How does the Rotational Velocity of the Milky Way correlate to its expected Mass Distribution?

[redacted]

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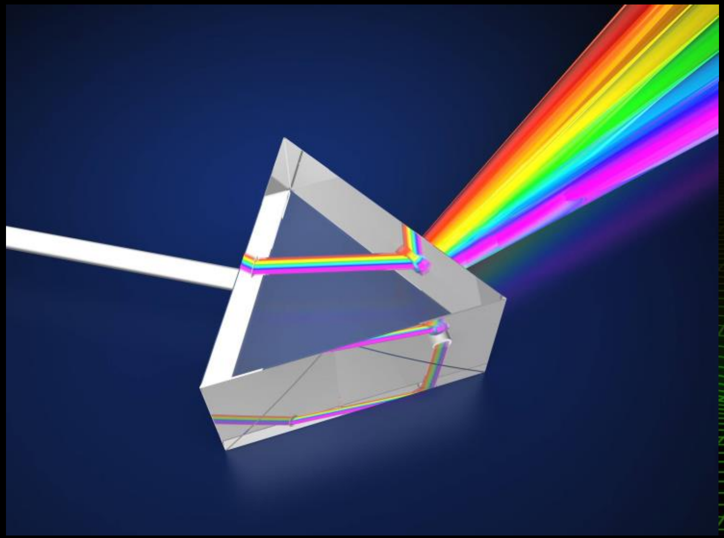
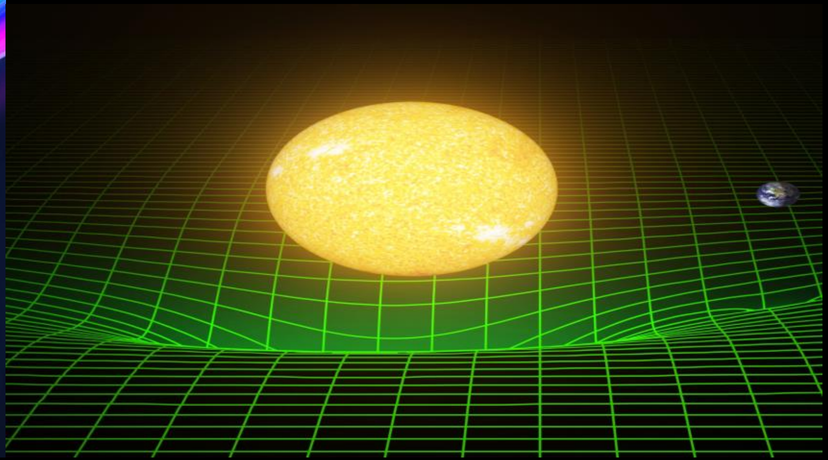
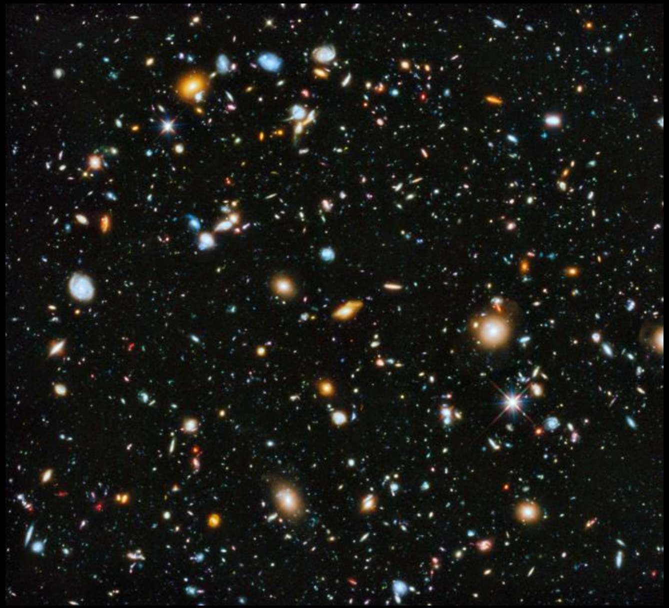




Main Ideas
&
Project
Journey

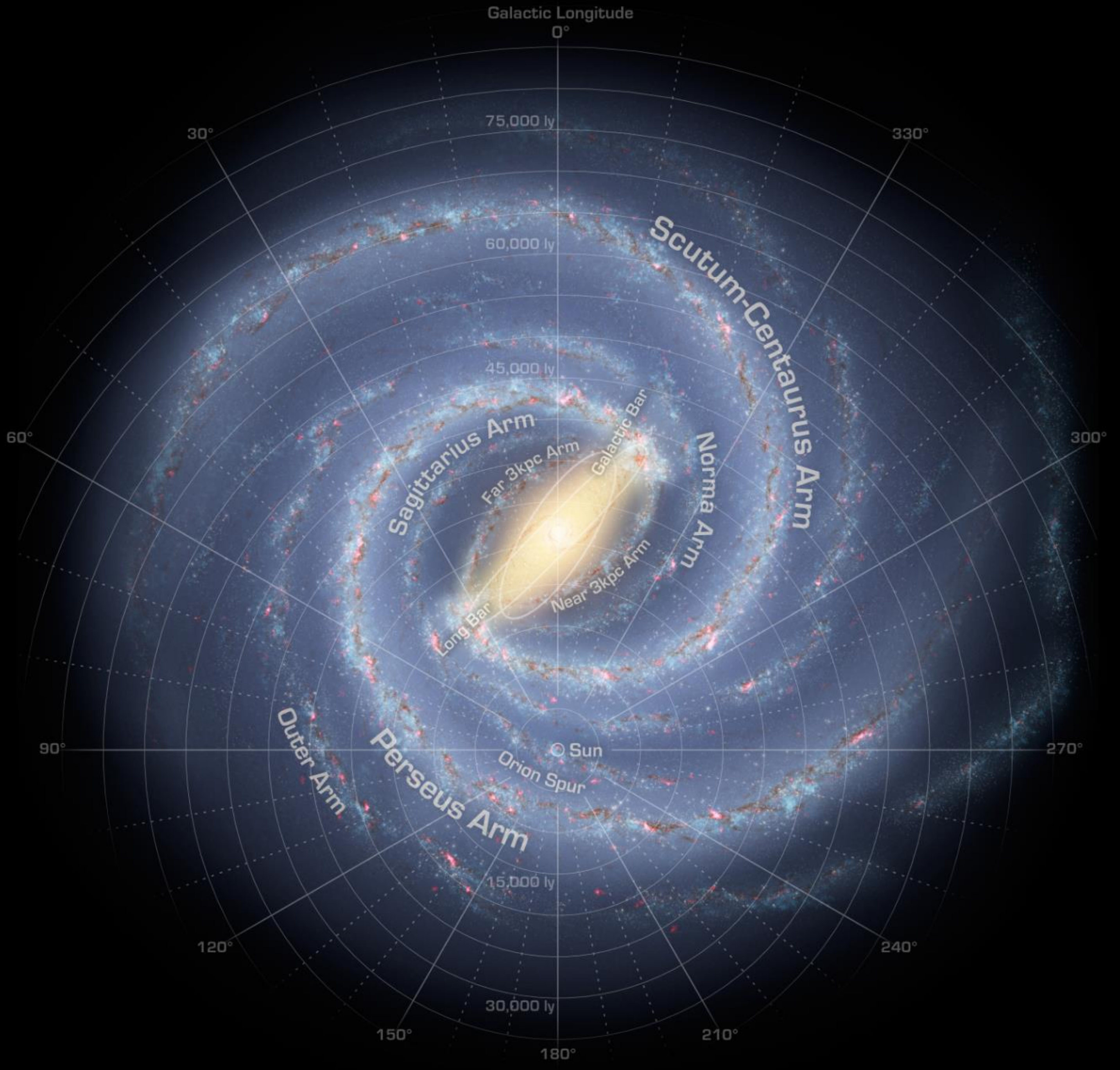
Galaxies

- Galaxies are **gravitationally bound systems** of stars, gas and dust.
- They originate from large gas clouds in that collapsed during the early universe.
- We are located inside the Milky Way Galaxy, which is a **barred spiral galaxy.**



Milky Way: Dynamics and Structure

- The Milky Way is a barred spiral galaxy.
- It is disk-shaped, with spiral arms and a dense central bar region.
- At its dynamical center, there is a supermassive black hole: Sagittarius A*.
- Our galaxy, like all spiral galaxies, rotates due to the conservation of angular momentum of the gas cloud that formed it.



The Interstellar Medium

- The space between stars is known as the interstellar medium.
- The interstellar medium is much less dense than any vacuum created on Earth, but over astronomical distances it adds up to a significant amount of the galaxy's matter.
- It is composed of gas (H and He), and very small dust particles.

HOT GAS

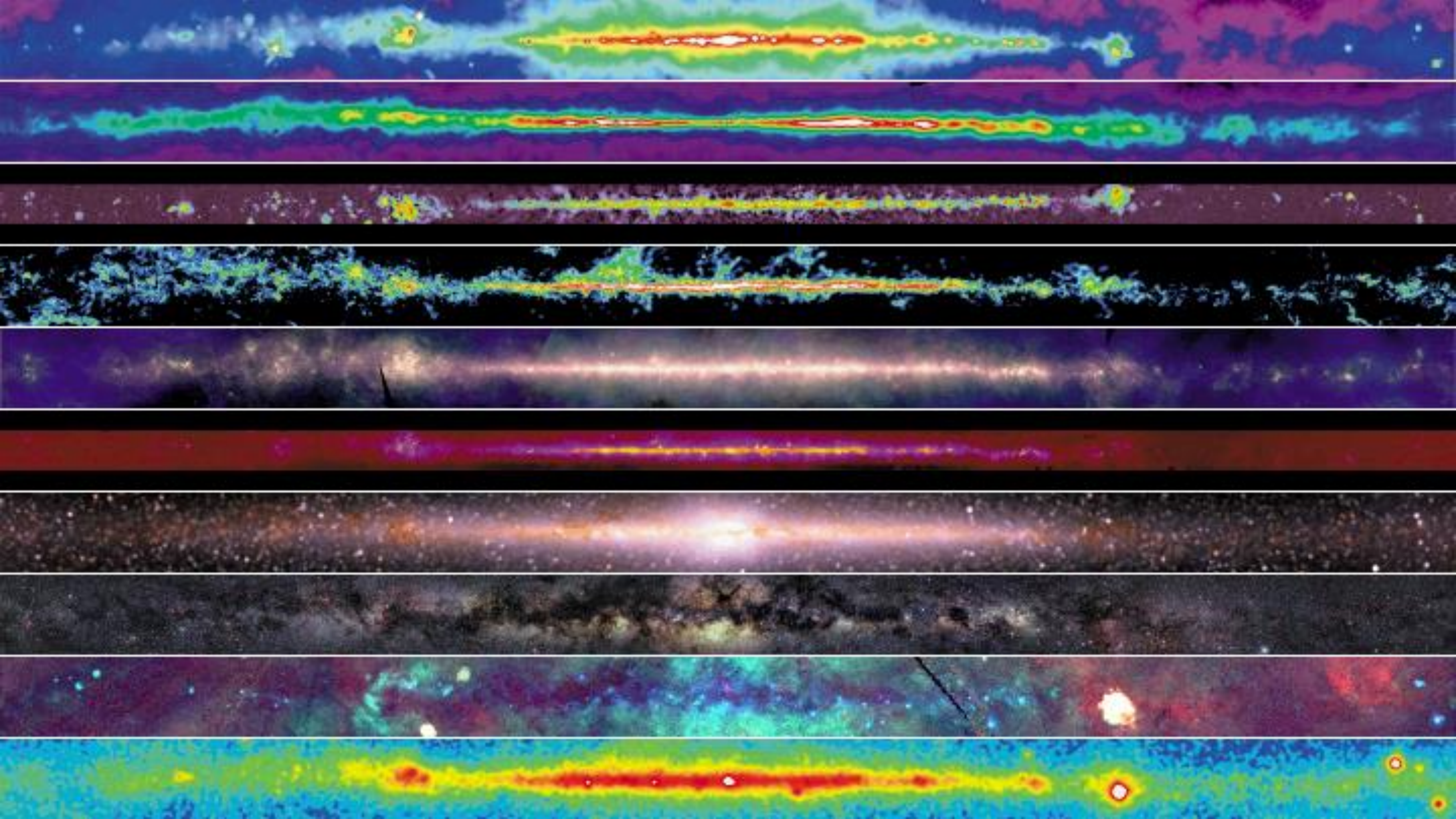
- Ionized Gas regions often nearby hot young stars
- Mostly hydrogen or helium
- Emit blackbody radiation and exhibit emission spectral lines
- Found in emission nebulae such as the Orion Nebula

COLD GAS

- Clouds of neutral hydrogen (atomic or molecular) and helium.
- Does not emit considerable blackbody radiation, so it cannot be detected
- Atomic hydrogen emits a hyperfine spectral line which can be detected by radio telescopes

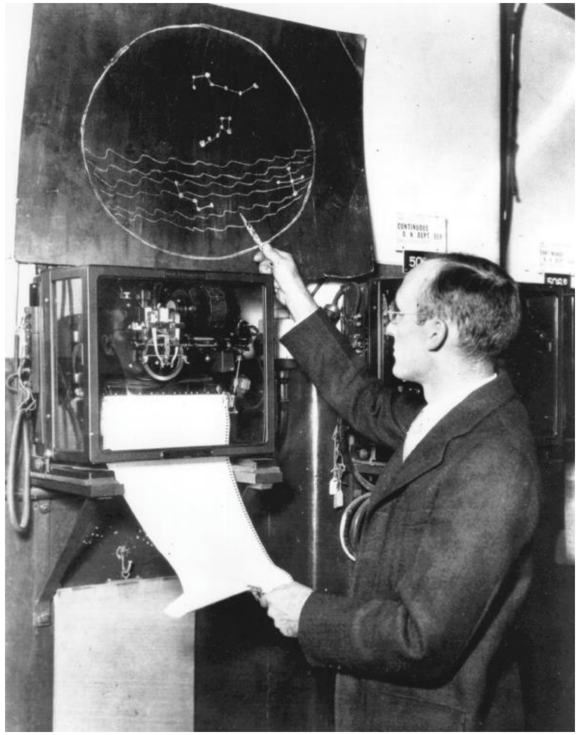
DUST

- Made of very small particles less than a micron across.
- Absorbs visible light, leading to extinction.
- Pervades the interstellar medium and obstructs our view of the galactic center.

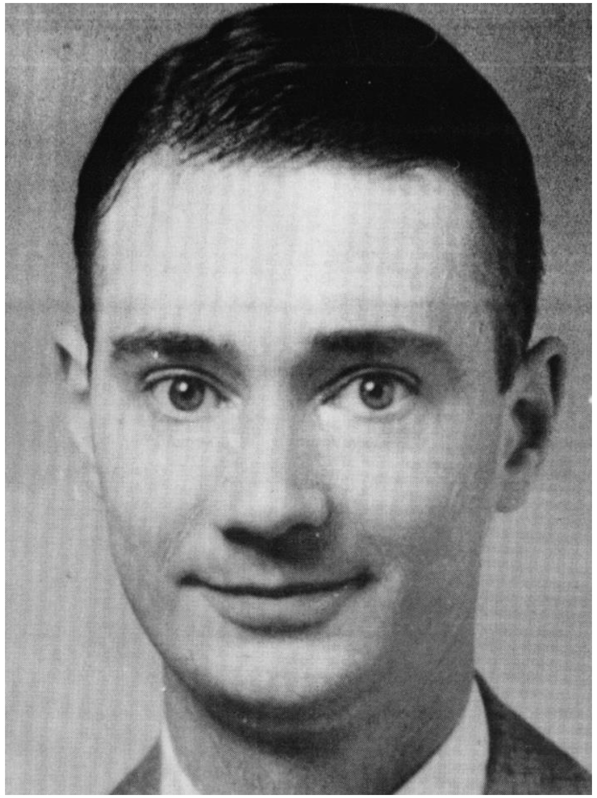


History of Radio Astronomy

- Before the 1930s, astronomers never studied the sky at non-visible wavelengths.
- This rendered most of the interstellar medium (**cold gas**) undetectable.
- In 1933, **Karl Jansky**, a radio engineer, discovered a strange interference that was fixed relative to distant stars.
- This turned out to be an emission from the Galactic Centre.



