GALACTIC GEOMETRY AND THE ROTATION OF THE MILKY WAY

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Tuesday, December 7, 2021

8.13 Experimental Physics 1 – Fall 2021

Experimental Goals

- **Derive a Rotation Curve of the Milky Way**
- **Compare results with predictive models**
  - i.e. classical models vs. newer models
  - What do they reveal?

Theory of Gravitation and Rotation

- What we know: *centripetal forces*
  - Newton's law of gravitation ←→centripetal force:

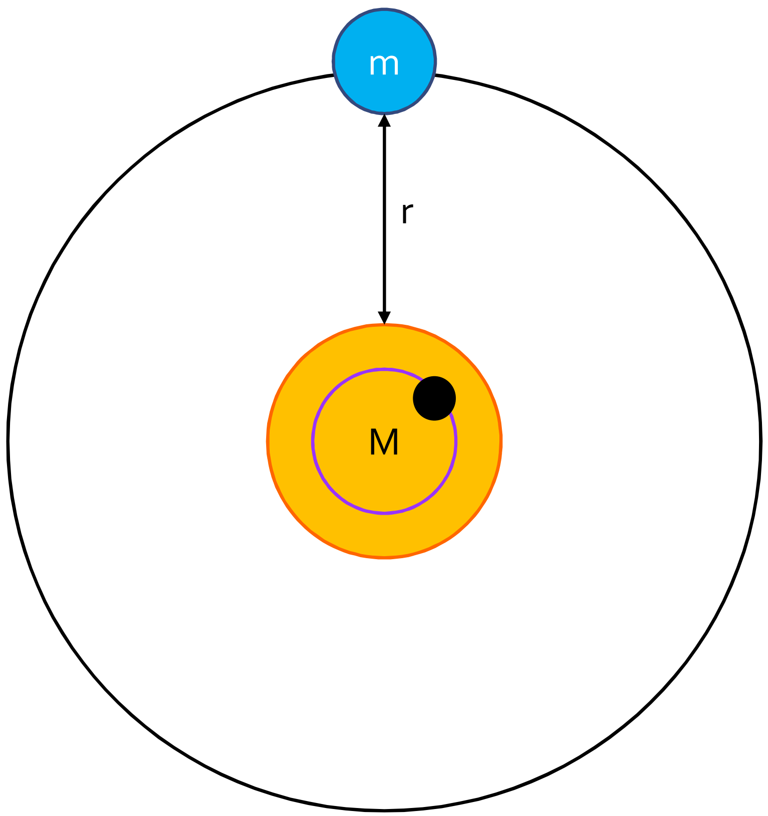
$$\frac{mv^2}{r} = \frac{GmM}{r^2} \Rightarrow v(r) = \sqrt{\frac{GM}{r}}$$

  - Hence, Keplerian prediction: $\boldsymbol{v(r) \sim \frac{1}{\sqrt{r}}}$

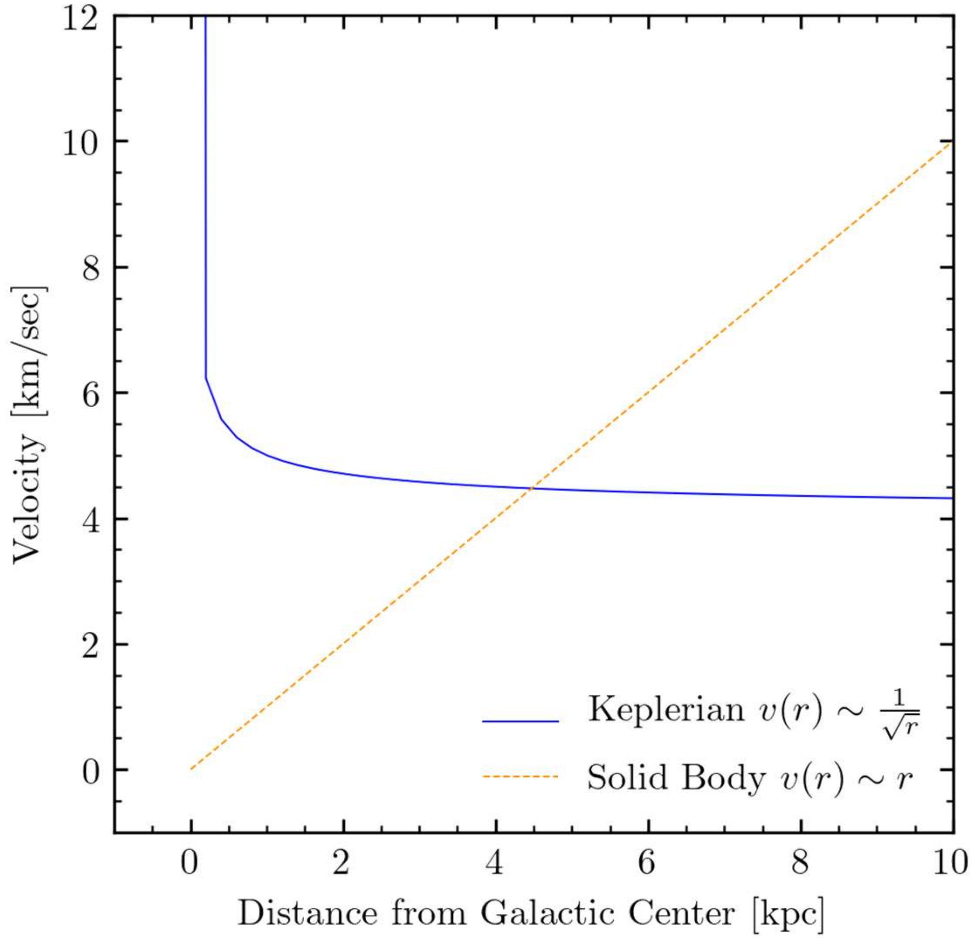
- What about *internal* to central object?

$$M(r) = \rho \frac{4}{3}\pi r^3 \Rightarrow v(r) = \sqrt{\frac{\rho G 4\pi r^2}{3}}$$

