

# THE GREEN BANK OBSERVATORY

# ULTRA WIDEBAND RECEIVER

ALYSSA BULATEK  
APRIL 2, 2020



Image credit: Greta Helmel

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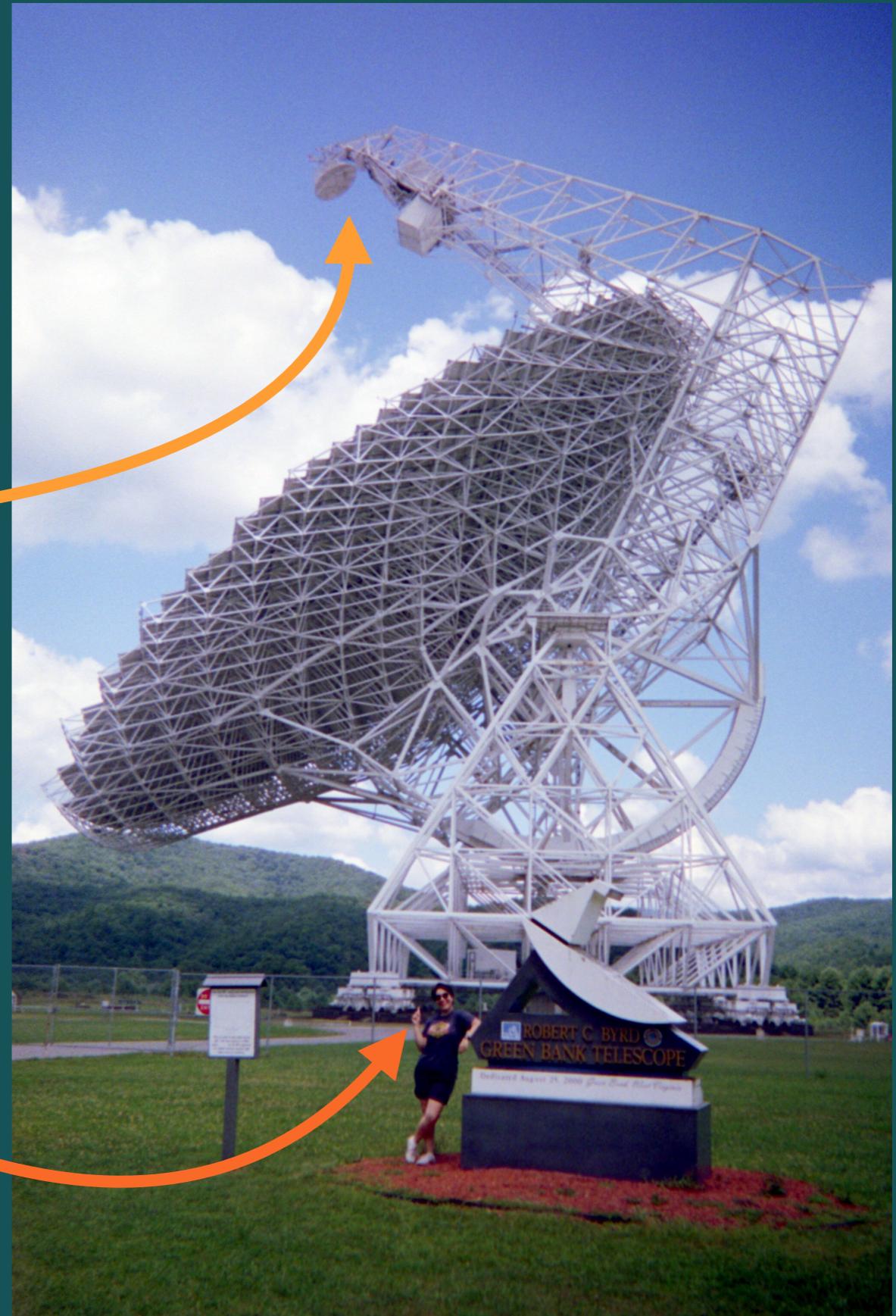