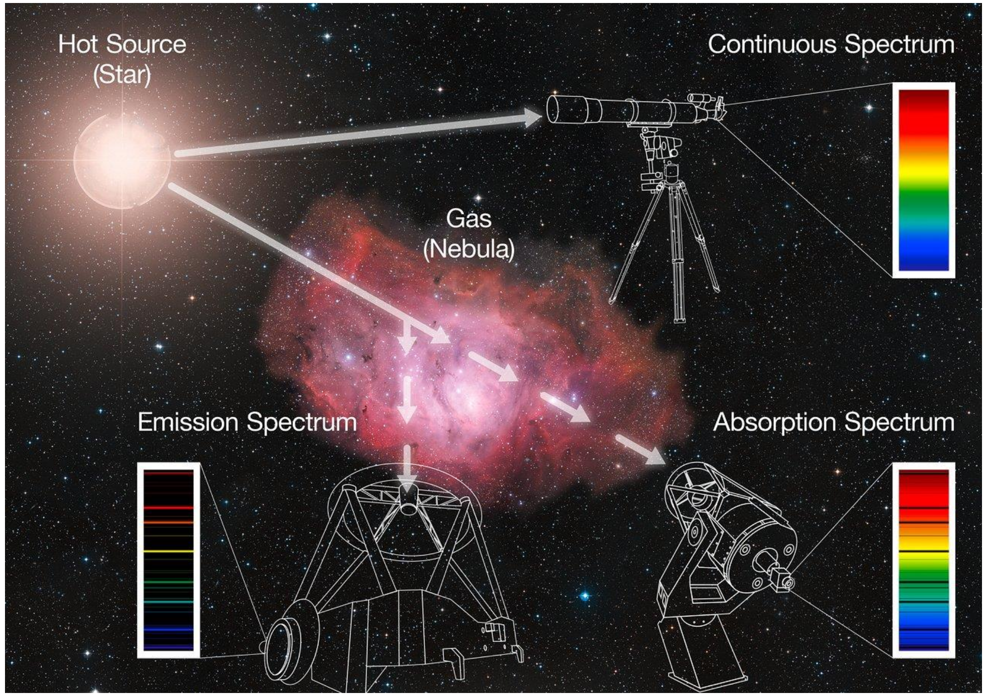
History of Radio Astronomy

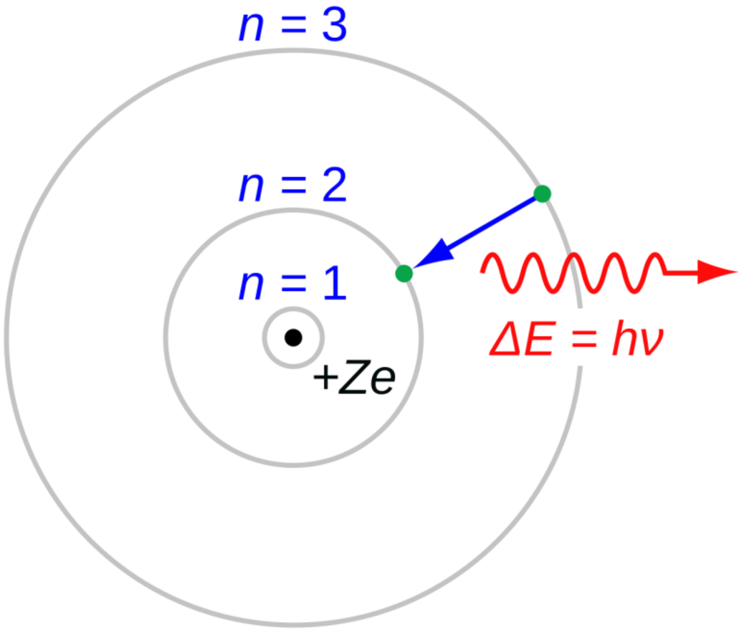


- Karl Jansky wished to continue studying the emission, but he was reassigned by Bell Laboratories.
- **Grote Reber** was the first and only radio astronomer in the late 1930s and 1940s.
- He constructed the first (9.6m) radio telescope in his backyard and produced the first radio sky map of the Milky Way.
- The discovery of radio astronomy was instrumental to our understanding of the galaxy, revealing the ISM for the first time.

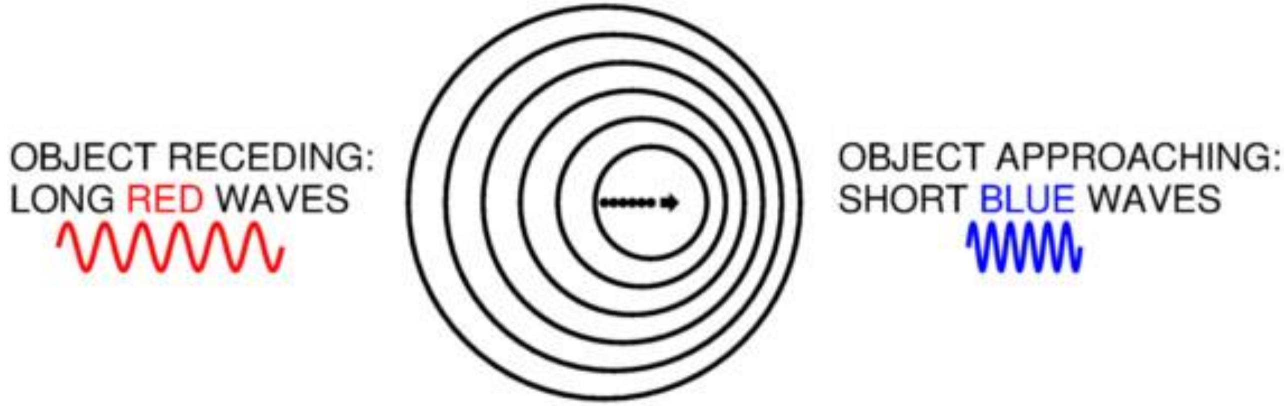
Spectroscopy

- All matter emits electromagnetic radiation with wavelength depending on its **temperature**.
- This is known as **blackbody radiation**.
- **Spectroscopy** is the study of light split into multiple wavelengths through a prism.
- The spectrum of light can reveal the chemical composition of its source, or any objects it passed through, through the existence of element-specific "**spectral lines**".
- Emitted when an **excited** electron jumps down to a lower energy level, releasing a **photon** of light.

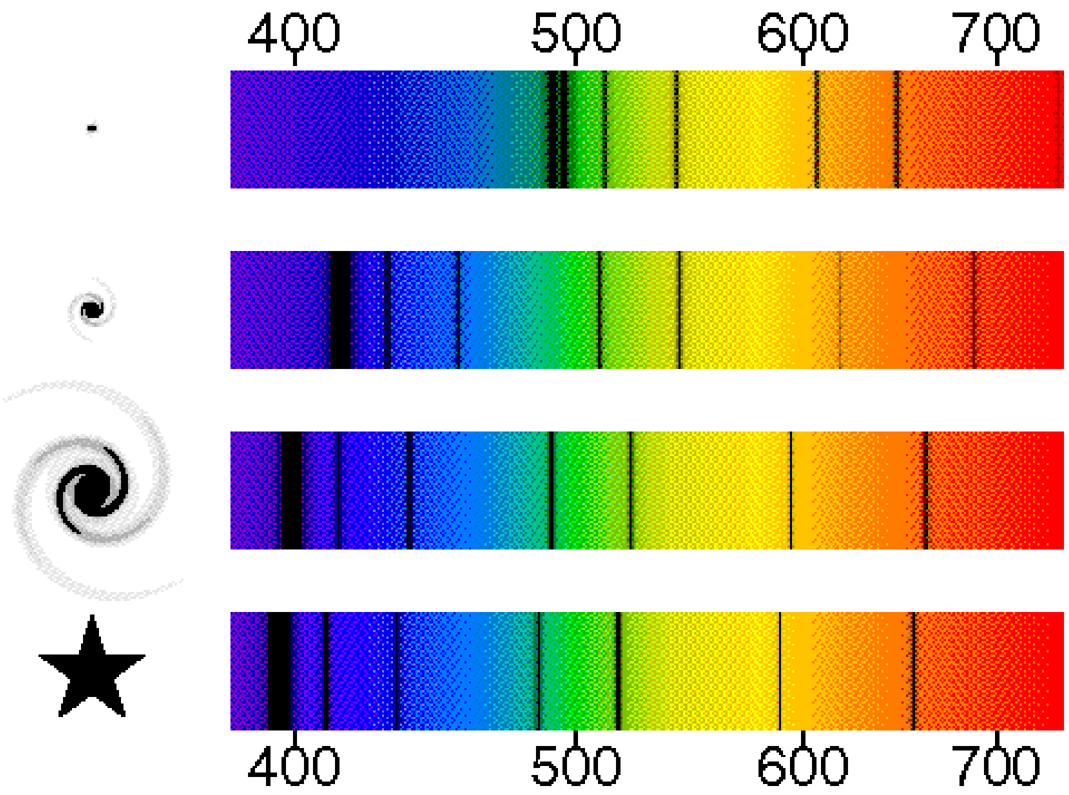




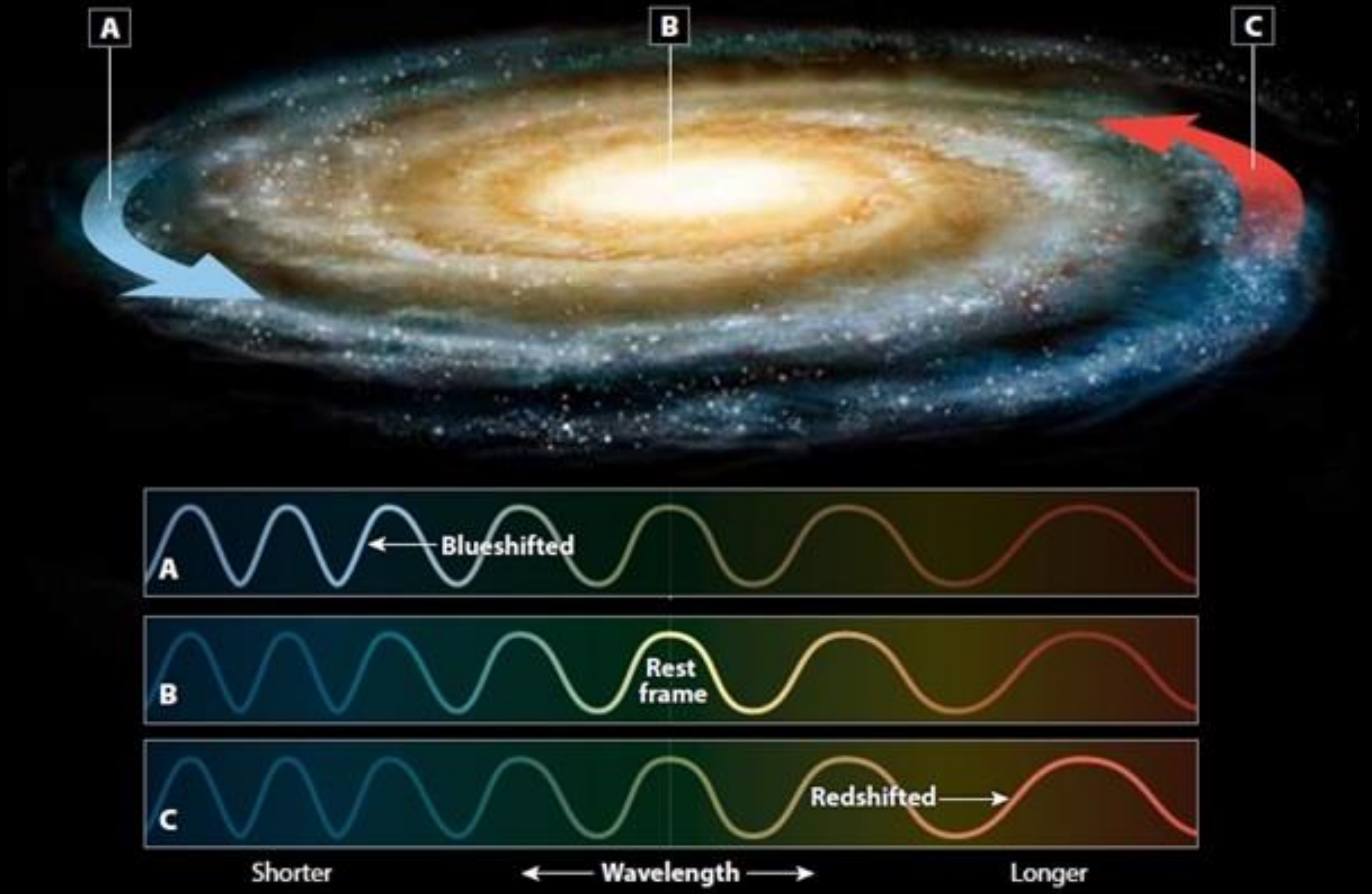
Doppler Shift



- Light from a **moving** source experiences a Doppler shift in its **frequency**.
- Astronomers measure the positions of **spectral lines** to determine velocities in space.
- The known position of a spectral line (which is specific to an **element** or **molecule**), is compared to the **observed** value.
- Therefore, by observing Doppler shifts, we can map the velocity dynamics of our galaxy.



Measuring a galaxy's rotation



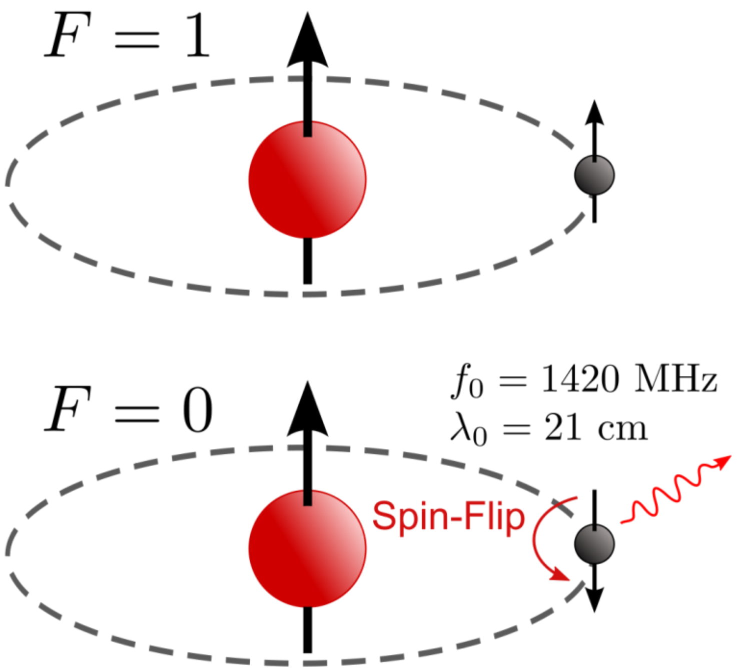
As a galaxy rotates, the material moving away from us shows a redshift in the wavelength of any emitted light (red arrow). Material moving toward us shows a blueshift (blue arrow). By measuring these shifts across a galaxy, astronomers can determine its rotation. *ASTRONOMY: ROEN KELLY*

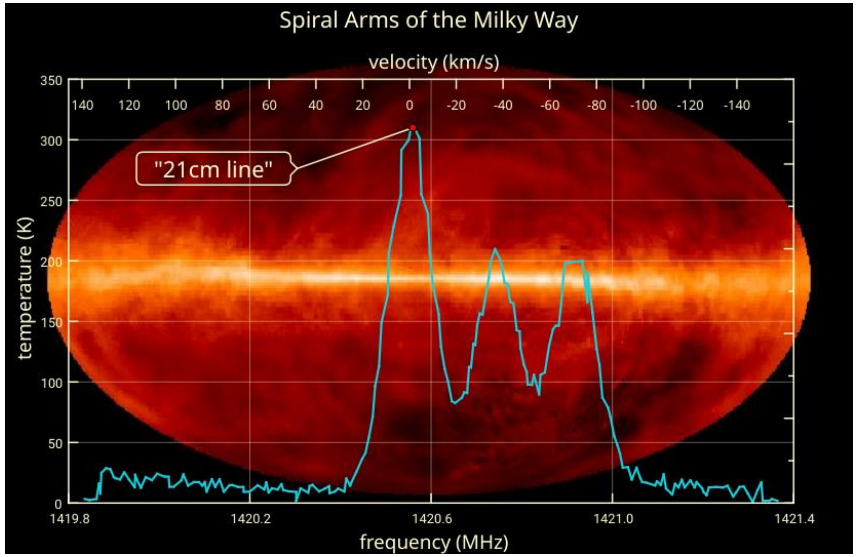
The 21-cm Line

- Jan Oort first realized the importance of a radio **spectral line** to the emerging field.
- His student Hendrik van de Hulst predicted the hyperfine neutral hydrogen line at **λ = 21cm**.
- Designing a receiver proved especially difficult, but the line was eventually discovered by Doc Ewen and Ed Purcell in **1951**.