  - Hence, solid mass prediction: $\boldsymbol{v(r) \sim r}$



Theoretical Models of Rotation Curves



Keplerian:

$$\boldsymbol{v(r)\sim\frac{1}{\sqrt{r}}}$$

Solid Mass:

$$\boldsymbol{v(r)\sim r}$$

Computing Velocities – Geometry of the Galaxy

- **Radius:**

$$r = R_0 \sin \frac{l\pi}{180},$$

- **Doppler Shift:**

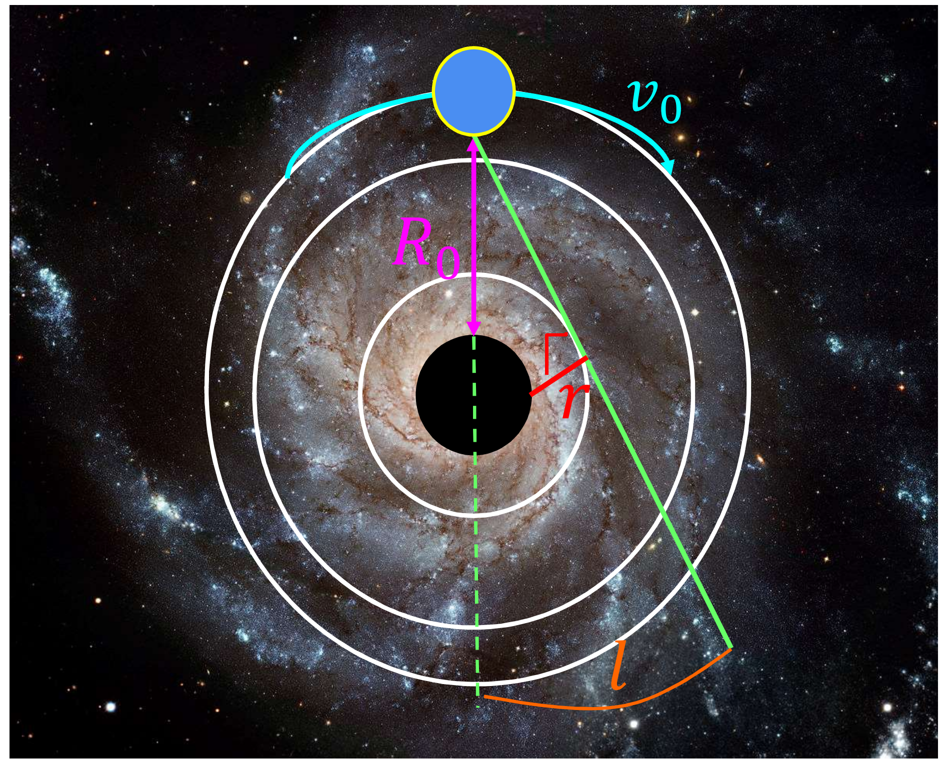
$$v_{shift} = c\,\frac{f_0 - f_{red}}{f_0}$$

