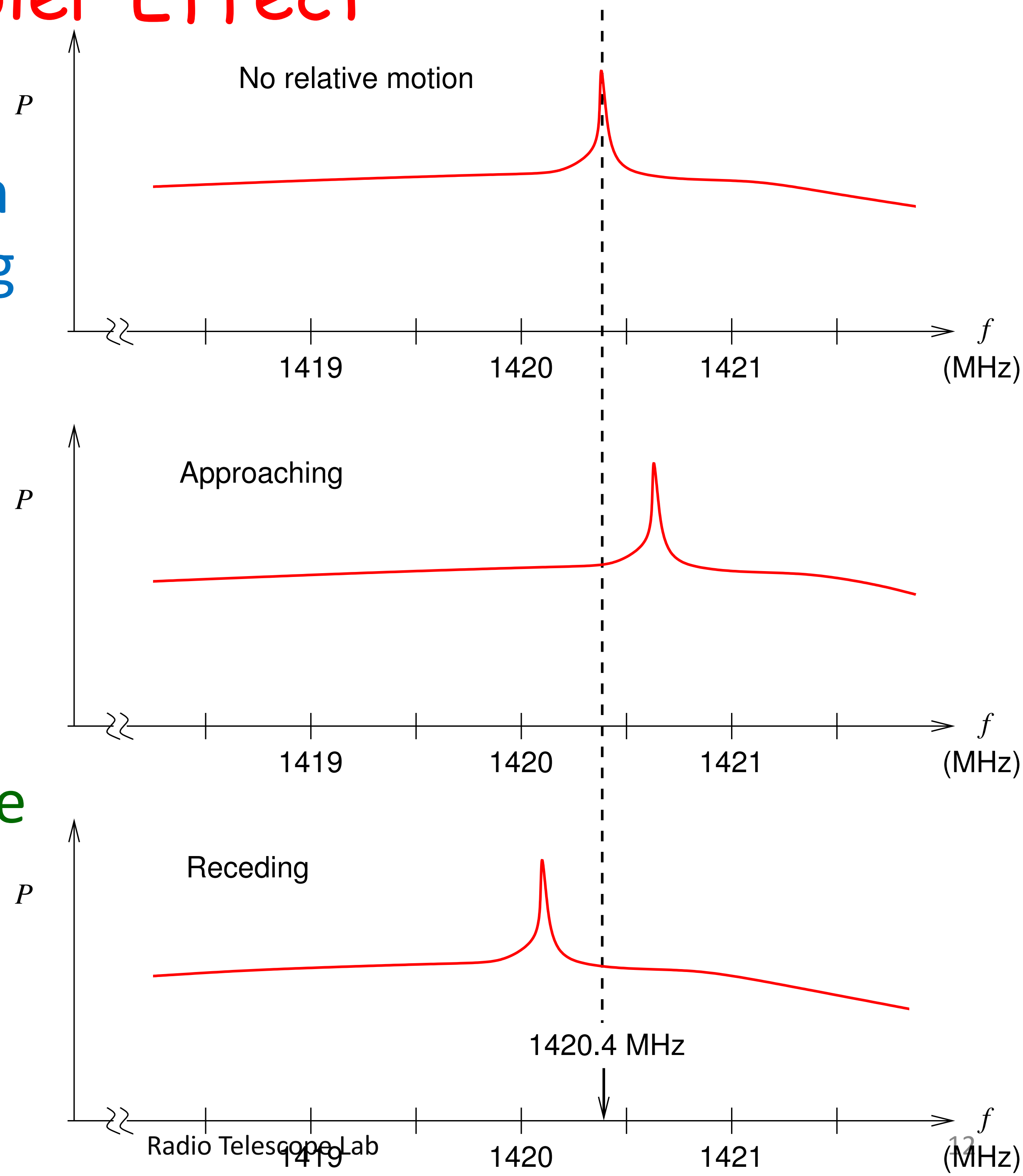
Cosmic Whistle

- The 21 cm signal from a single hydrogen atom is *extremely* weak (τ~10^7 years)
- The density of hydrogen atoms is *tiny* (one per cubic centimeter vs. ~10^{24}/cc in typical liquid water)
- But the galaxy is a (very!) big place and, taken as a whole, the signal is readily detected with modern radio technology.
- One can think of this signal as a cosmic whistle, detectable throughout the galaxy.

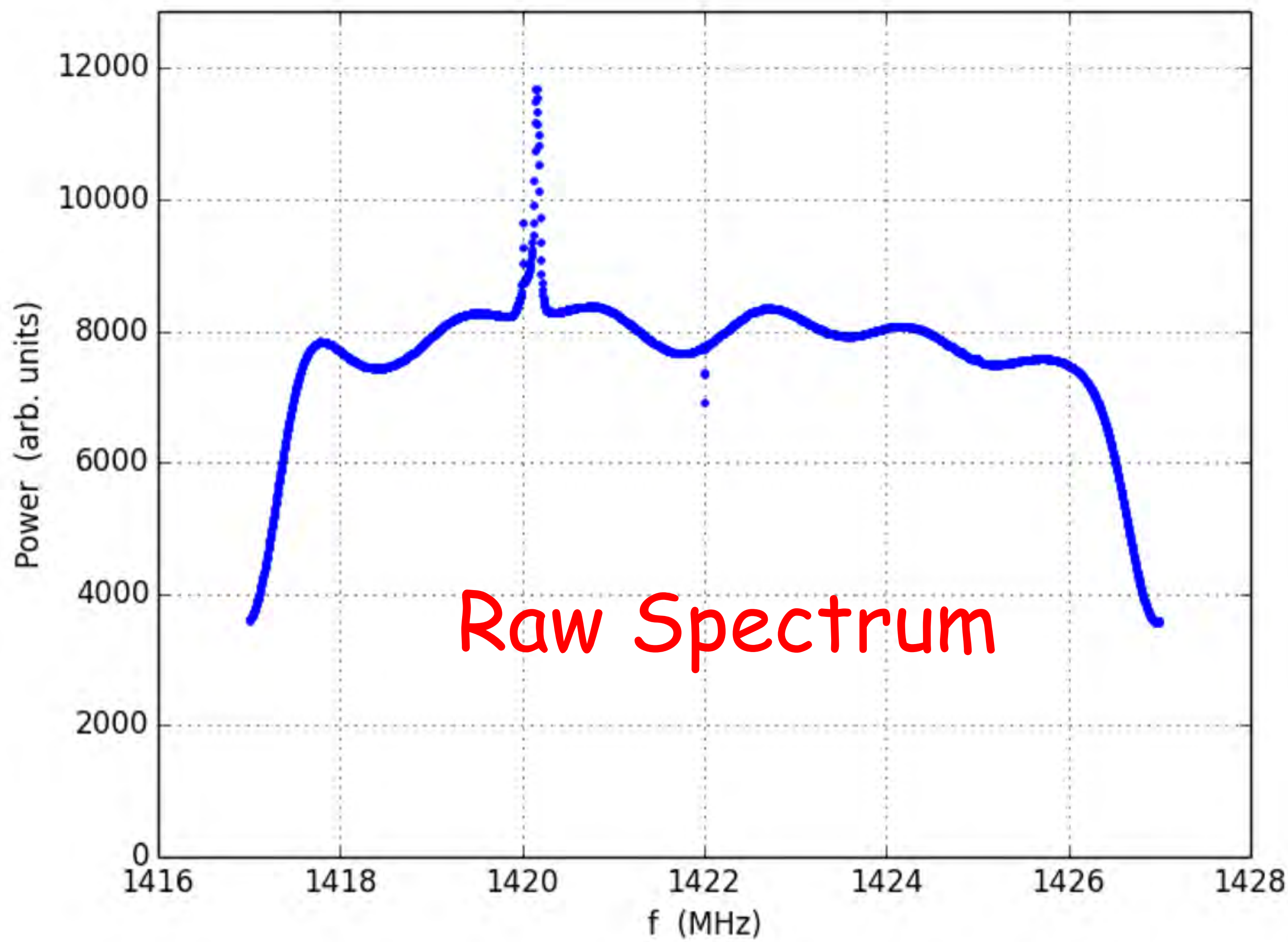
The Doppler Effect

The hydrogen gas in the galaxy is moving with respect to the Earth. The magnitude of this motion gives rise to a Doppler shift.

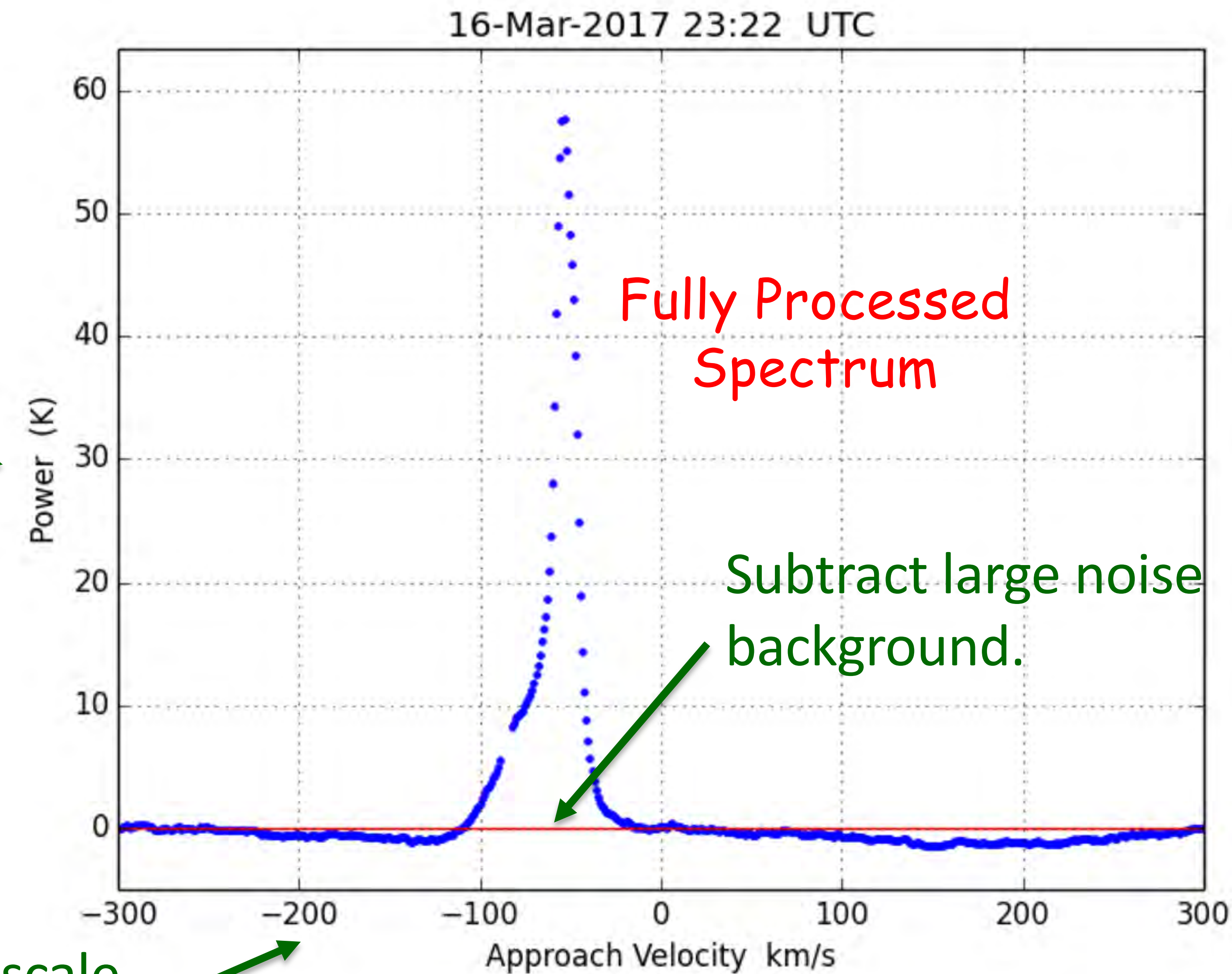
We can measure the speed of hydrogen gas clouds in the galaxy.



Data Reduction



Data Reduction

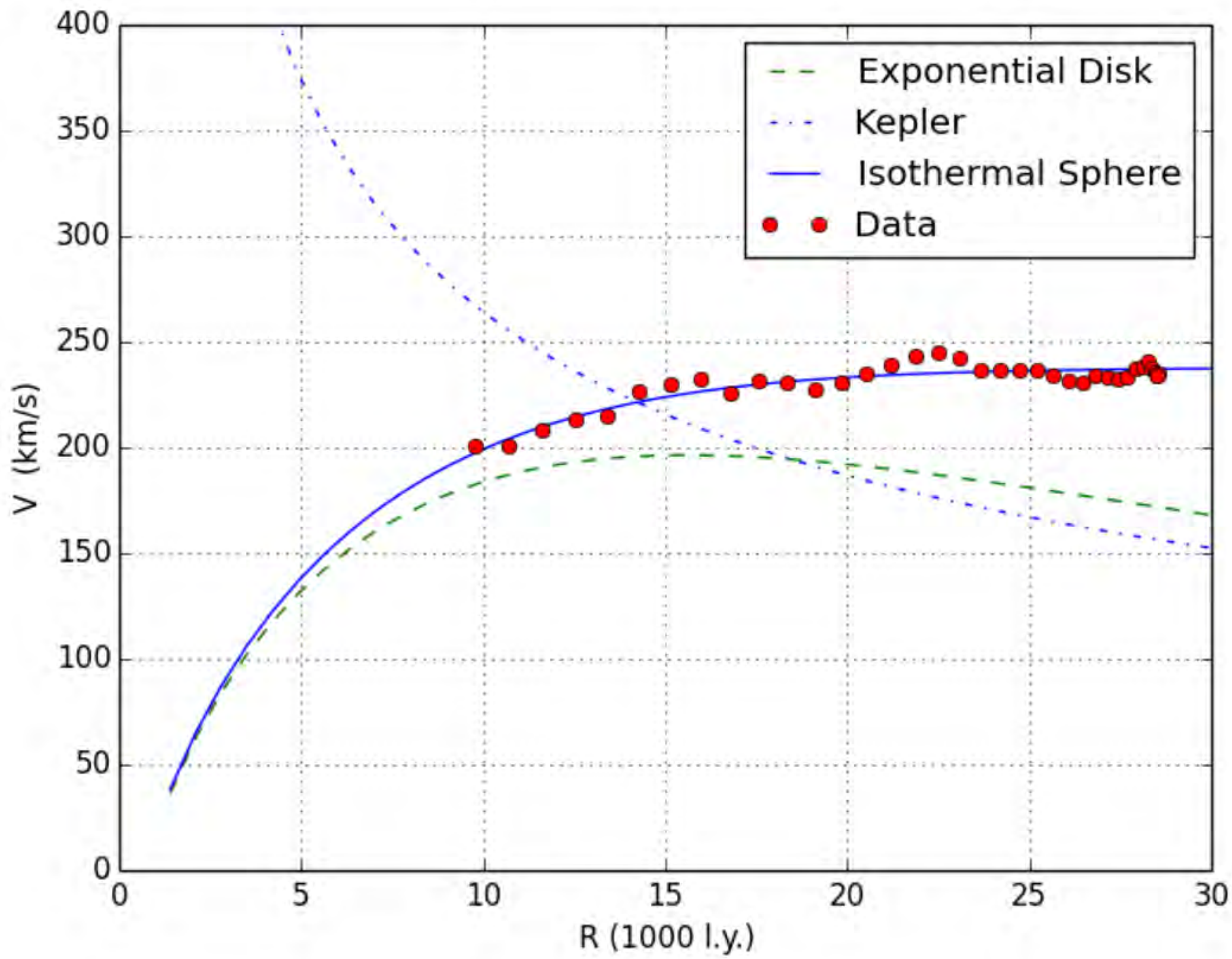


Express vertical scale in antenna temperature.

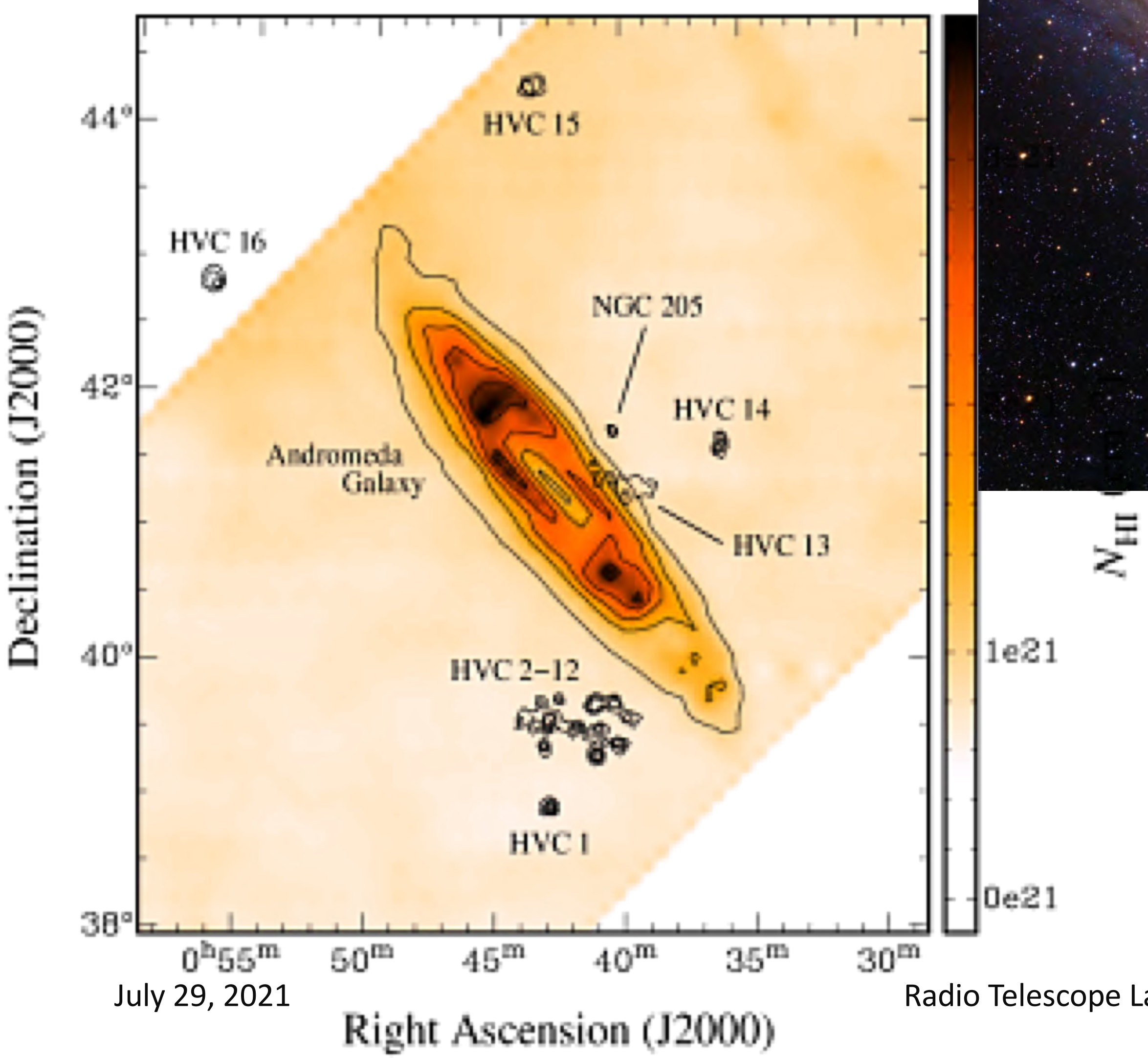
Express horizontal scale in Doppler velocity.

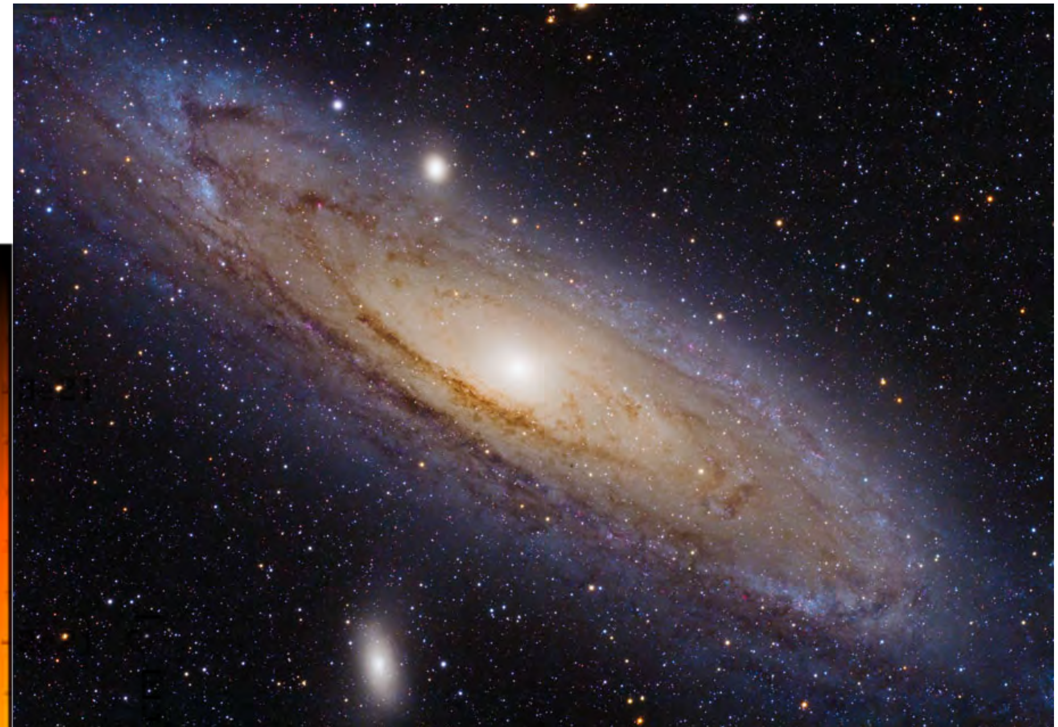
Rotation Curve

21 cm data can be used to map the rotation curve of the Milky Way, providing evidence for dark matter.