Image credit: Greta Helmel

# QUICK OUTLINE

## Act I

*The Future of Radio Astronomy (imo)*

Telescopes, pulsars, and gravitational waves

## Act II

*How do you make a radio receiver?*

Some basics

## Act III

*How do I know my receiver works?*

Receiver efficiency analysis

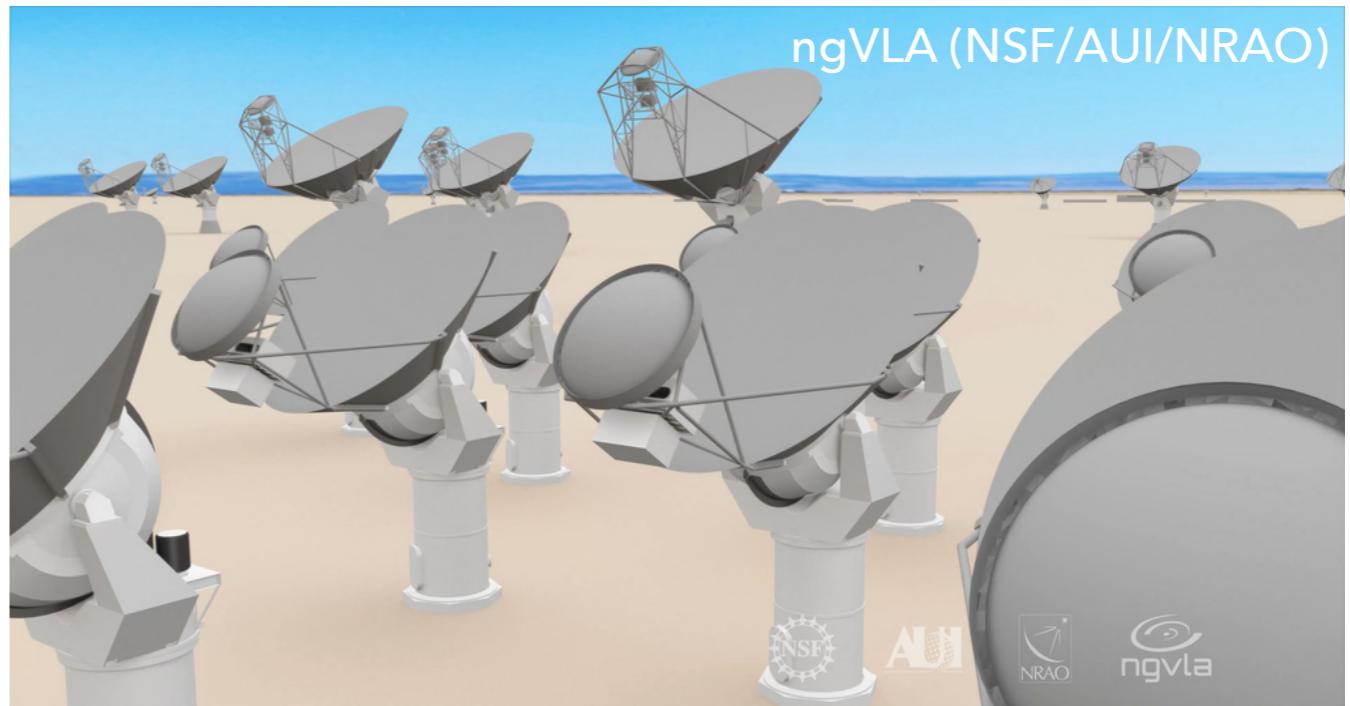
## Act IV

*Troubleshooting a receiver in 3 easy steps*

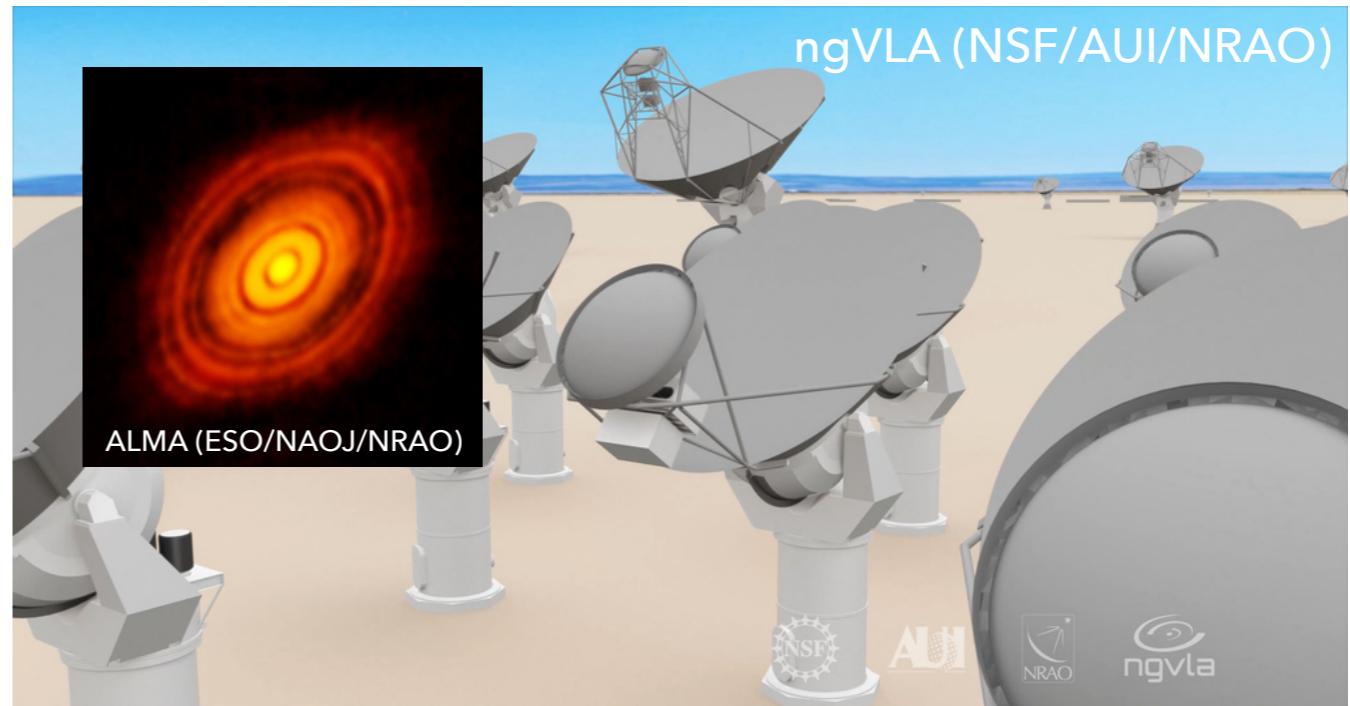
A waveguide mode breakdown tutorial

# ACT I

# THE FUTURE OF RADIO ASTRONOMY



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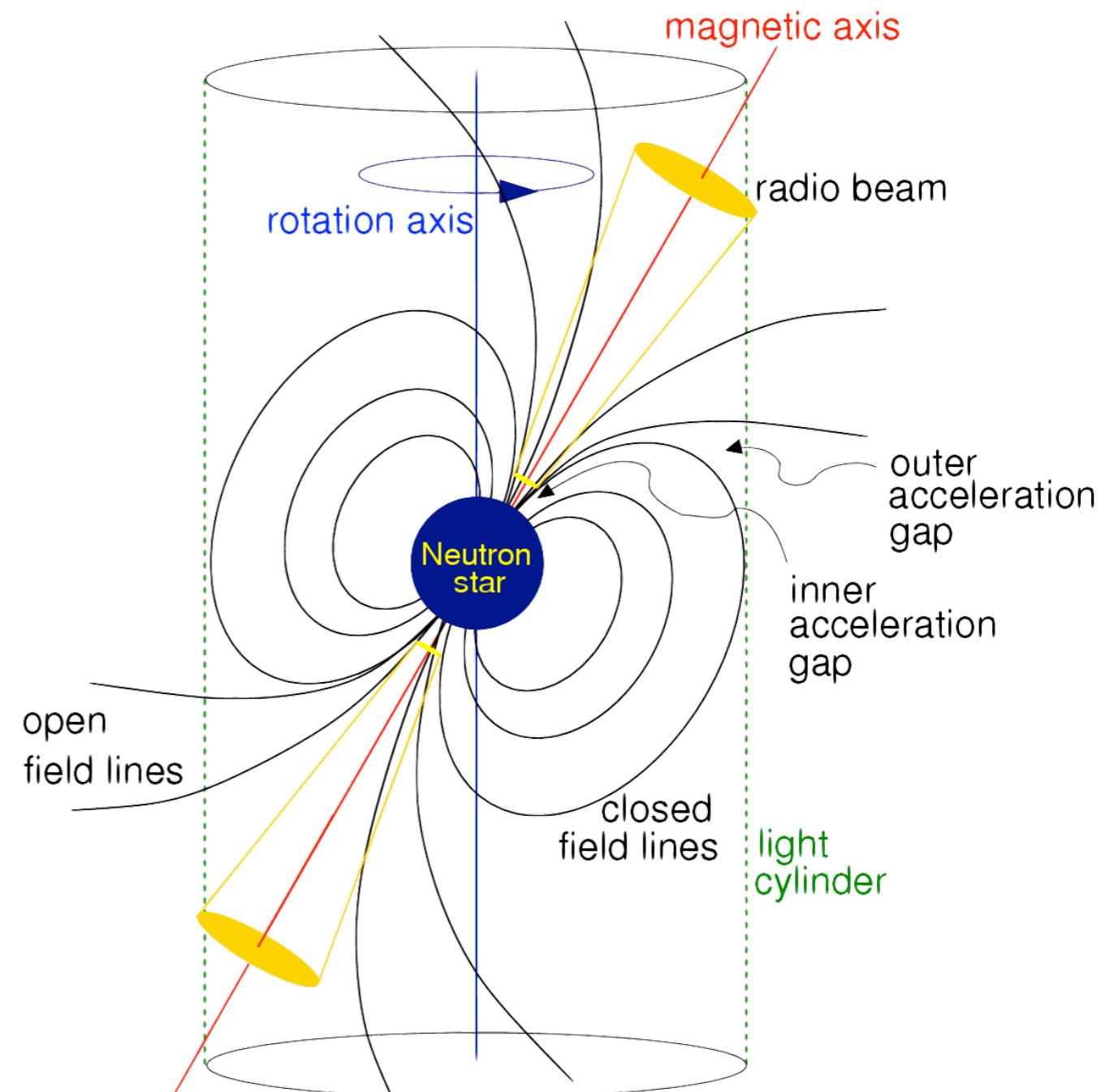


PULSARS



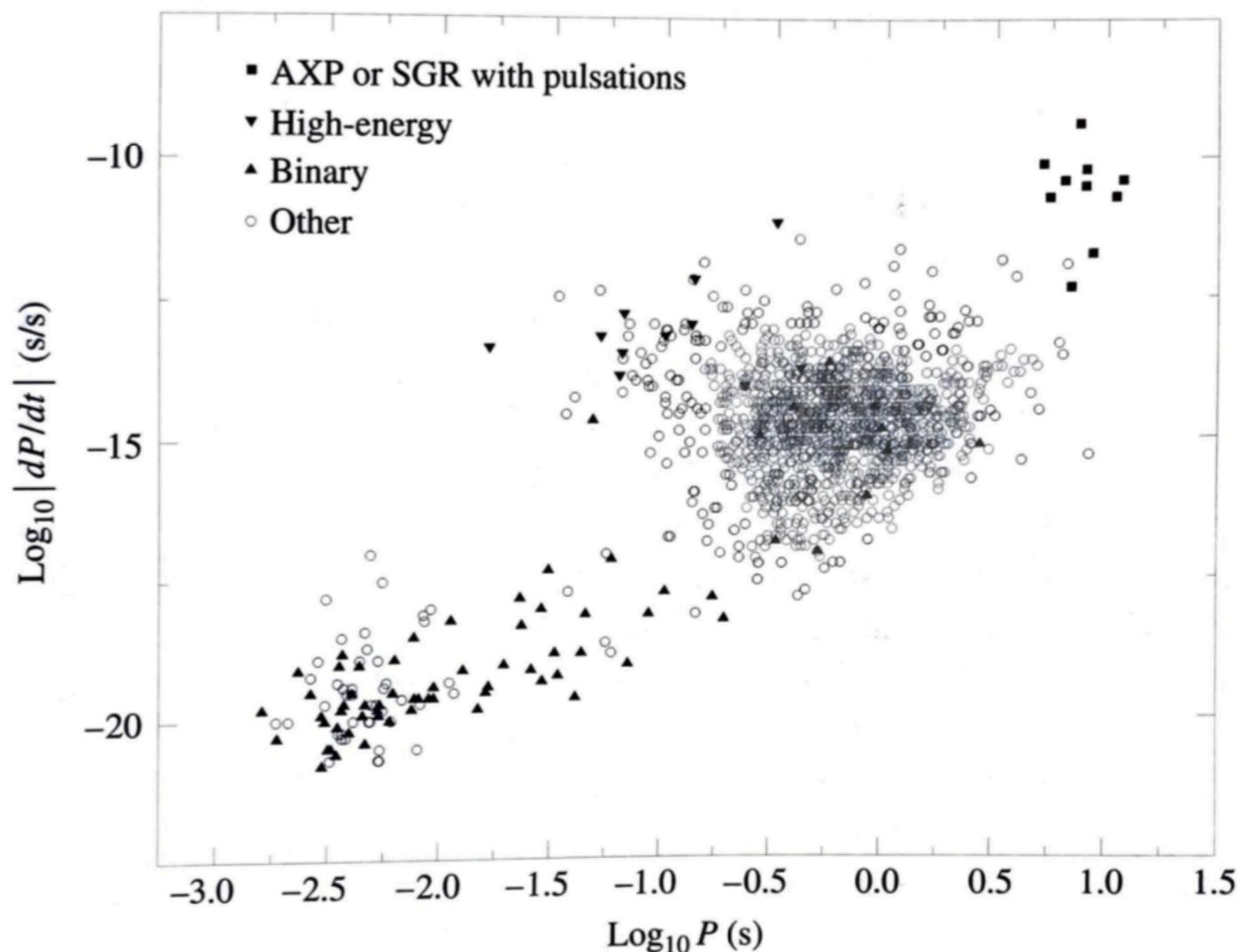
# PULSARS

- Pulsars are radio-bright, rapidly rotating neutron stars
- Signals look **periodic** due to Earth passing through radio beam
- Signals have a **wide bandwidth** (important later)



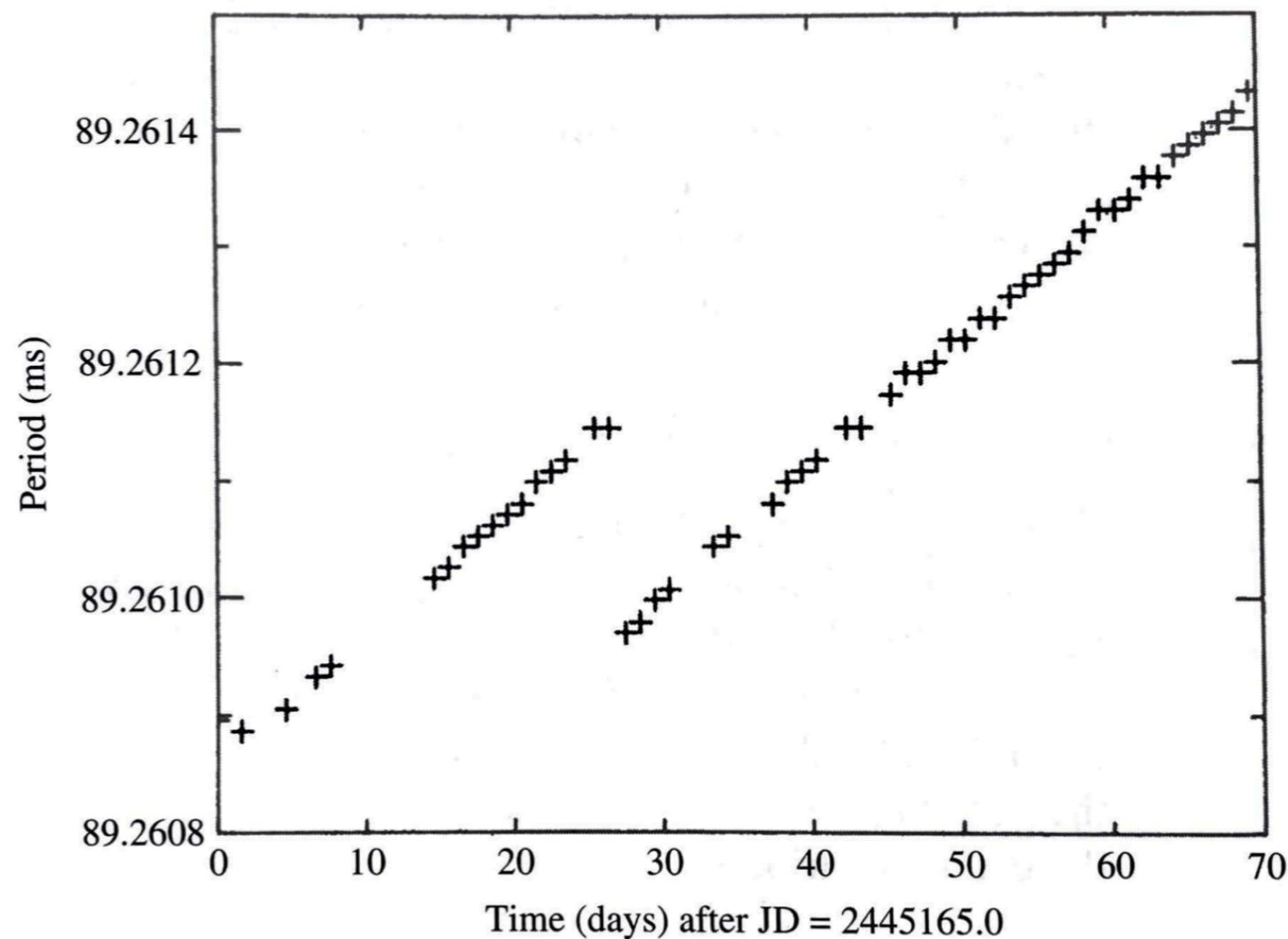
## PULSAR TIMING

- Tend to **slow** rotation over time (typical spin-down rate  $\sim 10^{-15}$ )
  - Fastest-rotating pulsars have more stable periods
- “Glitches” can spontaneously **increase** rotation speed
- In general, pulsars are good **clocks**