Hydrogen Spin-Flip Transition

- The **ground state** of a hydrogen atom is split into two hyperfine sub-states.
- These states are defined by the proton and electron's spin properties, which can be **parallel** or **anti-parallel**.
- The transition has a very low probability and has a mean lifetime of about **11 million years.**
- This results in a very **narrow** spectral line, which is very useful for Doppler Shift measurements.



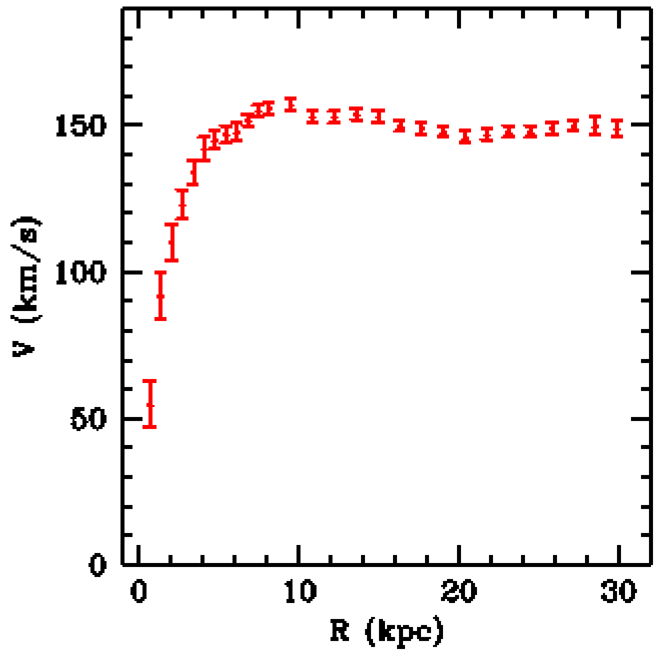


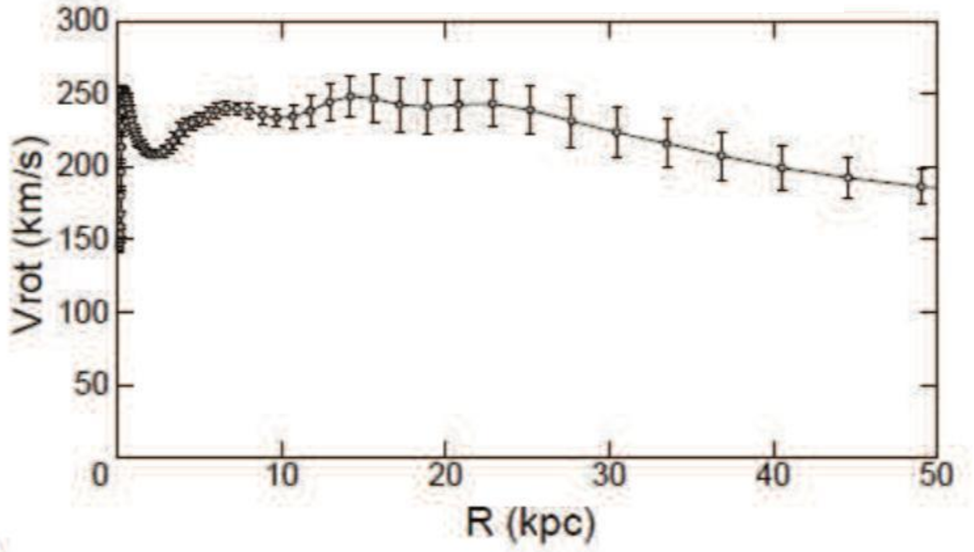
Rotation Curves

- Radio astronomers can plot **orbital velocity V** as a function of **orbital radius R**, displaying the relationship between the two variables.

- This graph is very useful, as it reveals the **mass distribution** of a galaxy at different distances from the center.

- The figures to the right show two such rotation curves obtained in literature.

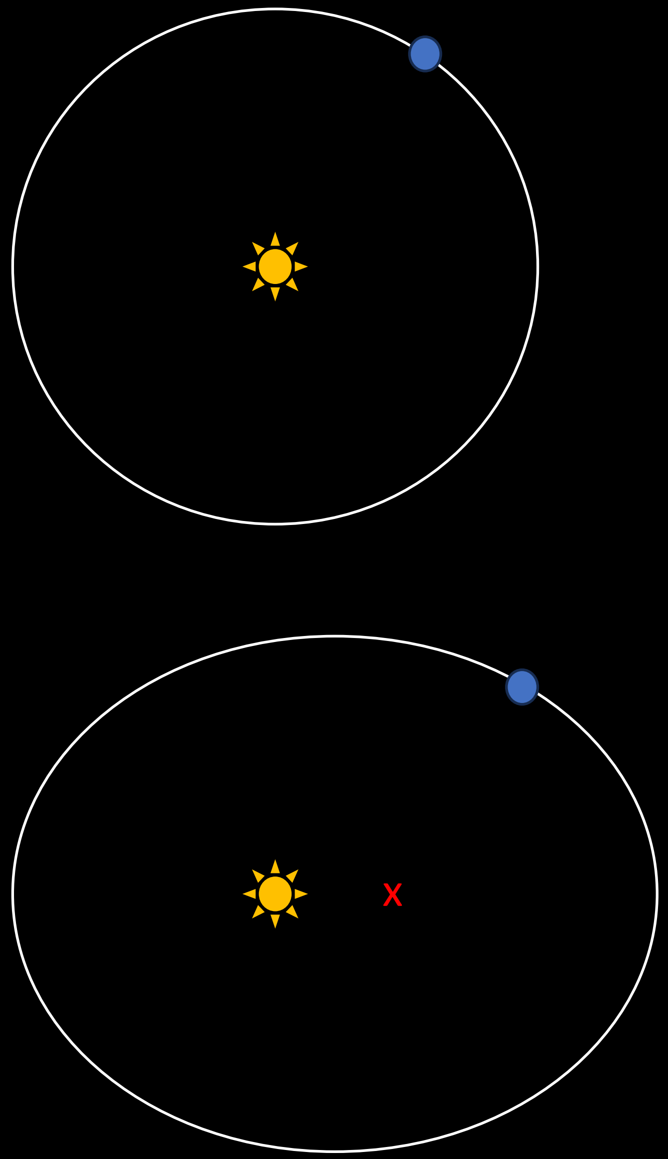




(a)

Keplerian Mechanics

- Johannes Kepler (1571-1630) discovered that the planets did not follow perfectly circular paths, but rather ellipses with the sun at a focus.
- His Three Laws of Planetary Motion established the foundation of orbital mechanics today.
- However, his work only referred to the bodies in our solar system. Decades later, Isaac Newton (1642-1726) unified mechanics through his Law of Universal Gravitation.



Universal Gravitation

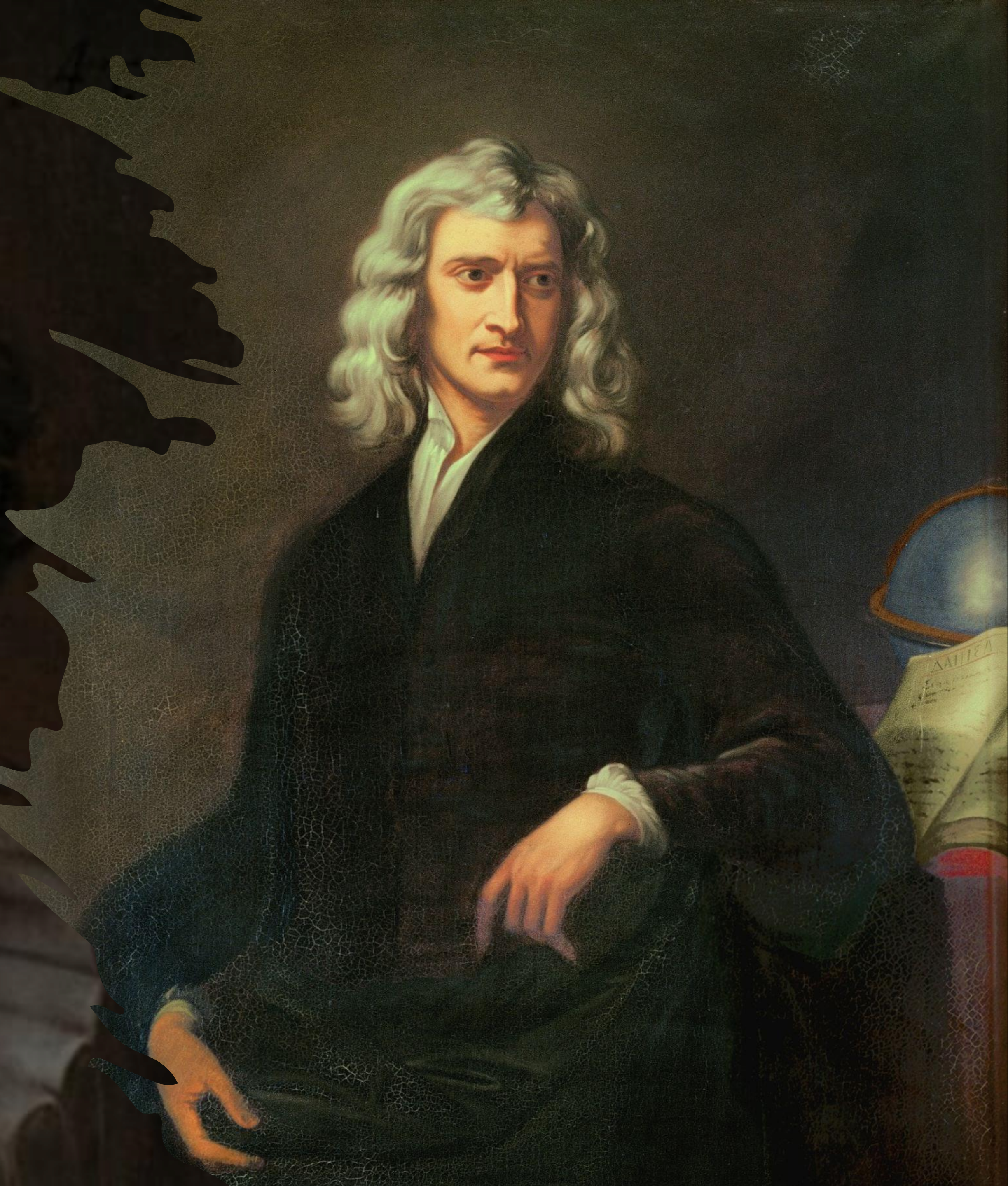
- Kepler's <u>empirically</u> determined Third Law of Planetary Motion:

*"the squares of the orbital periods **P** are directly proportional to the cubes of the semi-major axes **r** of their elliptical orbits"*

- Isaac Newton was able to re-derive this relationship for any body orbiting another body.

- His Law of Gravitation shows that gravitational force is inversely proportional to the square of the orbital radius.

- By recognizing gravity as the centripetal force, we can also determine that orbital velocity is proportional to $1/\sqrt{r}$



Deriving Newton's Law of Gravitation from Kepler's 3rd Law

(Carroll & Ostlie, 2007, pp.32-33)

$$P^2 \propto r^3$$

$$P^2 = kr^3, \text{ Where } k \text{ is a constant.}$$

$$P = \frac{2\pi r}{v}$$

$$\left(\frac{2\pi r}{v}\right)^2 = kr^3$$

$$\frac{4\pi^2 r^2}{v^2} = kr^3$$

$$\frac{v^2}{4\pi^2 r^2} = \frac{1}{kr^3}$$

$$\frac{v^2}{r} = \frac{4\pi^2}{kr^2}$$

$$\frac{mv^2}{r} = \frac{4\pi^2 m}{kr^2}.$$

$$F_c = F_g = \frac{4\pi^2 m}{kr^2}$$

$$F_c = F_g = \frac{4\pi^2 M}{k' r^2}$$

$$F_g = \frac{4\pi^2 Mm}{k'' r^2}, \text{ where } k' = \frac{k''}{M} \text{and } k = \frac{k''}{m}$$

$$F_g = G\frac{Mm}{r^2}, \text{ Where } G = \frac{4\pi^2}{k''} \text{ is the universal constant of gravitation.}$$

Deriving the Orbital Velocity equation

$$F_{centripetal} = \frac{mv^2}{r}$$

$$F_{gravitational} = G\frac{mM}{r^2}$$

$$F_c = F_g$$

$$\frac{mv^2}{r} = G\frac{mM}{r^2}$$

$$v^2 = \frac{GM}{r}$$

$$v = \sqrt{\frac{GM}{r}}$$

$$Therefore, \quad v \propto \sqrt{r}$$

$G = gravitational\ constant$
$M = mass\ of\ main\ body$
$m = mass\ of\ orbiting\ body$
$r = orbital\ radius$
$v = orbital\ velocity$

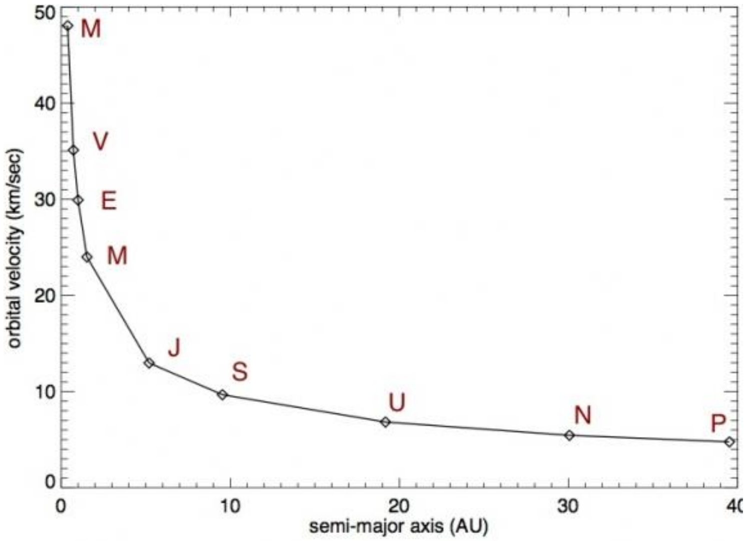
Hypothesis

- Based on photometric measurements (of light intensity), most of the galactic mass is concentrated in the bright central bulge.

- Similarly to our solar system, we can expect a decrease in orbital velocity towards greater radii.

- In reality, the galaxy is more complex, but this is a good approximation for the behavior we are observing.

$$v = \sqrt{\frac{GM}{r}}$$





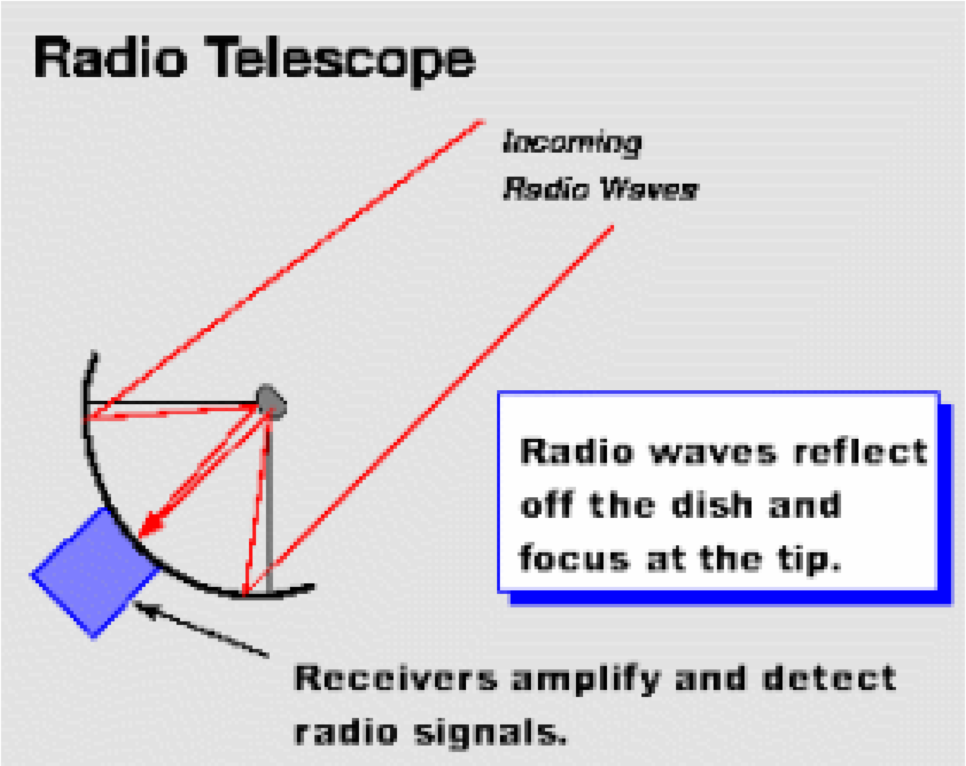


Pisgah Astronomical Research Institute

- Located in Western North Carolina, United States, the institute specializes in radio astronomy research.
- There are 4 radio telescopes in use, including a 4.6-meter, a 12-meter, and two 26-meter telescopes.
- It was a former NASA tracking station, and later a U.S. Department of Defense spy station.