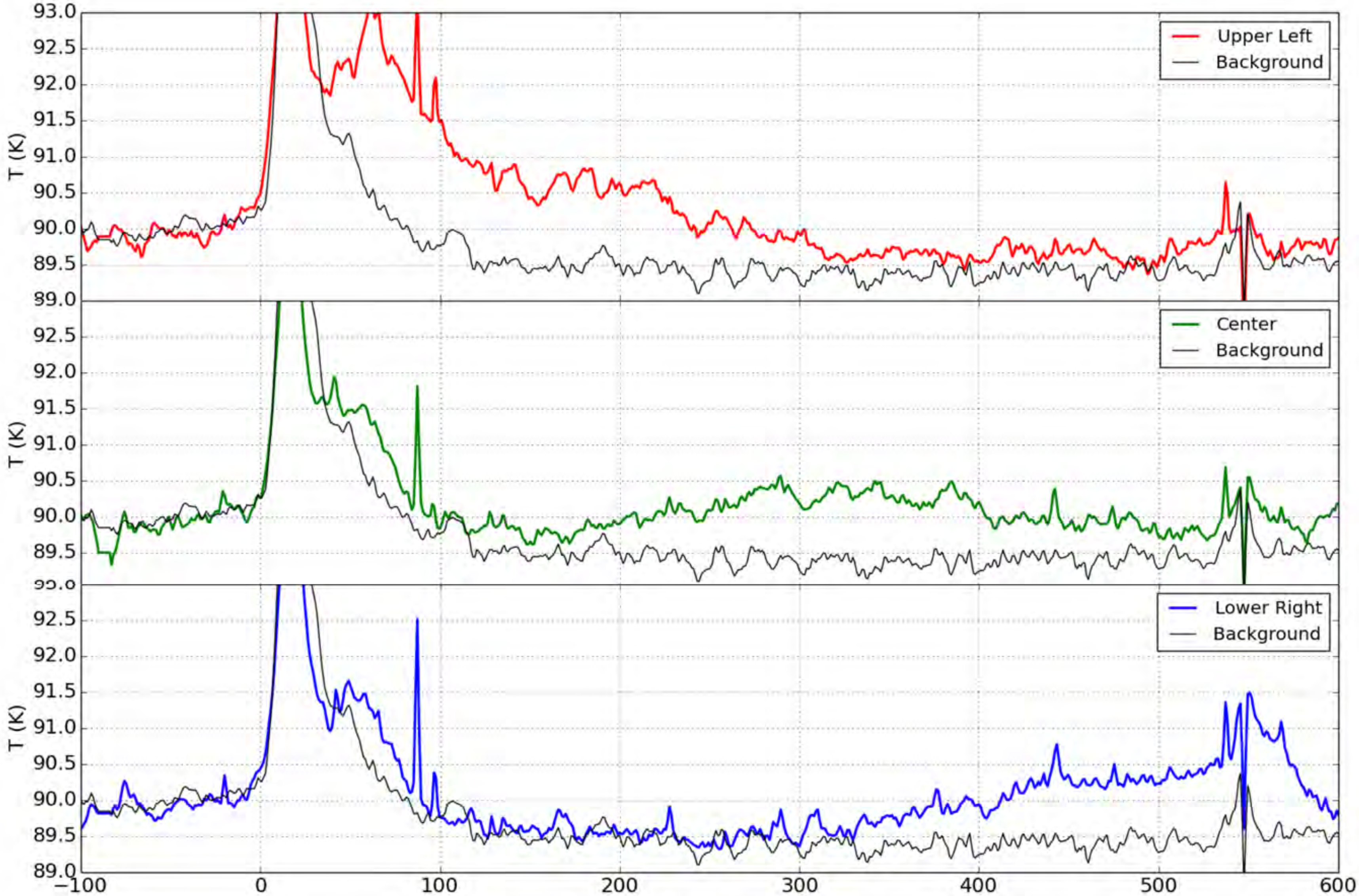


21 cm Radiation from Andromeda





21 cm Radiation from M31



Approach Velocity (km/s)

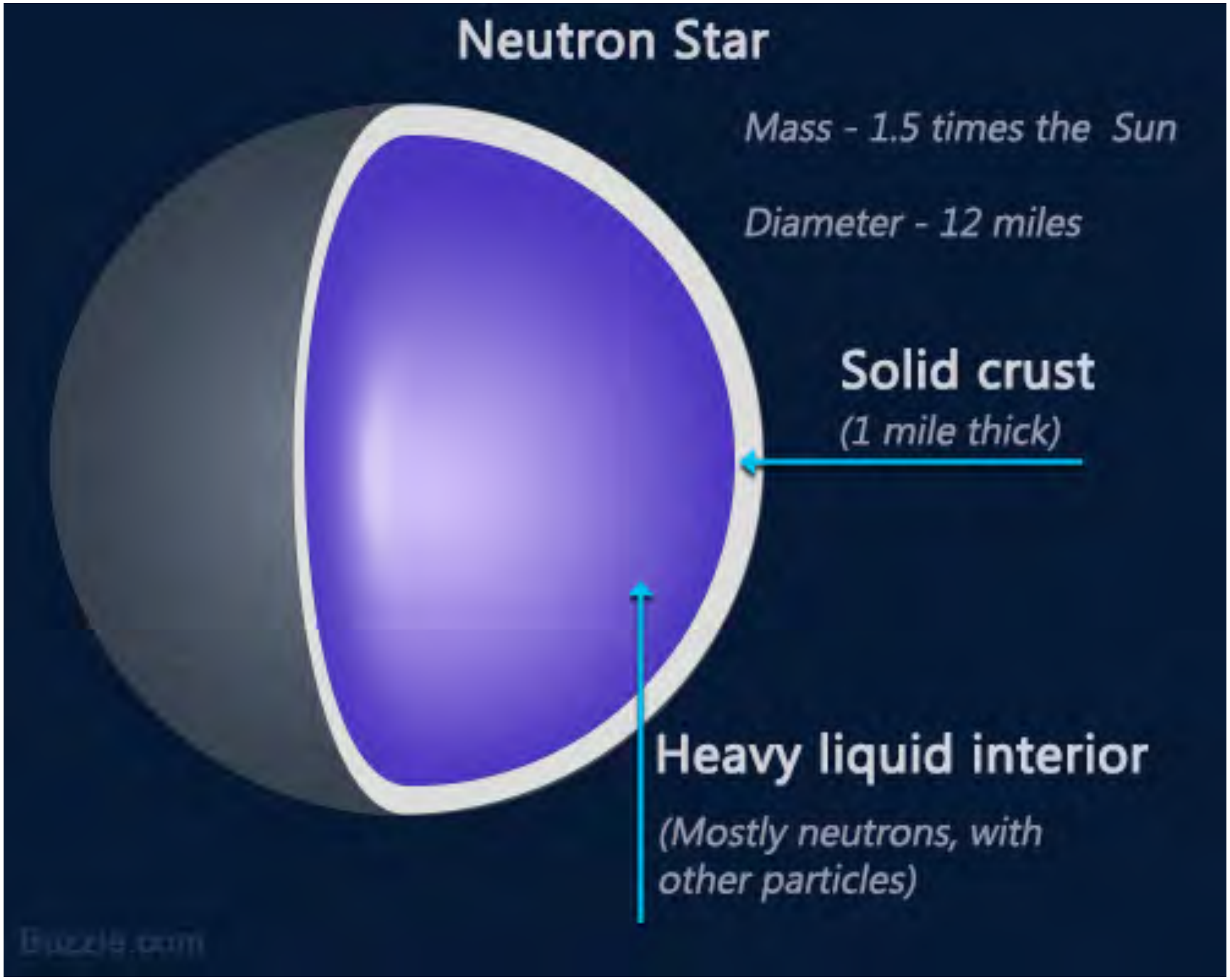
Pulsars

Pulsar Properties

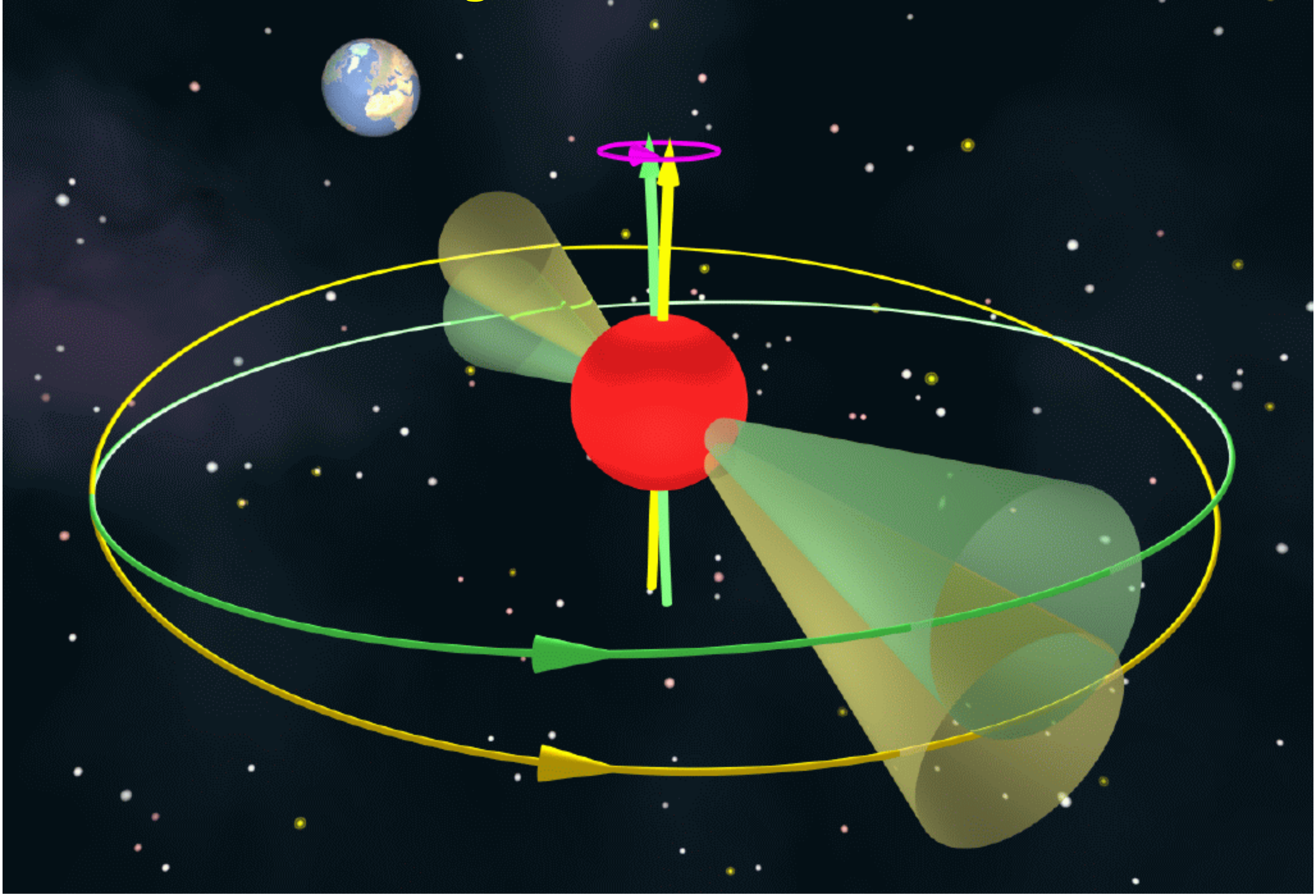
- Pulsars are formed when "progenitor" stars, having masses in the 10 $M_{sun} < M < 25 M_{sun}$ range, collapse after a relatively short life (millions of years, rather than the billions of years expected for the Sun)
- Collapse is supernova explosion
- Most of the star's mass is blasted into space
- About 1.4 M_{sun} remains
- Pulsars are neutron stars
  - Pressure is so great that atoms collapse
  - Electrons combine with protons to make neutrons
  - Star core consists of nuclear matter

Pulsar Properties

- Nuclear matter is very dense: one teaspoon’s worth weighs 3 billion tons.
- Pulsars spin quickly.
- Radiation is broad band.



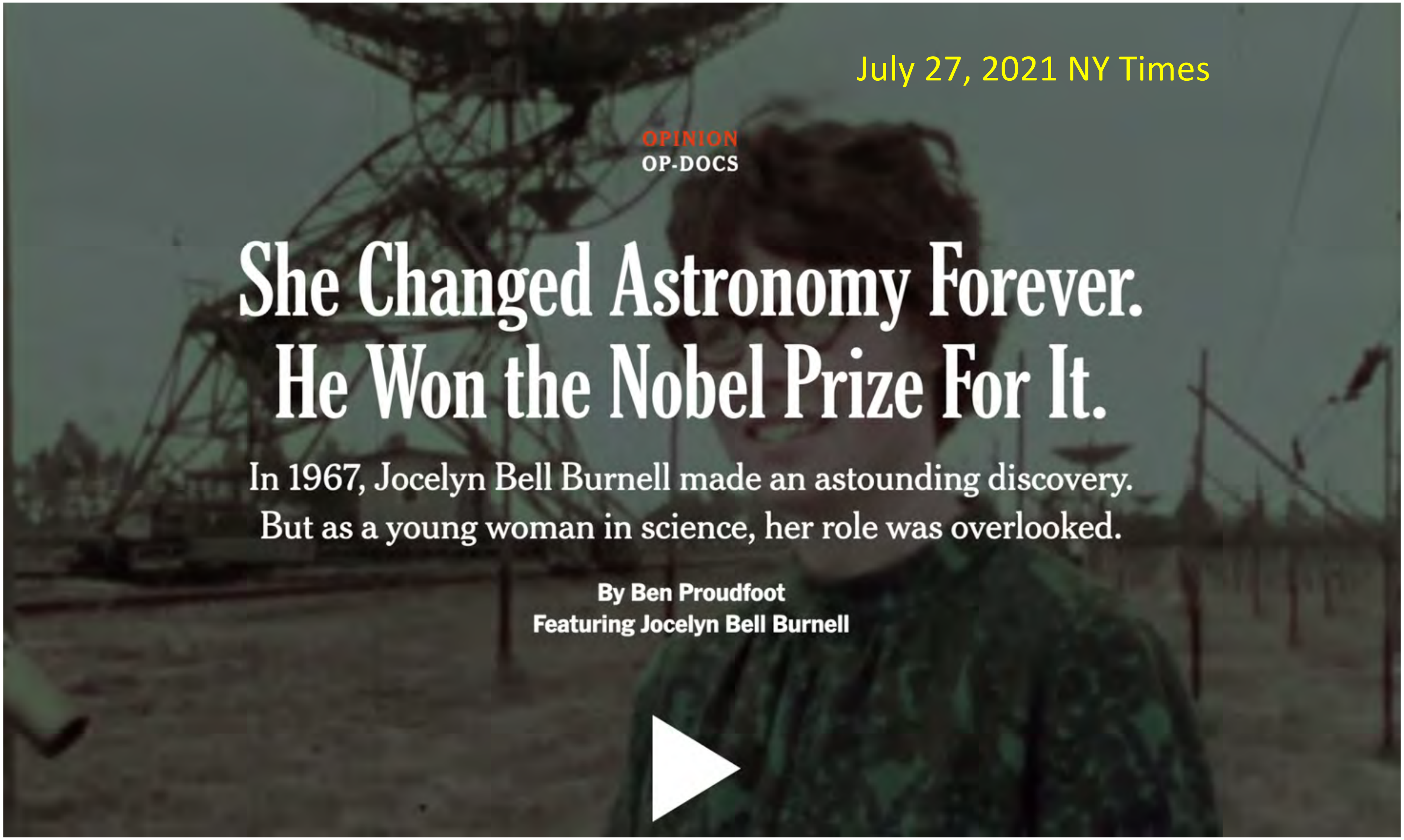
Lighthouse Effect



Pulsar Discovery

The first observation of a pulsar was made in 1967 by Jocelyn Bell Burnell, a Cambridge graduate student, who noticed an unexpected pattern in the time series from her antenna array.   (See recent NY Times article.)

Pulsar Discovery



Pulsar Signals

- Pulsar radiation is broad band
  - Most energy at longest wavelengths
  - Discovery was made at 80 MHz, considerably lower in frequency that our 1421 MHz operating point
  - Will not see peaks in spectrum the way we do when looking at galactic hydrogen
- Disadvantage of smaller signals at short wavelength is offset by higher antenna gain
- Will exploit repetitive nature of signal to average away noise.

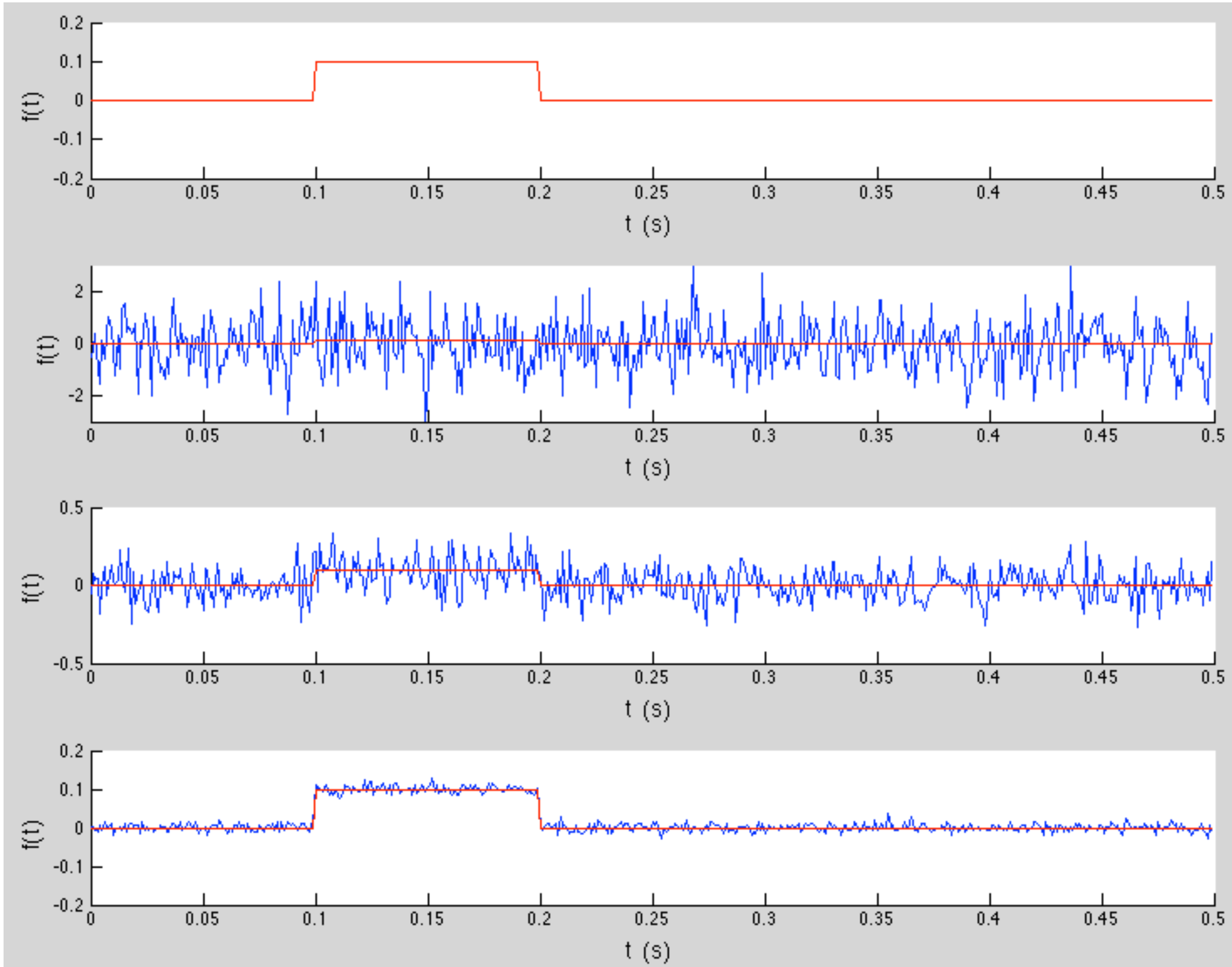
Signal Averaging

Signal without noise.

Signal with noise. Single sample.

Signal with noise. Average of 100 samples.

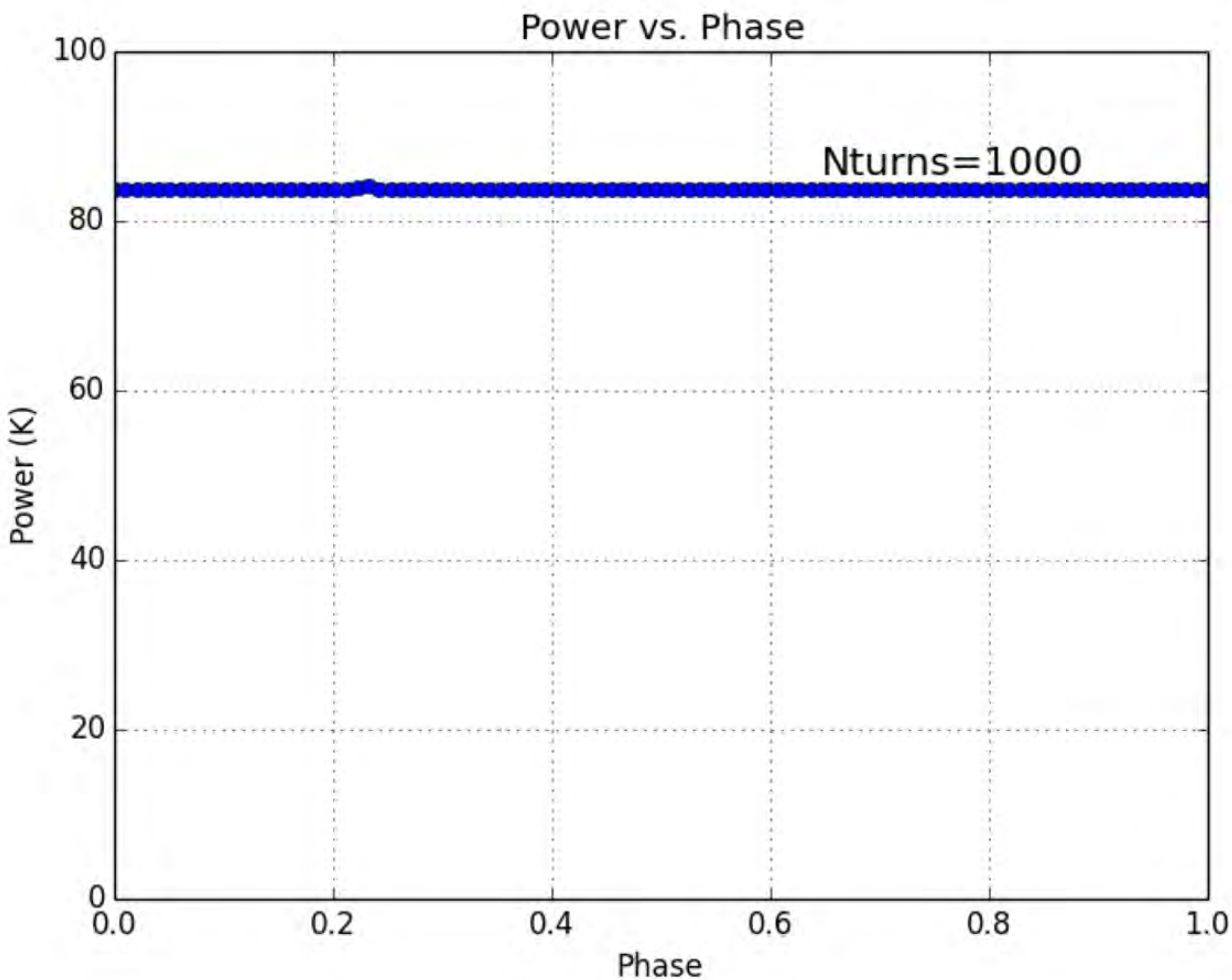
Signal with noise. Average of 10,000 samples.