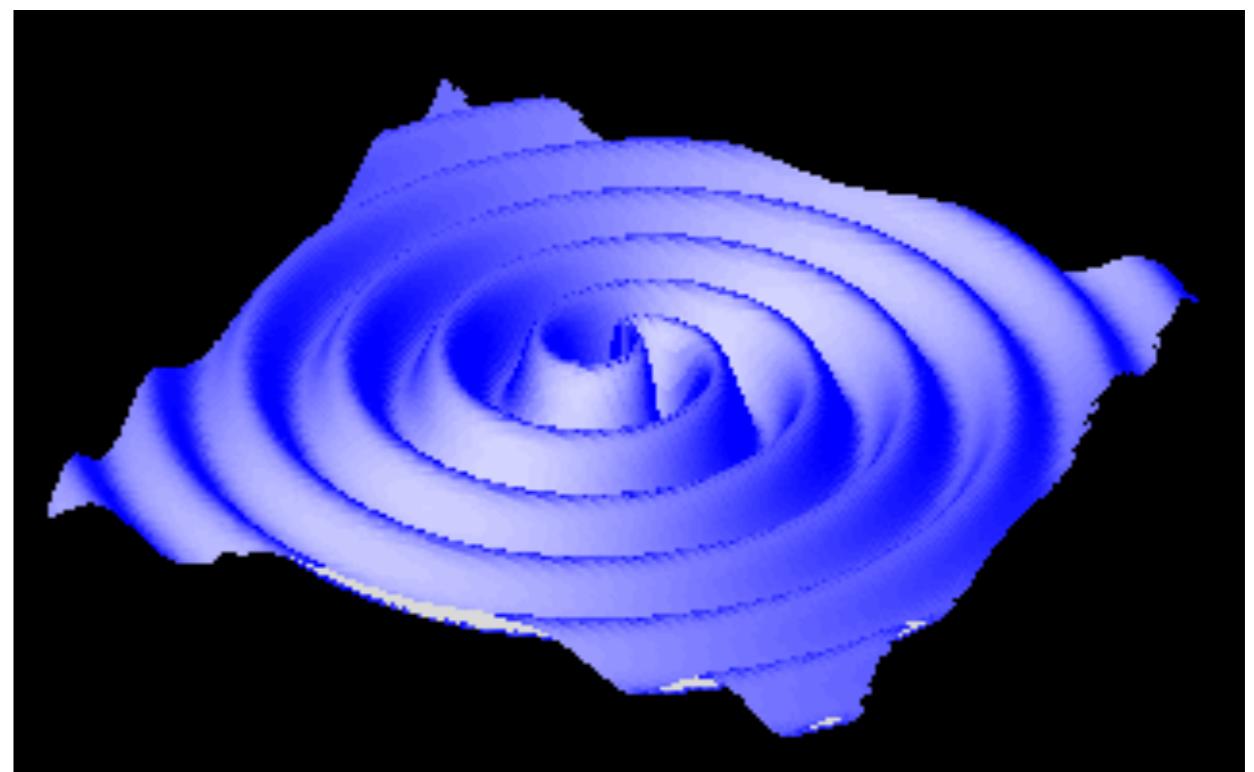
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## GRAVITATIONAL WAVES

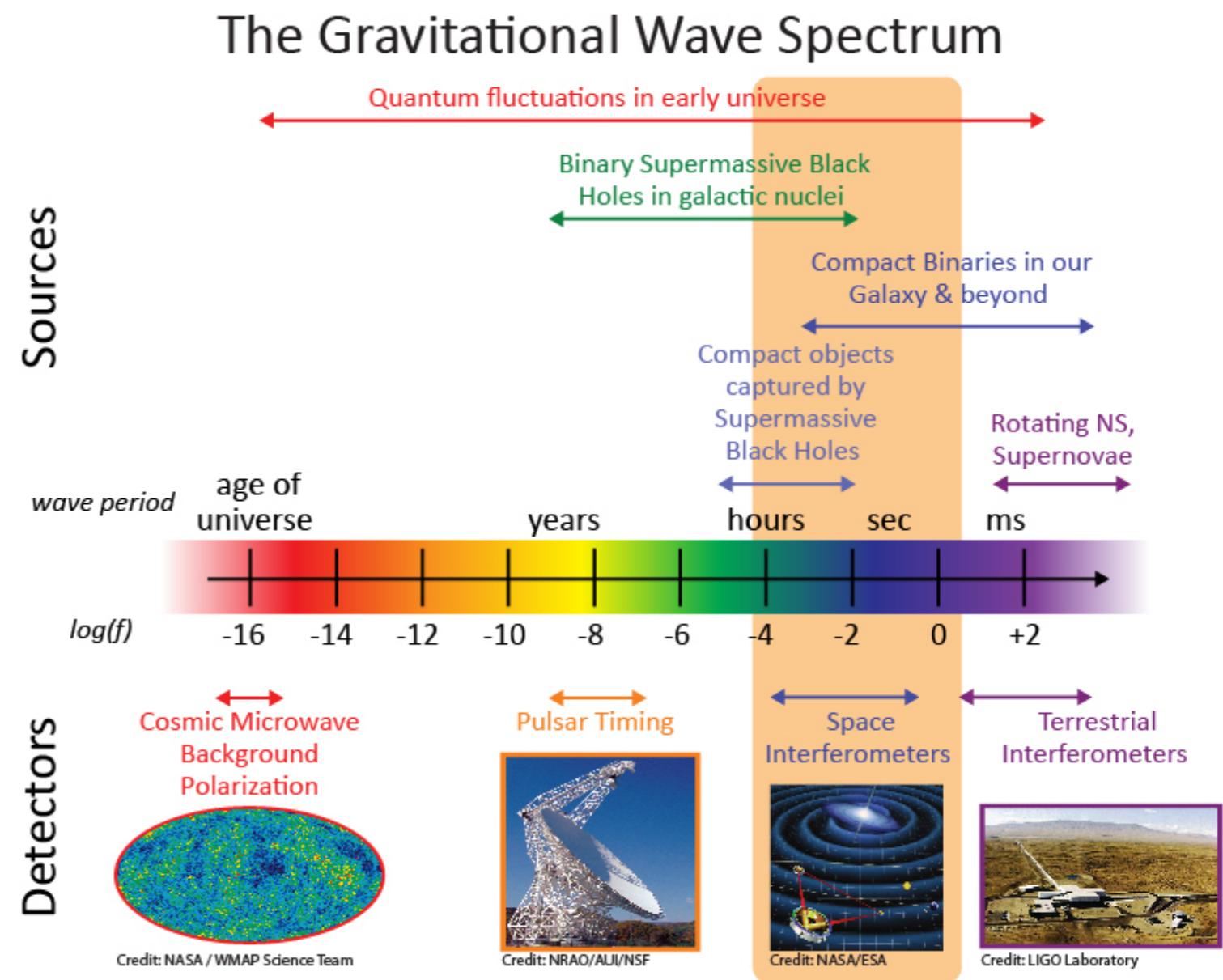
- Spacetime forms a fabric that is curved by mass (imagine bowling balls on a bedsheet)
- GWs are **propagating disturbances** in gravitational fields
- Expansion and contraction of space



(2-dimensional representation)

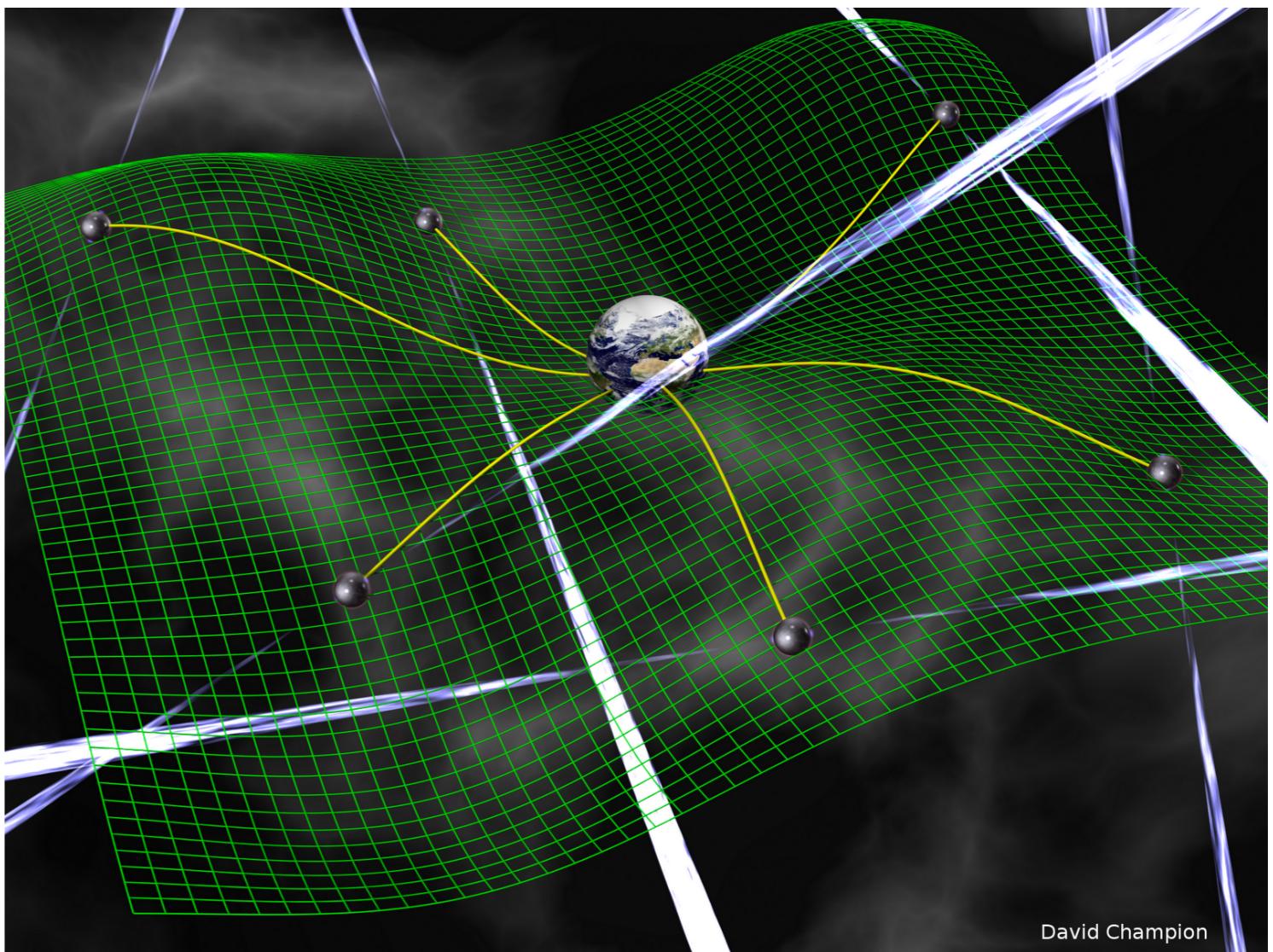
# GRAVITATIONAL WAVE DETECTION

- LIGO (~2002, laser interferometer)
- LISA (future space interferometer)
- Pulsar timing probes **nanohertz-frequency** GWs
  - Current telescopes not sensitive enough to detect GW signals