- **Max radial velocity along line of sight:**

$$v_{max} = c\,\frac{f_0 - f_{red}}{f_0} - v_{lsr}$$

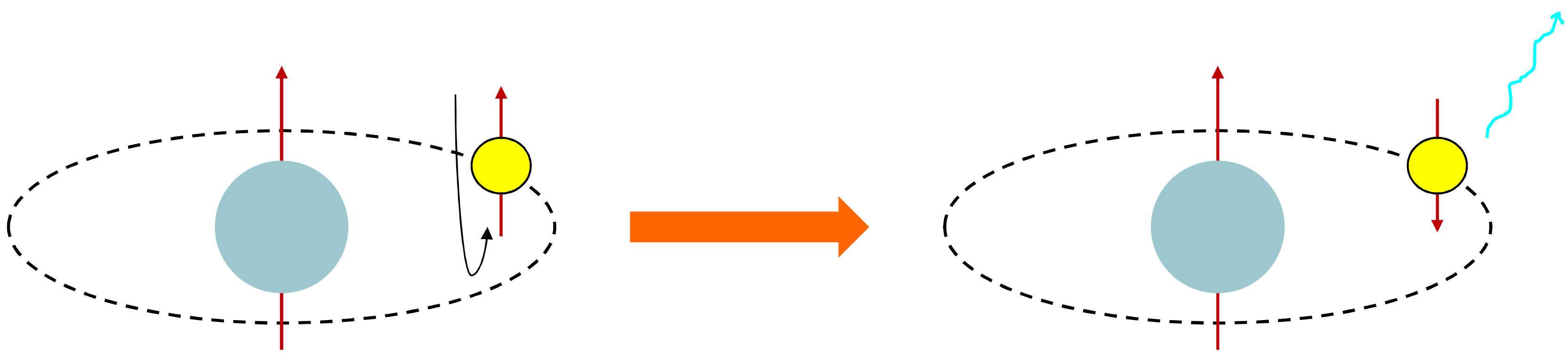
- **Galactic velocity:**

$$v(r) = v_{max} + v_0 \sin \frac{l\pi}{180}$$

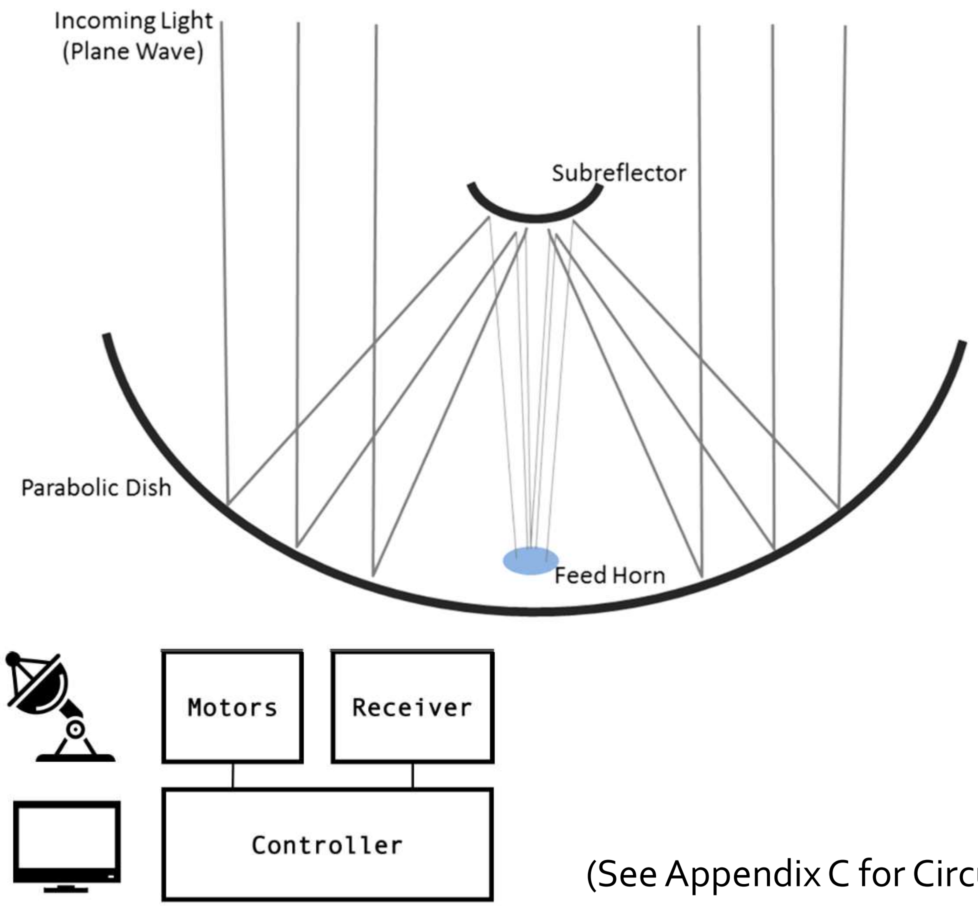


Theory of the 21cm Line of Hydrogen

- Optical light often suffers from absorption from stars and interstellar dust
  - Use instead the radio-wave range
- Quantum mechanics: discrete angular momentum → parallel & antiparallel states allowed
  - Electron transitions between two states of the 1s H atom configuration → spin flip
  - Energy $E = hf_0$, 21cm line frequency given by $f_0 = 1420.4$ MHz