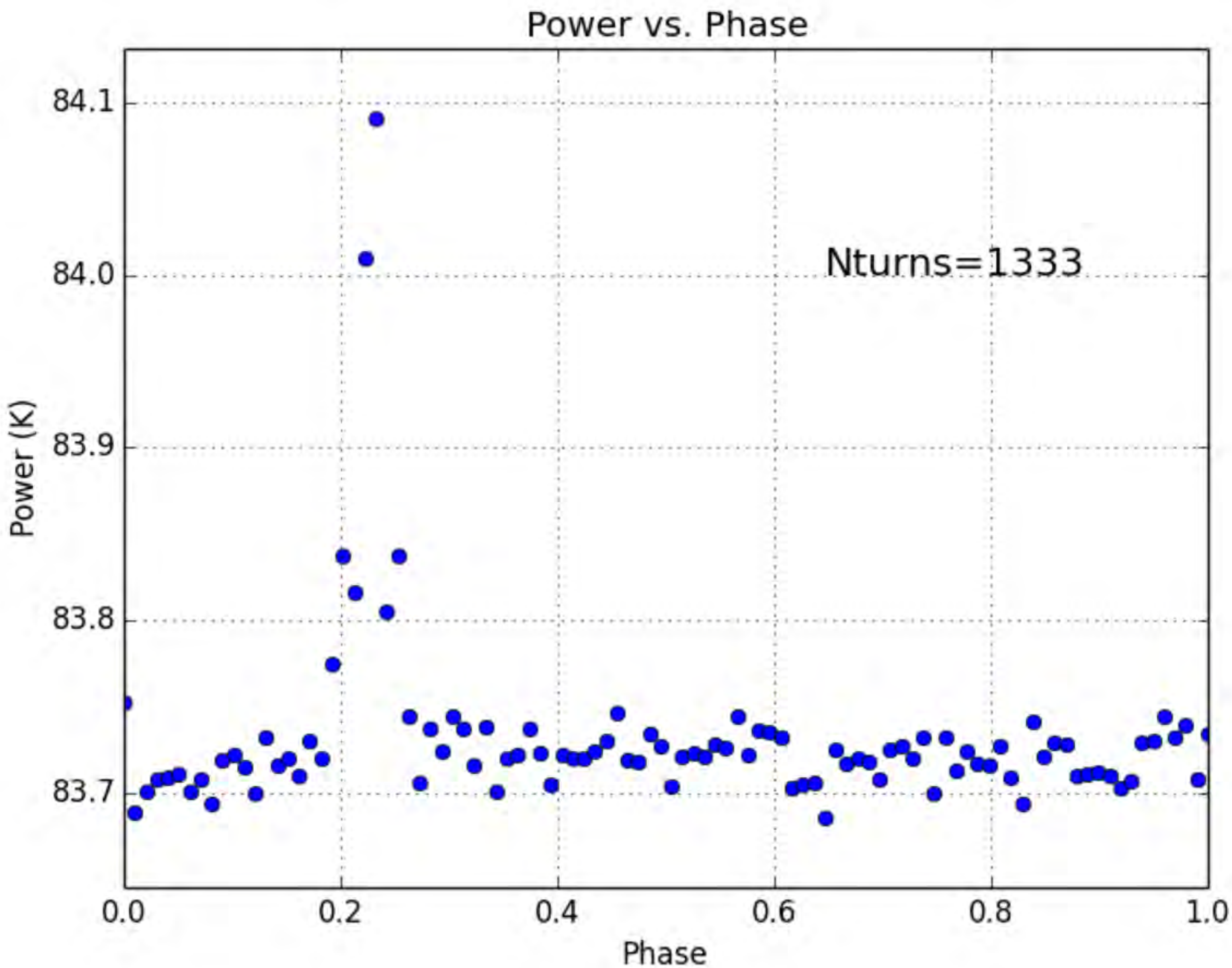
Student Tasks

- Identify promising pulsars using Australian National Telescope Facility catalog
  - Above horizon during lab period
  - Strong signal
  - Period > 0.2 s
  - Etc.
- Point telescope and take data for ~30 min/target (usually two targets)
- Reduce data on remote machine
- Copy reduced data to laptop
- Analyze using python or matlab

Pulsar Signal



Pulsar Signal

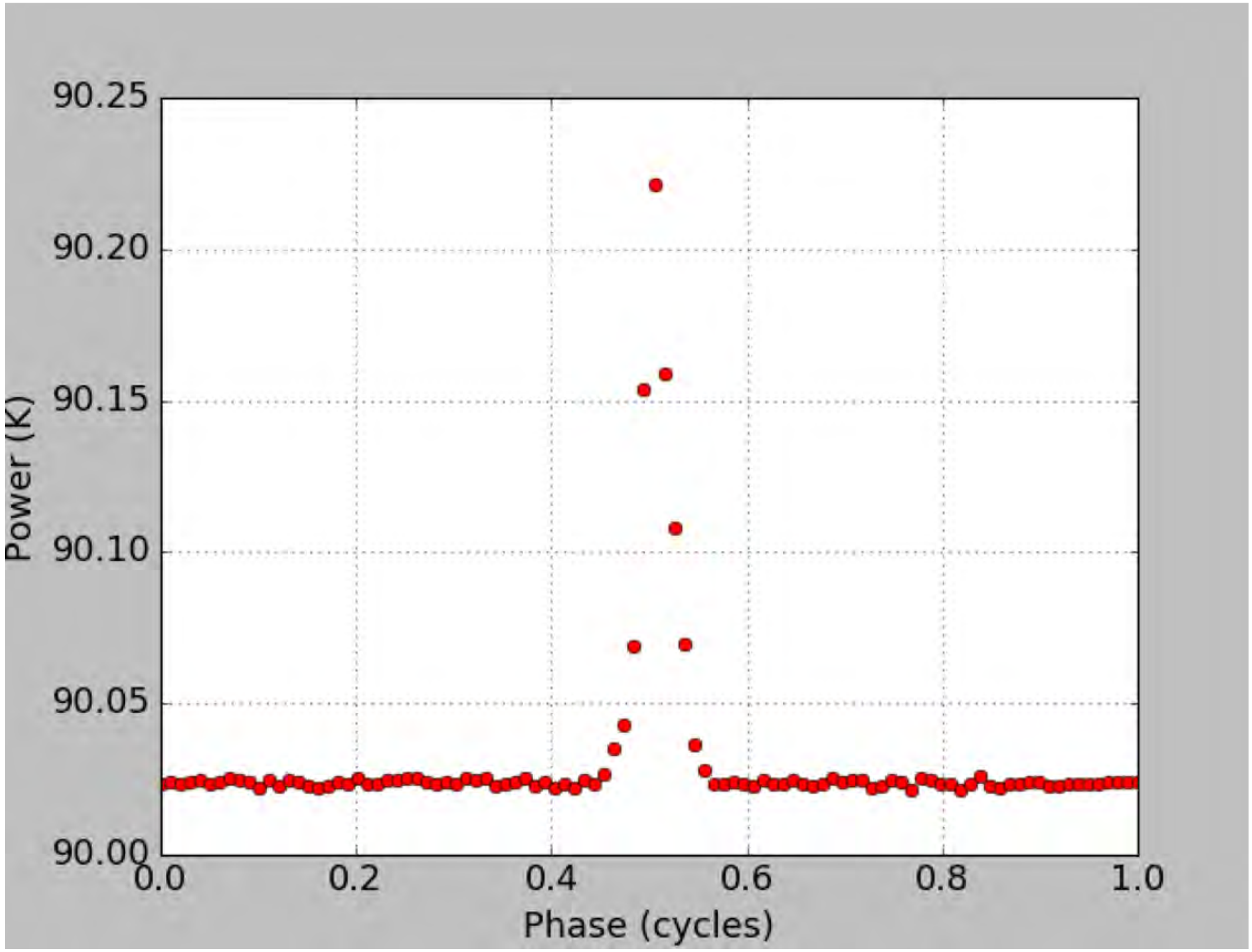


Upgraded System

- Increase from 25 MHz → 250 MHz bandwidth
  - Time to reliably detect J0332+543430 dropped to ~3 minutes
  - Effects of ISM will be mitigated
  - Expanded list of accessible targets
  - Measure distance to pulsars using dispersion measure

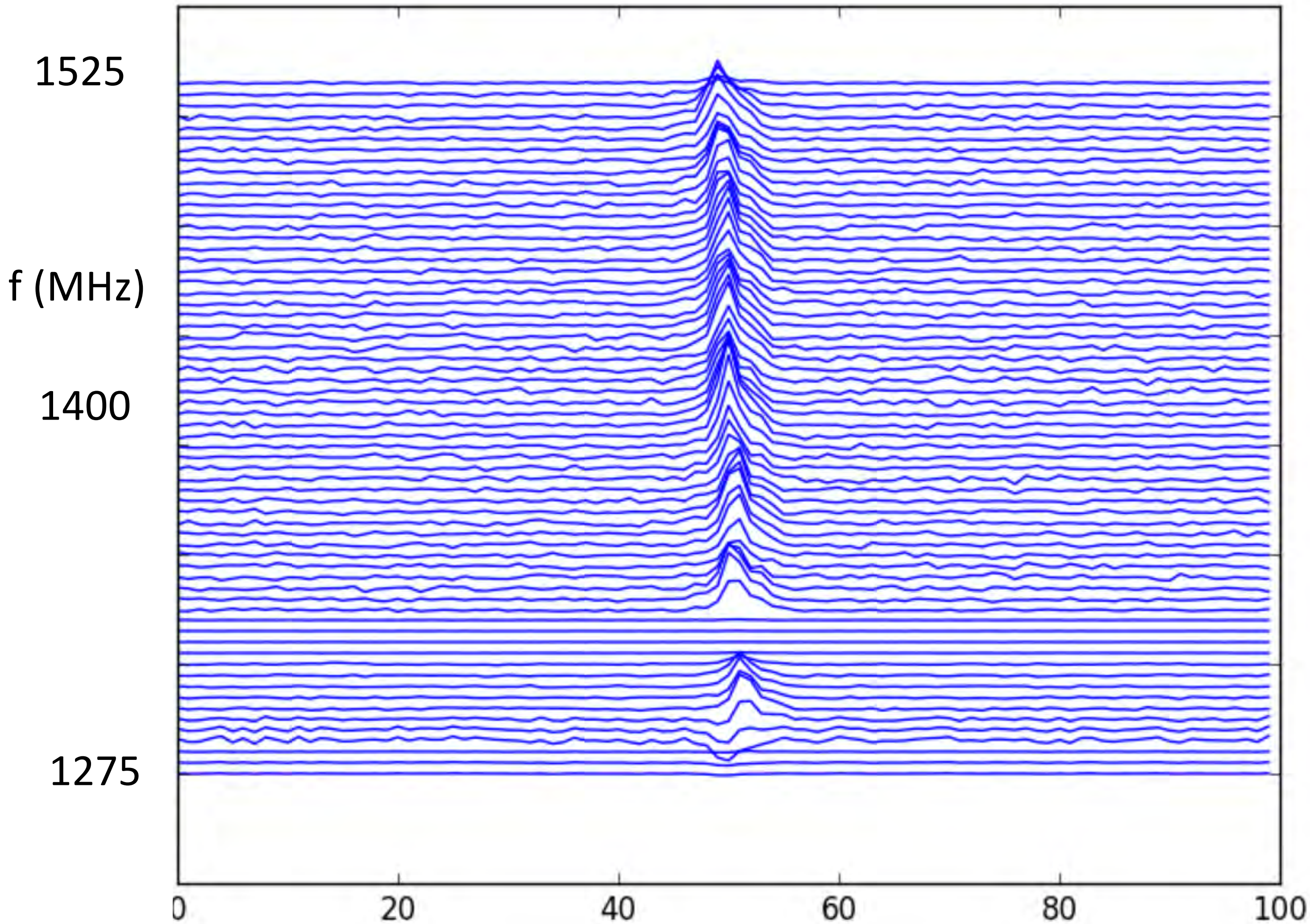
Pulsar Signal (250 MHz)

In a long (~2h) run, high S/N values are possible.



Dispersion (250 MHz)

Here we show a series of plots, each one corresponding to a small frequency range.



Closing Remarks

- Pulsars can be observed using a 60′ radio telescope.
- The system is remotely accessible and can therefor be operated from anywhere that has a good internet connection.
- At present, the dish is lightly used, and we are open to the possibility of other schools making use of it.
- If interested contact: marlow@princeton.edu

Additional Material

TIROS History
April 1960

Prior to TIROS and satellite based weather prediction, hurricanes often cost many lives.

TIROS History, April 1960

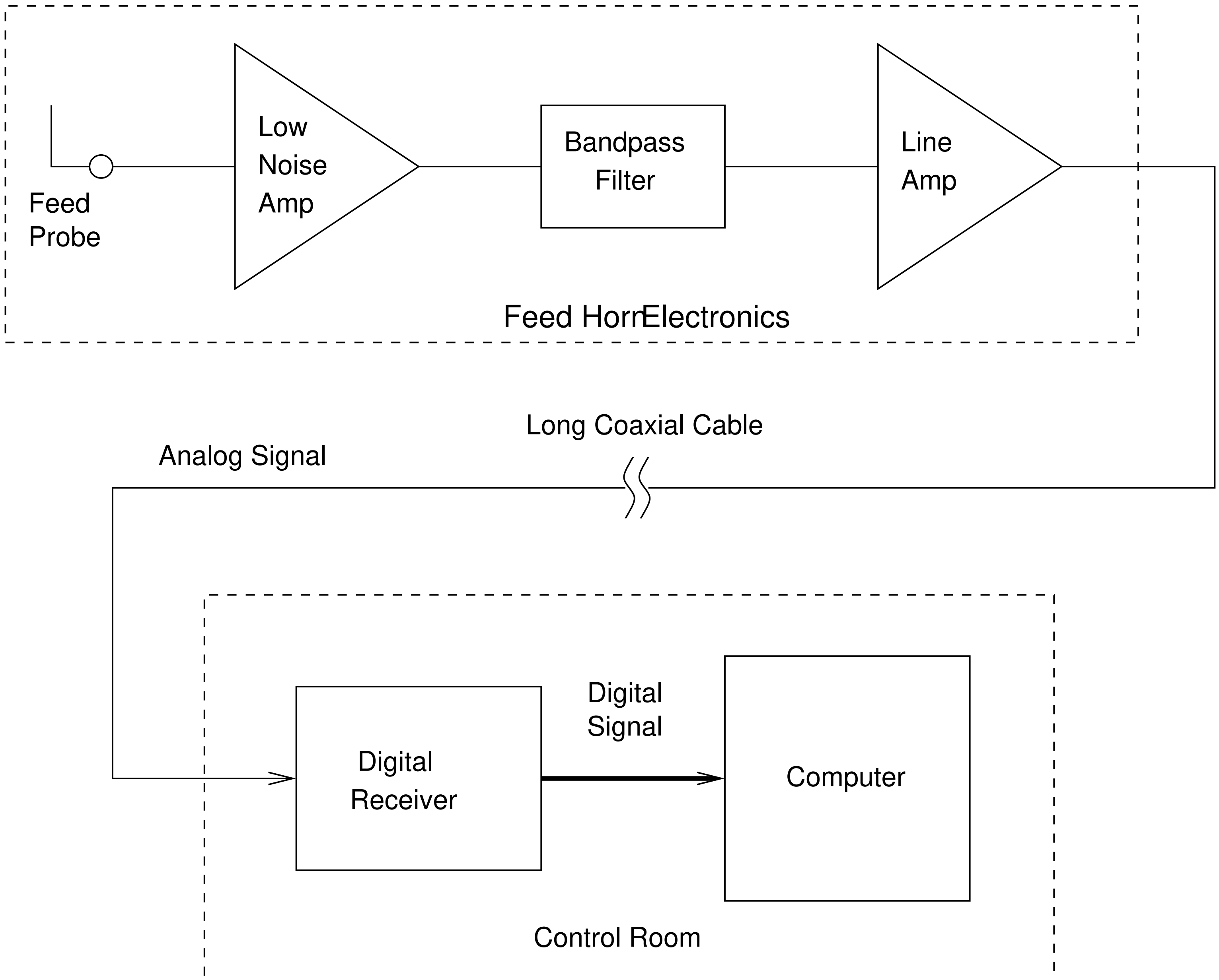
A tense moment as TIROS passes overhead.

Dish Repair

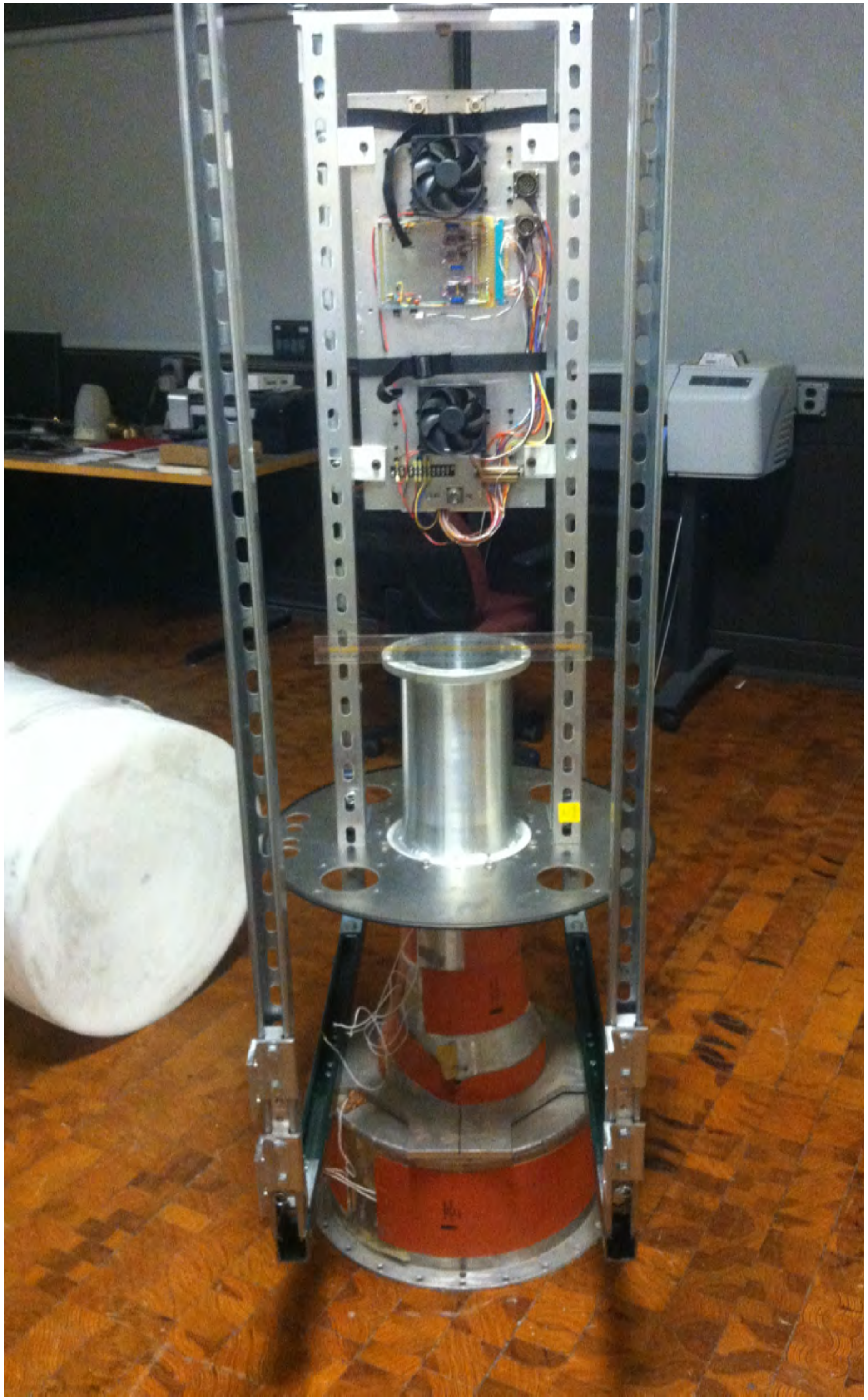
Although many parts of the dish were in good condition, the one-ton elevation drive assembly was badly rusted and needed to be sent out for refurbishment.

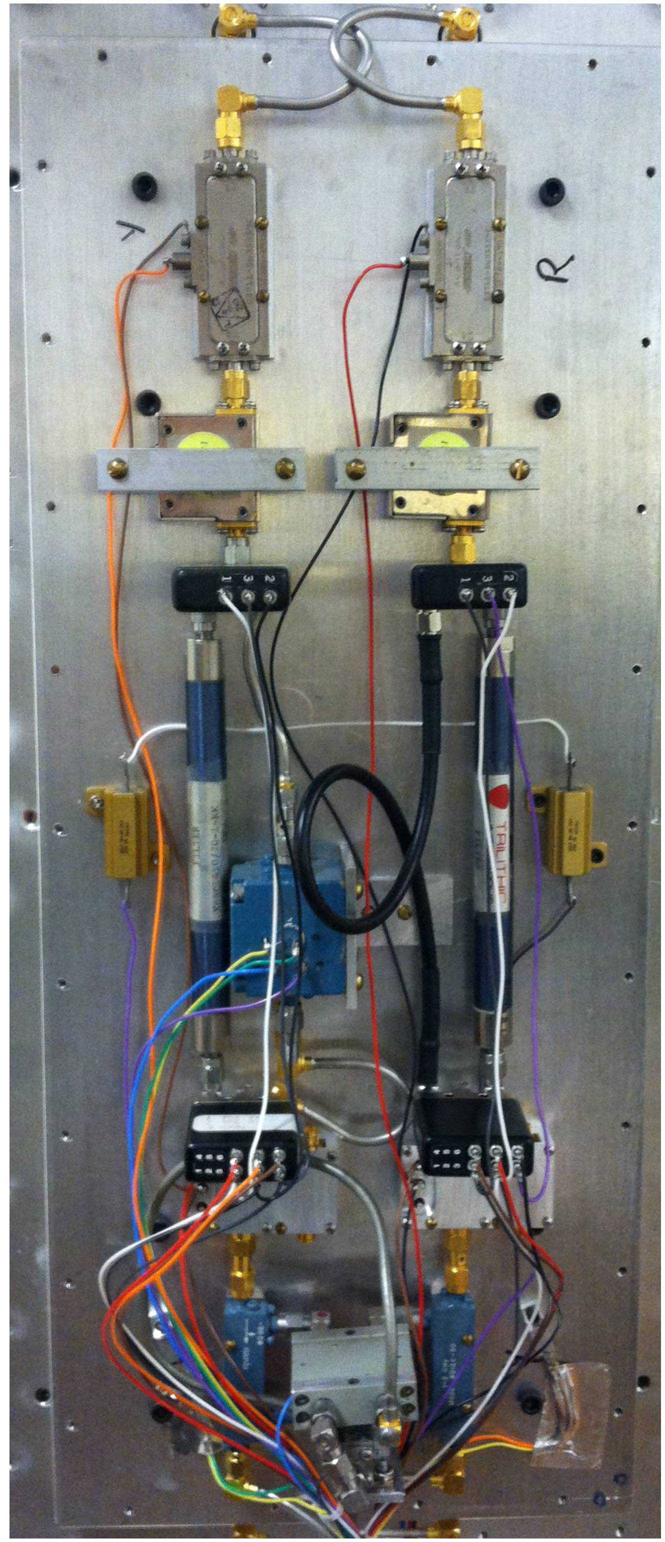
Technical Details

Readout Chain



There are actually two such chains, one for each polarization





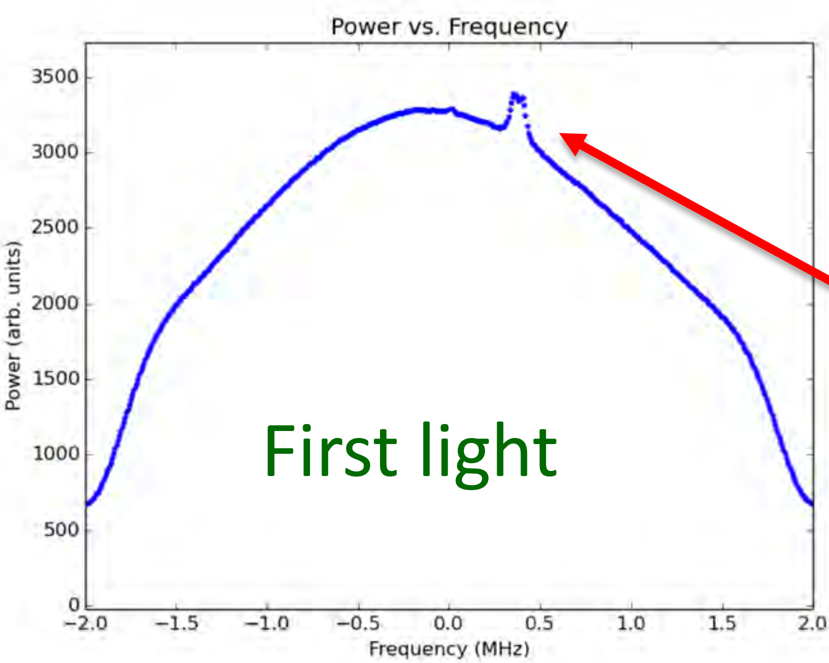
Output
Amplifiers

Bandpass
Filters

Low Noise
Preamps

Software Defined Radio

- Most of the complicated signal processing is done digitally, using public domain software running on commodity Linux machines.