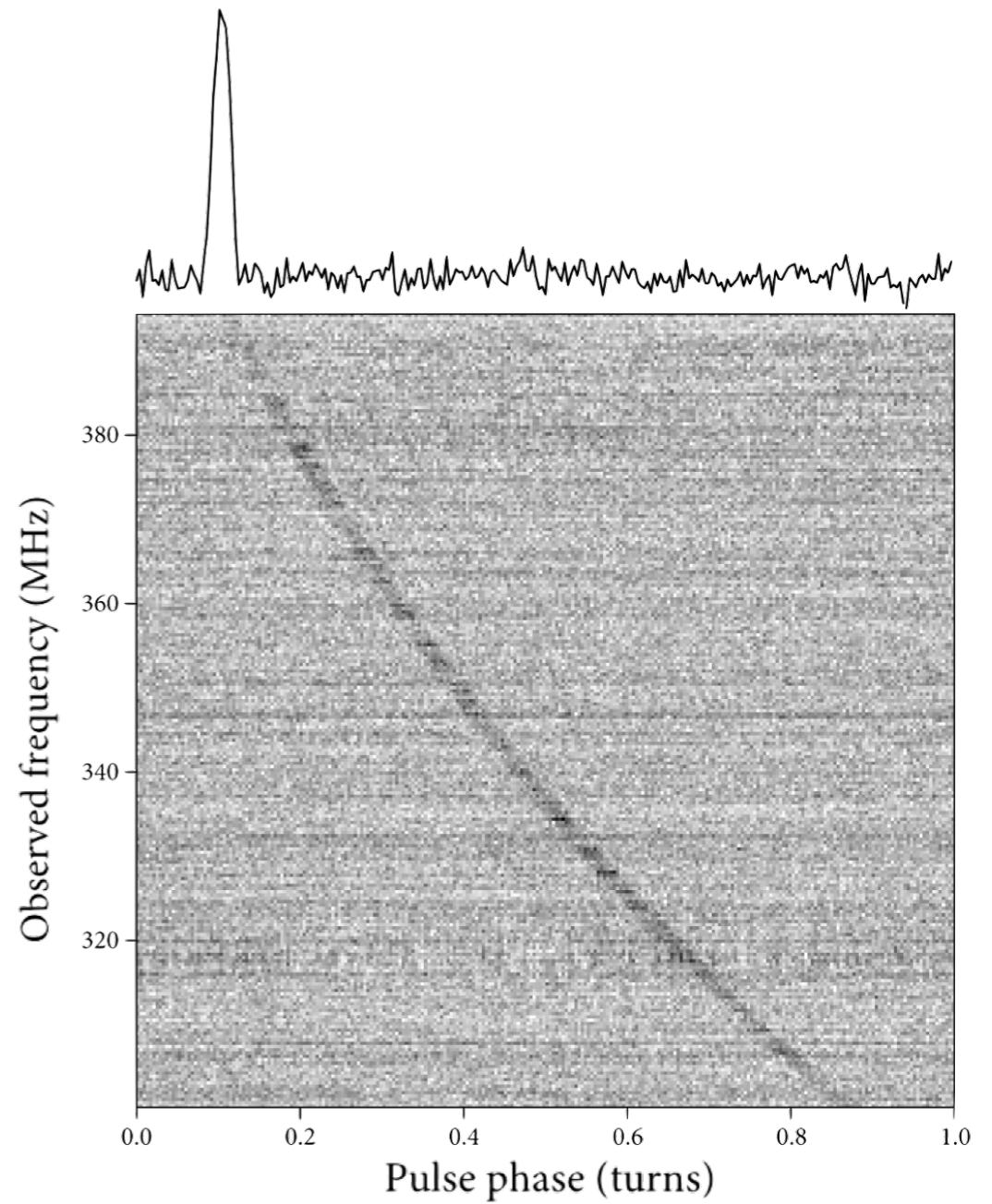
## GW DETECTION WITH PULSARS

- Radio telescopes measure signal times of arrival (TOAs) from an **array of pulsars**
  - Subtract predicted TOAs to get residuals
- Correlated residuals... **possible GW!**



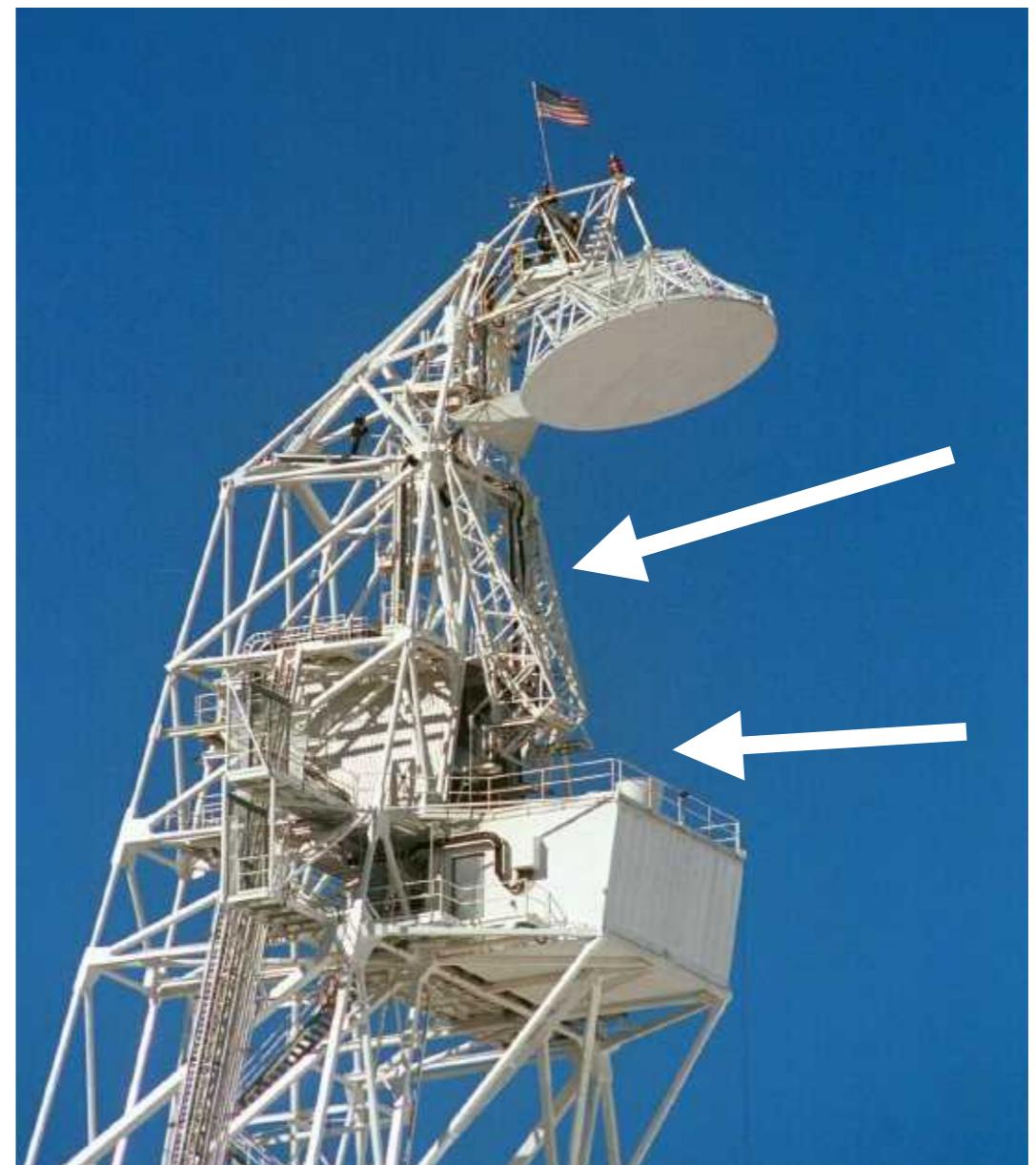
# SIGNAL DISPERSION

- Pulsar signals subject to **dispersion**
  - Lower frequency light is delayed more than higher frequencies
- Caused by free electrons in the ISM forming a **plasma**
- Need pulsar timing measurements at **widely-spaced frequencies**



## PROJECT MOTIVATION

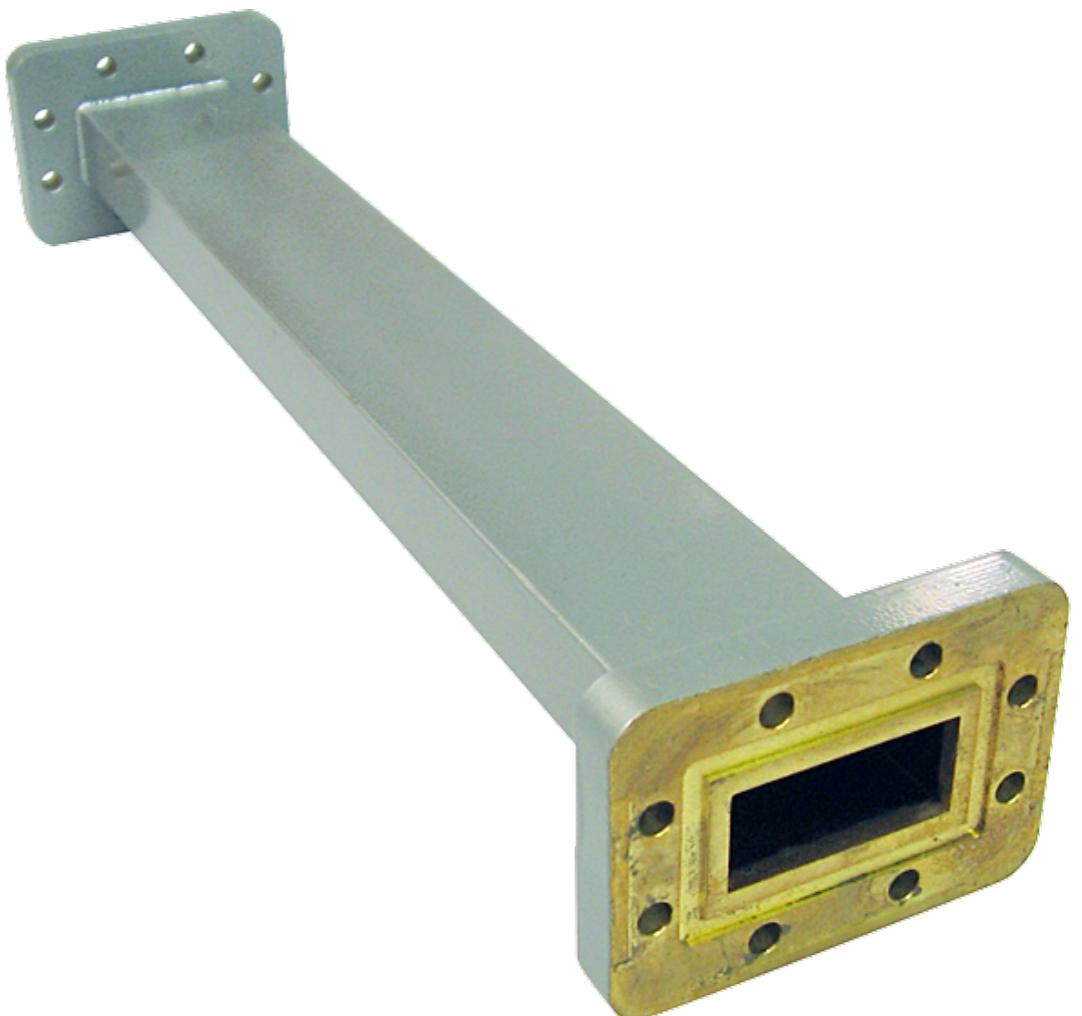
- GBT must use multiple receivers (800 MHz and L-band) to cover bandwidth
- Separated by ~days
- **Let's build a receiver that can do it all (and do it well)!**