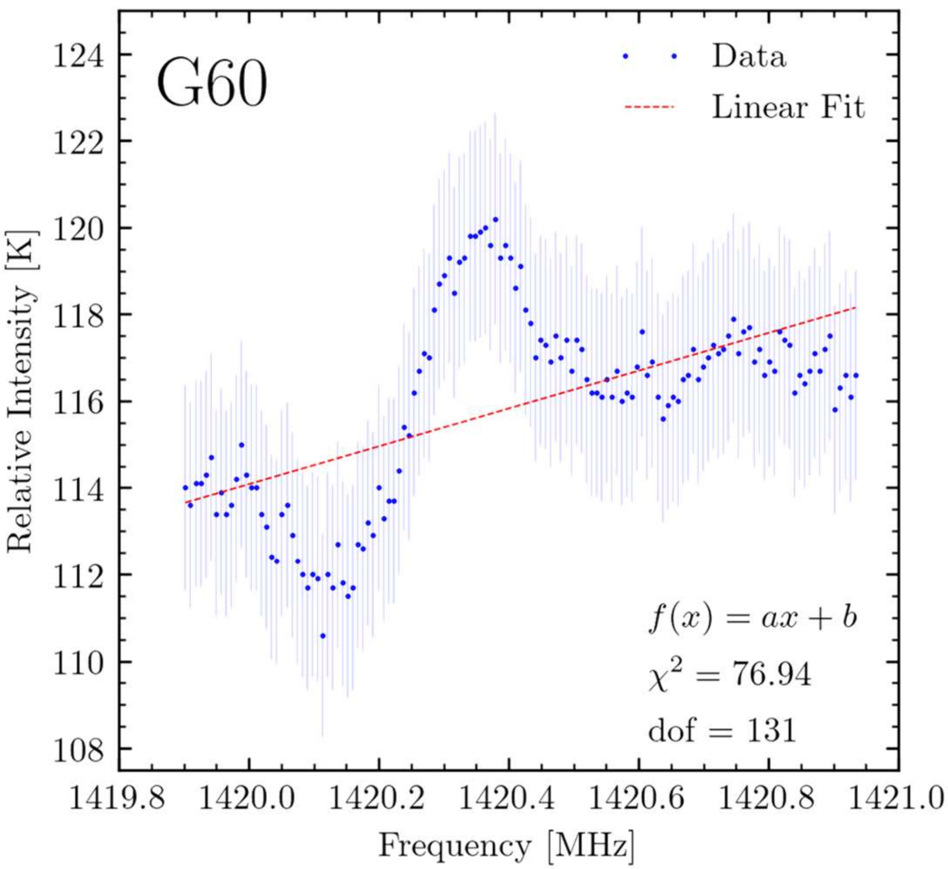


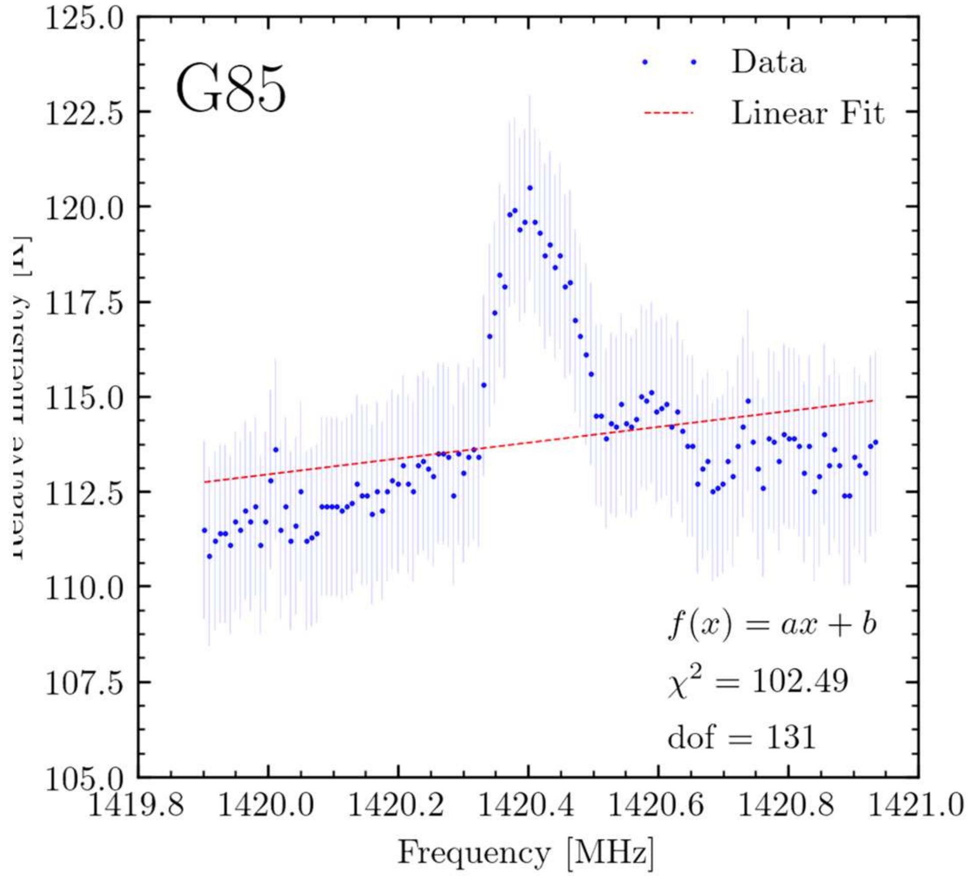
Small Radio Telescope (SRT) Apparatus



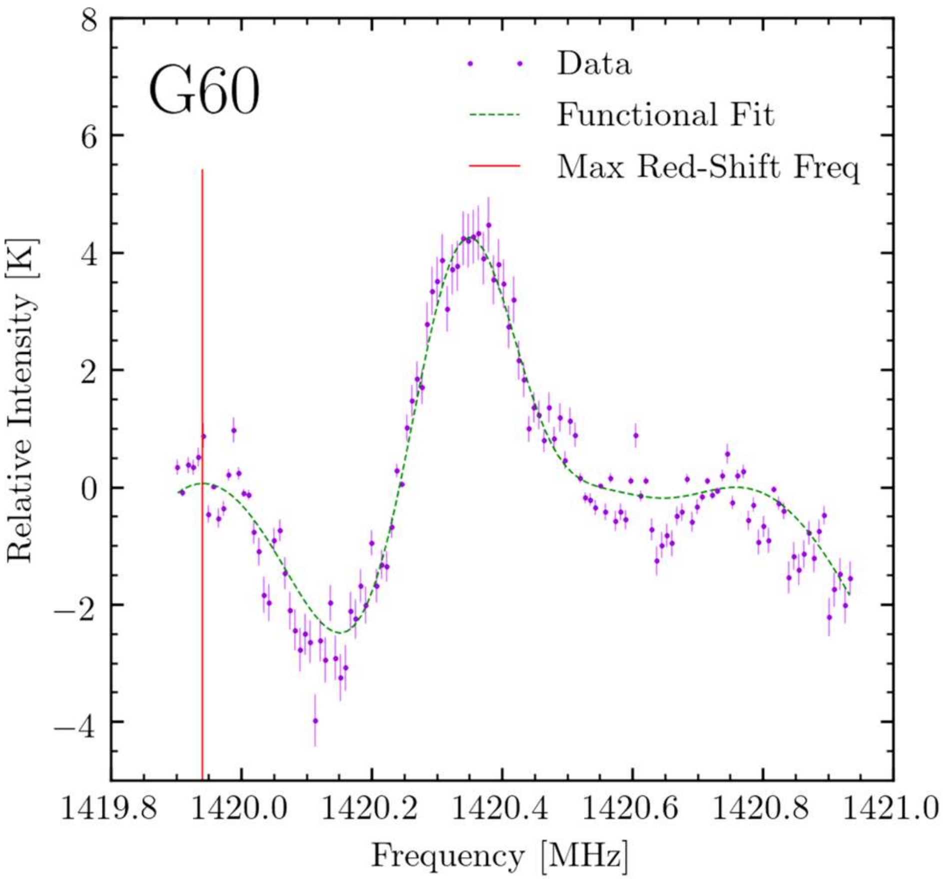
(See Appendix C for Circuitry)

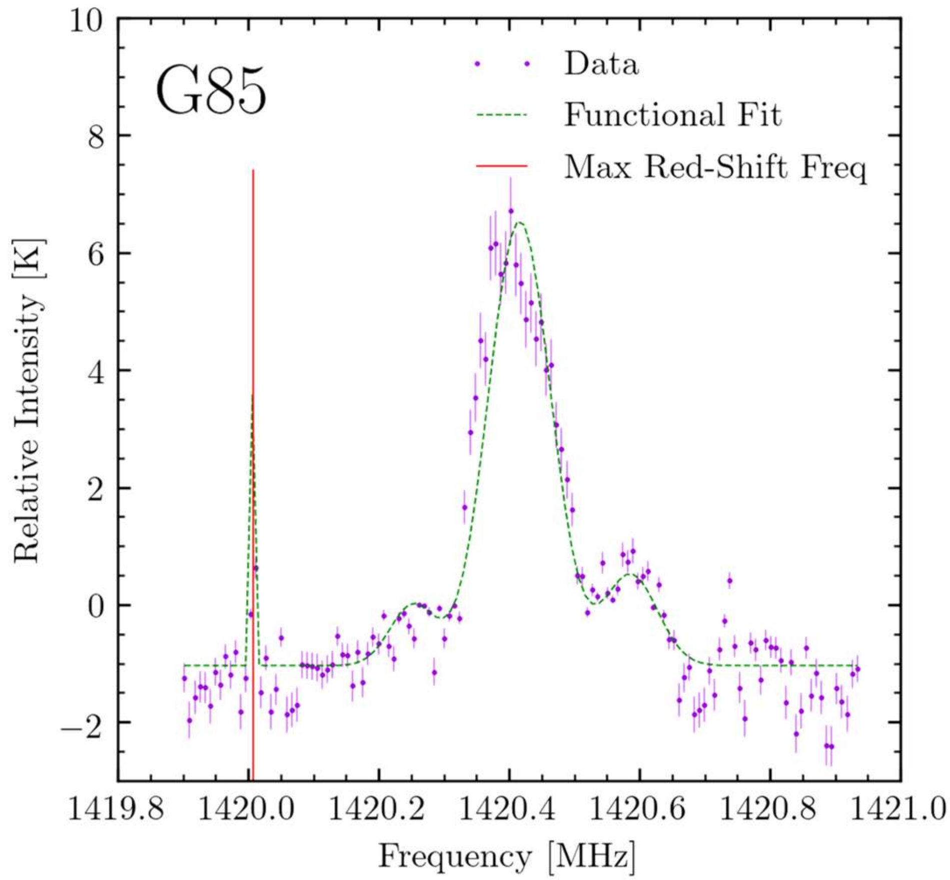
Intensity Spectra and Fitting to the Background