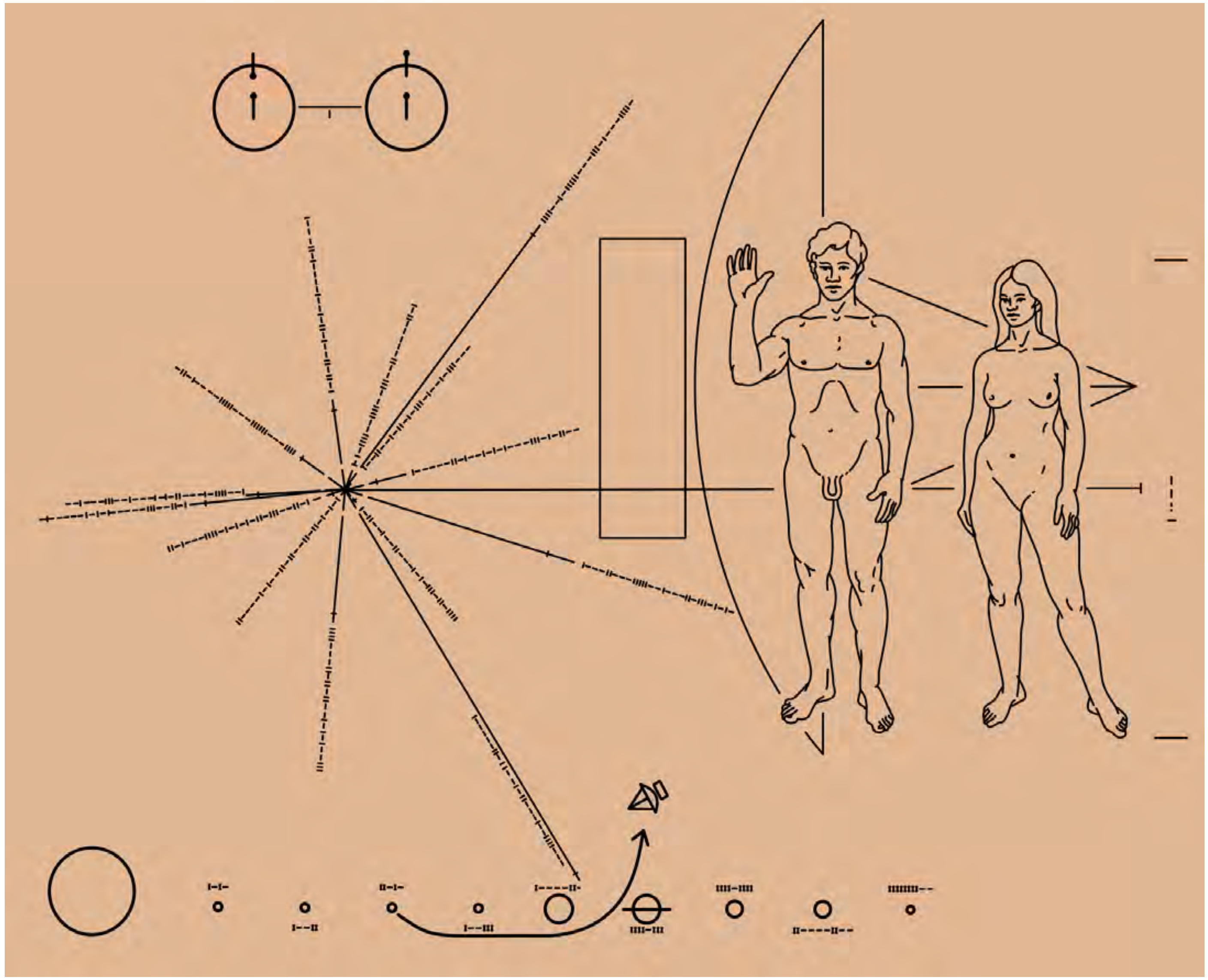


- The system worked right "out of the box".
- 21 cm line from galaxy.

The Pioneer Plaque

The 21-cm line is such a fundamental entity that Carl Sagan and Frank Drake proposed mounting a plaque on the Pioneer deep space probe.

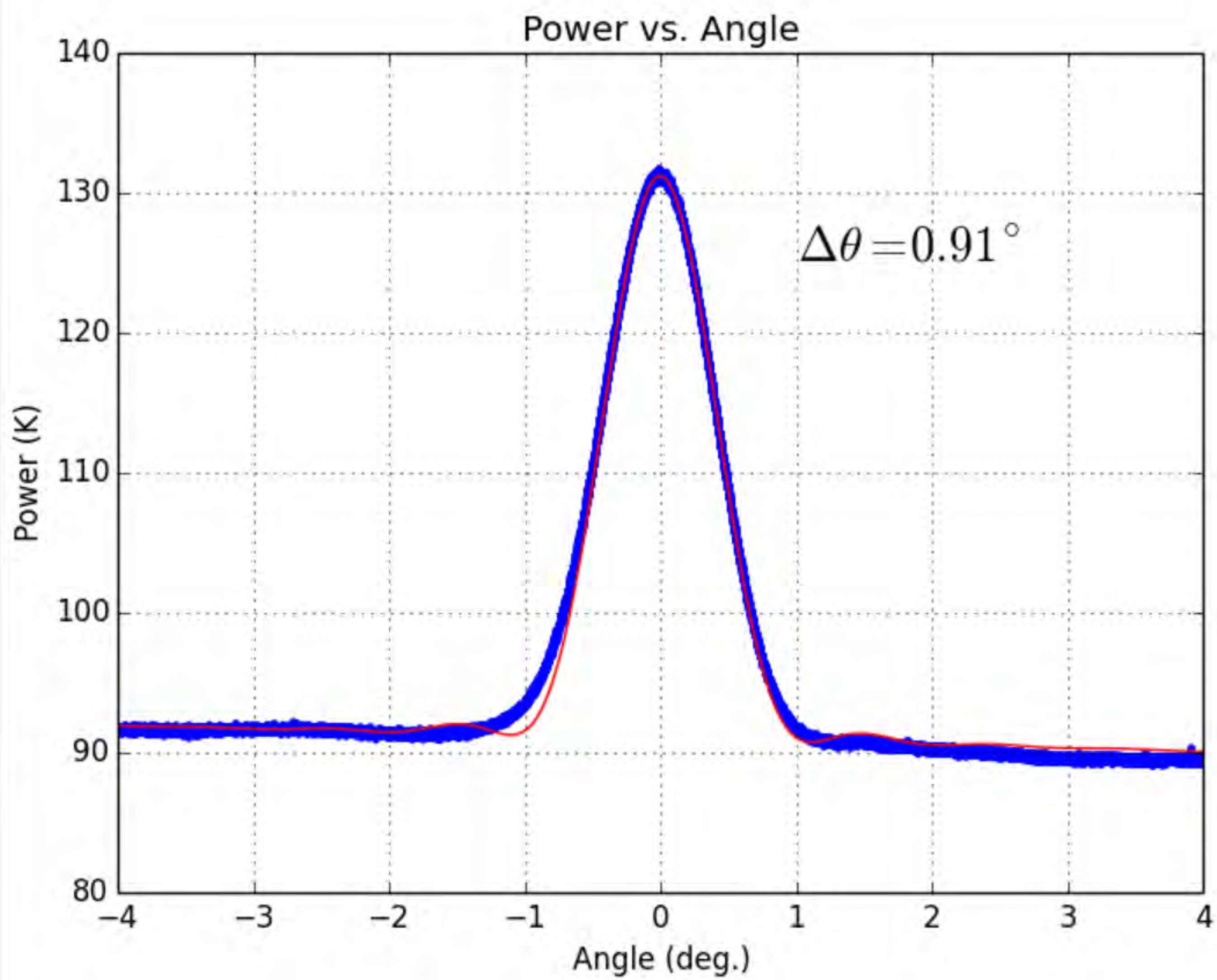
There, the 21 cm line sets the scale for the drawing of the humans engraved on the plaque.



Cassiopeia A Scan

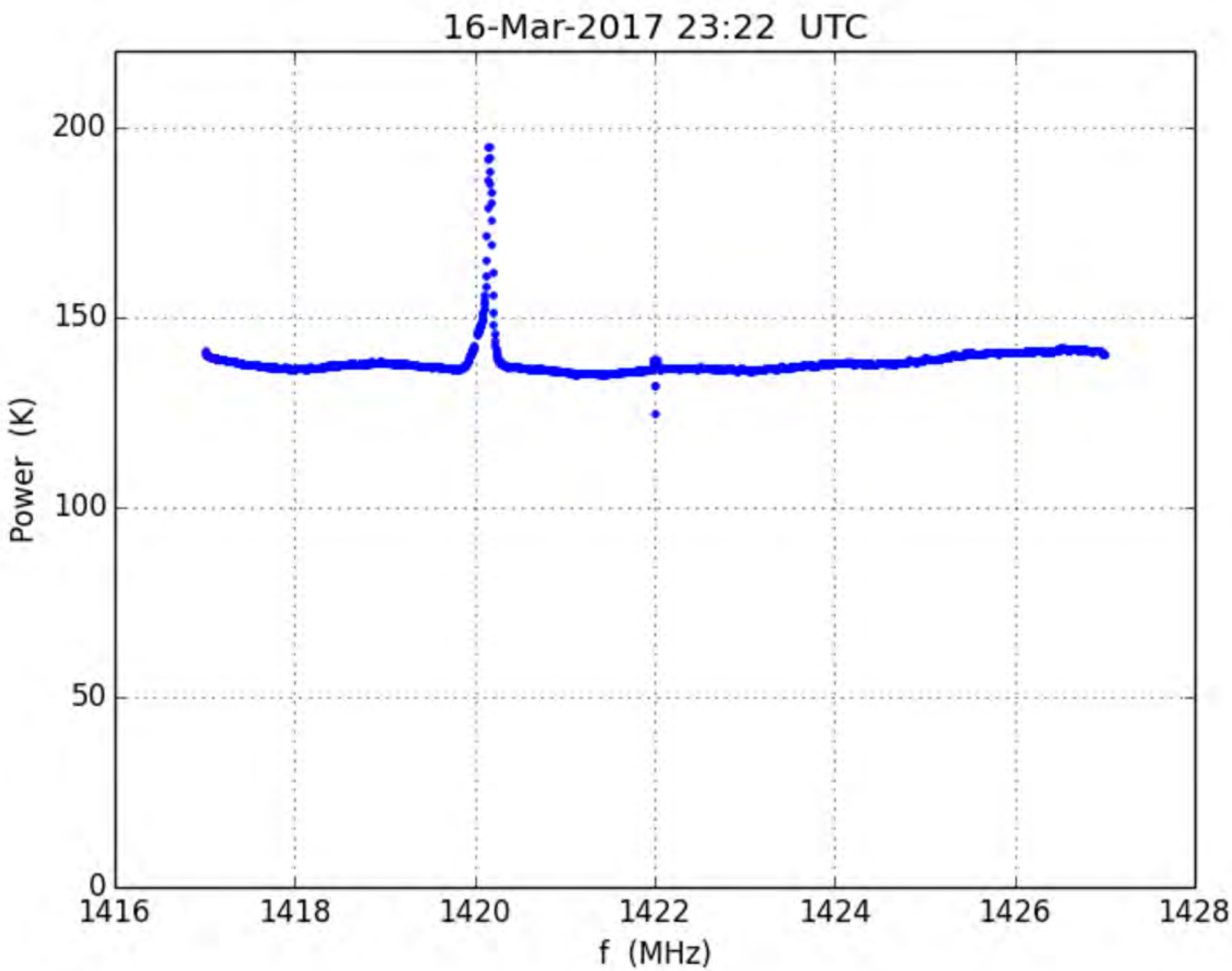
A similar exercise can be done using Cas A, which is the brightest radio point-source in the sky.

Compare to expectations from diffraction theory.

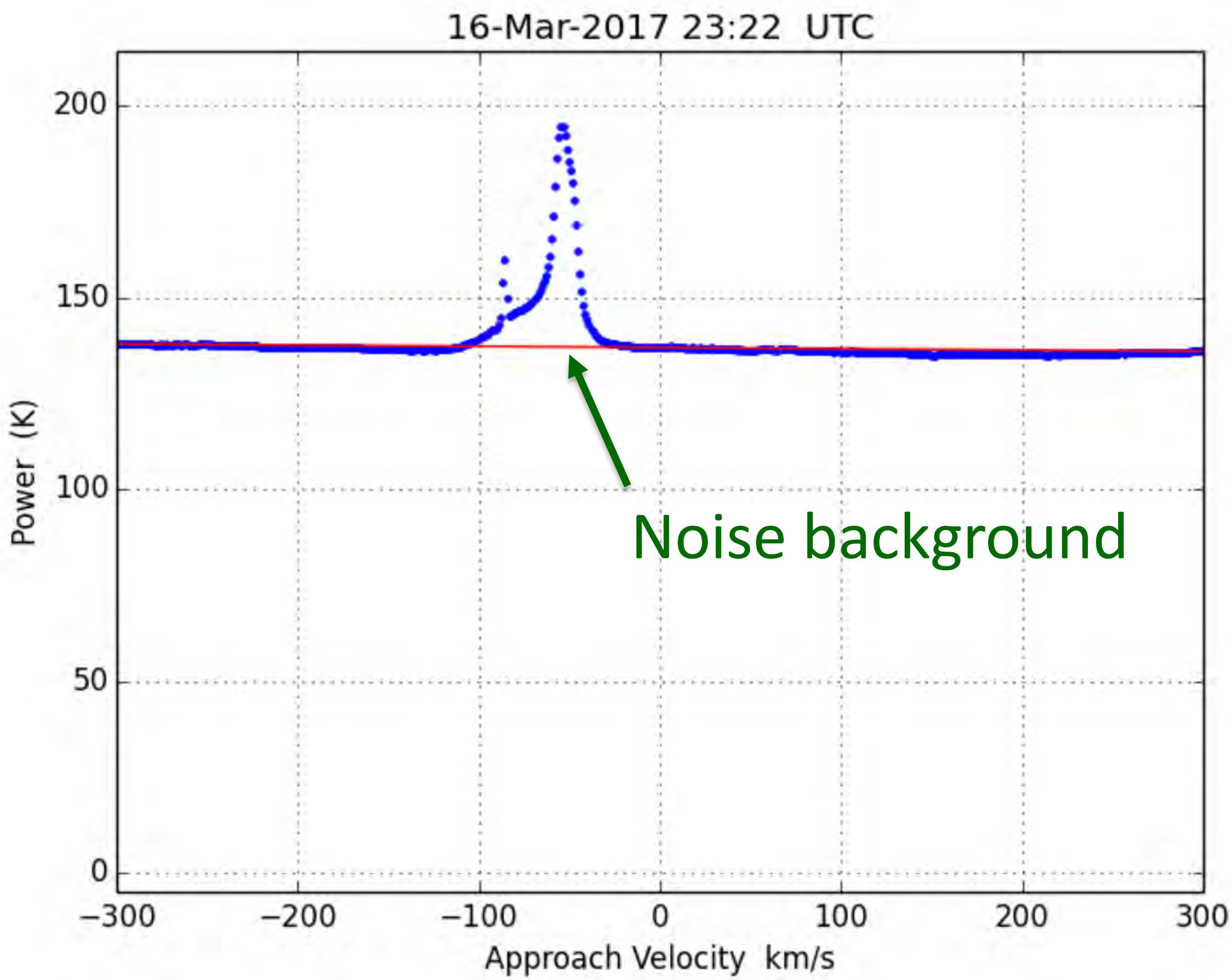


$$\Delta\theta = 1.22\frac{\lambda}{D} = 1.22\left(\frac{0.21\ \text{m}}{18\ \text{m}}\right) = 0.014\ \text{radians} = 0.82^\circ$$

Gain Corrected



Convert to Doppler and Limit Range

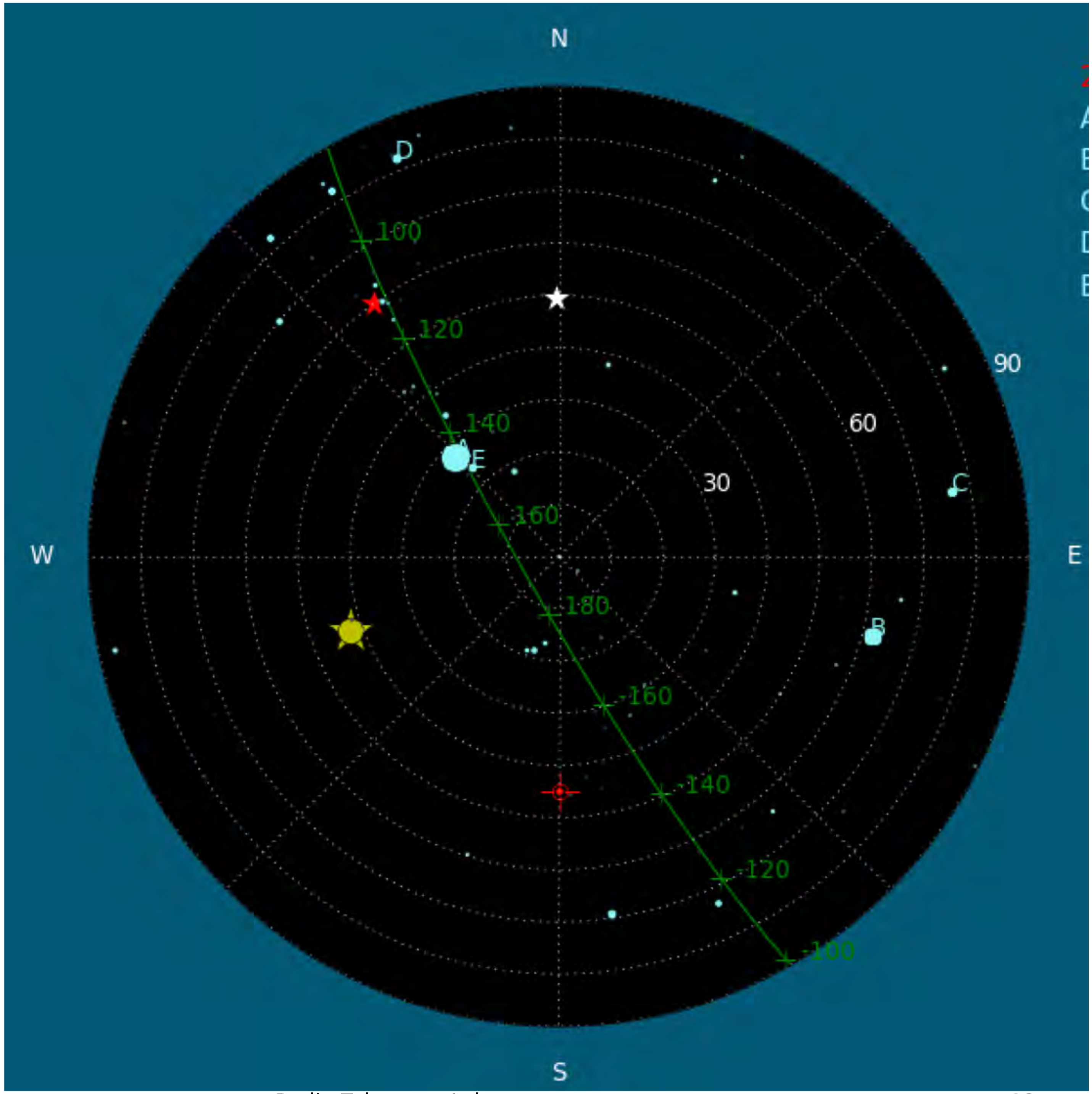


Size Doesn't Matter (for 21 cm)

- The signal size for 21 cm observations does not strongly depend on the size of the dish
  - Smaller dish means larger beam width, which means more hydrogen in the beam: $S \propto 1/D^2$
  - Larger size means larger collection area, which means larger signals $S \propto D^2$
  - Effects cancel
- The smaller angular resolution of the larger dish does help in some ways, however.