# **ACT III**

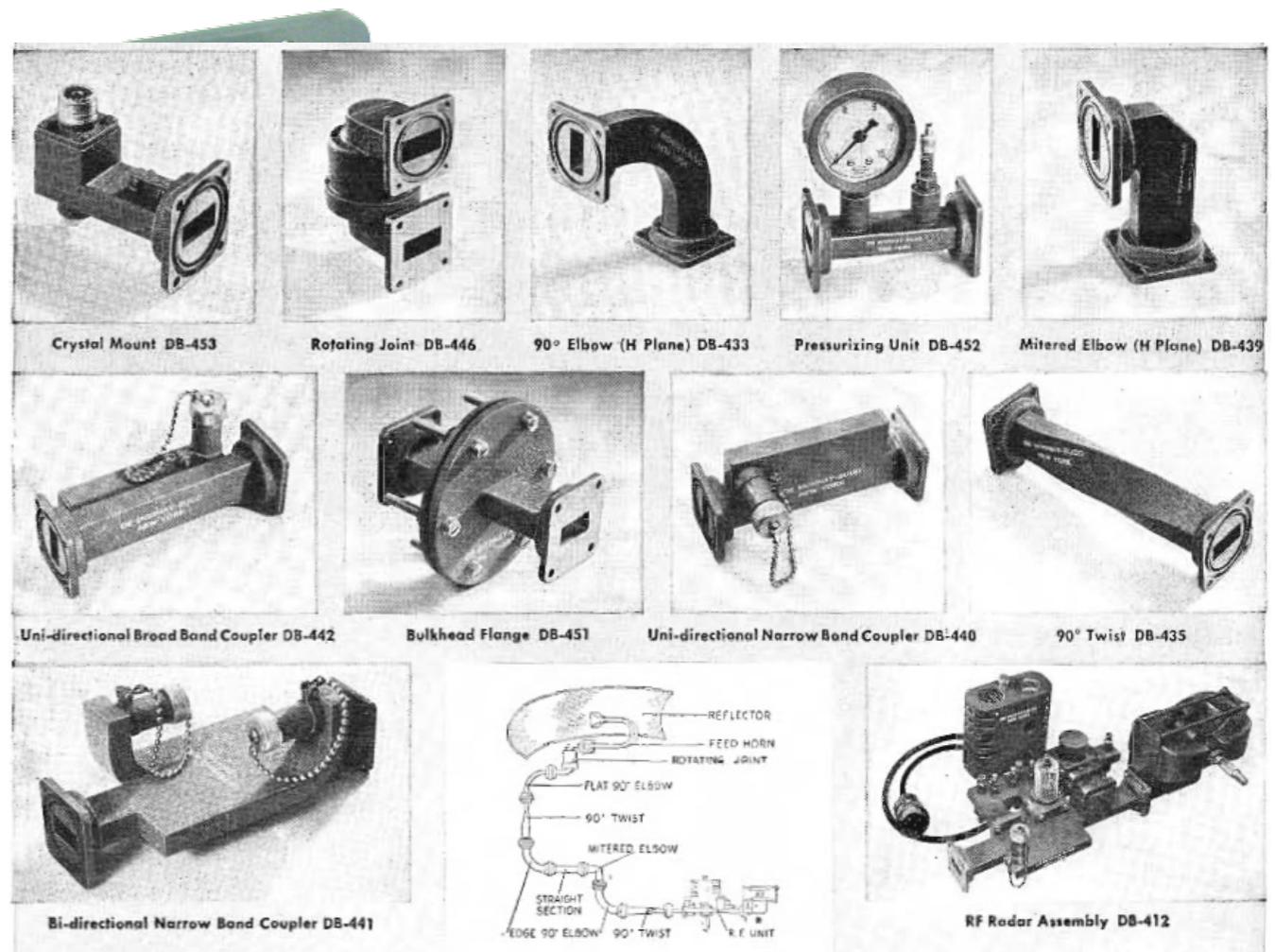
# WAVEGUIDES

- Receivers are highly specialized **waveguides**
  - Like optical fibers for radio
- Enforce boundary conditions on their surfaces
  - Quantized propagation
  - Perfect high-pass filters



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# RADIO RECEIVERS

- Characterized by **gain** as a function of direction (called a radiation or “far-field” pattern)
- Receivers guide waves reflected by a dish onto “crossed dipole” detector
- Can be used to transmit or receive radio waves

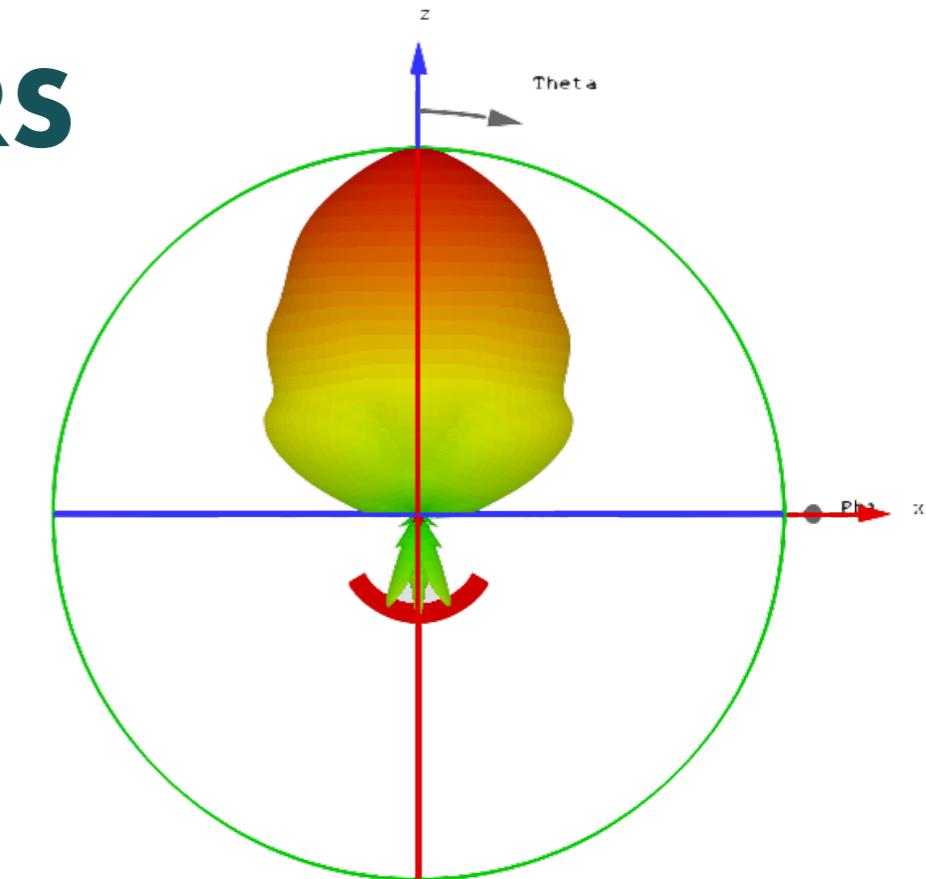


Image credit: NRC Canada

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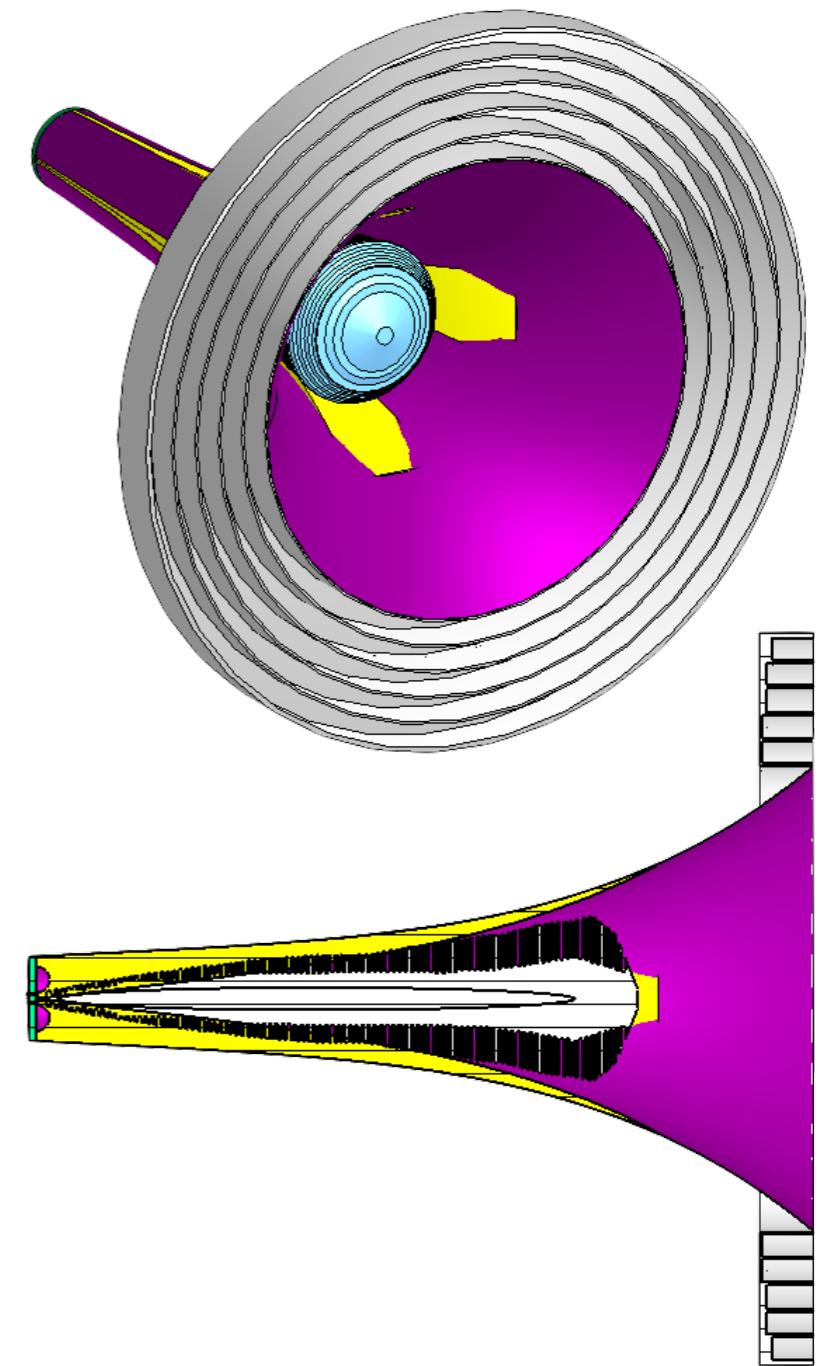
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Image credit: NRAO