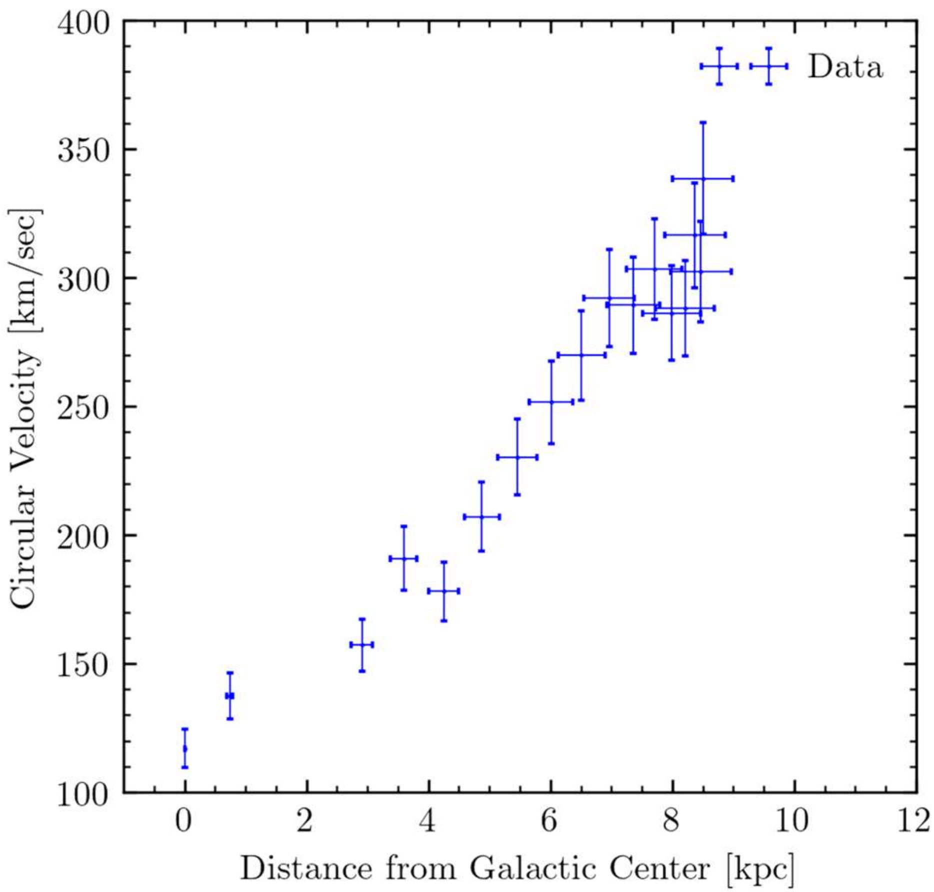


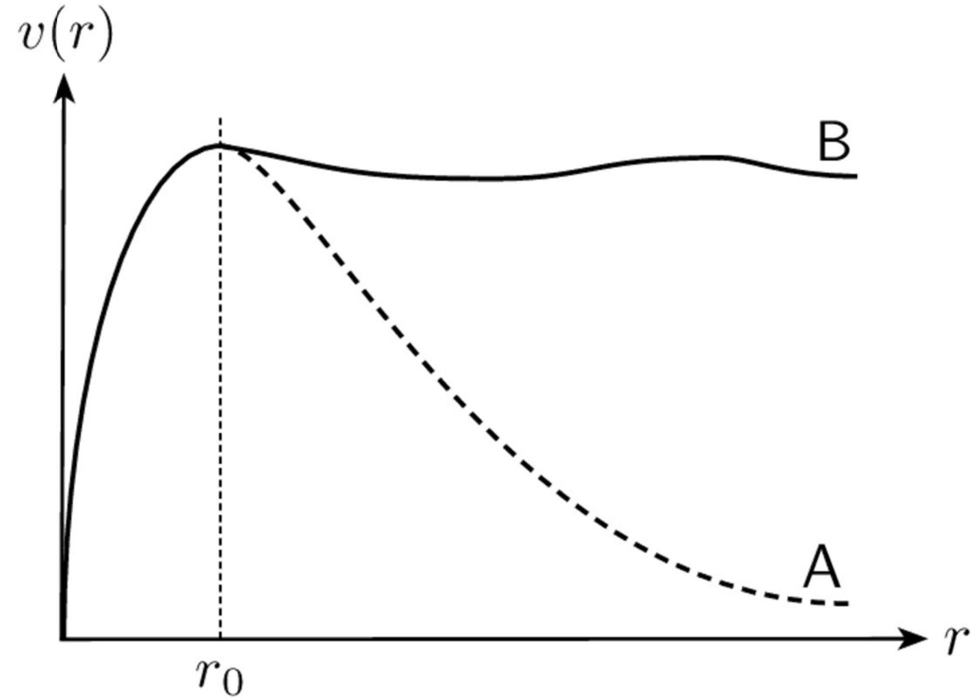
Background-Subtracted Fits to the Red Shift