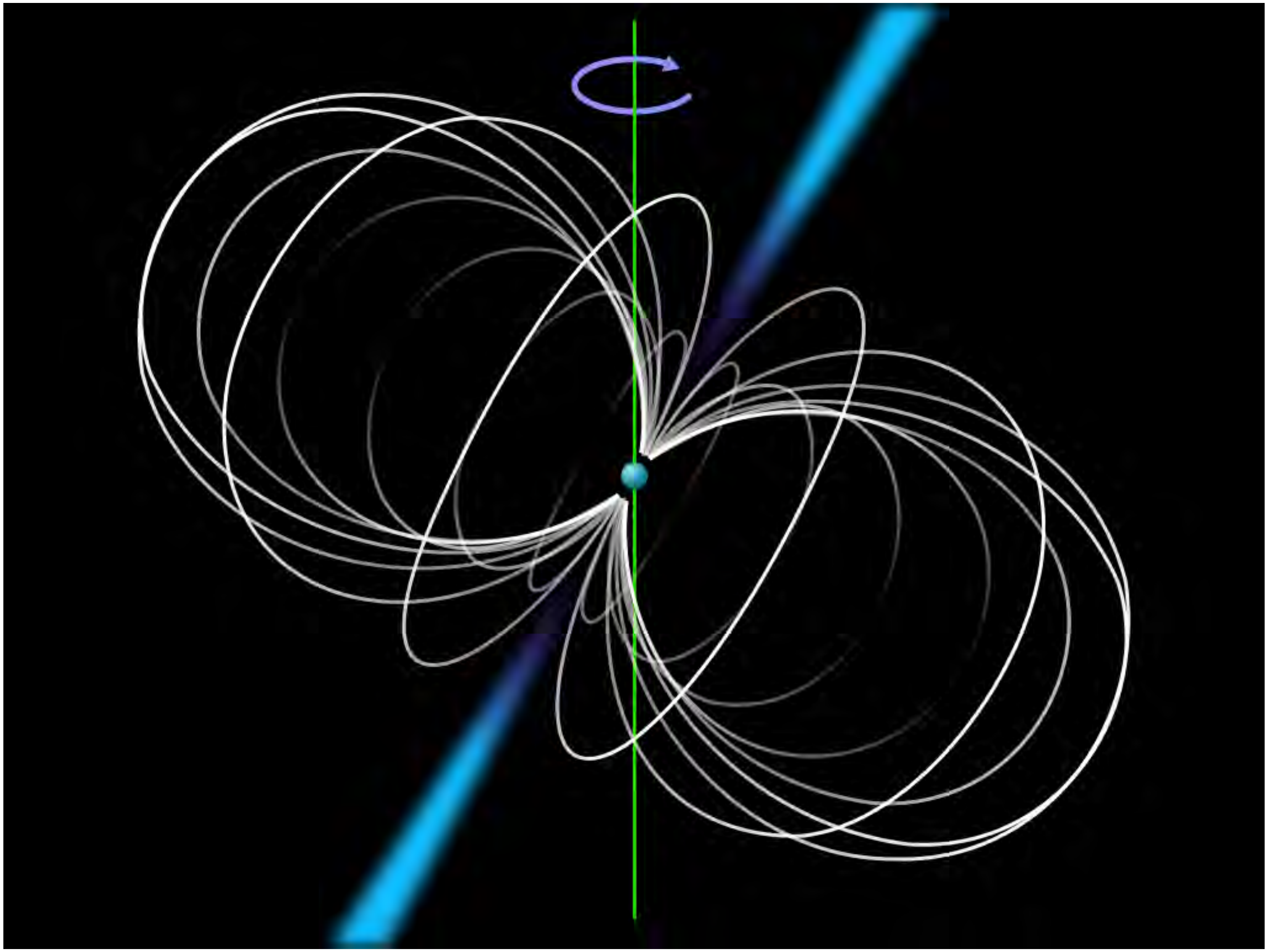
Drift Scan

Another way to visualize the situation is the “planetarium” plot, shown to the right.

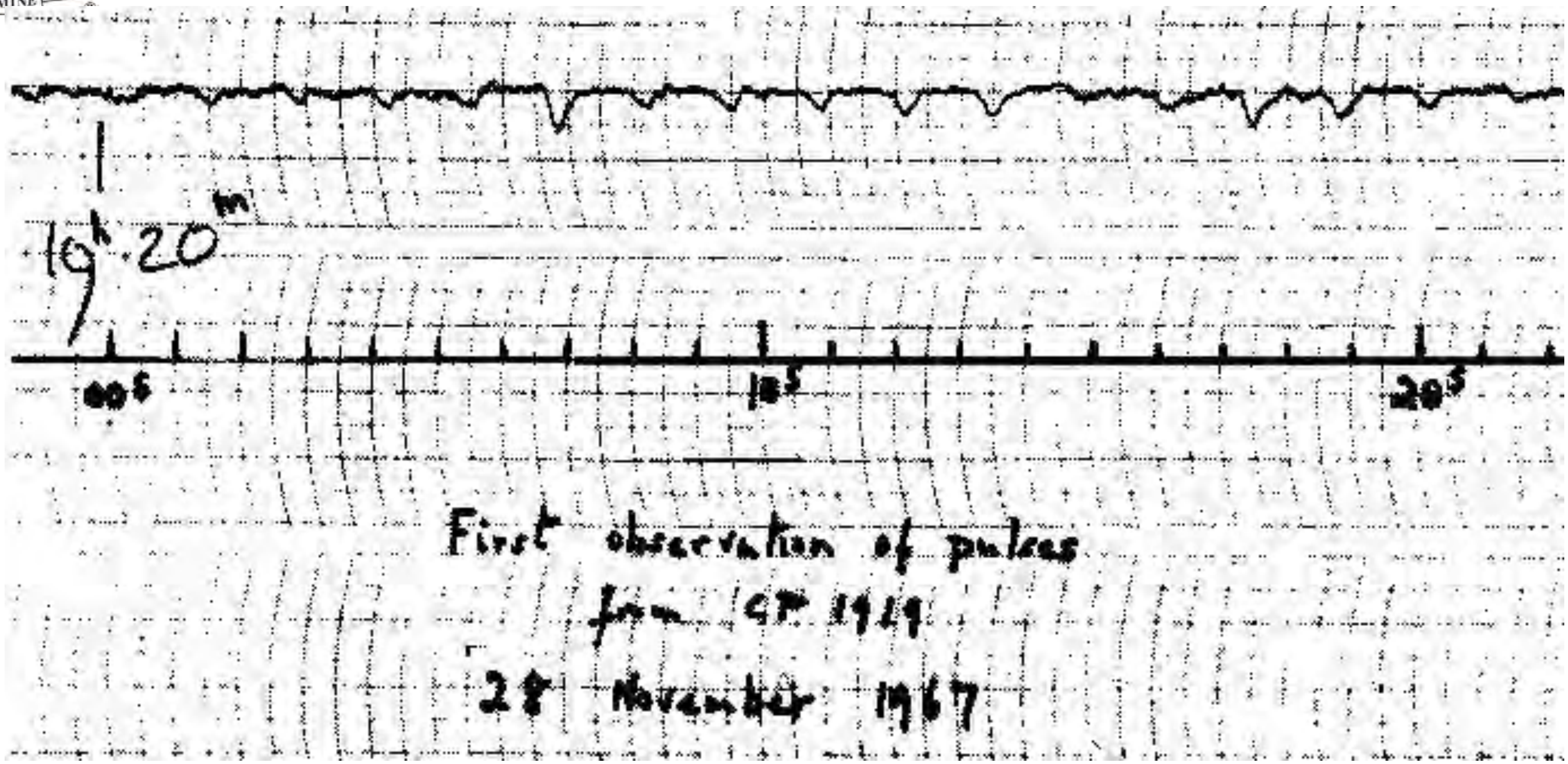


Pulsars Have Huge Magnetic Fields

The magnetic field lines that exist around most stars are compressed into the tiny volume of the neutron star, resulting in magnetic fields in the 10^{14} to 10^{15} gauss range. The magnetic field on Earth is about 1 gauss.



Pulsar Discovery



The ”fast” chart recorder trace above is from a confirming observation.

Signal Averaging

- The noise is reduced by $1/\sqrt{N}$
- This can be a very powerful technique, but one eventually runs up against practical realities. Consider the case where a single measurement requires one second.

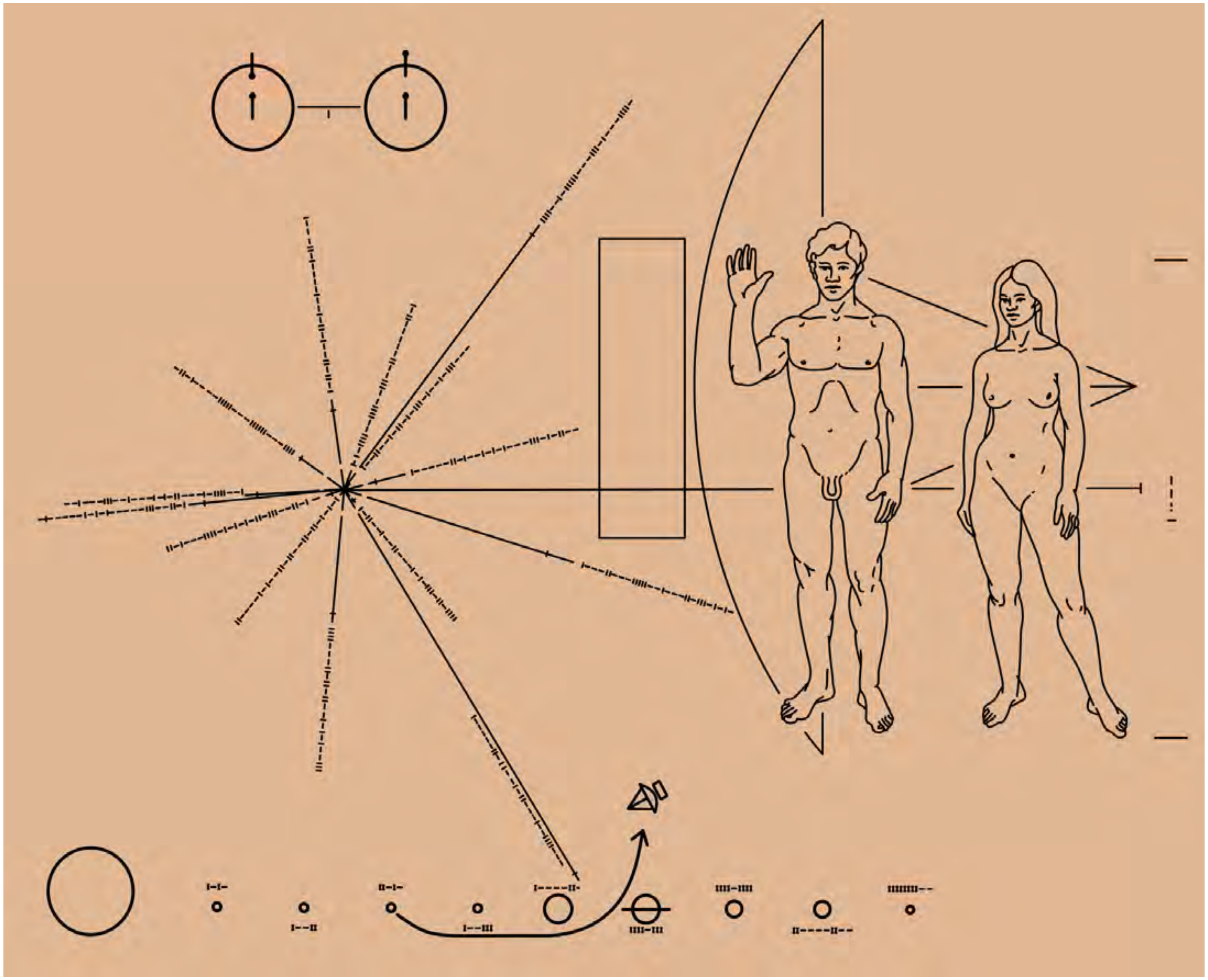
Improvement	N	T	While Waiting
10	100	1.6 min	Get a coffee
100	10^4	3 hrs	Complete a lab
1,000	10^6	12 days	Learn Python
10,000	10^8	3 years	Ph.D. Thesis
100,000	10^{10}	320 years	Succumb to global warming

The 21 cm Line

The Pioneer Plaque

The 21-cm line is such a fundamental entity that Carl Sagan and Frank Drake proposed mounting a plaque on the Pioneer deep space probe.

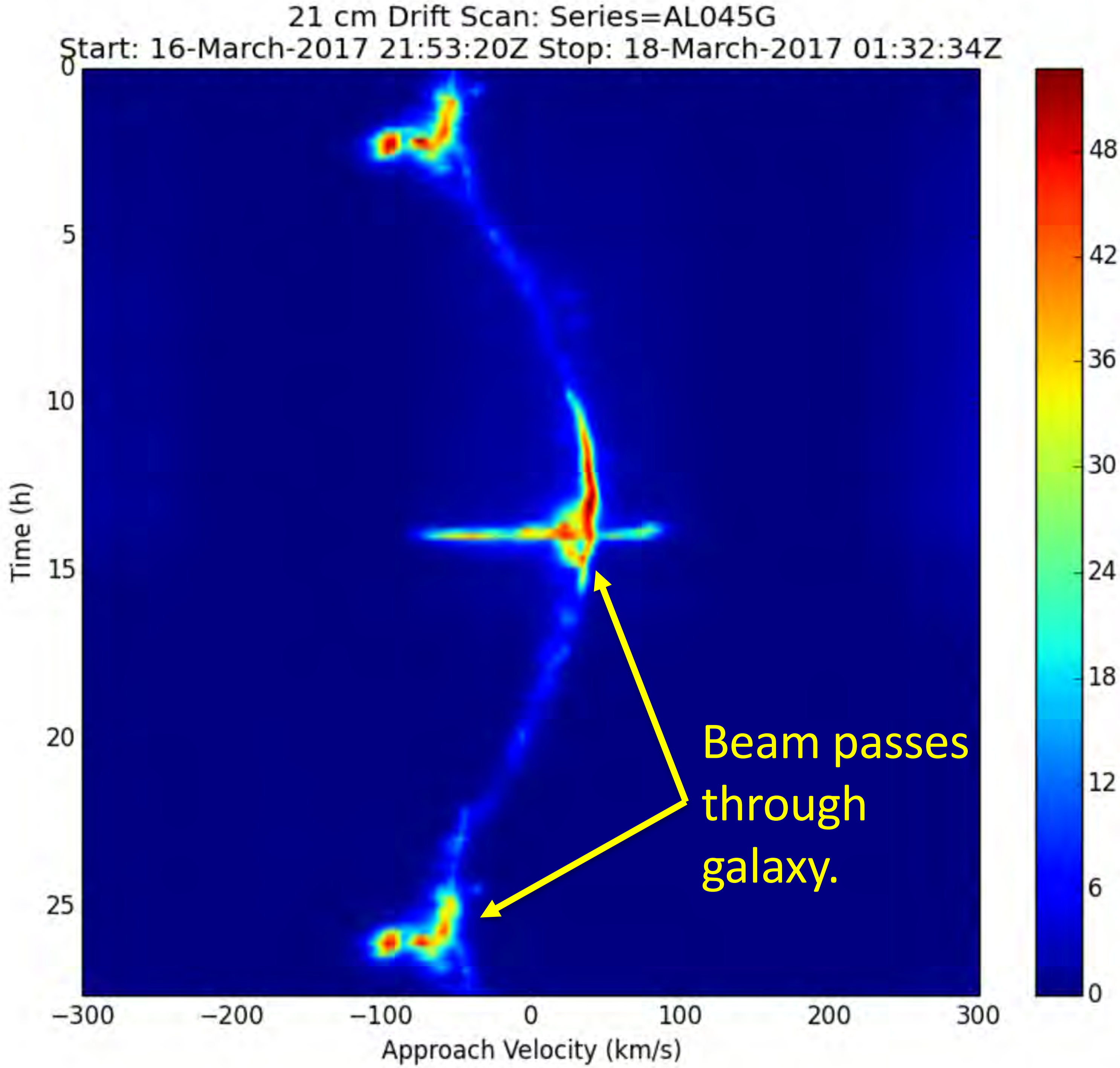
There, the 21 cm line sets the scale for the drawing of the humans engraved on the plaque.



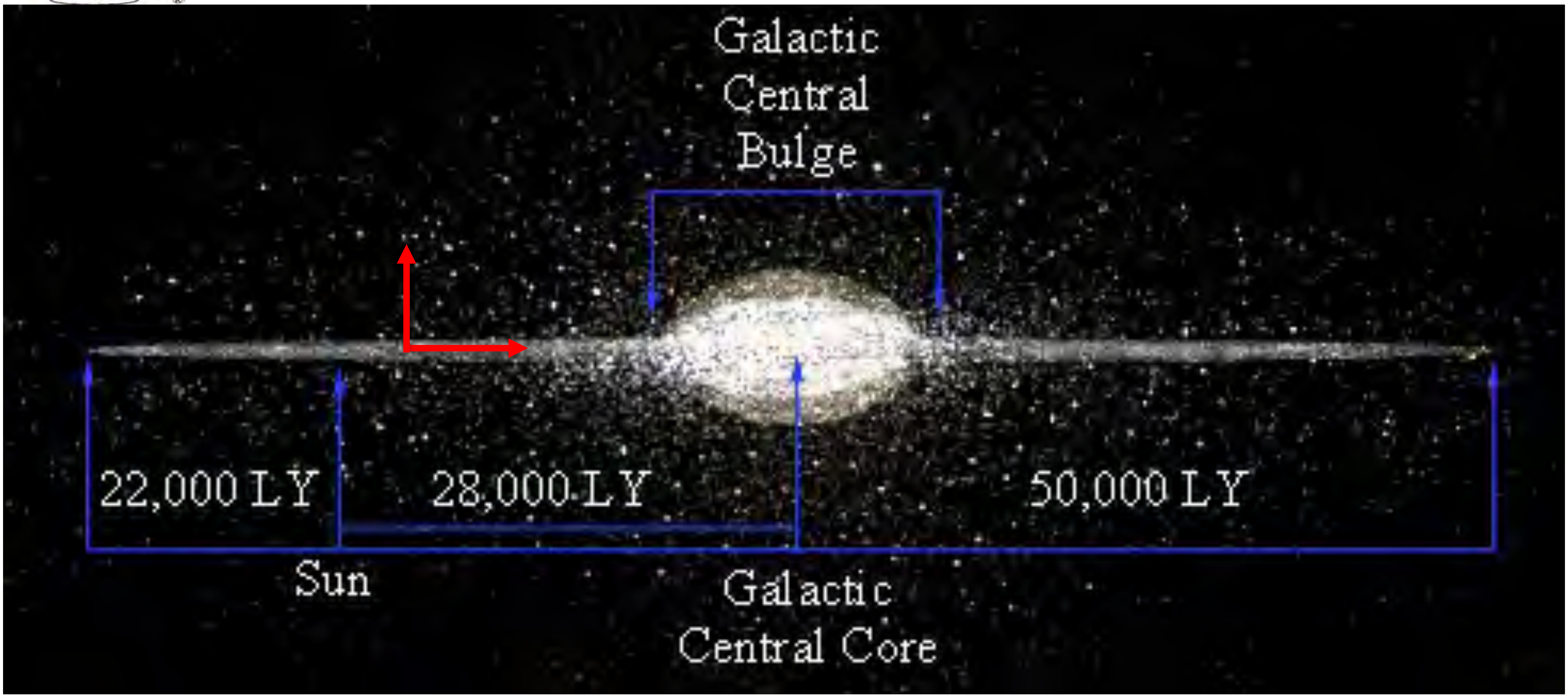
Drift Scan

- Point dish south at fixed altitude.
- Run data acquisition for ~24 hours, writing a spectrum every N minutes.
  - In most cases, N=10 minutes
  - A special run was taken with N=2 minutes so as to track the spectral evolution in finer detail.
  - (see animation)

Heat Map


21 cm Drift Scan: Series=AL045G
Start: 16-March-2017 21:53:20Z Stop: 18-March-2017 01:32:34Z
Time (h)
0
5
10
15
20
25
−300
−200
−100
0
100
200
300
Approach Velocity (km/s)
48
42
36
30
24
18
12
6
0
Beam passes through galaxy.