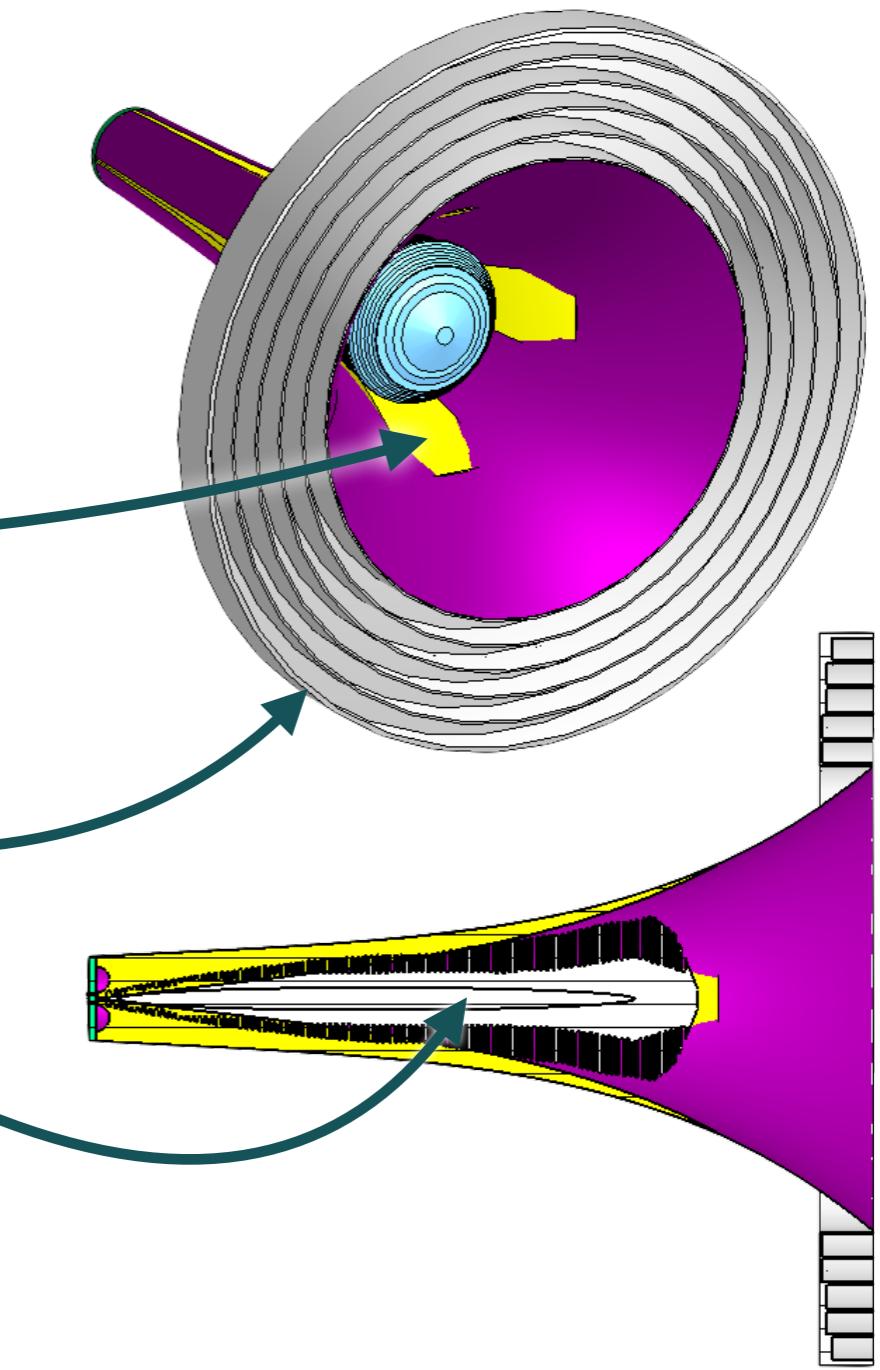
## ULTRA-WIDEBAND RECEIVER

- Frequency range: 0.7 – 4.2 GHz
  - Bandwidth: 3.5 GHz (**6:1**); L, S bands
- 1 m aperture, 1.5 m in length
- **Four ridges** lower cutoff frequency of dominant mode
- **Corrugated skirt** reduces spillover at low frequencies
- **Dielectric spear** reduces under-illumination at high frequencies



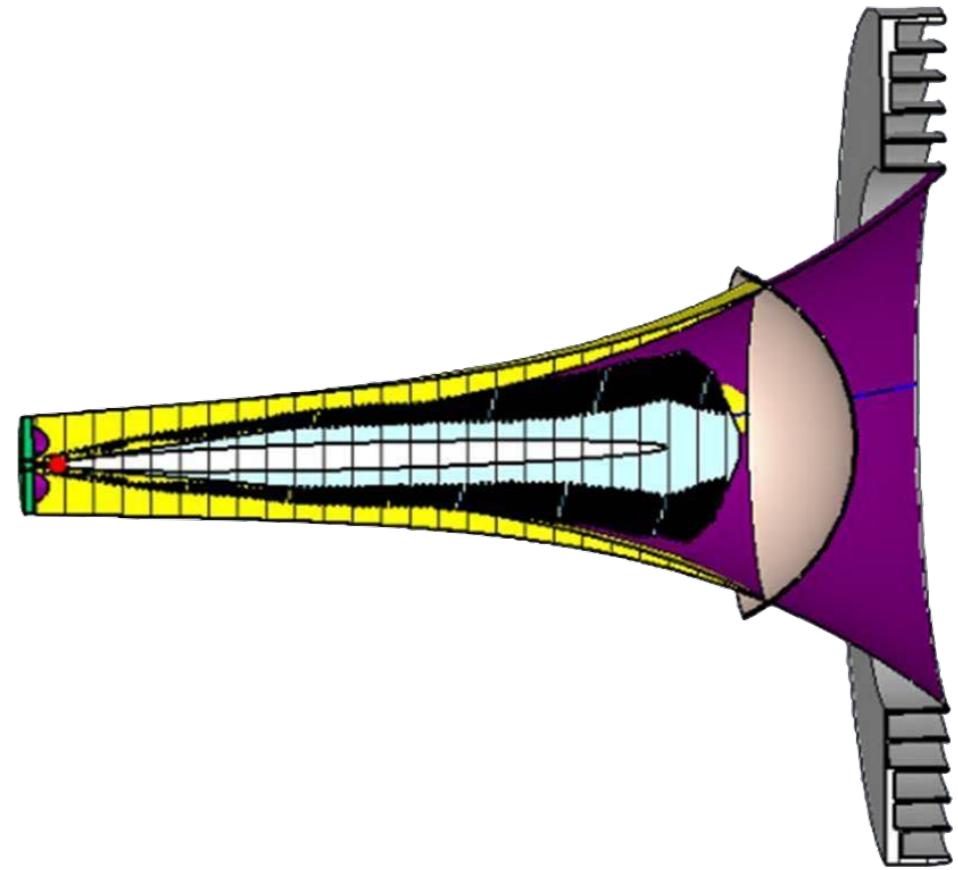
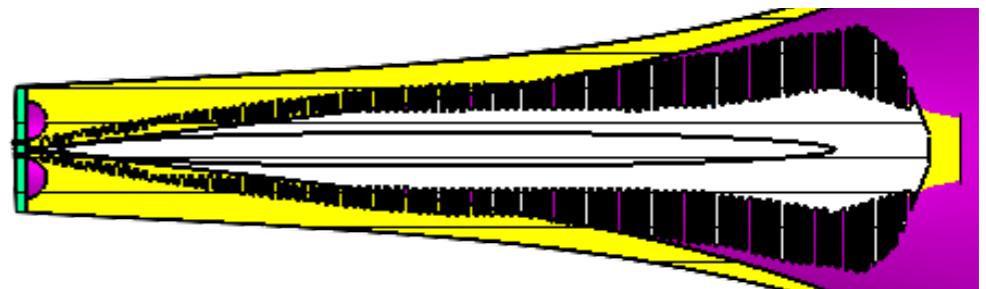
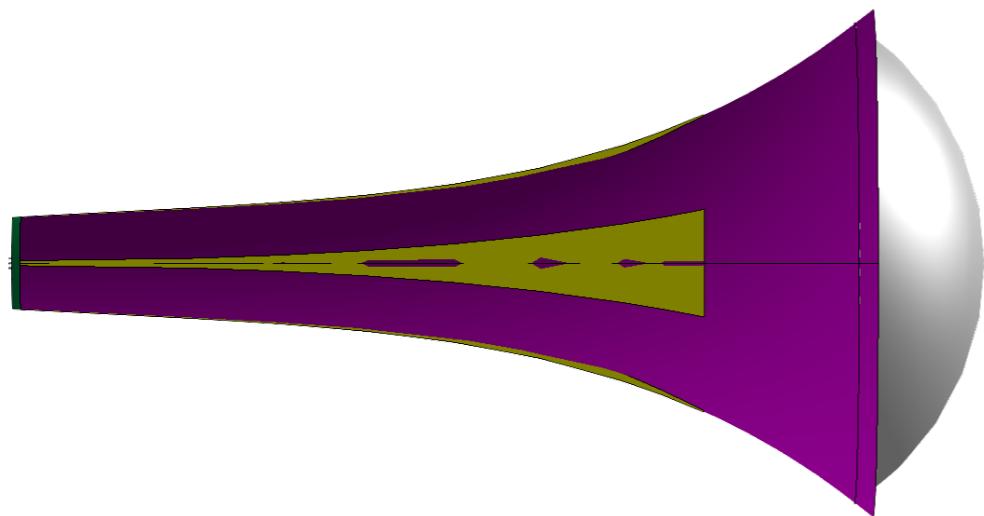
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## ULTRA-WIDEBAND RECEIVER

- **Teflon layers** on quartz spear for impedance matching
- Radio-transparent **window** as component of dewar
  - Two sizes considered: **large** (in aperture) and **small** (in throat)



## ULTRA-WIDEBAND RECEIVER MODELS

- Designed with software > iterative design process
- Four distinct models

Model name	Window	Spear?	Teflon?	Identifying factor
Model A	Large	Yes	No	Large window
Model B	Small	No	No	No dielectric
Model C	Small	Yes	No	No Teflon layers
Model D	Small	Yes	Yes	Teflon layers