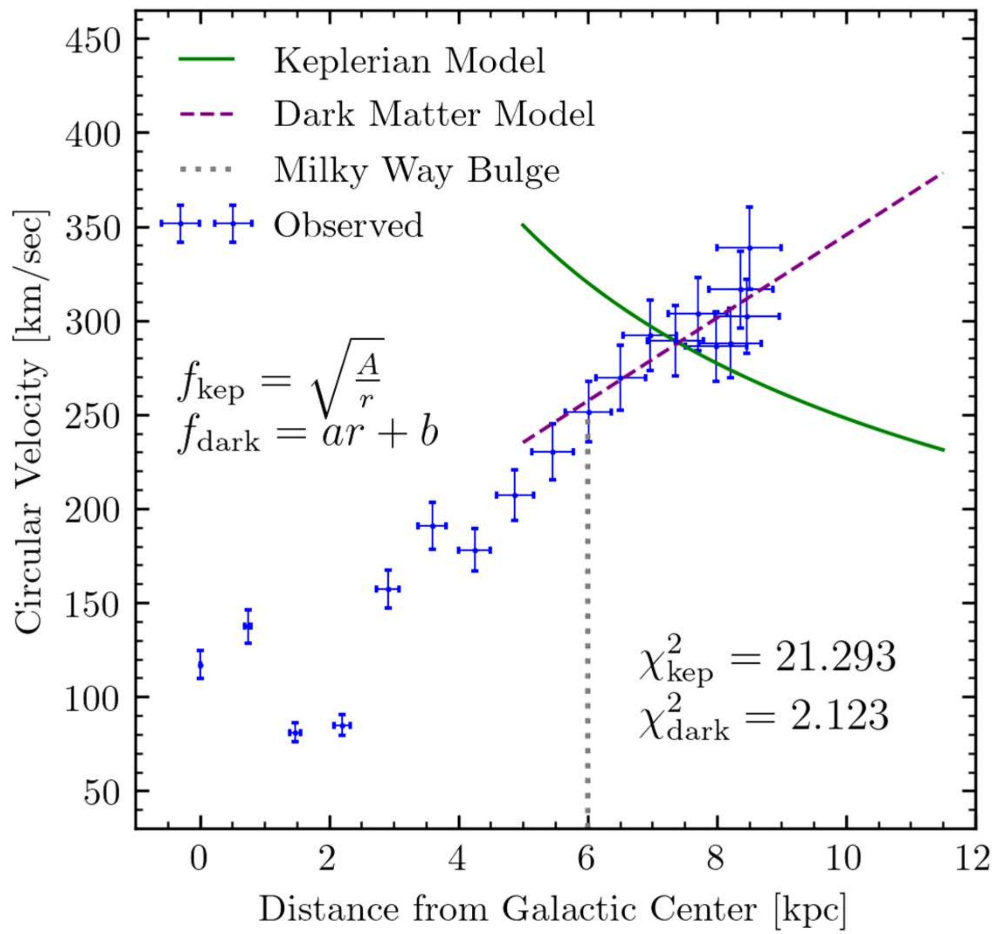


Comparing Our Rotation Curve with Other Observations

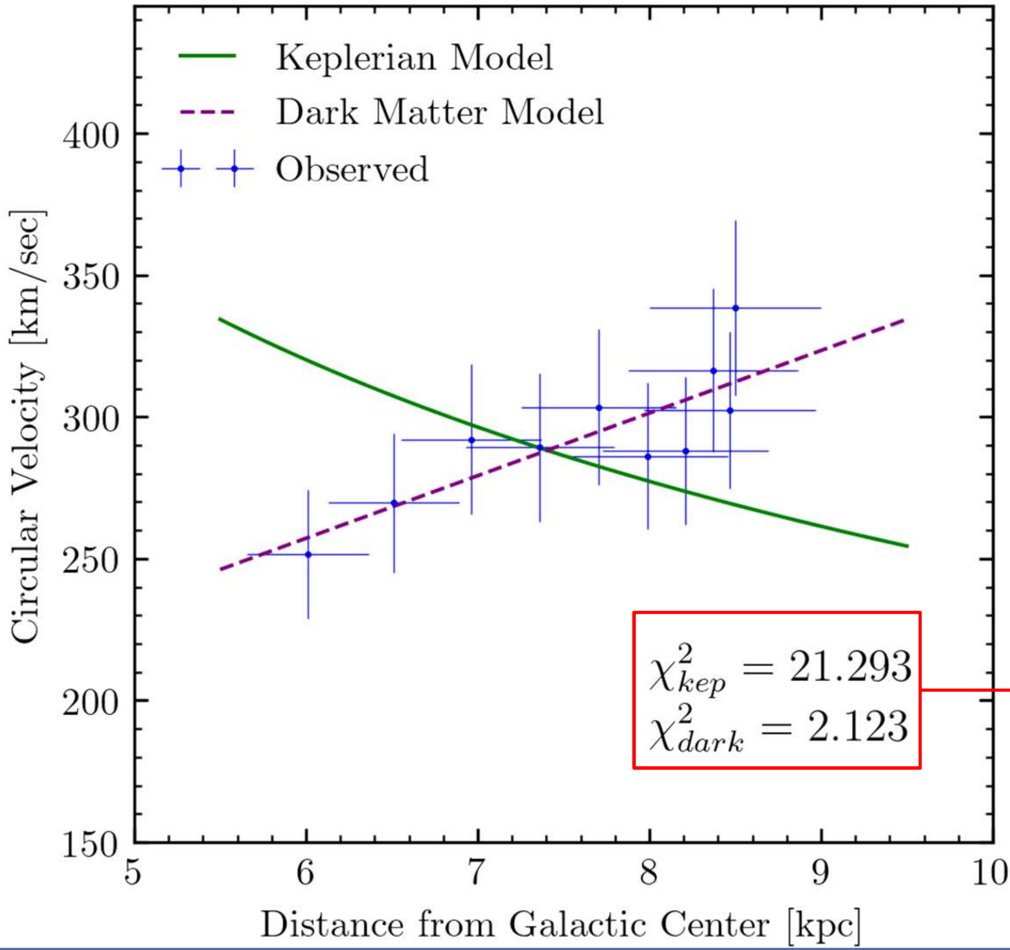




Fitting Velocity Data to Two Models of Rotation



Comparing Rotation Curve Model Fits



$$\boxed{\chi^2_{dark} < \chi^2_{kep}}$$

Results and Discussion of Errors

$$\chi^2{}_{kep} = 21.293 > 2.123 = \chi^2{}_{dark}$$

- We find a much stronger fit for the **'dark matter'** model

Statistical

- Not all longitudes scanned as often as others
- Fewer sessions of data gathering than desired
- Various sources of noise in the galactic plane at different times

Systematic

- Some low-longitude scans performed on longitudes that were partially/becoming invisible due to out of bonds of telescope view
- Fit function for red-shift frequency not precisely determined; only by inspection
- Days of data taking experienced varying weather