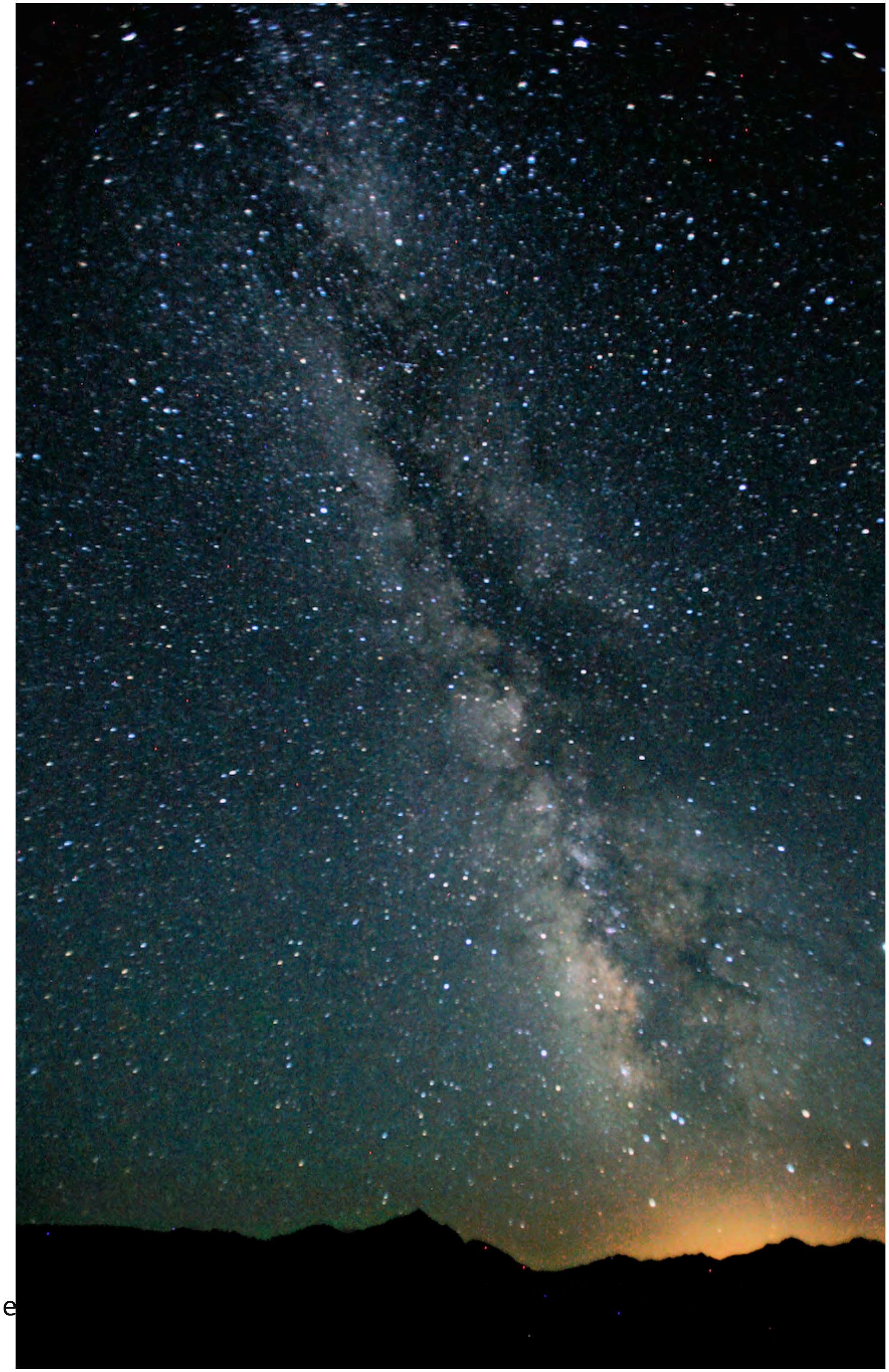
Drift Scan



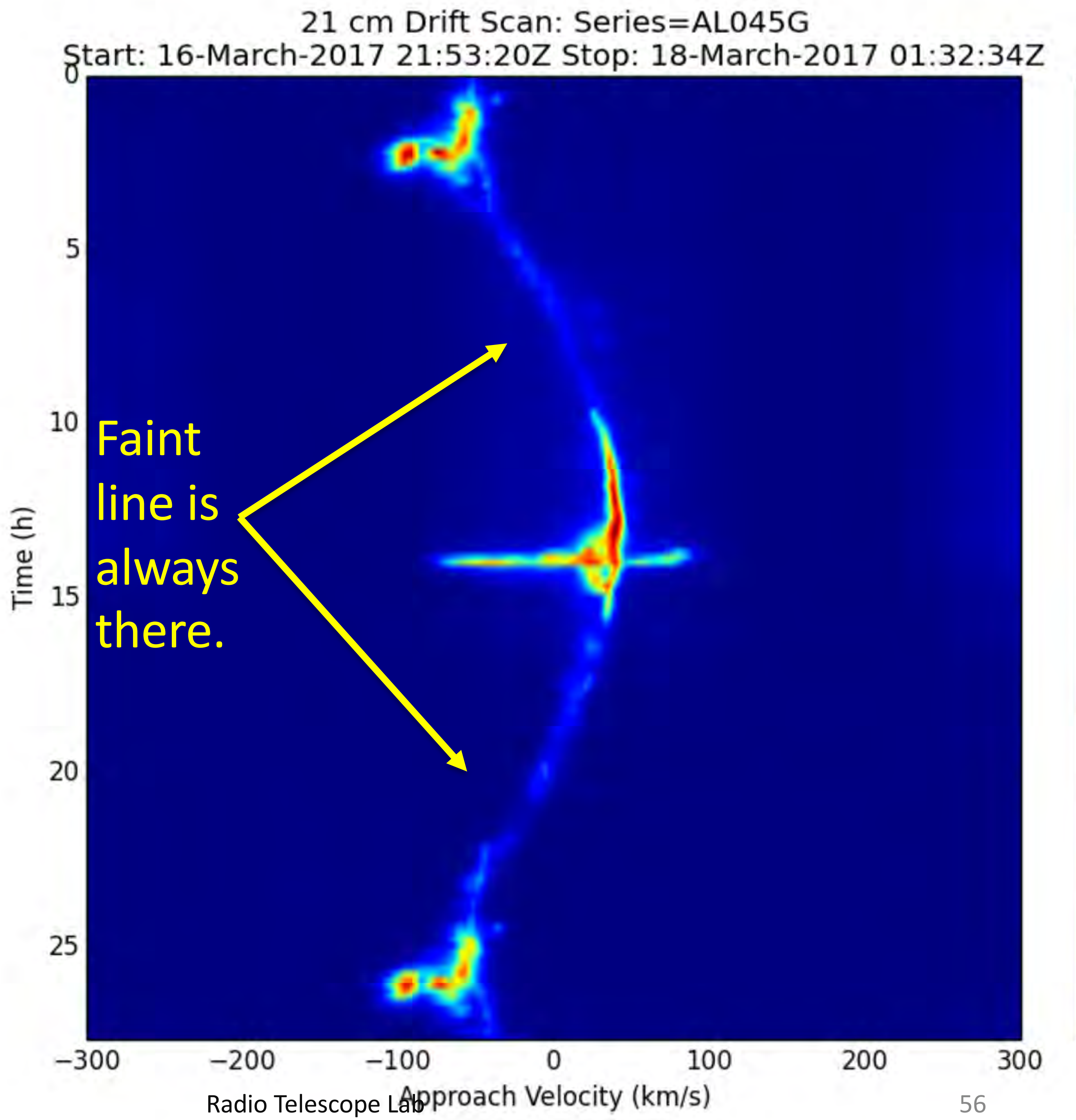
The hydrogen is concentrated in the galactic disk, so we see a much stronger signal when the beam points in that direction.

Drift Scan

To a terrestrial observer, the Milky Way appears as band of stars across the sky (surrounding the Earth).

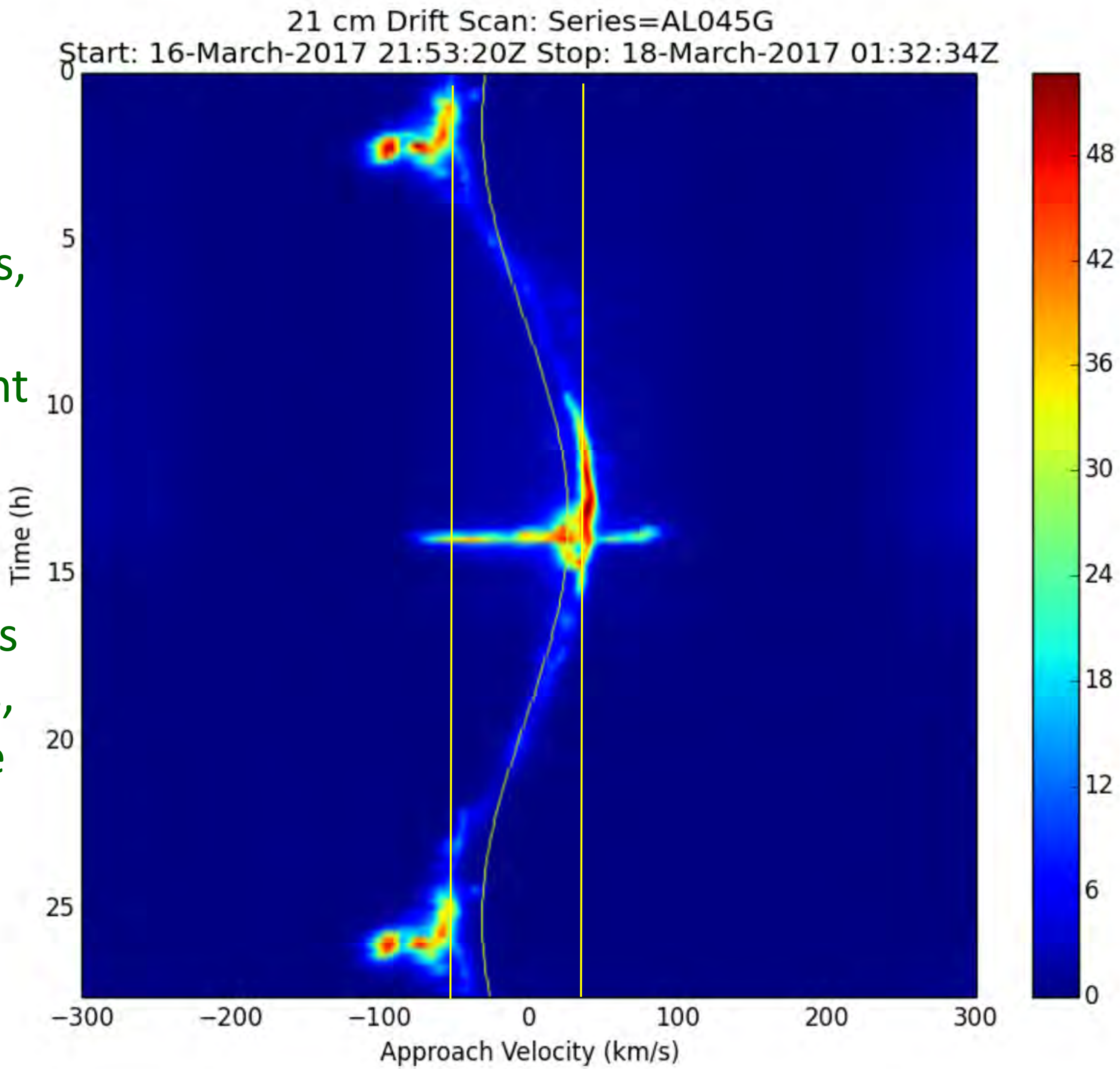


Even when the beam is pointed away from the galactic plane, there is a weak signal, which meanders through the plot.

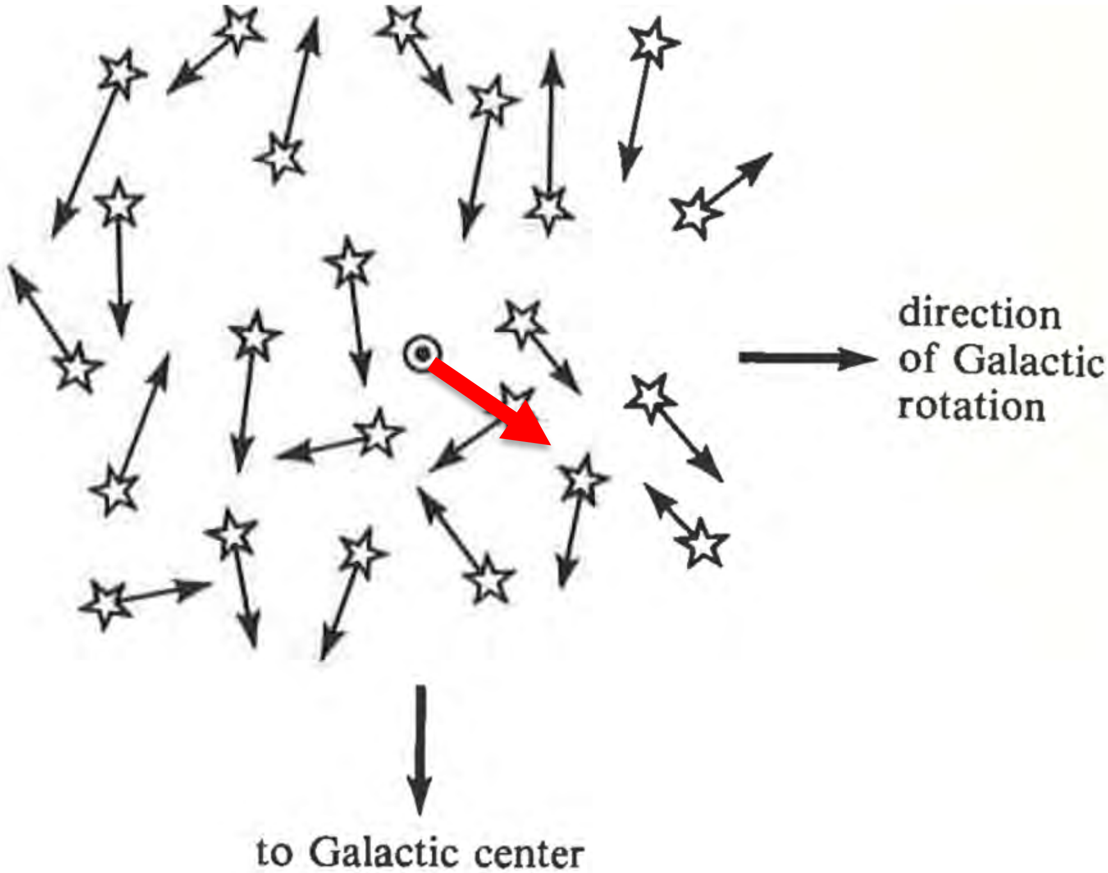


Correcting for the Sun's motion helps, but does not completely account for the data.

The amplitude is more like ±50 km/s than the ±30 km/s, expected from the Earth's motion around the Sun.



Peculiar Motion of the Sun

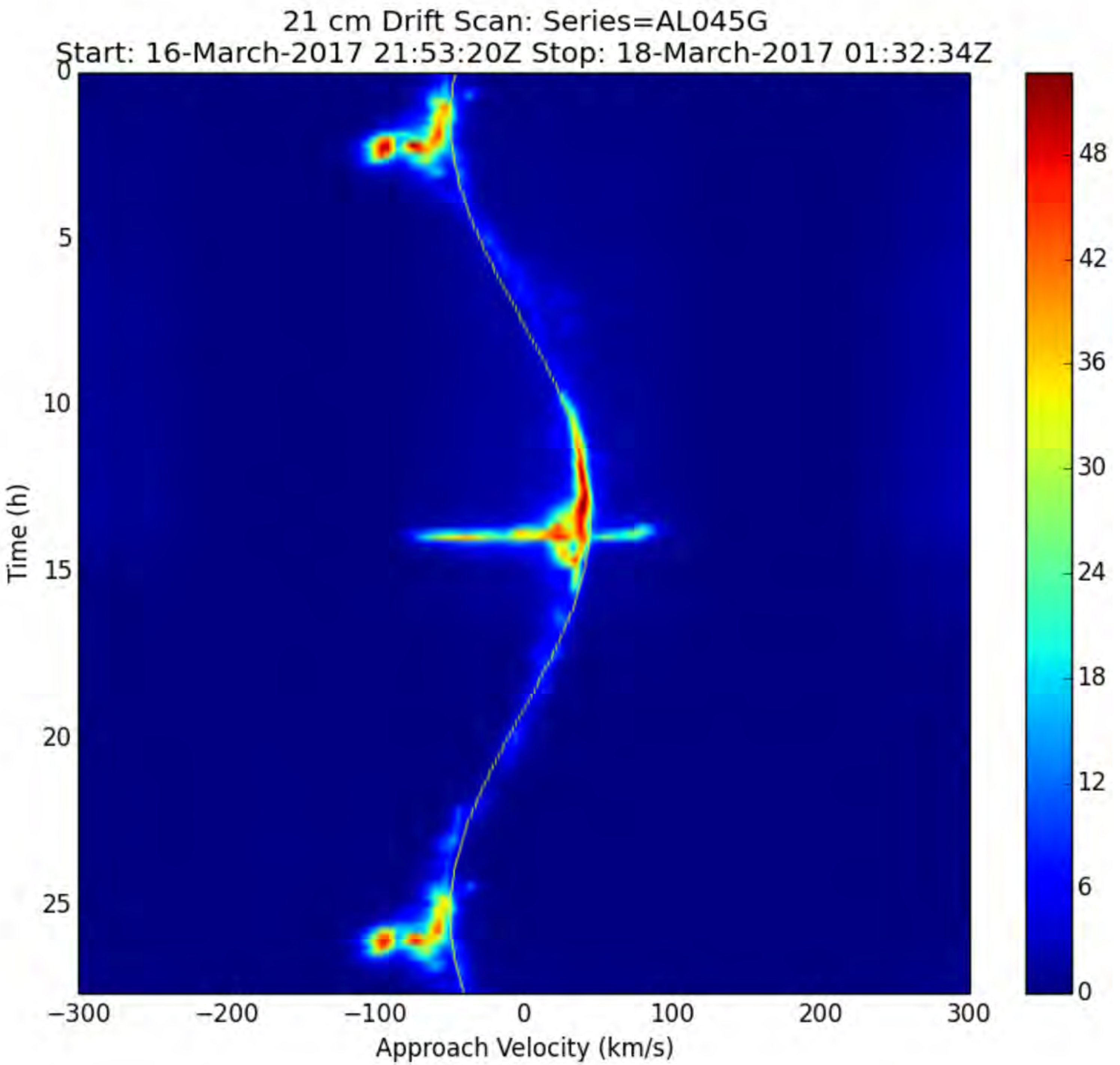


We also need to account for the Sun's ``peculiar motion" with respect to the Local Standard of Rest.

$$\vec{V}_\odot = (11.1 \pm 0.74, \quad 12.24 \pm 0.47, \quad 7.25 \pm 0.37) \ \mathrm{km/s}$$

(In Forward Up)

Adding the peculiar motion of the Sun to orbital motion of the Earth provides a good match.

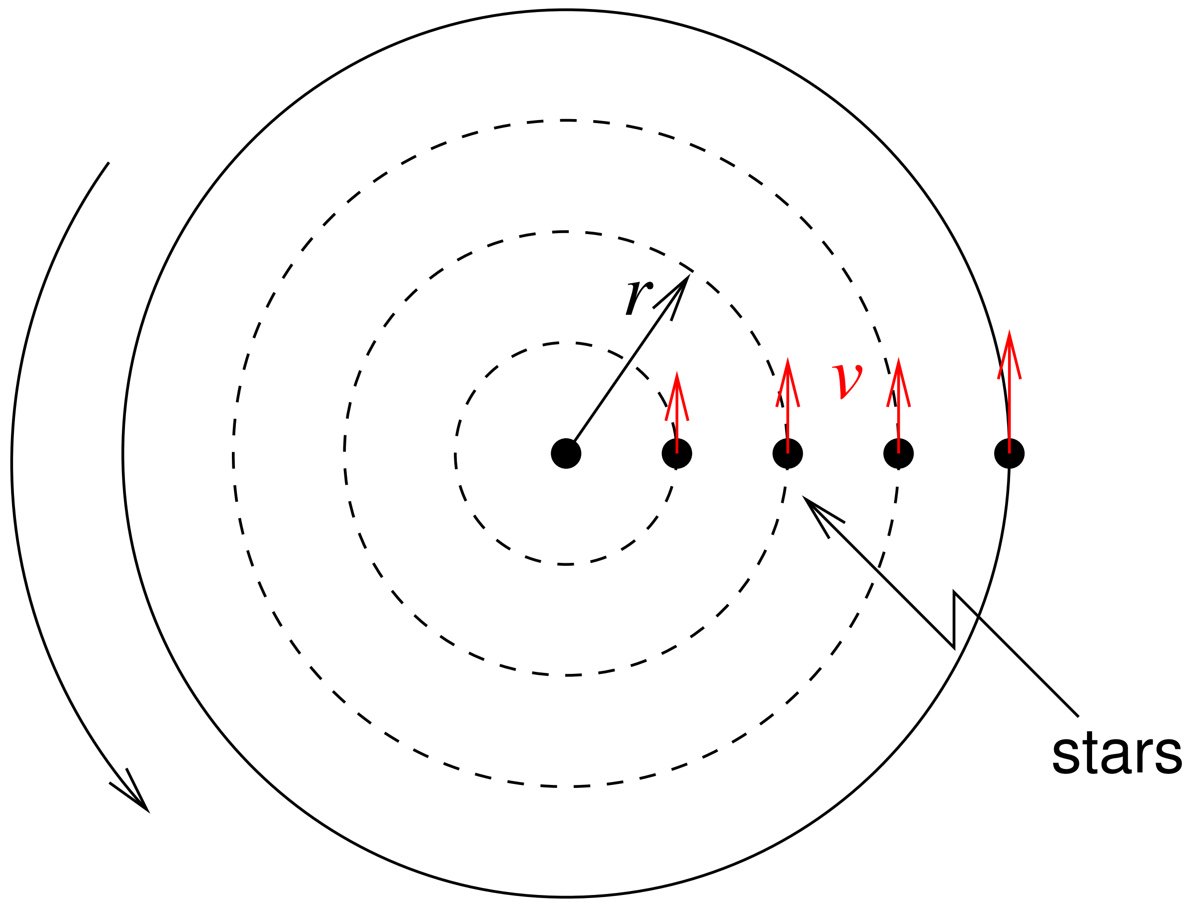


Galactic Rotation Curve

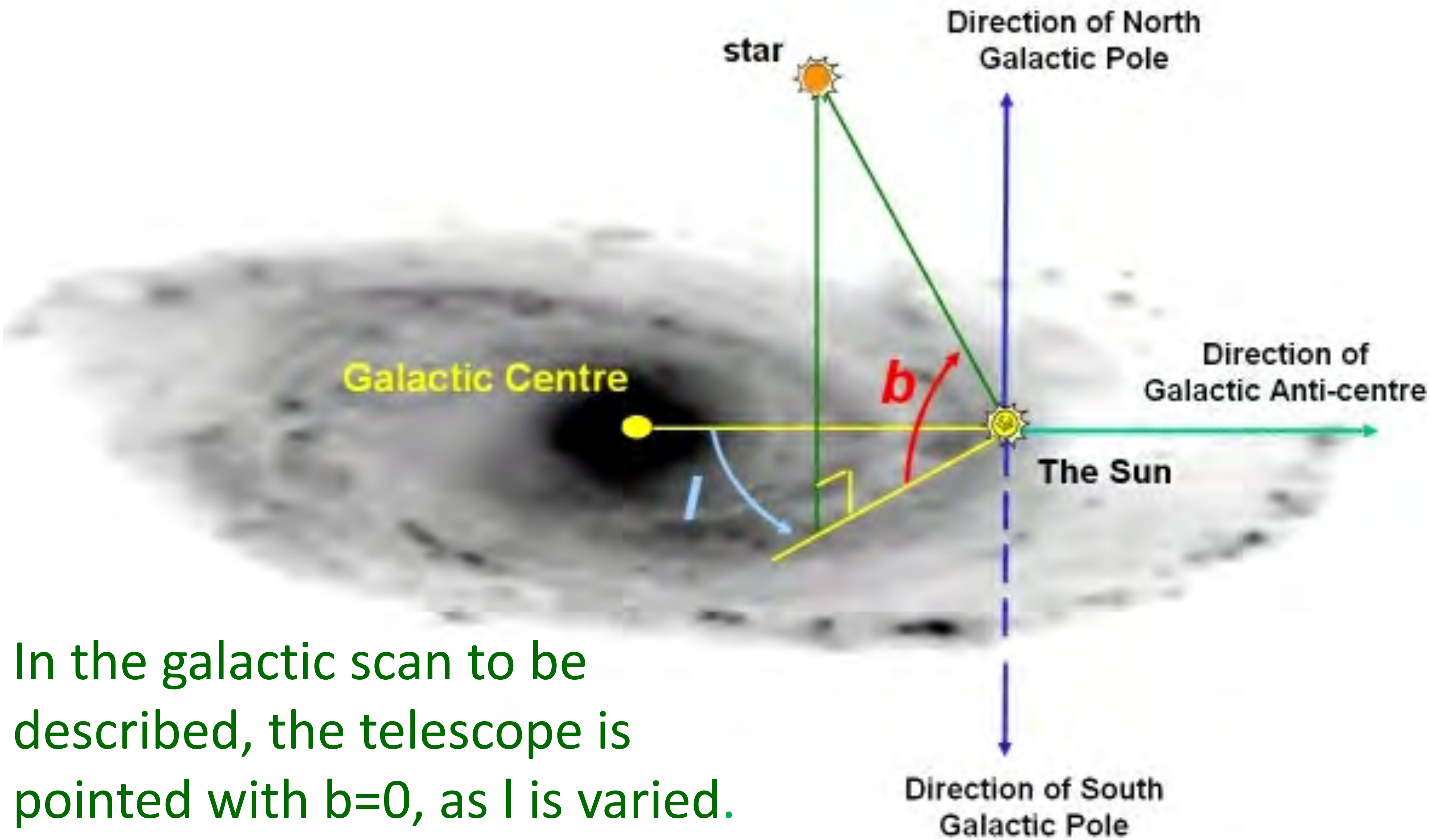
Galactic Rotation Curve

Galaxies are not rigid objects and exhibit *differential rotation.*

Measuring this rotation has provided key evidence for dark matter. In particular, we seek to measure v(r).