Radio Telescope Anatomy

- The radio telescope is made up of three main parts: the **antenna,** the **receiver,** and the **motor mount.**
- The motor mount rotates the telescope upwards and sideways for positioning.
- The parabolic dish collects the radio waves and focuses them into a receiver.



Observation

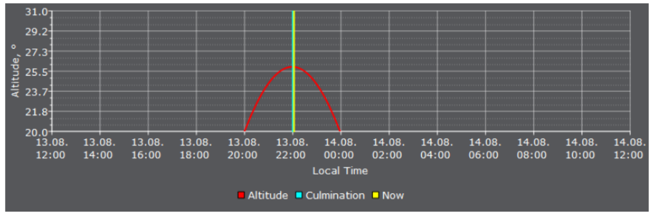
stellarium
latest version is 23.2

- I planned my observation sessions using the **Stellarium** software, which allowed me to plot and export graphs of altitude over time.

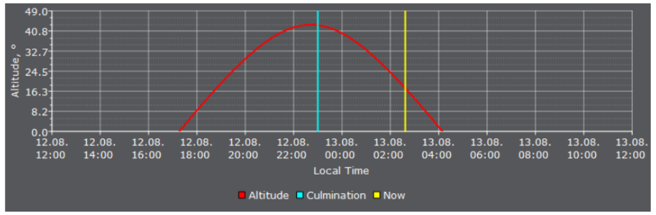
- The optimal observation timeframe for the Galactic Center was between **4:00** and **6:00** AM.

Table 3 - Observation schedule:

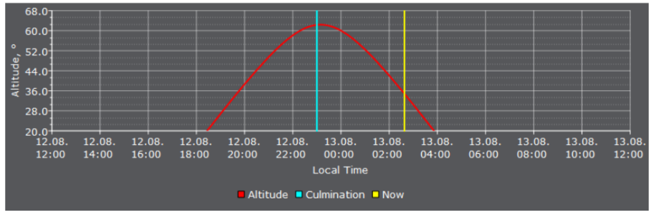
	Local (telescope) date and time	UTC date and time	Region observed / l°
Session 1	12/08/23 21:30	13/08/23 01:30	00 - 16
Session 2	12/08/23 22:00	13/08/23 02:00	36 - 60
Session 3	13/08/23 07:00	13/08/23 11:00	86 - 90
Session 4	14/08/23 01:30	14/08/23 05:30	62 - 84
Session 5	15/08/23 23:20	16/08/23 03:20	18 - 34



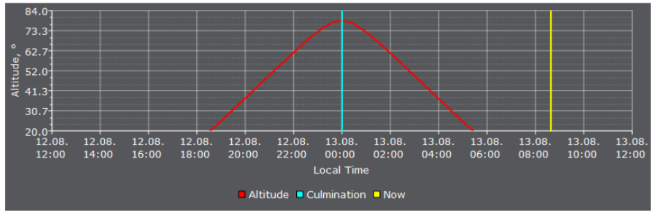
l = 0°



l = 20°



l = 40°



l = 60°

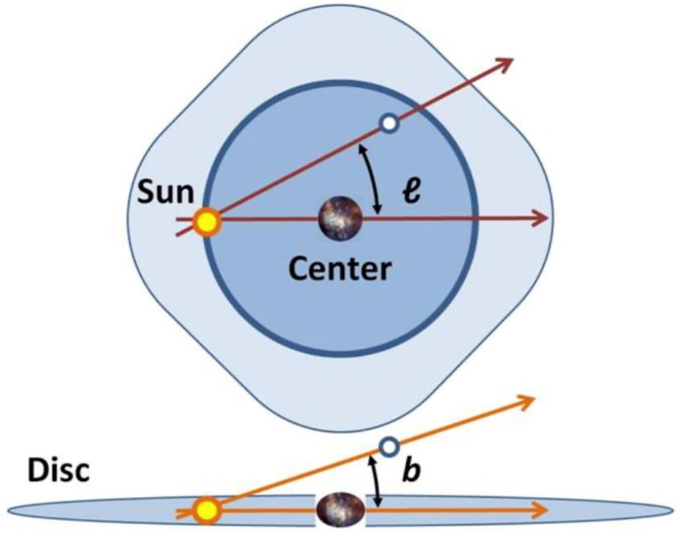
Coordinate Systems

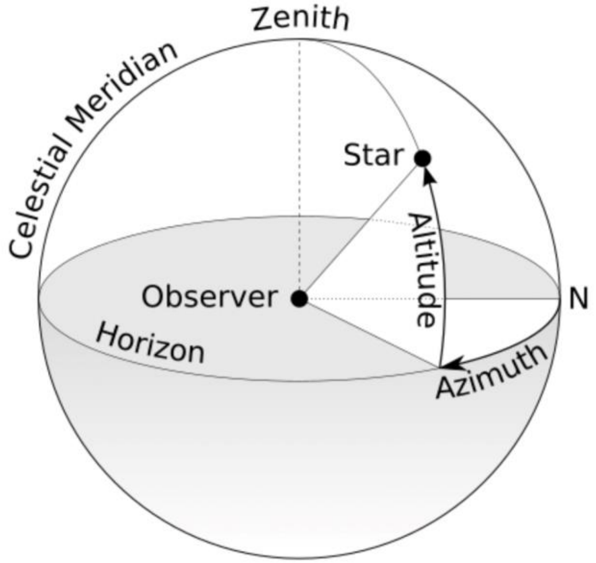
There are three main coordinate systems used for positioning the telescope.

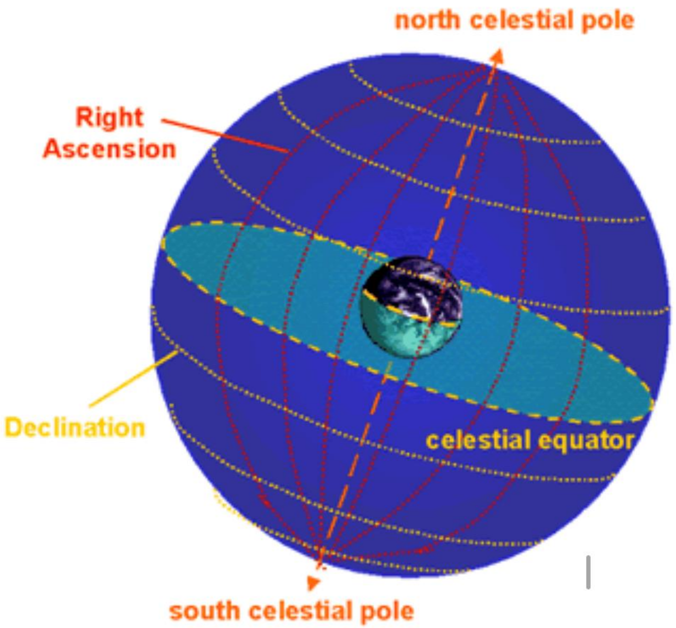
Horizontal
- Altitude (alt.)
- Azimuth (az.)

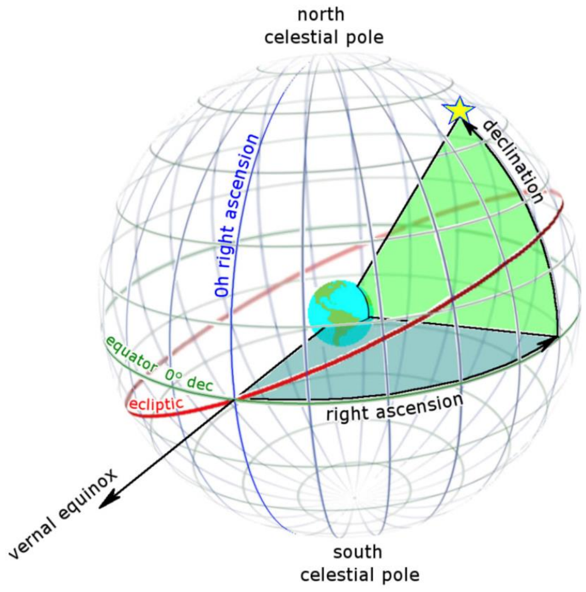
Equatorial
- Right Ascension (RA)
- Declination (Dec)

Galactic
- Latitude (b)
- Longitude (l)









Sample Scan

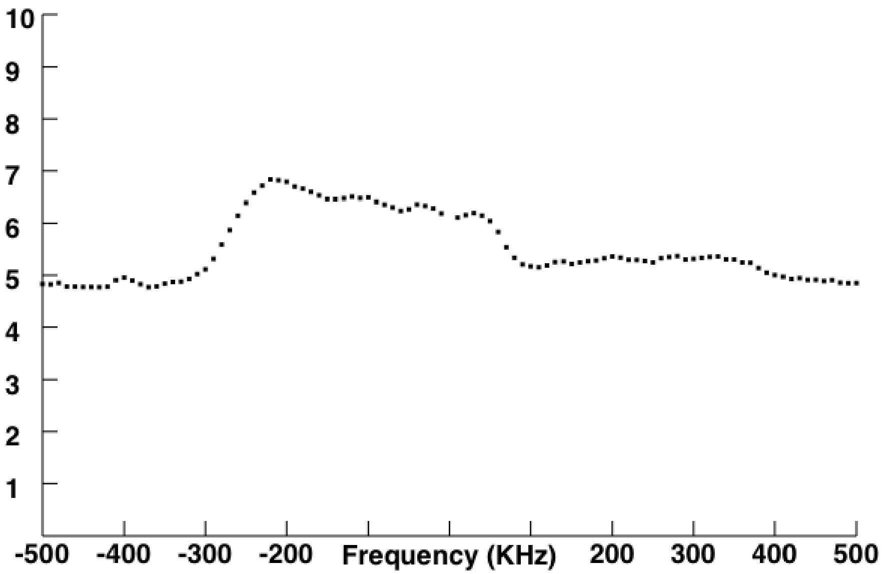
- The telescope measures the relative spectral flux intensity of a **1.2 degree** wide area.
- **Relative intensity** is tabulated against **frequency offset**, and plotted on a graph.

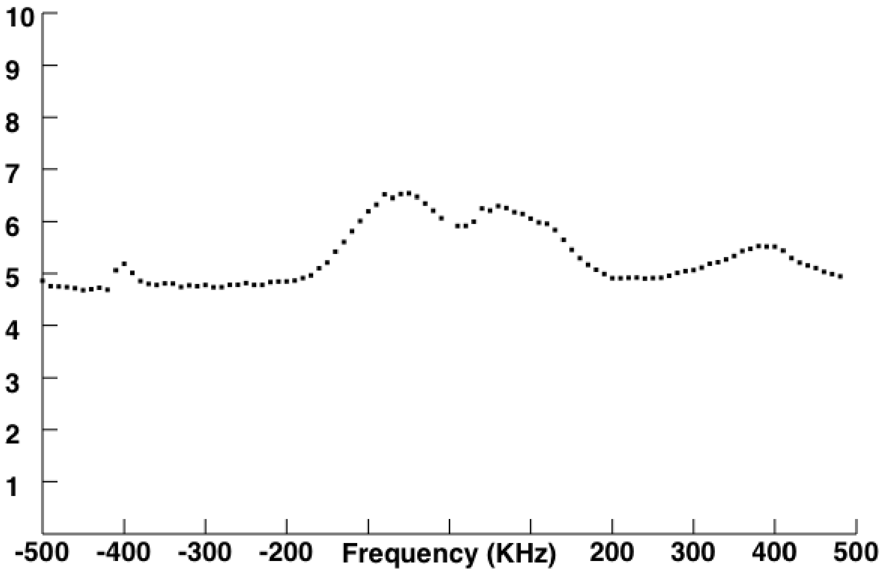
L56.fit ×

spectrum scan	
Origin	PARI
Telescope	Twelve
Observer	dariusvlad
Date(UTC)	2023-08-13T02:14:36.861
Frequency	1420
IF Gain	10
RA	19:37:36
DEC	20:27:38

Data

Freq Offset	Rel Intensity
-500	4.9459076
-490	4.8426437
-480	4.8358727
-470	4.824686
-460	4.8027134
-450	4.765444
-440	4.78405
-430	4.812002
-420	4.772835
-410	5.147972
-400	5.273285
-390	5.097418





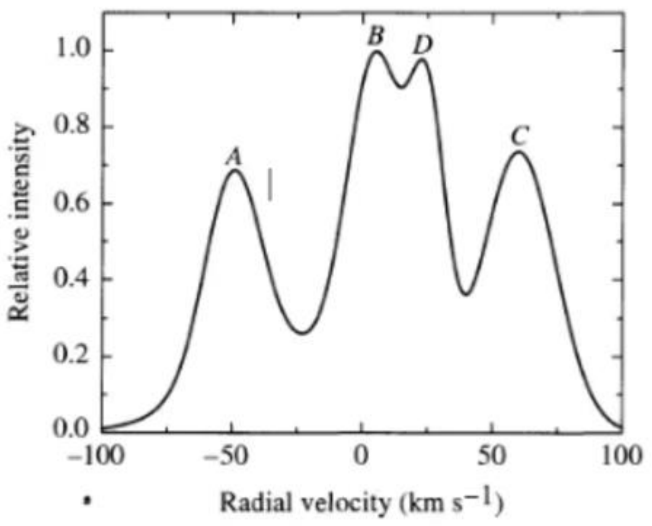
Tangent-Point Method

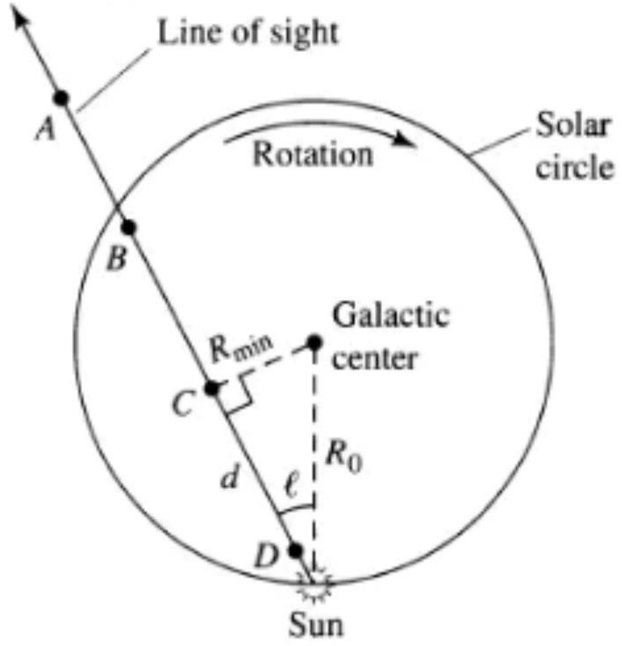
- The **most redshifted** signal corresponds to the **tangent-point**, where the **line of sight** makes a right angle with its orbital radius.