Summary, Conclusion, and Future Steps

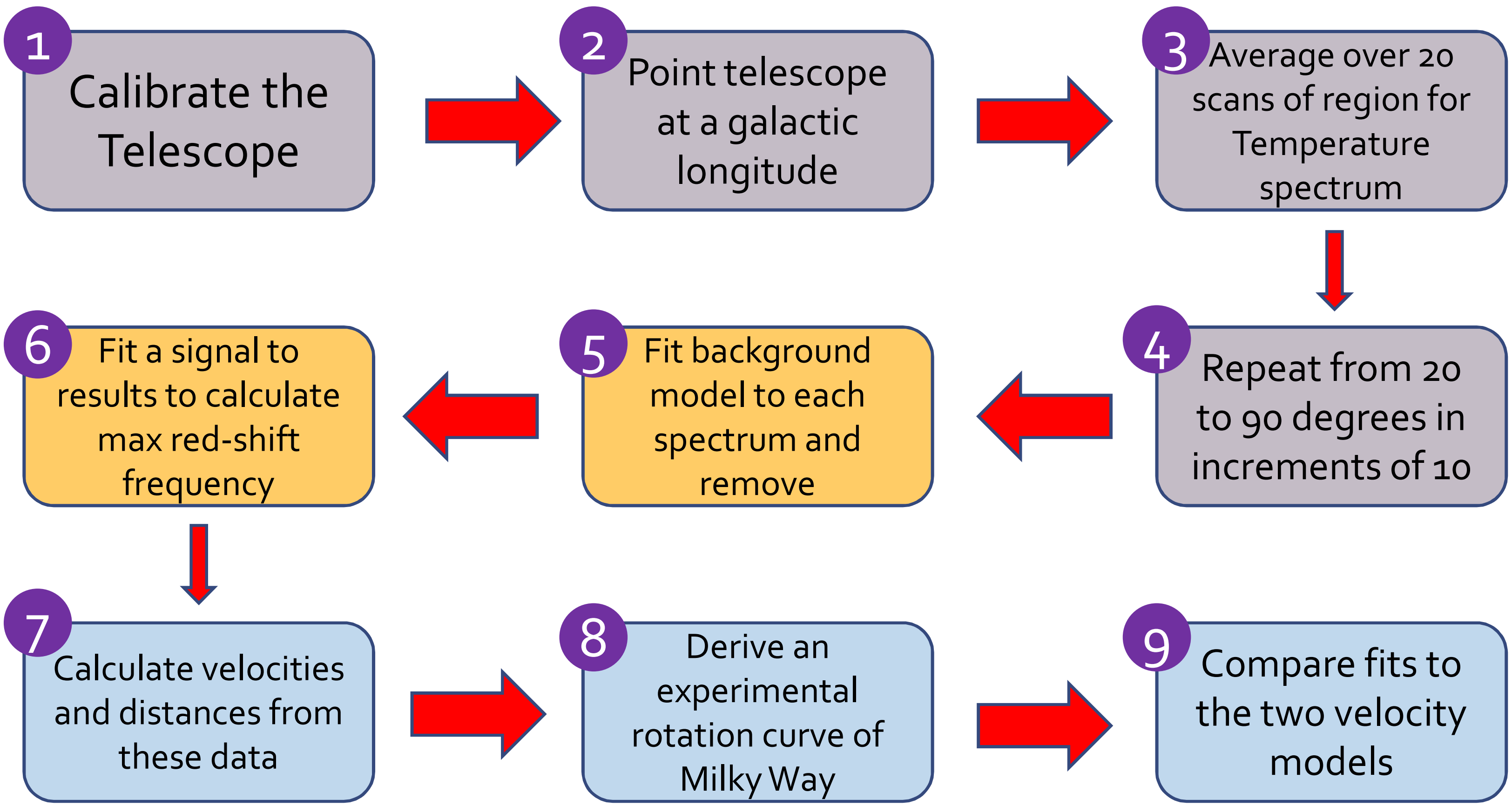
- **What have we accomplished?**
  - Derived an experimental velocity curve for the milky way
  - Explored its relationship to other models of rotational velocity
  - Confirmed that a 'dark matter' model fits the results better
  - Showed that 21cm technique is useful for studying the Milky Way
- **Where can these results lead?**
  - Probing the true mass density of potential dark matter
  - Constructing the spiral-arm structure of the milky way