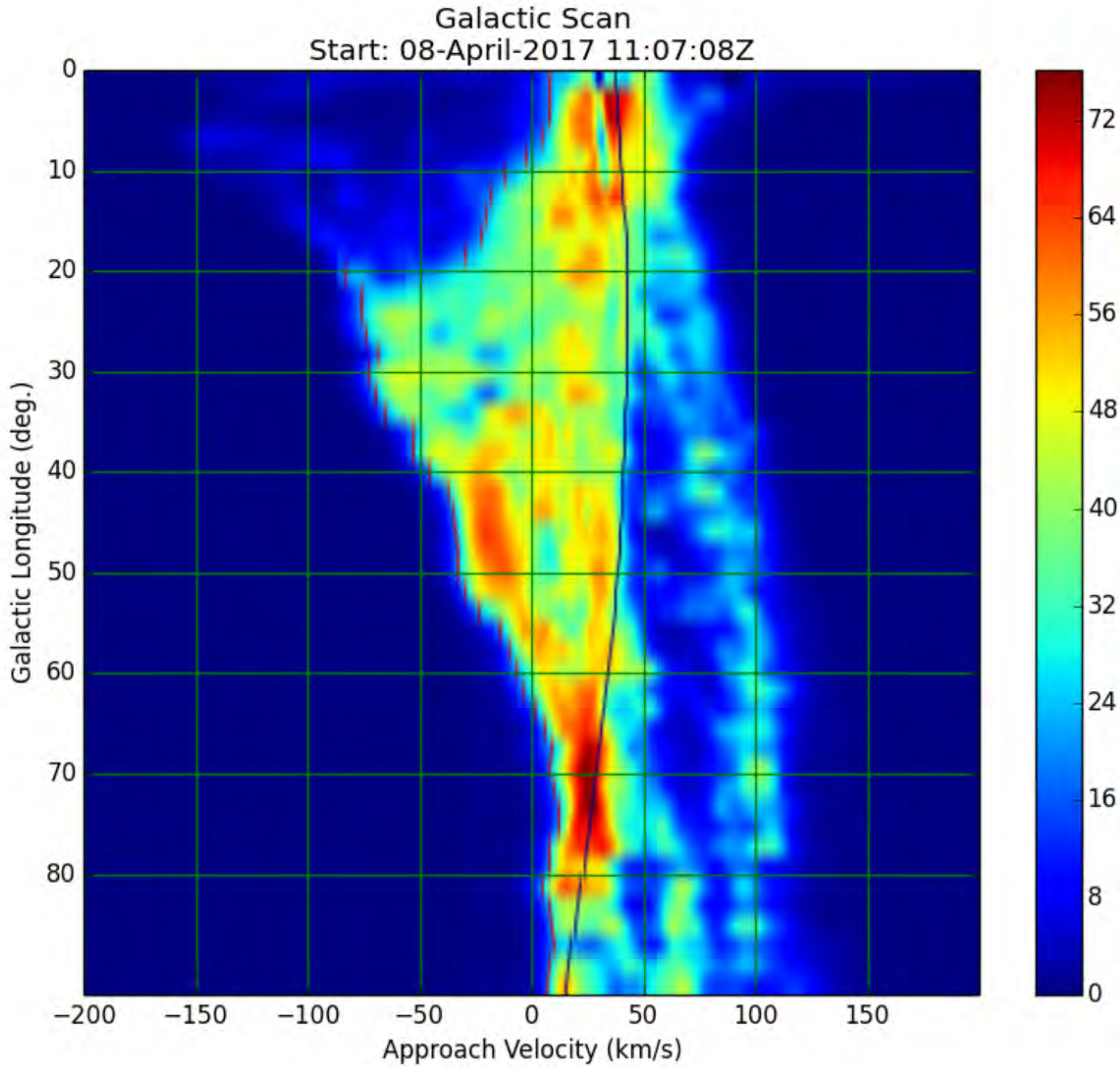


Galactic Coordinates



In the galactic scan to be described, the telescope is pointed with b=0, as l is varied.

Each row in the image is a Doppler spectrum, taken at the indicated galactic longitude.



Galactic Scan Analysis

The largest relative motion (recession) along the line of sight occurs for the case where the beam comes closest to the galactic center.

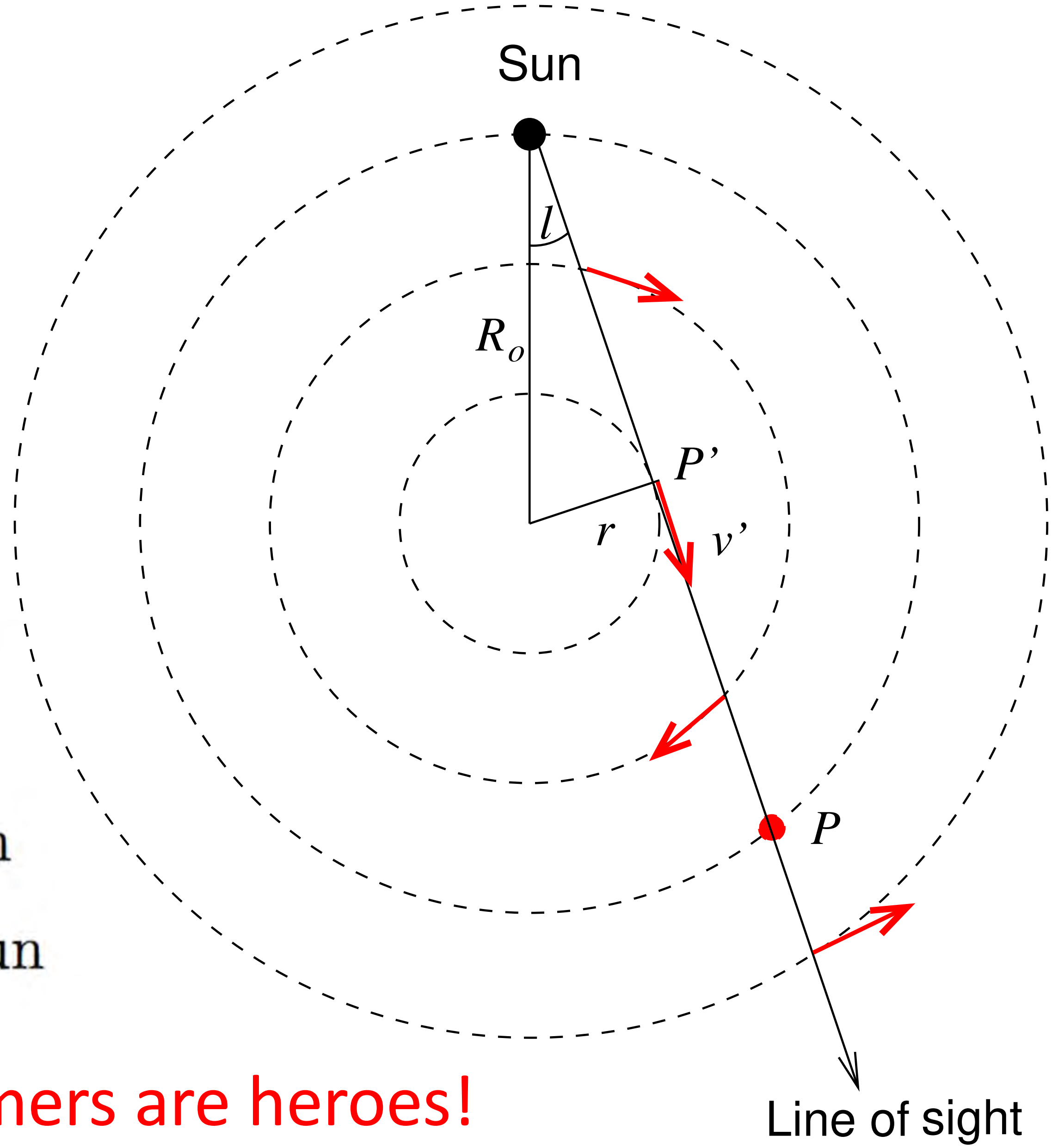
$$v(r) = v' + \Omega_0 R_0 \sin \ell$$

where

$$R_0 = \text{orbital radius of Sun}$$

$$\Omega_0 = \text{angular velocity of Sun}$$

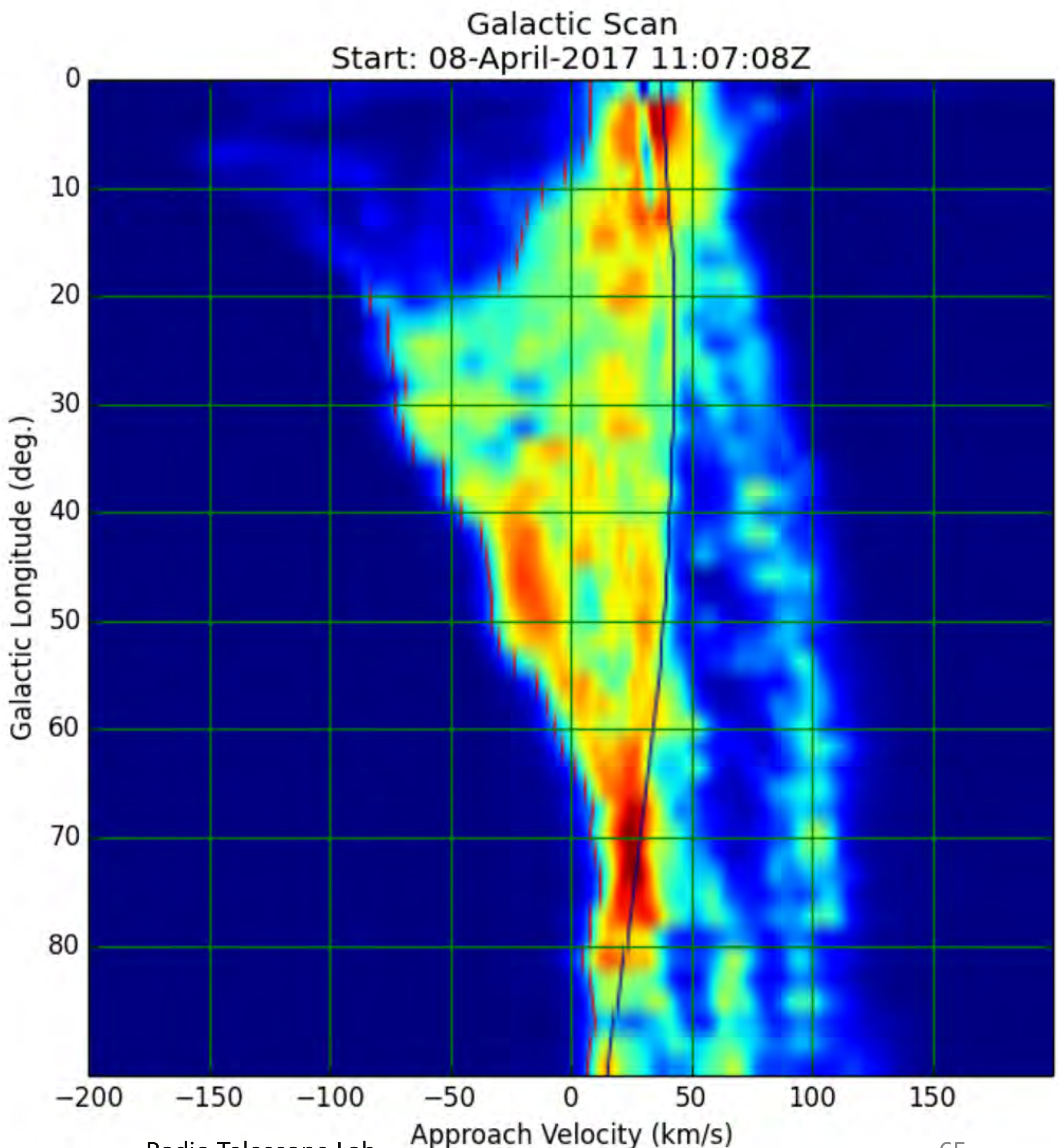
Known because astronomers are heroes!



Galactic Scan

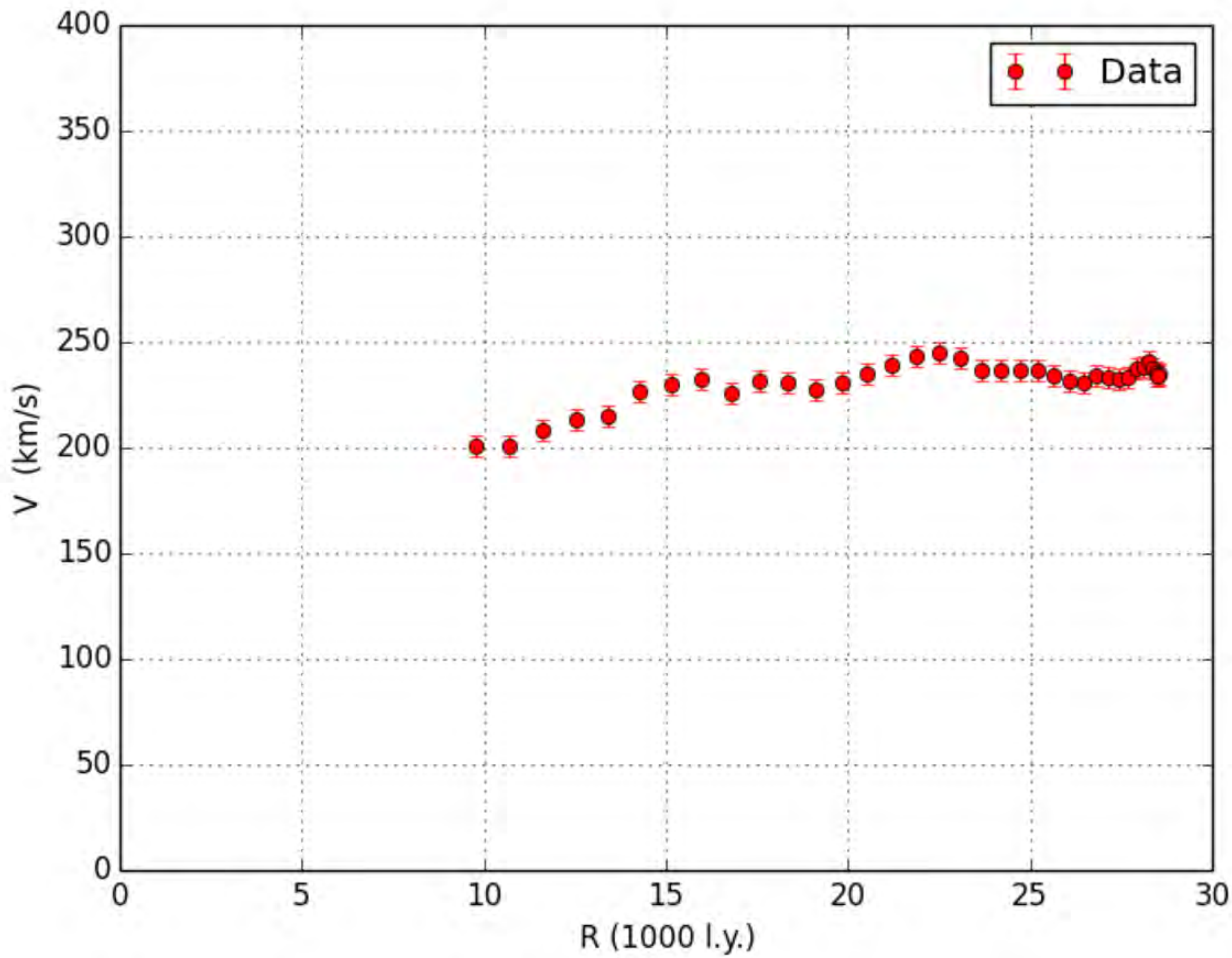
The velocity we are interested in is the difference between the left edge of the spectrum and the line corresponding to the Earth's motion. We plot this as a function of

$$r = R_0 \sin \ell$$



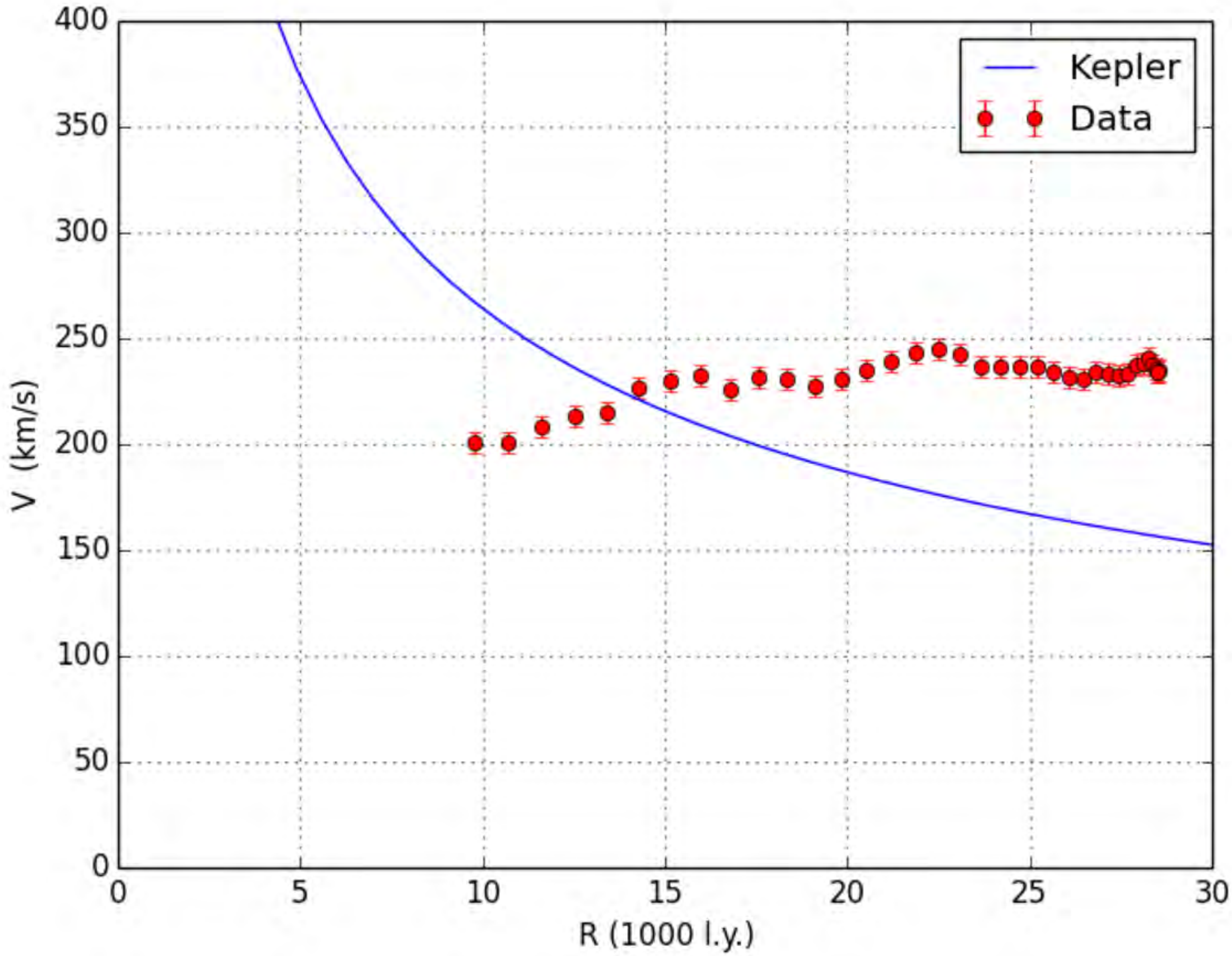
Galactic Rotation Curve

At first glance, this is almost disappointingly bland.



Galactic Rotation Curve

The Kepler model fails badly, but this is not surprising.



Galactic Rotation Curve

- A better model for the galaxy is the "Exponential Disk."
- This model is based on observations of other galaxies, where the brightness is seen to fall off as

$$I(r) = I_0 e^{-R/R_D}$$

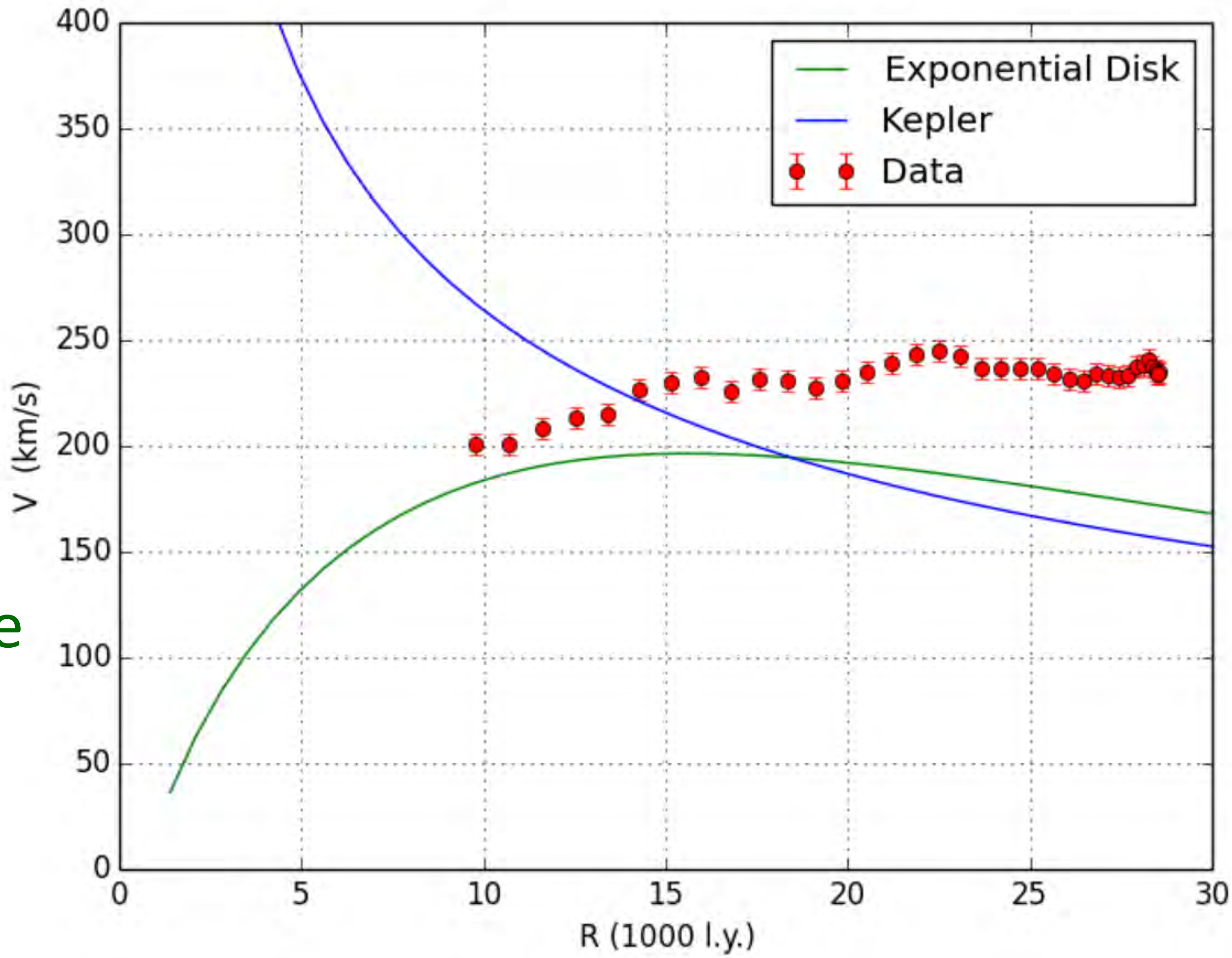
- We then assume that the surface mass density scales accordingly—i.e.,

$$\mu(r) = \mu_0 e^{-R/R_D}$$

- Here R_D=7000 light-years.