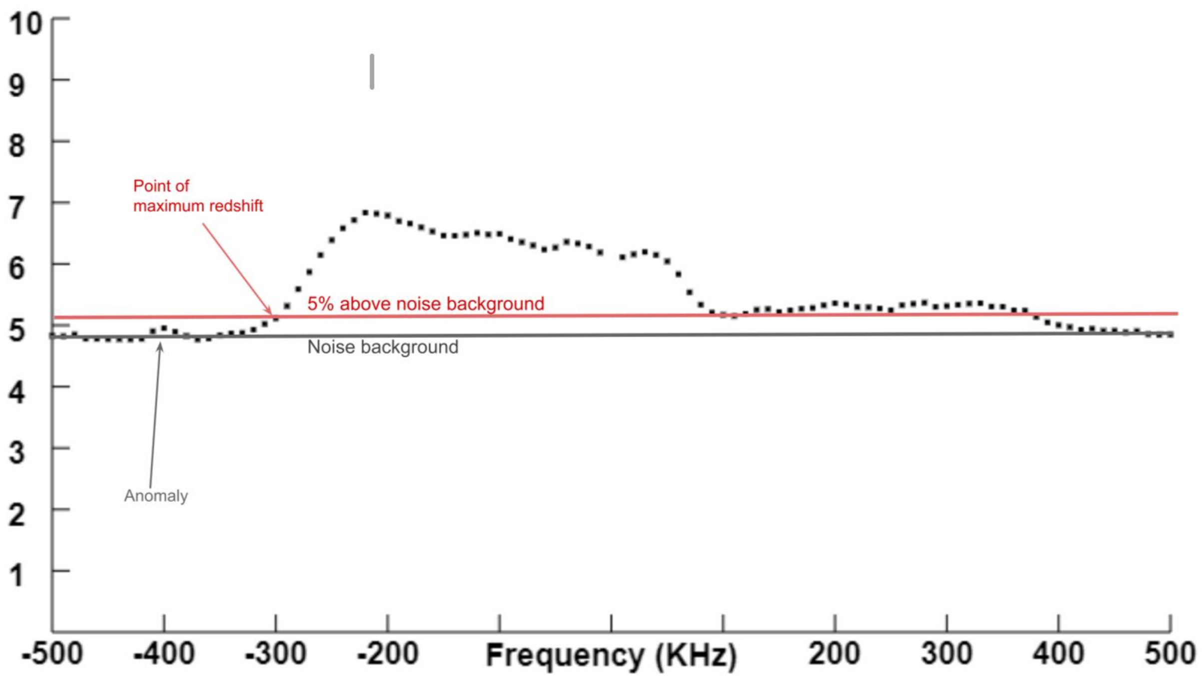
- Therefore, the orbital radius can be easily determined if the sun’s radius is known.

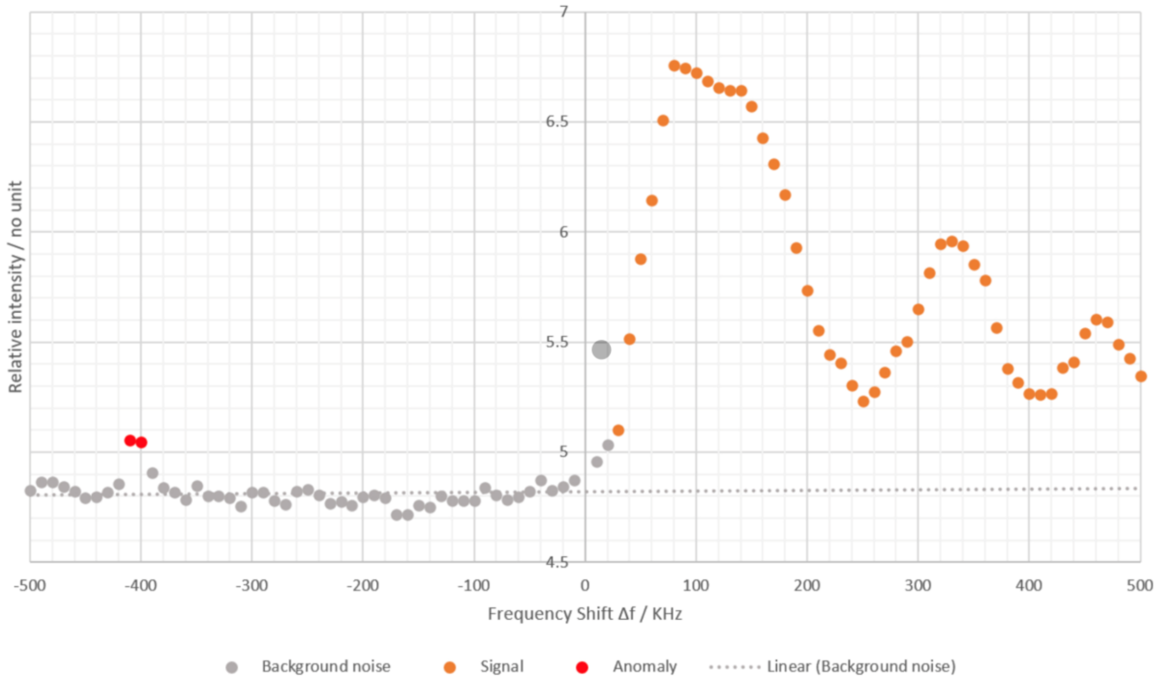
- There are other signals present, however their distances cannot be identified trigonometrically in the same way.

- Furthermore, this method only applies to galactic longitudes **0 < l < 90**, and is more inaccurate at **extremum** longitudes.









ν = observed frequency

ν_0 = source frequency

v_s = source velocity

c = velocity of light

$$\frac{\nu - \nu_0}{\nu_0} = \frac{\Delta \nu}{\nu_0} \approx \frac{v_s}{c}$$

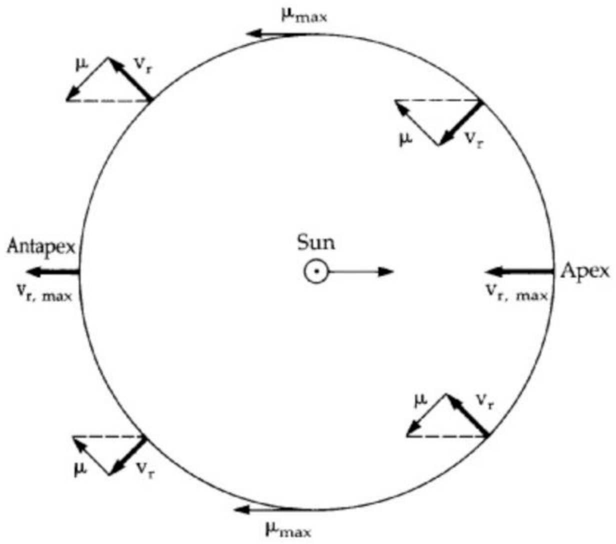
Low velocity Doppler shift expression

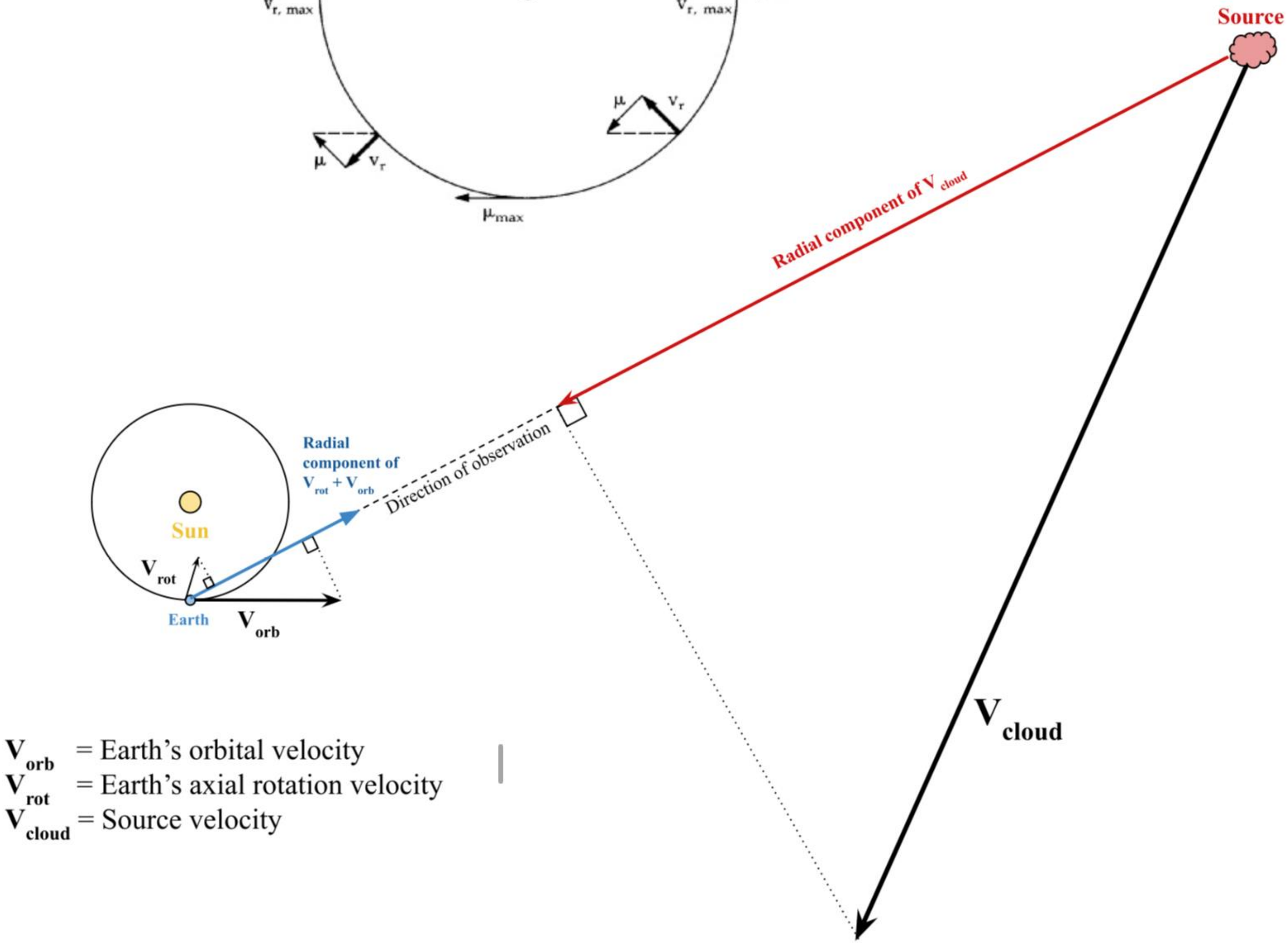
Local Standard of Rest

- The recessional velocity calculated also includes the Earth‘s rotation and revolution in the **direction of observation.**

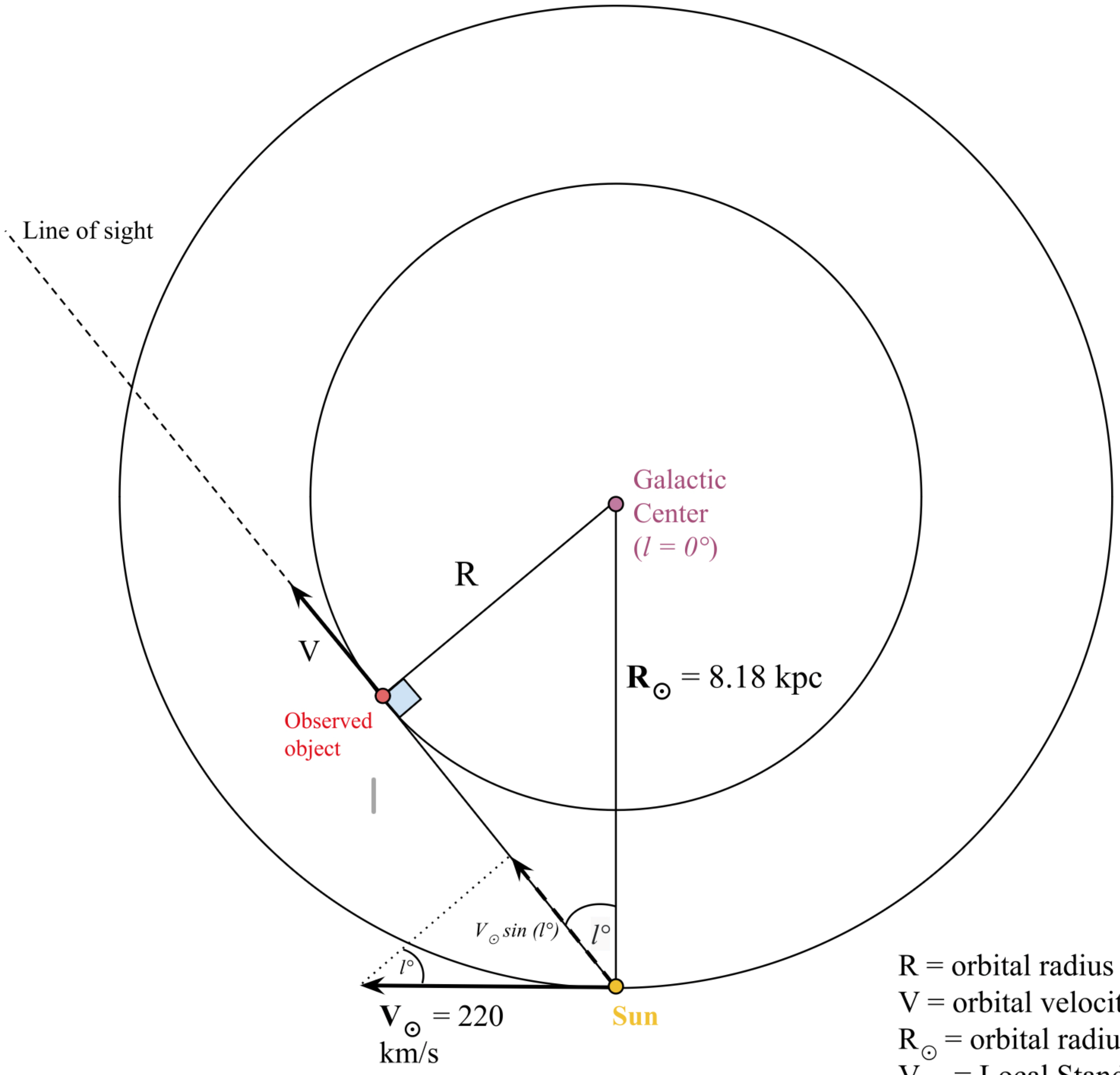
- The Sun’s trajectory deviates slightly from the tangent-point model, contributing an additional vector.

- This is called **peculiar motion.**





Corrections: Part 2



- Once the Recessional Velocity has been calculated relative to the Local Standard of Rest, the last set of calculations result in values for V and R.
- After this point, the rotation curve V(R) can be plotted.

R = orbital radius of observed object
V = orbital velocity of observed object
$R_\odot$ = orbital radius of the Sun
$V_\odot$ = Local Standard of Rest velocity
l° = Galactic longitude
$V_\odot \sin(l°)$ = Component of $V_\odot$ in the line of sight

$$V = V_{rec} + V_\odot sin(l)$$

$$R = R_\odot sin(l)$$

Coordinates

l / deg	RA / deg	Dec / deg	Telescope input	
0	266.7704369	-28.94377867	17h47m04.90486s	-28d56m37.6032s
2	267.9373087	-27.22903107	17h51m44.95408s	-27d13m44.5119s
4	269.0686901	-25.50490612	17h56m16.48563s	-25d30m17.6620s
6	270.1679681	-23.77234542	18h00m40.31234s	-23d46m20.4435s
8	271.2382788	-22.03220969	18h04m57.18691s	-22d01m55.9549s
10	272.2825497	-20.28528449	18h09m07.81192s	-20d17m07.0242s
12	273.3035	-18.53231056	18h13m12.84000s	-18d31m56.3180s
14	274.303684	-16.77396493	18h17m12.88416s	-16d46m26.2738s
16	275.2854996	-15.01088246	18h21m08.51990s	-15d00m39.1769s
18	276.2512138	-13.24366574	18h25m00.29131s	-13d14m37.1967s
20	277.2029907	-11.47287394	18h28m48.71778s	-11d28m22.3462s
22	278.1428811	-9.69904204	18h32m34.29147s	-09d41m56.5513s
24	279.0728653	-7.92268462	18h36m17.48767s	-07d55m21.6646s
26	279.9948498	-6.14428374	18h39m58.76396s	-06d08m39.4215s
28	280.9106916	-4.36431463	18h43m38.56598s	-04d21m51.5327s
30	281.8221978	-2.58323922	18h47m17.32747s	-02d34m59.6612s
32	282.7311485	-0.8015122	18h50m55.47563s	-00d48m05.4439s
34	283.6393109	0.9804225	18h54m33.43462s	+00d58m49.5210s
36	284.5484438	2.76211144	18h58m11.62650s	+02d45m43.6012s
38	285.4603039	4.54310454	19h01m50.47294s	+04d32m35.1763s
40	286.376679	6.32294457	19h05m30.40295s	+06d19m22.6004s
42	287.2993814	8.10117093	19h09m11.85153s	+08d06m04.2154s
44	288.230274	9.87730714	19h12m55.26577s	+09d52m38.3057s
46	289.1712659	11.65086475	19h16m41.10382s	+11d39m03.1131s
48	290.1243366	13.42132941	19h20m29.84078s	+13d25m16.7859s
50	291.0915562	15.18816246	19h24m21.97347s	+15d11m17.3848s
52	292.0750944	16.95079389	19h28m18.02264s	+16d57m02.8580s
54	293.0772326	18.70861834	19h32m18.53583s	+18d42m31.0260s
56	294.1003867	20.46100153	19h36m24.09282s	+20d27m39.6055s
58	295.1471295	22.20725561	19h40m35.31109s	+22d12m26.1202s
60	296.2202051	23.94665436	19h44m52.84922s	+23d56m47.9557s
62	297.3225549	25.67839914	19h49m17.41318s	+25d40m42.2369s
64	298.4573471	27.40162358	19h53m49.76329s	+27d24m05.8449s
66	299.6279935	29.11537913	19h58m30.71843s	+29d06m55.3649s
68	300.8381893	30.81862768	20h03m21.16544s	+30d49m07.0596s
70	302.0919386	32.51022286	20h08m22.06527s	+32d30m36.8023s
72	303.3935939	34.18890552	20h13m34.46253s	+34d11m20.0599s
74	304.7479008	35.85328164	20h18m59.49618s	+35d51m11.8139s
76	306.1600033	37.50181063	20h24m38.40080s	+37d30m06.5183s
78	307.6355355	39.13277195	20h30m32.52851s	+39d07m57.9790s
80	309.1806176	40.74425227	20h36m43.34822s	+40d44m39.3082s
82	310.8019151	42.33411079	20h43m12.45963s	+42d20m02.7988s
84	312.5066644	43.89995101	20h50m01.59945s	+43d53m59.8236s
86	314.3027061	45.43908954	20h57m12.64946s	+45d26m20.7223s
88	316.1984911	46.94851166	21h04m47.63786s	+46d56m54.6420s
90	318.2030661	48.4248447	21h12m48.73587s	+48d25m29.4409s