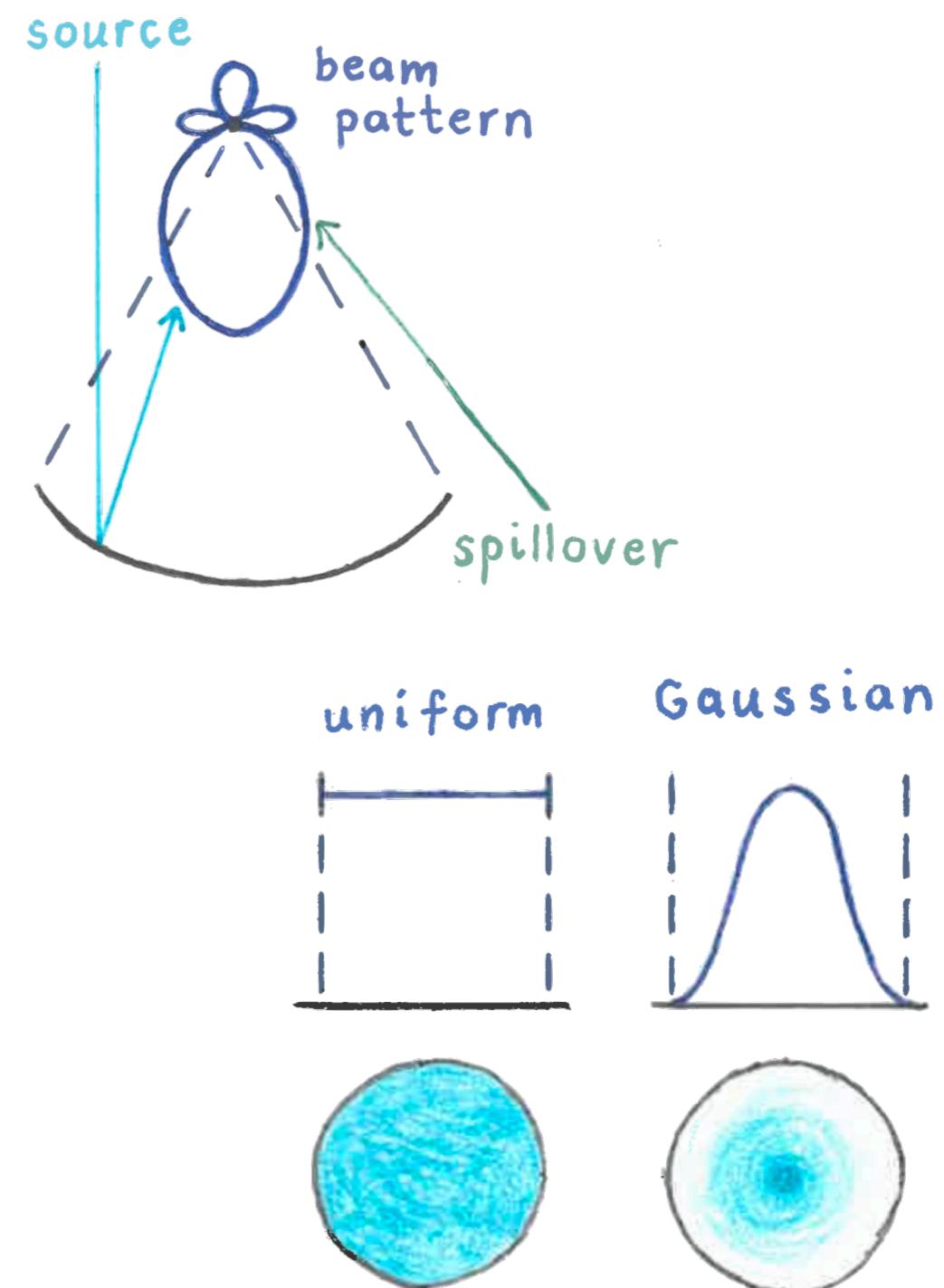
# ACT III

## EFFICIENCY ANALYSIS

- Total feed efficiency,  $e_{tot}$ 
  - Amount of light that hits the dish which actually gets received
  - Depends on shape of radiation pattern (**frequency-dependent**)
- Design goal: 60–70% at lower frequencies, above 50% at higher frequencies
- Can be divided into **sub-efficiencies**:
$$e_{tot} = e_{sp} \cdot e_{ill} \cdot e_{xp} \cdot e_{ph}$$
- There are other factors, but not for the GBT

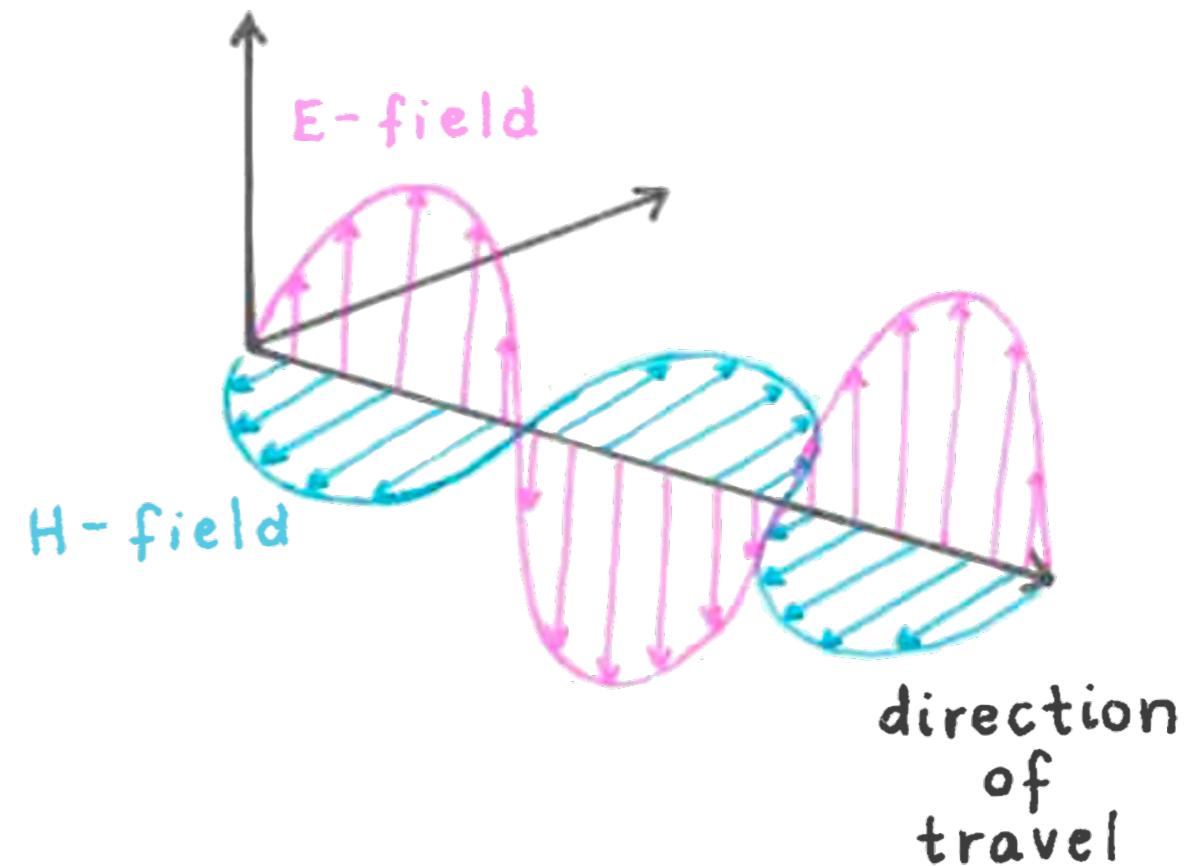
## EFFICIENCY ANALYSIS

- Spillover efficiency,  $e_{sp}$ 
  - Radiation that “spills over” the edge of the dish (or is accepted from beyond the edge of the dish)
- Illumination efficiency,  $e_{ill}$ 
  - Measure of how much radiation pattern deviates from uniform across aperture > zero outside dish
- **Balance between spillover and illumination is important**



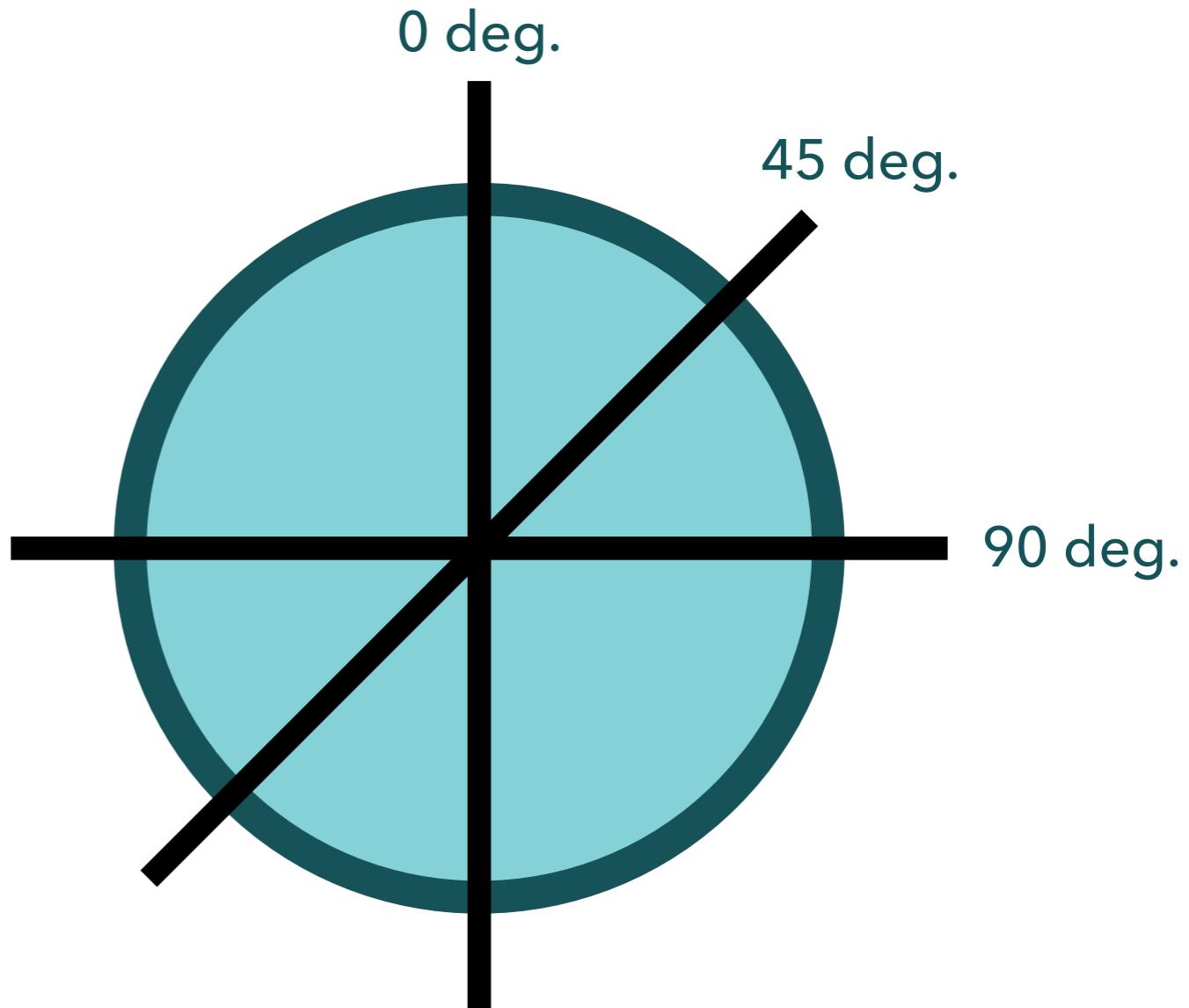
## EFFICIENCY ANALYSIS

- **Polarization:** direction of electric field oscillation
- Cross-polarization efficiency,  $e_{xp}$ 
  - Power leaks from one polarization to the orthogonal one
- Phase efficiency,  $e_{ph}$ 
  - Different modal components of waves out of phase in aperture