Galactic Rotation Curve

The Exponential Disk does much better, but still falls short of the data. Also, the predicted fall-off with r does not appear.



Galactic Rotation Curve

- Dark matter is thought to be a spherical cloud forming a large "halo" around the galaxy.
- In the limit that this cloud is constant density, the Shell Theorem would predict a linearly rising rotation curve

$$
\begin{aligned}
F &= \frac{mv^2}{r} \\
\frac{GmM_{\rm enc}}{r^2} &= \frac{mv^2}{r} \\
\frac{Gm\left(r/R_0\right)^3 M}{r^2} &= \frac{mv^2}{r} \\
v &= \sqrt{\frac{GM}{R_0^3}r}
\end{aligned}
$$

Galactic Rotation Curve

- Such a cloud is unrealistic, since among other things, it would imply infinite mass.
- We employ a modified model, called the Isothermal Sphere

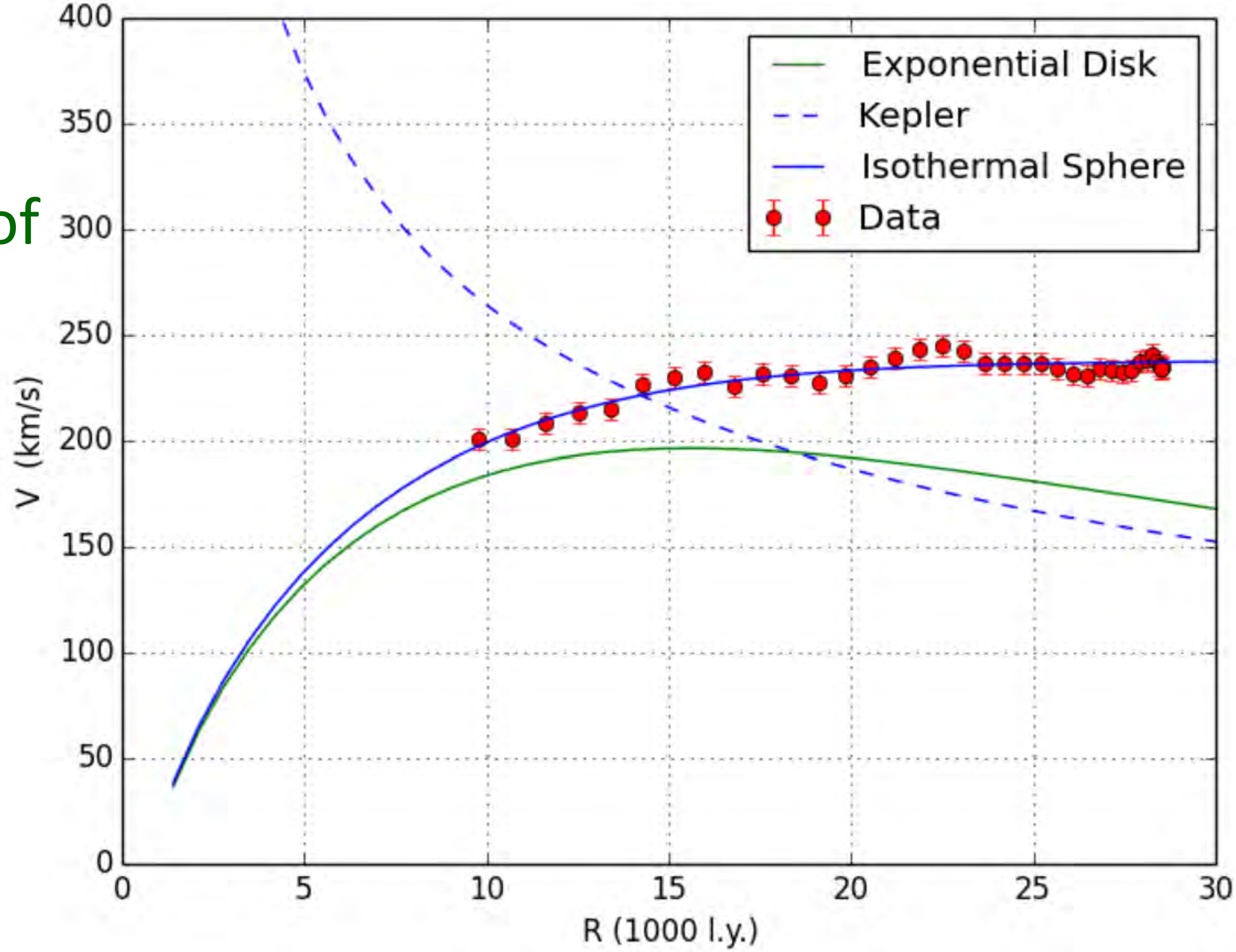
$$\rho(r) = \rho_0 \frac{R_0^2 + a^2}{r^2 + a^2}$$

$$v^2(r) = \frac{GM_<(r)}{r} = 4\pi\rho_0 G\left(R_0^2 + a^2\right)\left[1 - \frac{a}{r}\tan^{-1}\frac{r}{a}\right]$$

- Here ρ_0 and *a* are parameters.
- We combine this mass distribution with the Exponential Disk distribution.

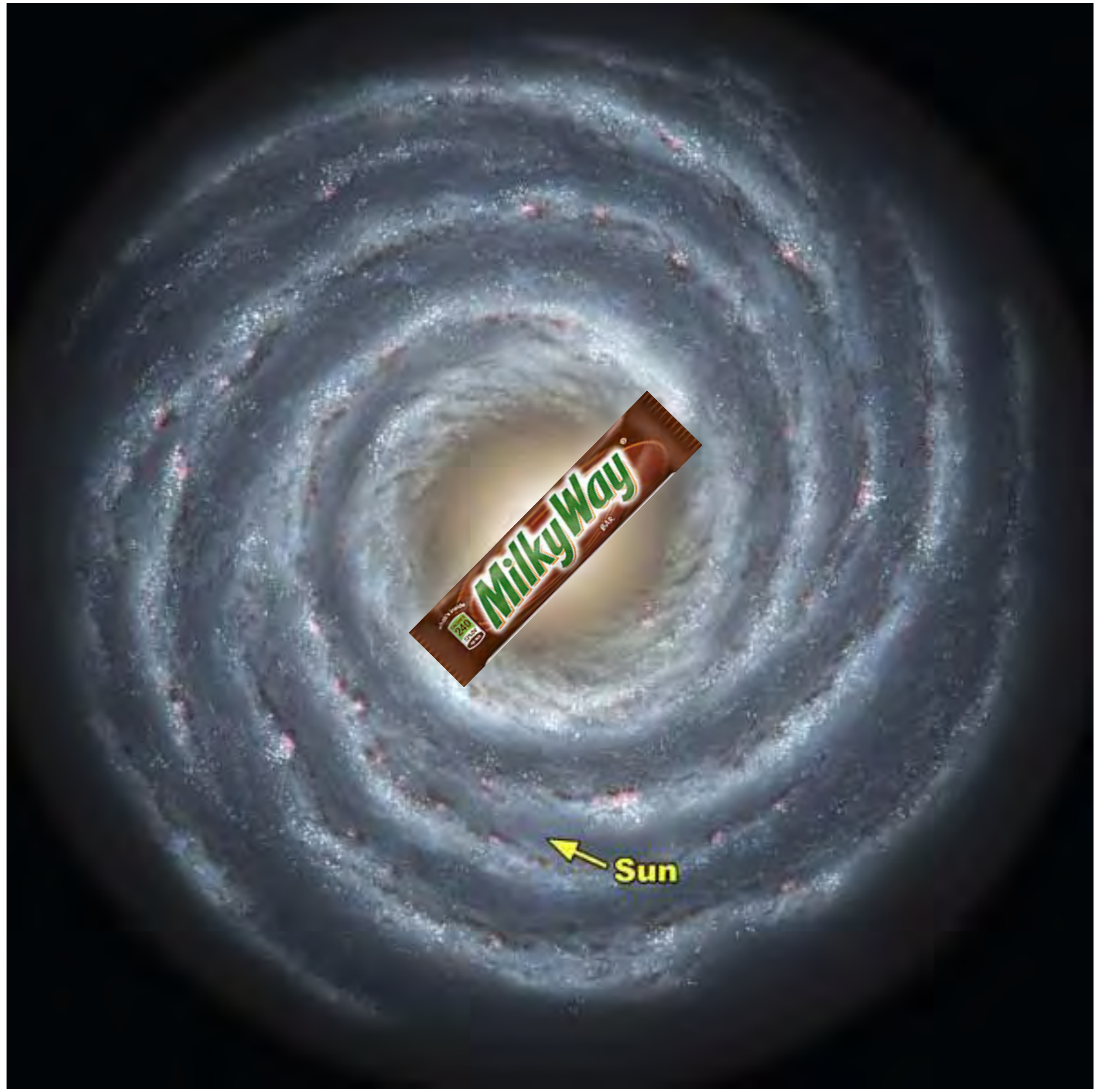
Galactic Rotation Curve

A good description of the data is obtained.



Caveats

The preceding analysis assumes that the galaxy is cylindrically symmetric. This is clearly not the case for the Milky Way, which is a "barred spiral galaxy."

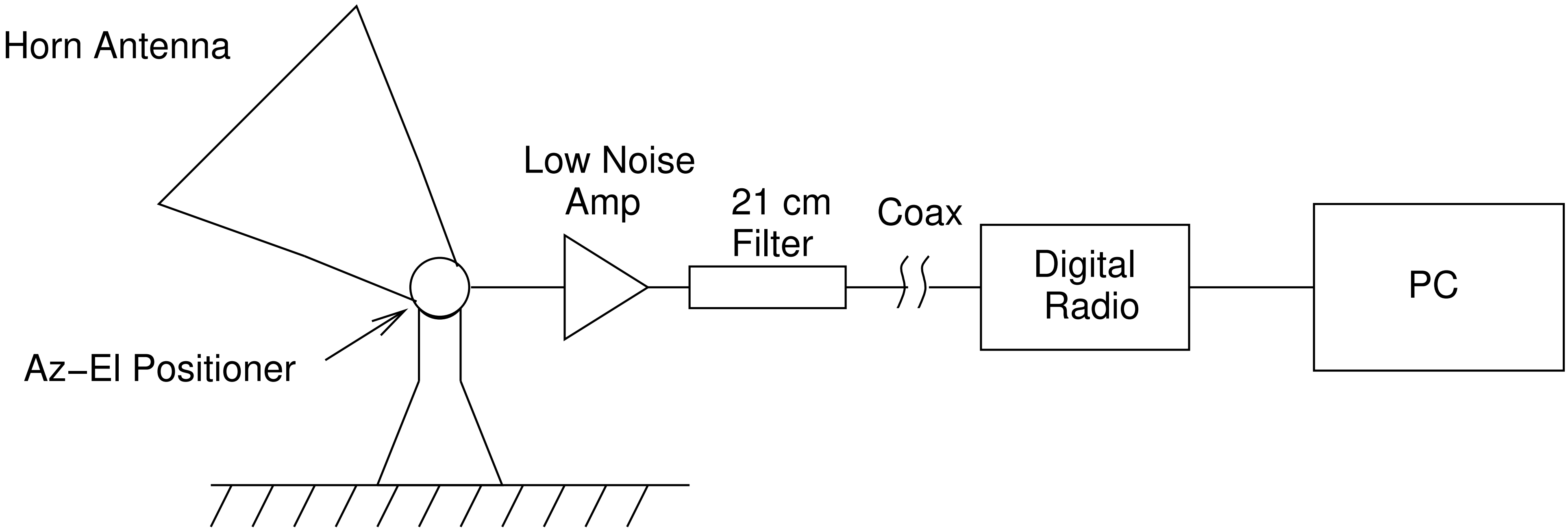


Caveats

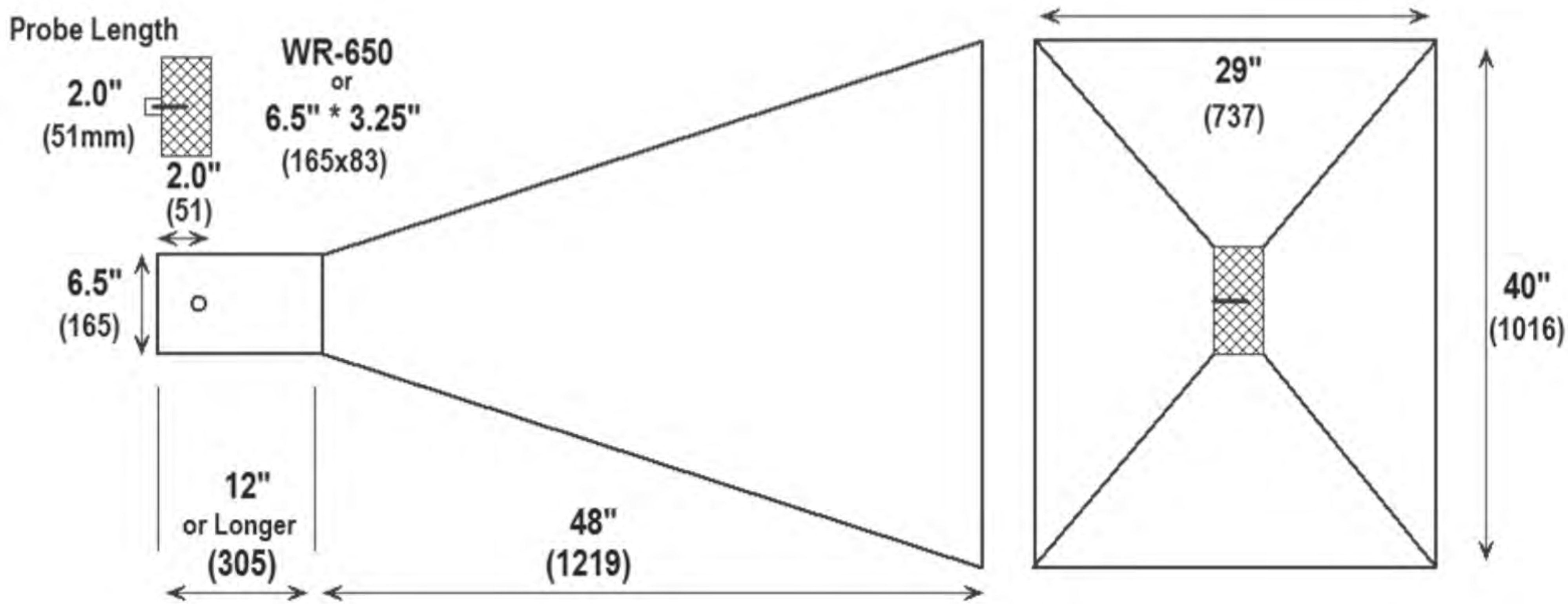
- The Isothermal Model also leads to infinite mass as $r \rightarrow \infty$
- The Isothermal Model does not provide a good description of the rotation curve for small r.

Do-It-Yourself Dark Matter

DIY Dark Matter



DIY Dark Matter: Horn Antenna



From ``Low Cost Horn Antennas for 23 cm EME,” by Thomas Henderson, WD5AGO

DIY Dark Matter: Horn Antenna

Foam siding insulation backed with aluminum film is an economical material for the horn.

DIY Dark Matter: Az-El Positioner

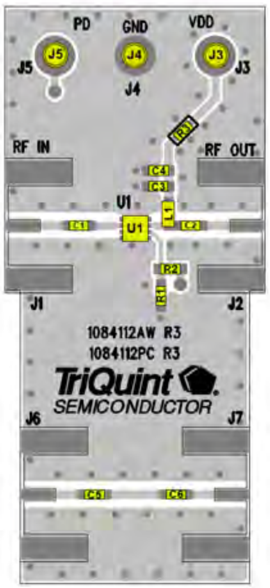
Autonomous Satellite Tracker, E. Downey QEX Nov/Dec 2015

Table 1
Bill of Materials

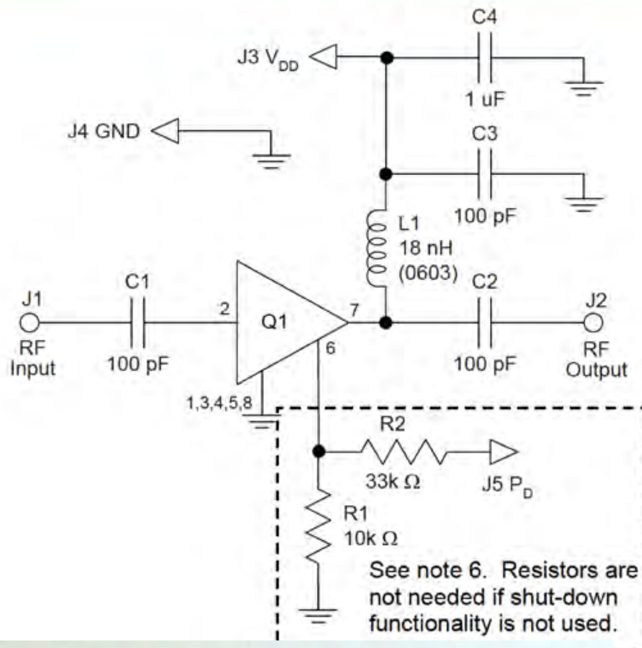
Item	*Approximate price*
Ardunio Mega 2560	$18
Wired Ethernet shield	$16
Wi-Fi router	$20
GPS module	$40
Servo controller	$15
Bosch 9 DOF sensor	$35
Pan platform	$100
Tilt stage	$95
	$339

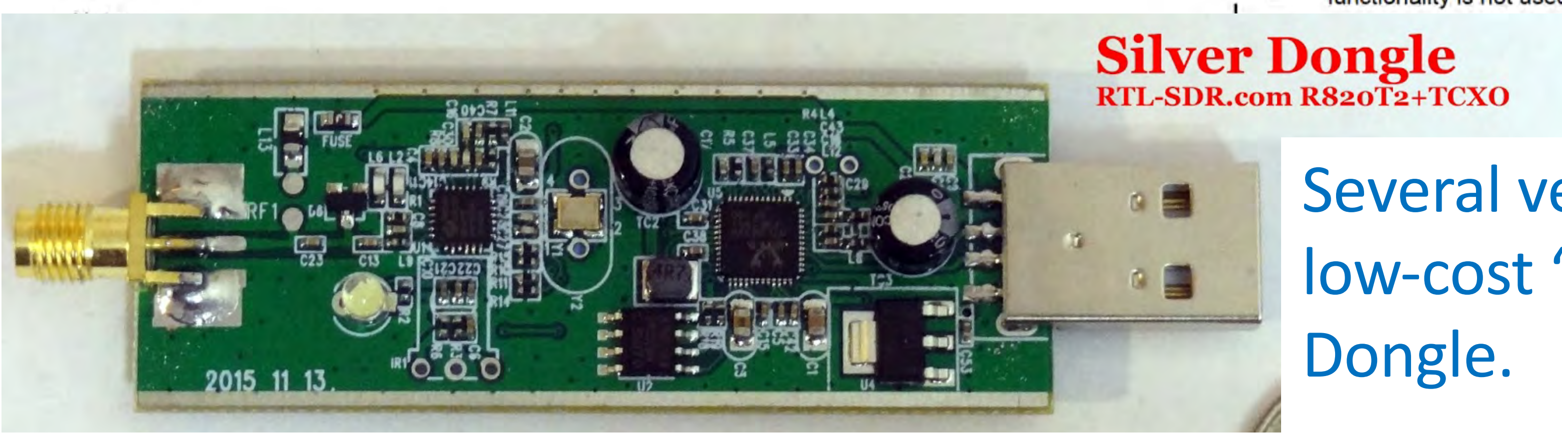
DIY Dark Matter: Readout Chain

TQP3M9037-PCB Evaluation Board



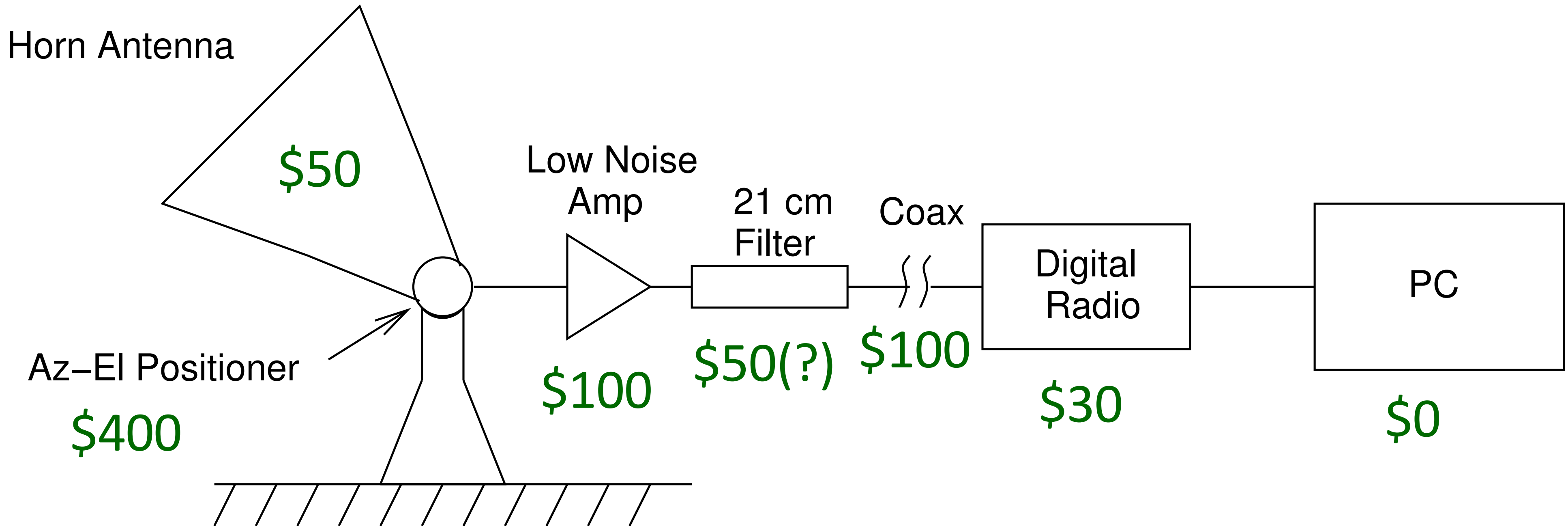
Low noise preamp





Several vendors sell a low-cost "RTL-SDR" USB Dongle.

DIY Dark Matter



Total amount $730 → $1000 with "contingency."