Data

l / deg	Lowest Δf / KHz	Orbit radius / kp	Orbit radius / kly	Rec. velocity/km/s	V_LSR correction	Corrected rec. /km/s	Orbital velocity
0	-150	**0**	0	31.659	13.128	18.531	**18.531**
2	-160	**0.285408084**	0.93089655	33.76978249	12.341	21.42878249	**29.10667176**
4	-180	**0.570468442**	1.860658947	37.9910053	11.539	26.4520053	**41.79842952**
6	-190	**0.854833773**	2.788154417	40.1016167	10.724	29.3776167	**52.37387862**
8	-200	**1.13815762**	3.71225295	42.21222811	9.895	32.31722811	**62.93531032**
10	-240	**1.420094797**	4.631828675	50.65467373	9.053	41.60167373	**79.80427282**
12	-250	**1.700301808**	5.545761231	52.76528514	8.201	44.56428514	**90.30485712**
14	-290	**1.978437262**	6.45293713	61.20773076	7.339	53.86873076	**107.0915478**
16	-310	**2.254162296**	7.35225112	65.42895357	6.468	58.96095357	**119.6011718**
18	-340	**2.52714098**	8.242607524	71.76078778	6.851	64.90978778	**132.8935265**
20	-420	**2.797040732**	9.12292158	88.64567903	5.979	82.66667903	**157.9111106**
22	-540	**3.063532721**	9.992120762	113.9730159	5.101	108.8720159	**191.2854664**
24	-530	**3.326292267**	10.84914608	111.8624045	4.216	107.6464045	**197.128466**
26	-520	**3.584999238**	11.69295339	109.7517931	3.325	106.4267931	**202.8684454**
28	-490	**3.83933844**	12.52251464	103.4199589	2.431	100.9889589	**204.2727027**
30	-510	**4.089**	13.33681913	107.6411817	1.534	106.1071817	**216.1071817**
32	-470	**4.333679743**	14.13487476	99.19873605	0.635	98.56373605	**215.1459742**
34	-440	**4.573079565**	14.91570922	92.86690184	-0.265	93.13190184	**216.1543406**
36	-370	**4.806907793**	15.67837119	78.092622	-2.443	80.535622	**209.8483775**
38	-370	**5.034879545**	16.42193148	78.092622	-3.341	81.433622	**216.8791466**
40	-350	**5.256717072**	17.14548418	73.87139919	-4.236	78.10739919	**219.5206733**
42	-320	**5.472150099**	17.84814774	67.53956497	-5.124	72.66356497	**219.8722984**
44	-300	**5.680916154**	18.52906609	63.31834216	-6.007	69.32534216	**222.1501837**
46	-290	**5.882760887**	19.18740962	61.20773076	-6.883	68.09073076	**226.3454868**
48	-280	**6.077438383**	19.82237625	59.09711935	-7.75	66.84711935	**230.338981**
50	-270	**6.264711456**	20.43319237	56.98650795	-8.607	65.59350795	**234.1232854**
52	-240	**6.444351943**	21.01911379	50.65467373	-9.454	60.10867373	**233.4710395**
54	-210	**6.61614098**	21.57942665	44.32283951	-10.29	54.61283951	**232.5965783**
56	-160	**6.779869268**	22.11344831	33.76978249	-11.113	44.88278249	**227.2710484**
58	-140	**6.93533733**	22.62052814	29.54855968	-11.923	41.47155968	**228.0421408**
60	-130	**7.082355752**	23.10004834	27.43794827	-12.718	40.15594827	**230.6815371**
62	-100	**7.220745414**	23.55142469	21.10611405	-12.811	33.91711405	**228.1655845**
64	-80	**7.350337711**	23.97410726	16.88489124	-13.585	30.46989124	**228.2045814**
66	-40	**7.470974753**	24.36758107	8.442445622	-14.343	22.78544562	**223.7654463**
68	10	**7.582509563**	24.73136674	-2.110611405	-15.083	12.97238859	**216.9528366**
70	-10	**7.684806253**	25.06502104	2.110611405	-15.805	17.91561141	**224.647988**
72	10	**7.77774019**	25.36813748	-2.110611405	-16.507	14.39638859	**223.6288222**
74	30	**7.861198149**	25.64034675	-6.331834216	-17.189	10.85716578	**222.3347389**
76	20	**7.935078449**	25.88131721	-4.221222811	-17.851	13.62977719	**227.094837**
78	30	**7.999291079**	26.09075527	-6.331834216	-18.49	12.15816578	**227.3506379**
80	30	**8.053757804**	26.26840576	-6.331834216	-19.107	12.77516578	**229.4328714**
82	30	**8.098412266**	26.41405225	-6.331834216	-19.701	13.36916578	**231.2281409**
84	30	**8.13320006**	26.52751728	-6.331834216	-20.271	13.93916578	**232.7339828**
86	60	**8.158078803**	26.60866262	-12.66366843	-20.797	8.133331568	**227.5974226**
88	70	**8.173018183**	26.6573894	-14.77427984	-21.307	6.532720162	**226.3987021**
90	70	**8.178**	26.67363826	-14.77427984	-21.79	7.015720162	**227.0157202**

Errors

l / deg	X positive error	X negative erro	Ver fov up	Ver fov down	Y positive error	Y negative error
0	0.085638251	0.085638251	2.303792506	2.303792506	4.414403911	4.414403911
2	0.085601731	0.085570433	2.302810081	2.301968114	4.413421486	4.412579519
4	0.085460919	0.085398361	2.299022037	2.297339129	4.409633442	4.407950534
6	0.085215986	0.085122244	2.292432989	2.28991119	4.403044394	4.400522595
8	0.084867231	0.084742419	2.283050964	2.279693346	4.39366237	4.390304752
10	0.084415078	0.084259348	2.270887394	2.266698048	4.381498799	4.377309453
12	0.083860078	0.083673621	2.255957096	2.250941127	4.366568502	4.361552533
14	0.083202907	0.082985949	2.238278263	2.232441782	4.348889669	4.343053187
16	0.082444367	0.082197173	2.217872433	2.211222549	4.328483838	4.321833955
18	0.081585381	0.081308251	2.194764466	2.187309283	4.305375872	4.297920689
20	0.080626996	0.080320269	2.168982517	2.160731117	4.279593923	4.271342523
22	0.079570379	0.079234428	2.140557997	2.131520434	4.251169403	4.242131839
24	0.078416817	0.078052052	2.109525537	2.099712821	4.220136942	4.210324226
26	0.077167717	0.076774582	2.075922945	2.065347031	4.18653435	4.175958436
28	0.075824601	0.075403574	2.03979116	2.028464934	4.150402566	4.139076339
30	0.074389103	0.073940698	2.001174205	1.989111465	4.11178561	4.09972287
32	0.072862974	0.072387737	1.960119126	1.94733457	4.070730532	4.057945976
34	0.071248072	0.070746582	1.916675945	1.903185148	4.02728735	4.013796554
36	0.069546366	0.069019234	1.870897589	1.856716988	3.981508994	3.967328394
38	0.067759928	0.067207797	1.822839833	1.807986704	3.933451238	3.91859811
40	0.065890935	0.065314477	1.772561227	1.757053667	3.883172632	3.867665073
42	0.063941664	0.063341581	1.720123028	1.703979931	3.830734433	3.814591337
44	0.06191449	0.061291514	1.665589124	1.648830158	3.776200529	3.759441563
46	0.059811883	0.059166772	1.609025956	1.591671539	3.719637362	3.702282945
48	0.057636404	0.056969945	1.550502439	1.532573714	3.661113844	3.643185119
50	0.055390704	0.054703708	1.490089873	1.471608683	3.600701278	3.582220089
52	0.05307752	0.052370824	1.427861861	1.408850724	3.538473267	3.51946213
54	0.050699668	0.049974133	1.36389422	1.344376298	3.474505626	3.454987703
56	0.048260046	0.047516557	1.298264885	1.278263956	3.40887629	3.388875361
58	0.045761628	0.04500109	1.231053813	1.210594246	3.341665218	3.321205652
60	0.043207455	0.042430795	1.162342892	1.141449614	3.272954297	3.252061019
62	0.040600641	0.039808805	1.092215835	1.070914301	3.20282724	3.181525706
64	0.037944362	0.037138314	1.020758081	0.999074244	3.131369487	3.10968565
66	0.035241853	0.034422576	0.948056691	0.926016969	3.058668096	3.036628375
68	0.032496407	0.031664899	0.87420024	0.851831485	2.984811645	2.96244289
70	0.02971137	0.028868644	0.79927871	0.776608176	2.909890116	2.887219581
72	0.026890133	0.026037216	0.723383383	0.700438689	2.833994788	2.811050094
74	0.024036135	0.023174066	0.646606724	0.623415825	2.75721813	2.73402723
76	0.021152853	0.020282683	0.569042275	0.545633425	2.67965368	2.656244831
78	0.0182438	0.017366587	0.490784535	0.467186255	2.60139594	2.577797661
80	0.015312519	0.014429333	0.41192885	0.388169891	2.522540255	2.498781296
82	0.012362582	0.0114745	0.332571293	0.308680601	2.443182698	2.419292007
84	0.009397583	0.008505686	0.252808549	0.228815232	2.363419954	2.339426637
86	0.006421135	0.00552651	0.172737797	0.148671086	2.283349202	2.259282491
88	0.003436864	0.0025406	0.09245659	0.068345808	2.203067996	2.178957213
90	0.000448405	0	0.01206274	0	2.122674145	2.110611405

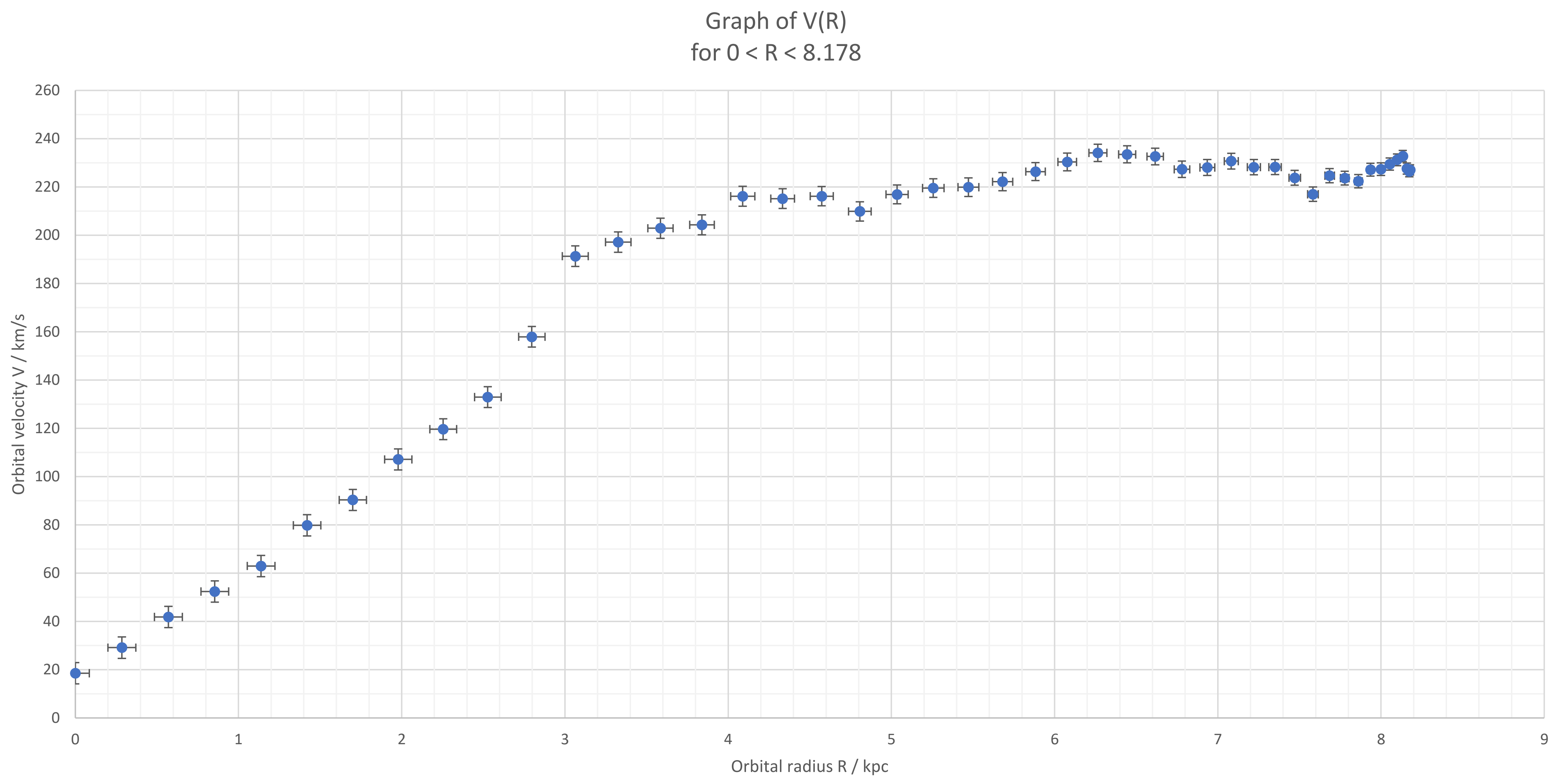
References

λ_0 21cm line /m	c / vacuum / m/s	f 21cm line/ H	pi for conversion	solar orbit r / pc
0.211061141	299792458	1420405752	3.141592654	8178
LSR velocity km/s	1 AU in m	1 pc to m	1 ly to m	G constant
220	1.49598E+11	3.0857E+16	9.46053E+15	6.67428E-11
Solar mass	Interior mass MO			
1.988E+30	9.94E+40			

- The above Microsoft Excel spreadsheet was used to organize and process data efficiently, to reproduce the calculation for each data point.

- The columns are color coded for input and processed data, as well as the data category.

- The rotation curve was graphed in Excel, with the error bars in X and Y also shown.