Acknowledgements

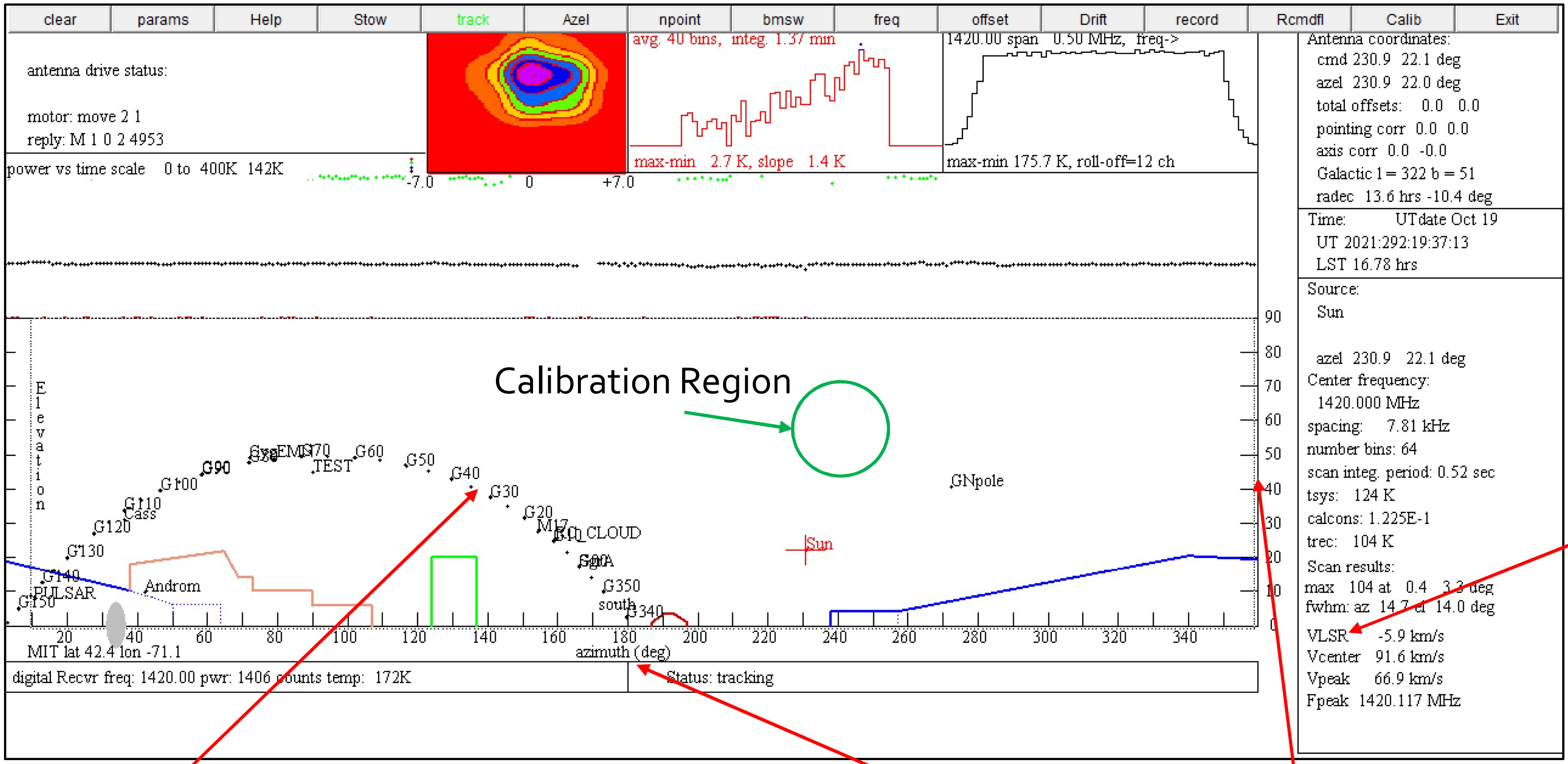
- My lab partner, Luke Gianni, for his collaboration on this project
- The 8.13 teaching staff for their instruction and aid in the lab
- MIT's lab facilities and equipment

THANK YOU!

Appendix A: Data Collecting Scheme



Appendix B: Telescope and Experimental Procedure



Calibration Region

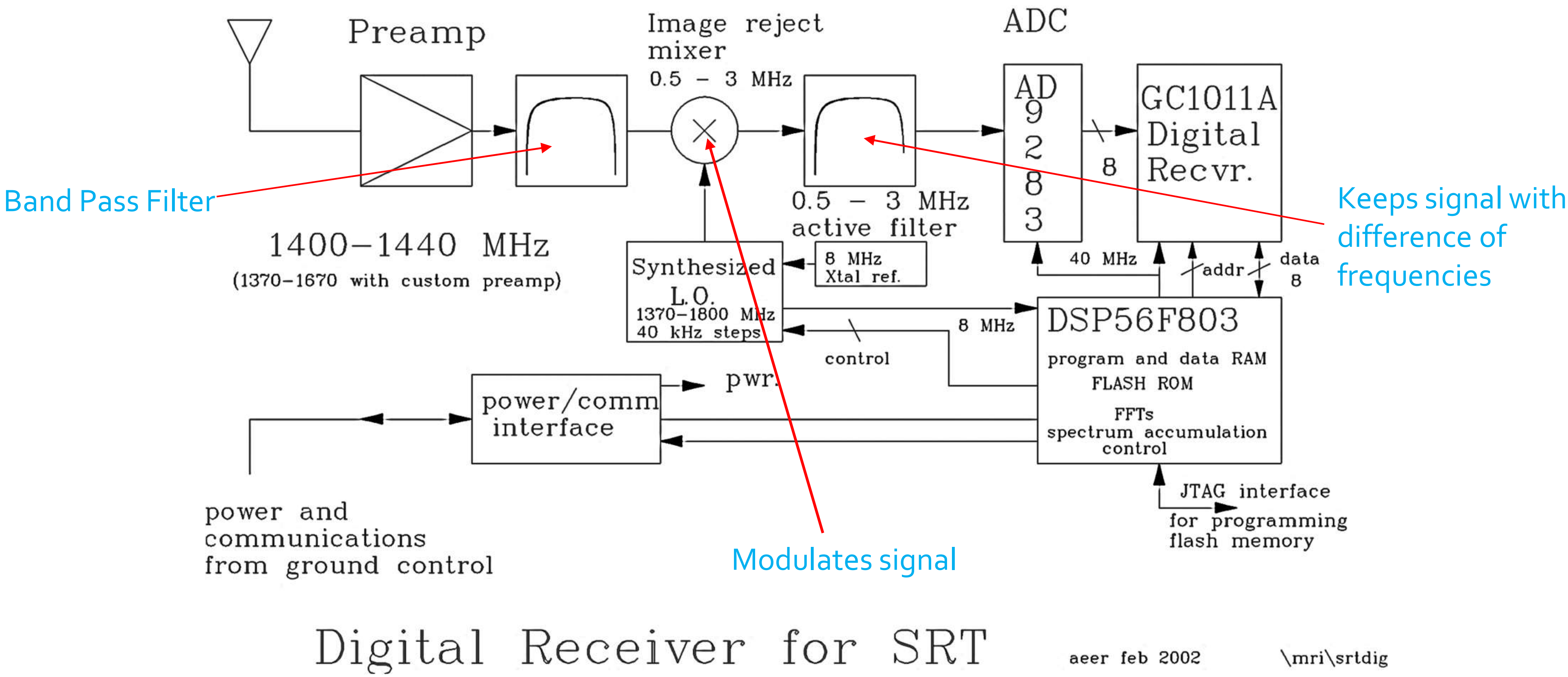
vLSR

Galactic longitudes

Azimuthal axis

Elevation axis

Appendix C: SRT Signal Chain



Appendix D: Functional Form for Fitting

$$f(x) = a_1 e^{\frac{-(x-\mu_1)^2}{2\sigma_1{}^2}} + a_2 e^{\frac{-(x-\mu_2)^2}{2\sigma_2{}^2}} + a_3 e^{\frac{-(x-\mu_3)^2}{2\sigma_3{}^2}} + a_4 e^{\frac{-(x-\mu_4)^2}{2\sigma_4{}^2}} + b$$