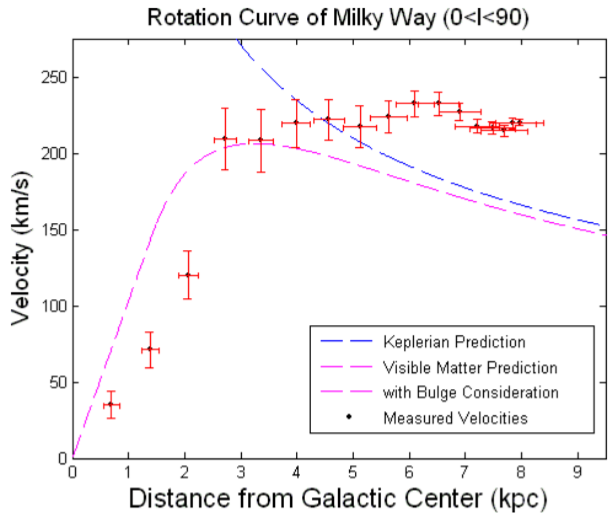


Graph of V(R)
for 0 < R < 8.178
Orbital velocity V / km/s
Orbital radius R / kpc
0
20
40
60
80
100
120
140
160
180
200
220
240
260
0
1
2
3
4
5
6
7
8
9

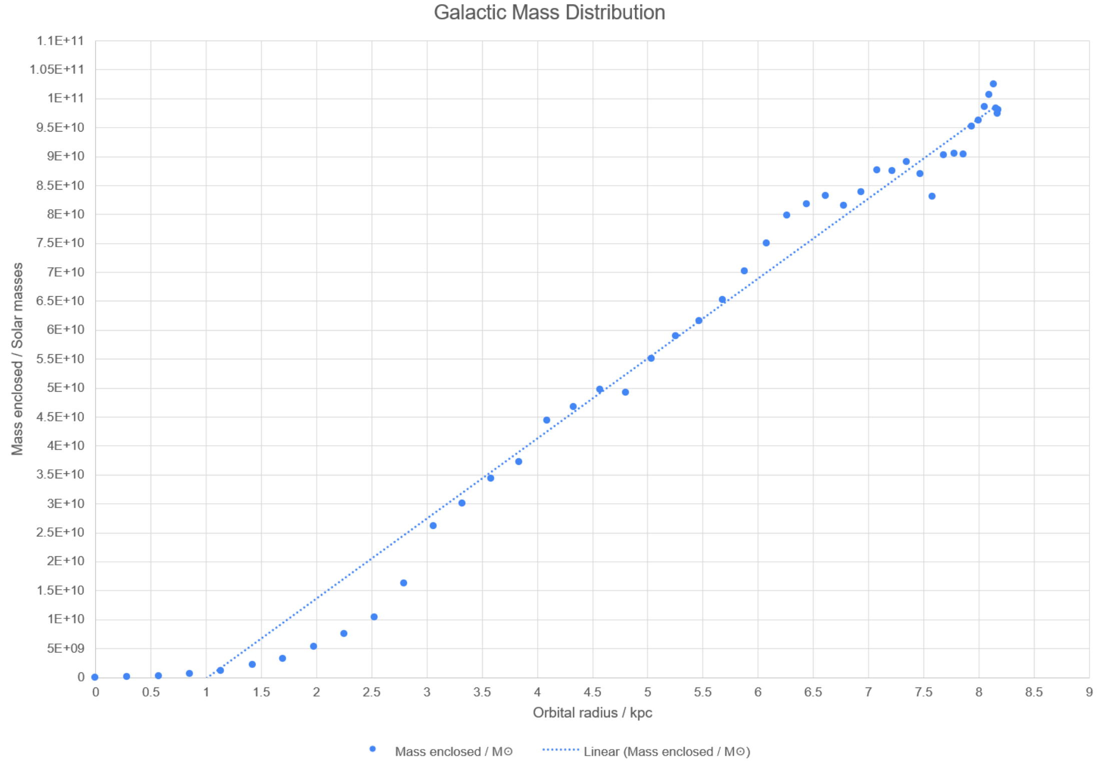
Analysis

- The rotation curve observed is **strongly inconsistent** with the Keplerian hypothesis.
- However, my results are concordant with the literature, which suggests **“dark matter”** as a possible explanation.
- This enigmatic concept refers to a gravitational influence that **does not interact with light** and is thus invisible to us.
- The mass enclosed at each radius can be calculated by re-deriving the orbital velocity equation:

$$V = \sqrt{\frac{GM}{R}} \qquad V^2R = GM \qquad M = \frac{V^2R}{G}$$

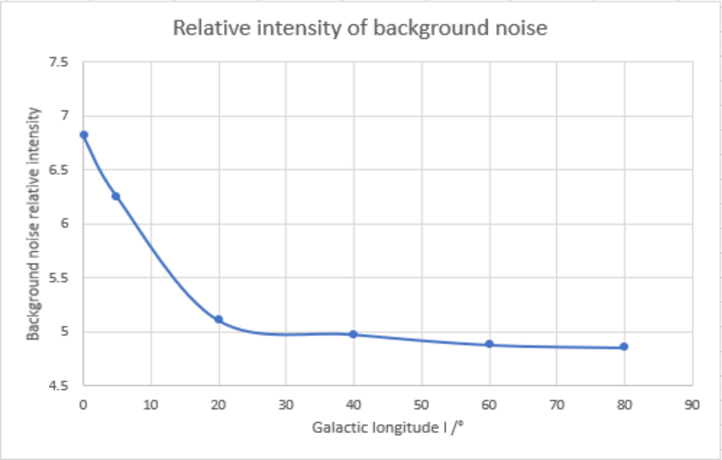


Liu & Chronopoulos (2008)



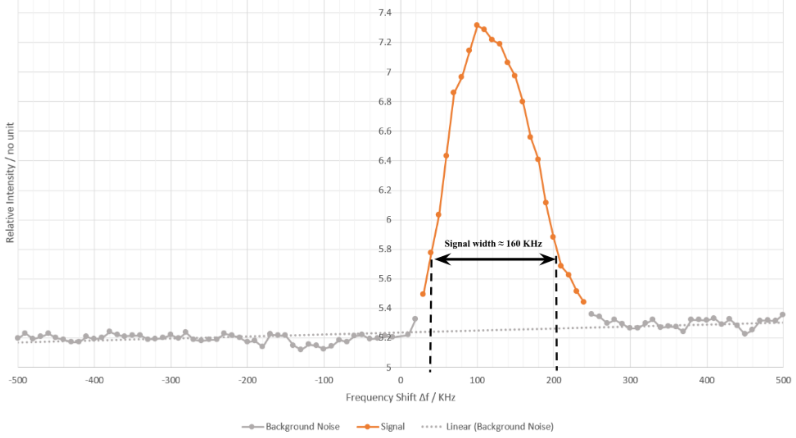
Interpretation of Raw Data

Increase in Background Noise:



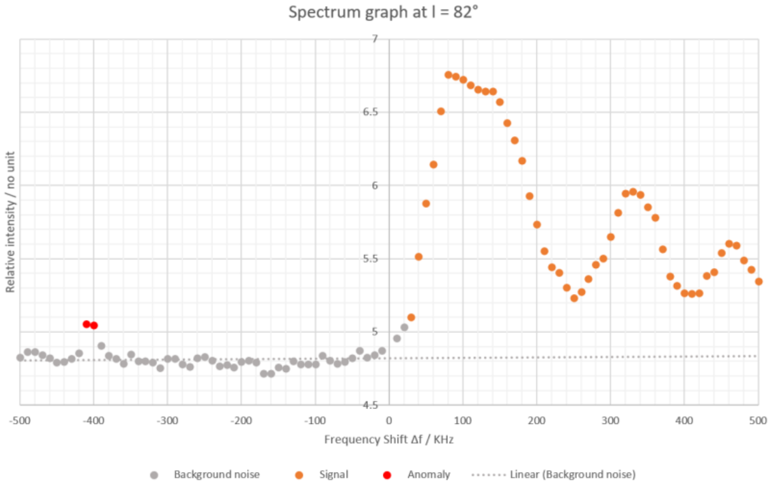
- Higher atmospheric interference and ground-based emission near the horizon
- Increased matter density near the Galactic Center.

Local Velocity Dispersion



- The random motions of local hydrogen gas contribute to the observed Doppler shift
- According to Liu & Chronopoulos, this is shown by the signal width at l = 180.

Nature of Intensity Peaks:



- Separated, individual peaks represent different spiral arms of the galaxy
- A unified signal with more peaks indicates a single complex mass that can be rotating or expanding.

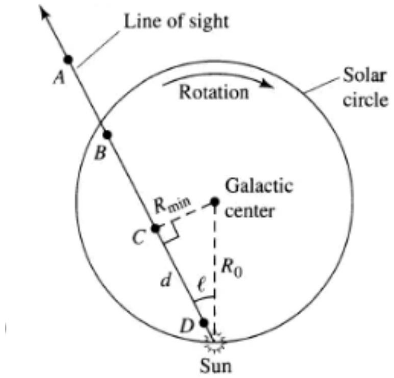
Errors and Uncertainties

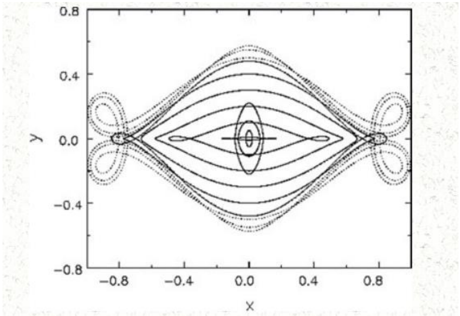
Systematic Error:

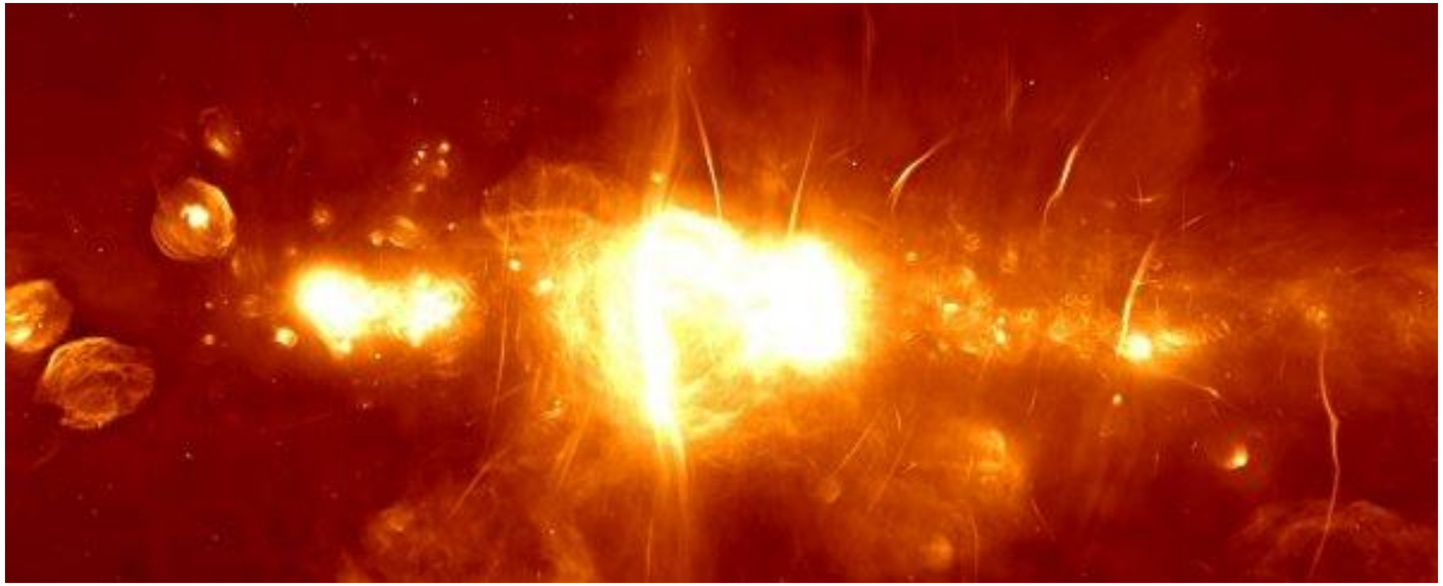
- Background noise near the Galactic Center
- Assumption of orbital circularity
- Tangent-point method at extremum longitudes

Random Error:

- Field of View Uncertainty (error bars included)



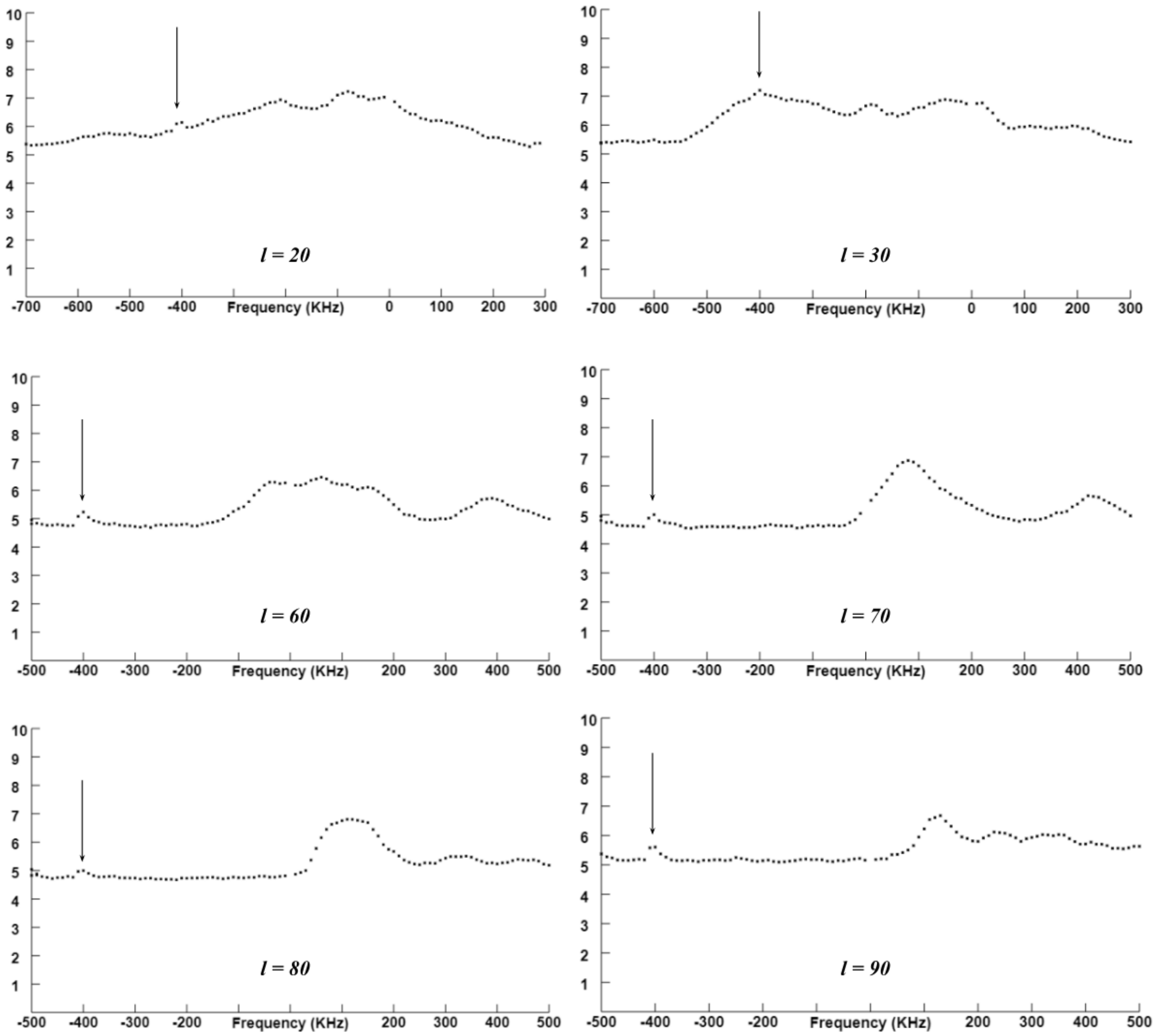




The Anomaly

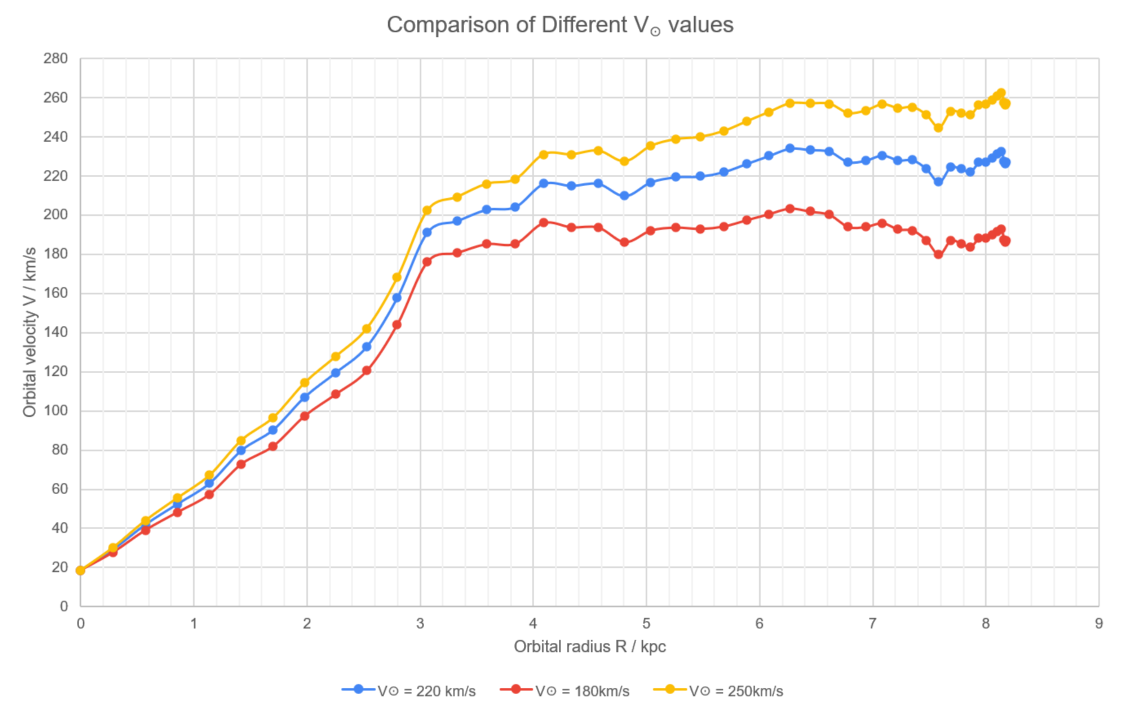
Throughout almost all observations, an anomalous signal was detected nearby 1420.0 MHz ([H I] - 400 KHz).

Possible causes include electrical component interference or a ground-based emission source near the telescope.



Galactic Constant Uncertainty

- Perhaps the greatest sources of uncertainty in my investigation are the values for the Sun's orbital velocity and radius.
- Astronomers have not reached a consensus on either of these values
- Modern estimates have greater accuracies, but individual results still diverge greatly.



Applications

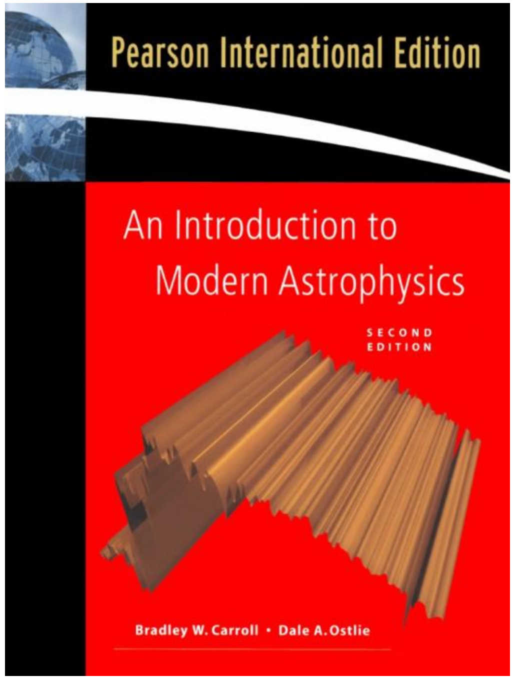
- Determining the distribution of dark matter in the galaxy that would mathematically fit the rotation curve.
- Producing a more accurate model of the mass distribution at the center of the galaxy.
- Mapping out the spiral arms of the galaxy by analyzing the other peaks.
- Mapping the velocity dispersion of local atomic hydrogen clouds.

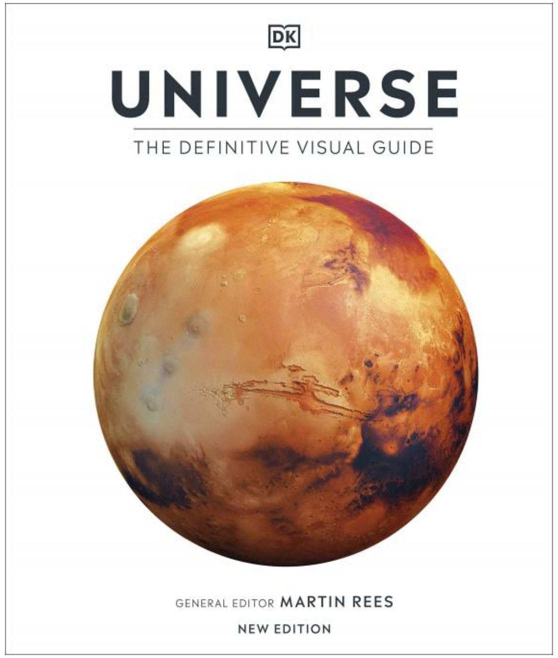
Research and Sources

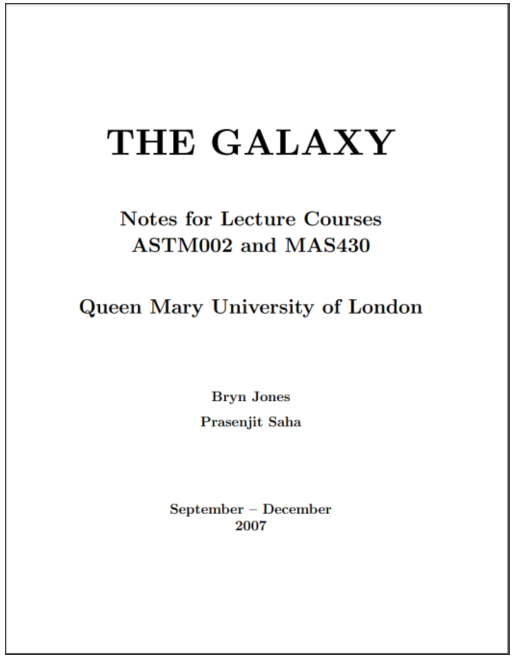
- Pisgah Astronomical Research Institute
- NRAO, GBO, NASA, ESA, IAU, MIT, Caltech, CSIRO Australia, Swinburne University, Institute of Physics
- ArXiv, SAO/NASA Astrophysics Data System, ResearchGate, JSTOR, Google Scholar, ScienceDirect

<u>Other Important Sources</u>

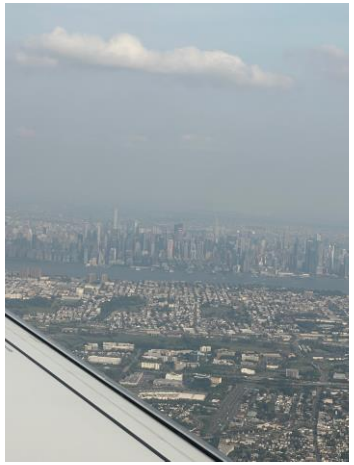
- Universe: A Definitive Visual Guide, The Galaxy, An Introduction to Modern Astrophysics
- Yoshiaki Sofue's work
- Liu & Chronopoulos (2008)
- Bertone & Hooper (2018)
- Carl Nave's Hyper Physics
- Nick Strobel's Astronomy Notes

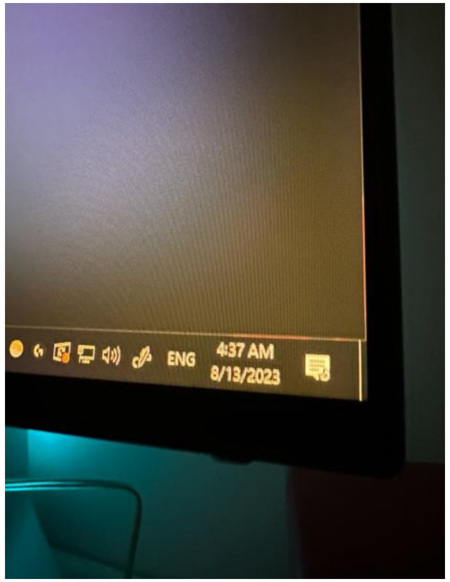


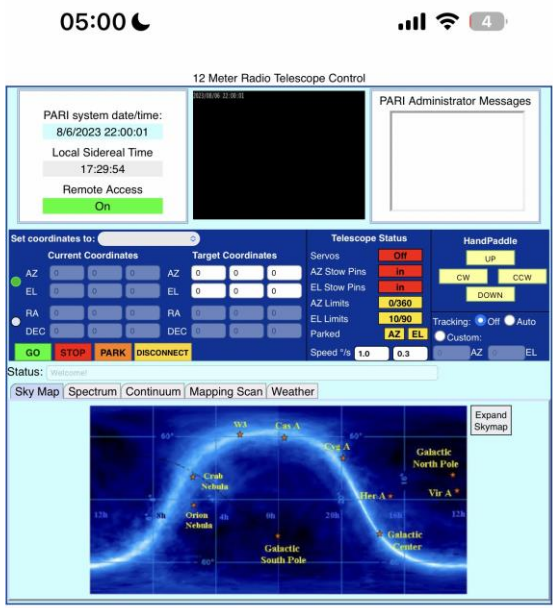


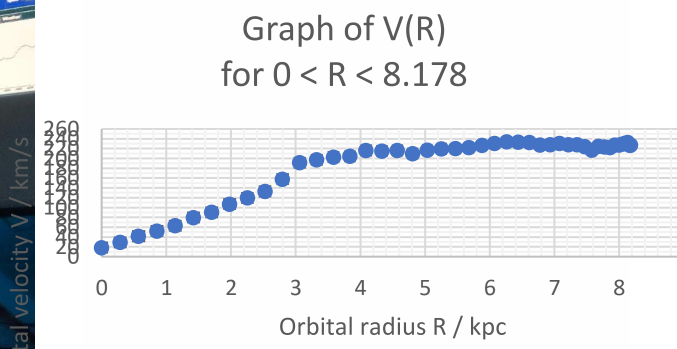


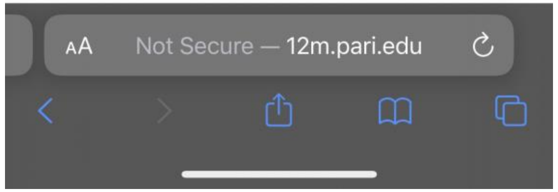
Reflection & Conclusion











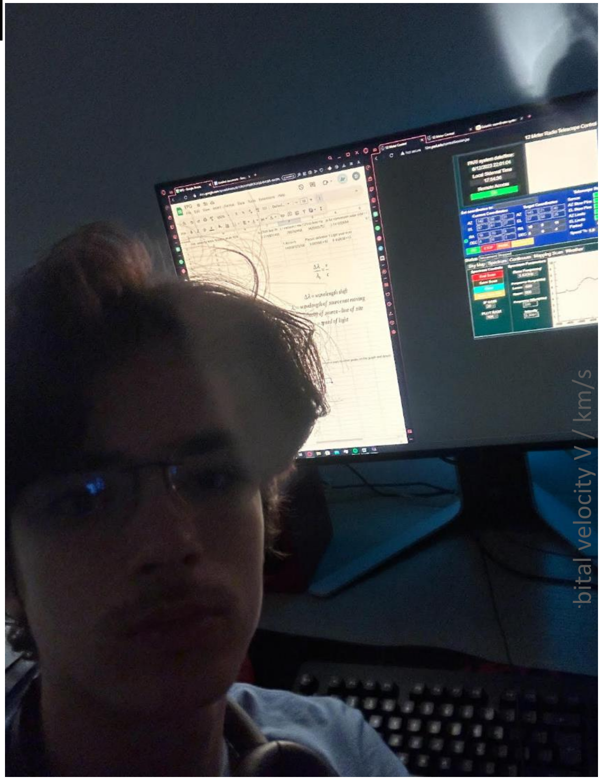


Image Links:

- Many of the images in this presentation were also part of my EPQ project document, and already cited in my Reference List, so I did not include them again here to avoid redundancies. All of my EPQ's citations apply to this Presentation. Some images were also taken by myself, so I obviously did not cite them. The web links for all other images are shown below:

- https://en.wikipedia.org/wiki/Australia_Telescope_Compact_Array
- https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.atascientific.com.au%2Fspectrometry%2F&psig=AOvVaw0Gr_1CnWbwCw__EmrHtKhF&ust=1695414088028000&source=images&cd=vfe&opi=89978449&ved=0CA4QjRxqFwoTCLD39-XDvIEDFQAAAAAdAAAAABAD
- https://www.ligo.caltech.edu/system/avm_image_sqls/binaries/49/titanic/ligo20160211e.jpg?1455160282
- https://www.astronomy.com/science/how-do-you-measure-the-rotational-speed-of-a-galaxy-taking-into-consideration-the-motion-of-our-galaxy-solar-system-planet-etc/
- https://www.nmspacemuseum.org/wp-content/uploads/2019/03/Johannes_Kepler_1610.jpg
- https://encrypted-tbn1.gstatic.com/licensed-image?q=tbn:ANd9GcTK7CkPsFE6PaRQai1flgCnxCBnGzZFxyKIUXdrzjOZv5CqfN1ILfB5TQH967my7suUylY5IZmKbc8ikPk
- https://cdn.eso.org/images/screen/_DSC7159-CC.jpg
- http://www-ssg.sr.unh.edu/ism/what1.html
- https://www.gb.nrao.edu/fgdocs/HI21cm/
- https://www.nrao.edu/archives/static/Ewen/ewen_HI_slide18.shtml
- http://astronomyonline.org/ViewImage.asp?Cate=Home&SubCate=MP01&SubCate2=&Img=%2FScience%2FImages%2FHydrogen%2Egif&Cpt=The+spin-flip+transition+of+a+hydrogen+atom%2E
- https://commons.wikimedia.org/wiki/File:Hydrogen-SpinFlip.svg
- https://w.astro.berkeley.edu/~mwhite/darkmatter/rotcurve.html
- https://bigthink.com/starts-with-a-bang/21cm-magic-length/
- https://imgv2-1-f.scribdassets.com/img/document/331051489/original/a44b2bf4c2/1691163811?v=1
- https://www.nasa.gov/sites/default/files/thumbnails/image/nasa-logo-web-rgb.png

Image Links pt. 2

- https://public.nrao.edu/wp-content/uploads/2018/02/NRAO-Logo_Round.png
- https://www.iau.org/static/archives/images/screen/iau_wb.jpg
- https://i.pinimg.com/originals/5b/49/f8/5b49f80da12e639ff39eaadb28c3ddaa.png
- https://upload.wikimedia.org/wikipedia/commons/thumb/0/0c/MIT_logo.svg/2560px-MIT_logo.svg.png
- https://info.arxiv.org/brand/images/brand-logo-primary.jpg
- https://media.licdn.com/dms/image/C4D03AQEJDZBft3SB0A/profile-displayphoto-shrink_200_200/0/1517361669091?e=1700697600&v=beta&t=cMhKTwCyoH2oIRo_tZPokx-_RURqPKp6mgJGo1O88O0
- https://i1.rgstatic.net/ii/profile.image/278797816483845-1443481987488_Q128/Rod-Nave.jpg
- https://bio.illibraio.it/images/2843670217541_92_300_0_75.jpg
- https://www.bakersfield.com/entertainment/nick-strobel-astronomy-research-to-feel-impact-of-satellite-network/article_11c79c6a-7e79-11ea-95d2-0feba76cba04.html
- https://en.wikipedia.org/wiki/Dan_Hooper#/media/File:HooperLectures_2017.jpg
- https://science.nasa.gov/horsehead-nebula
- https://scitechdaily.com/cold-interstellar-molecular-clouds-as-cosmic-ray-detectors/
- https://en.wikipedia.org/wiki/Orion_Nebula#/media/File:Orion_Nebula_-_Hubble_2006_mosaic_18000.jpg
- https://www.centauri-dreams.org/2005/08/27/a-stunning-view-of-interstellar-dust/

Image Links Pt. 3

- https://www.worldatlas.com/space/the-interstellar-medium.html
- https://photojournal.jpl.nasa.gov/figures/PIA10748_fig1.jpg
- https://hubblesite.org/contents/articles/hubble-deep-fields
- https://www.nasa.gov/images/content/537083main_hs-2011-11-a-print_full.jpg
- https://upload.wikimedia.org/wikipedia/commons/thumb/0/06/Logo_of_Swinburne_University_of_Technology.svg/1200px-Logo_of_Swinburne_University_of_Technology.svg.png
- https://public.nrao.edu/wp-content/uploads/2013/09/gallery-images-largeJanskywGraph_large.jpg
- https://astro.ucla.edu/~wright/doppler.htm
- http://www.solstation.com/x-objects/darkhalo.htm
- https://en.wikipedia.org/wiki/Dark_matter_halo#/media/File:Dark_matter_halo.png
- https://www.sciencealert.com/something-near-the-galactic-centre-is-flashing-radio-signals-and-we-don-t-know-what-it-is


QUESTIONS