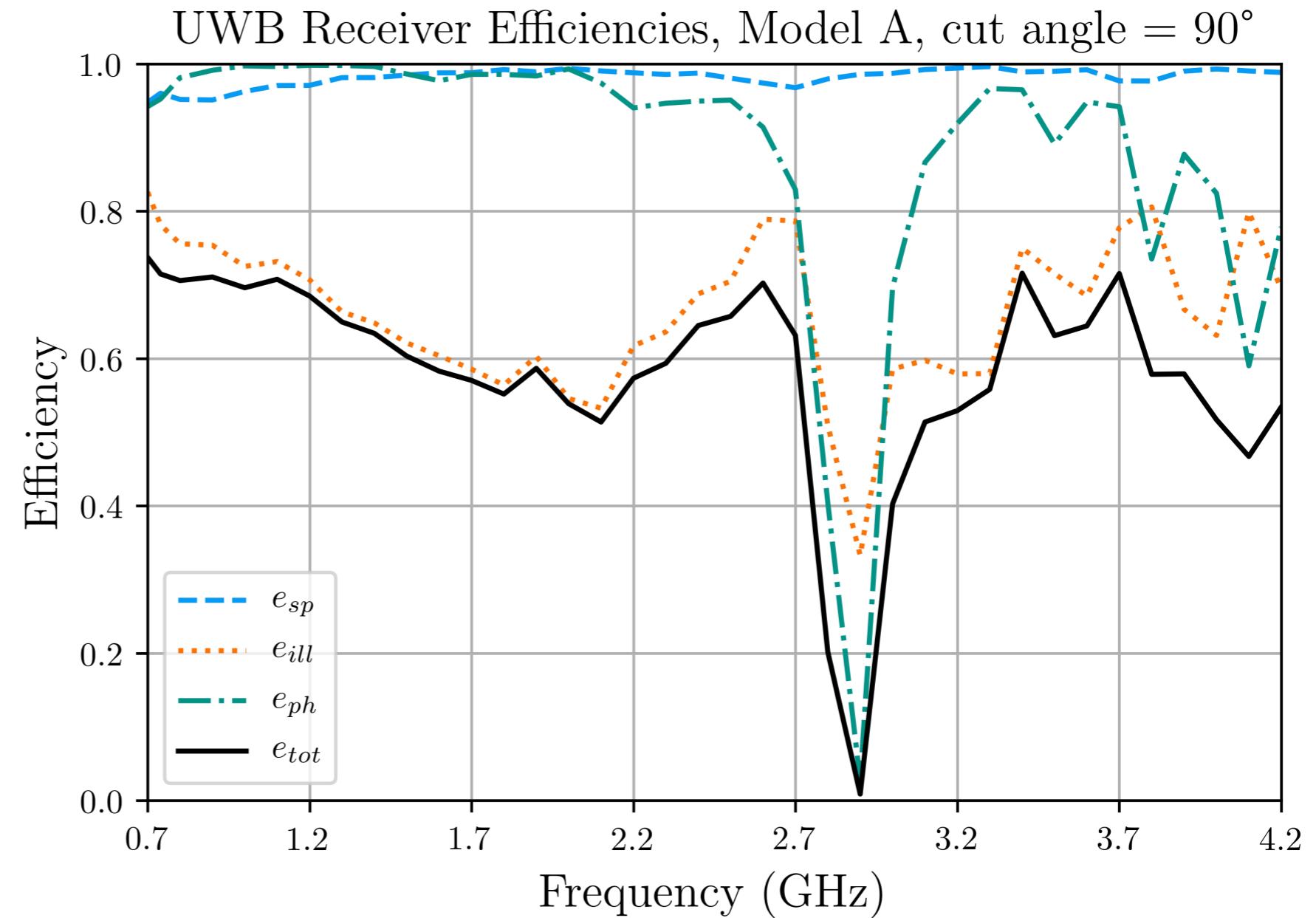
# EFFICIENCY ANALYSIS

- Use three “slices” through simulated far-field pattern
- Co-polar, cross-polar, and 45 degrees in-between
- Cross-polar tends to show the worst performance



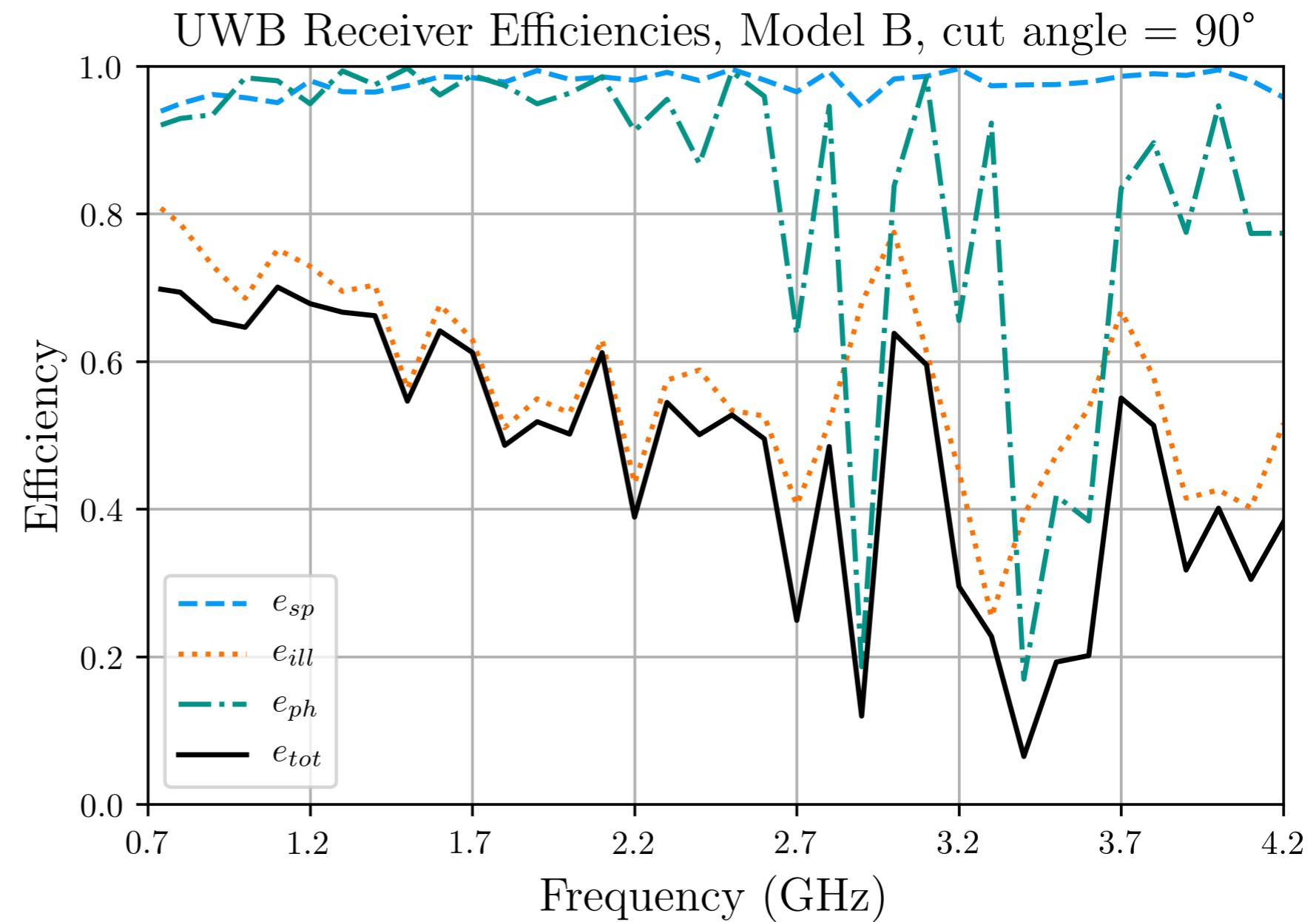
## EFFICIENCY ANALYSIS RESULTS

- **A: no Teflon**
- Relatively good across entire bandwidth
- Large drop in phase efficiency at 2.9 GHz



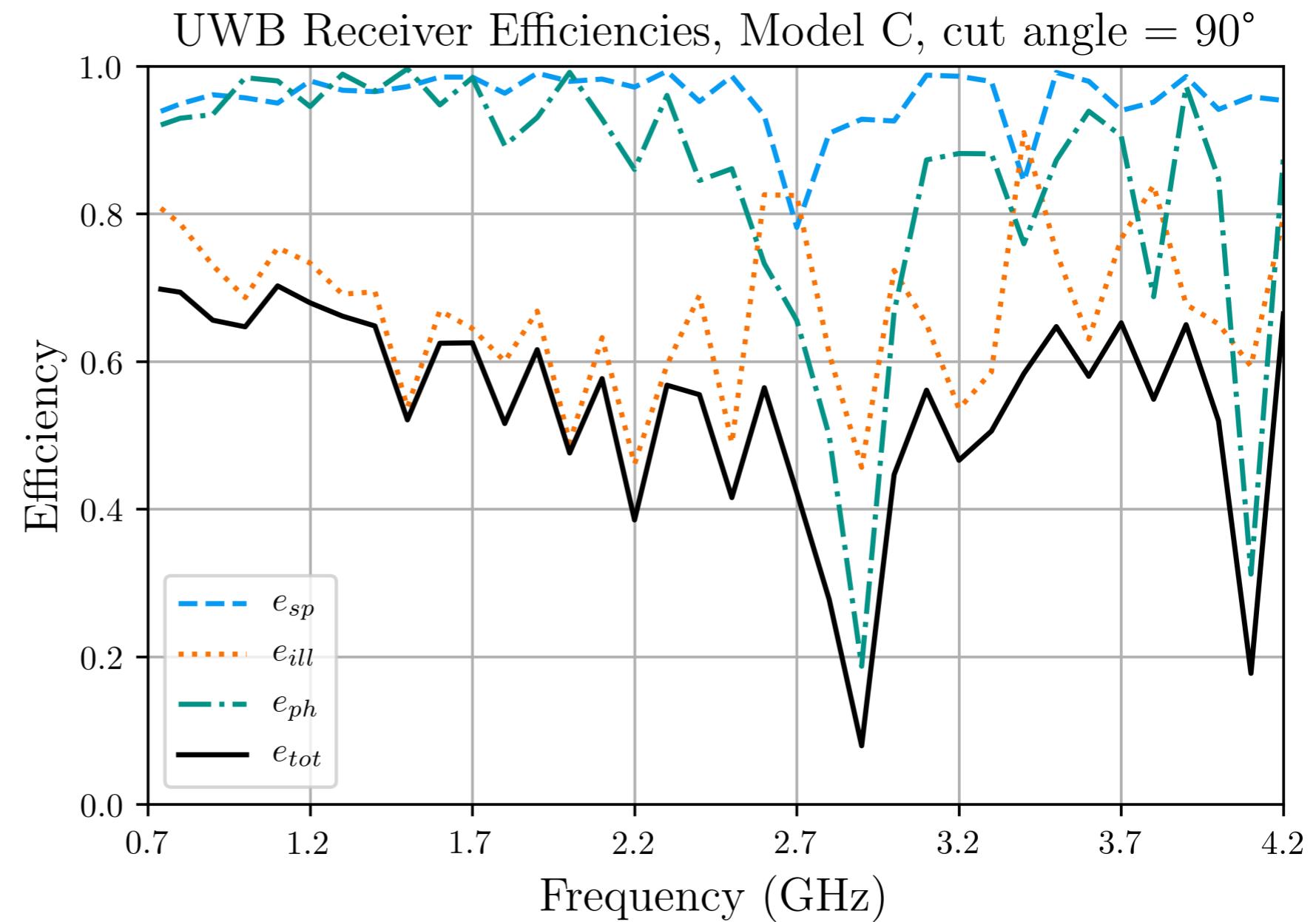
## EFFICIENCY ANALYSIS RESULTS

- **B: no spear**
- Lowers efficiency at higher freq.
  - $e_{ill}$  and  $e_{ph}$
- Efficiency still high at low frequencies



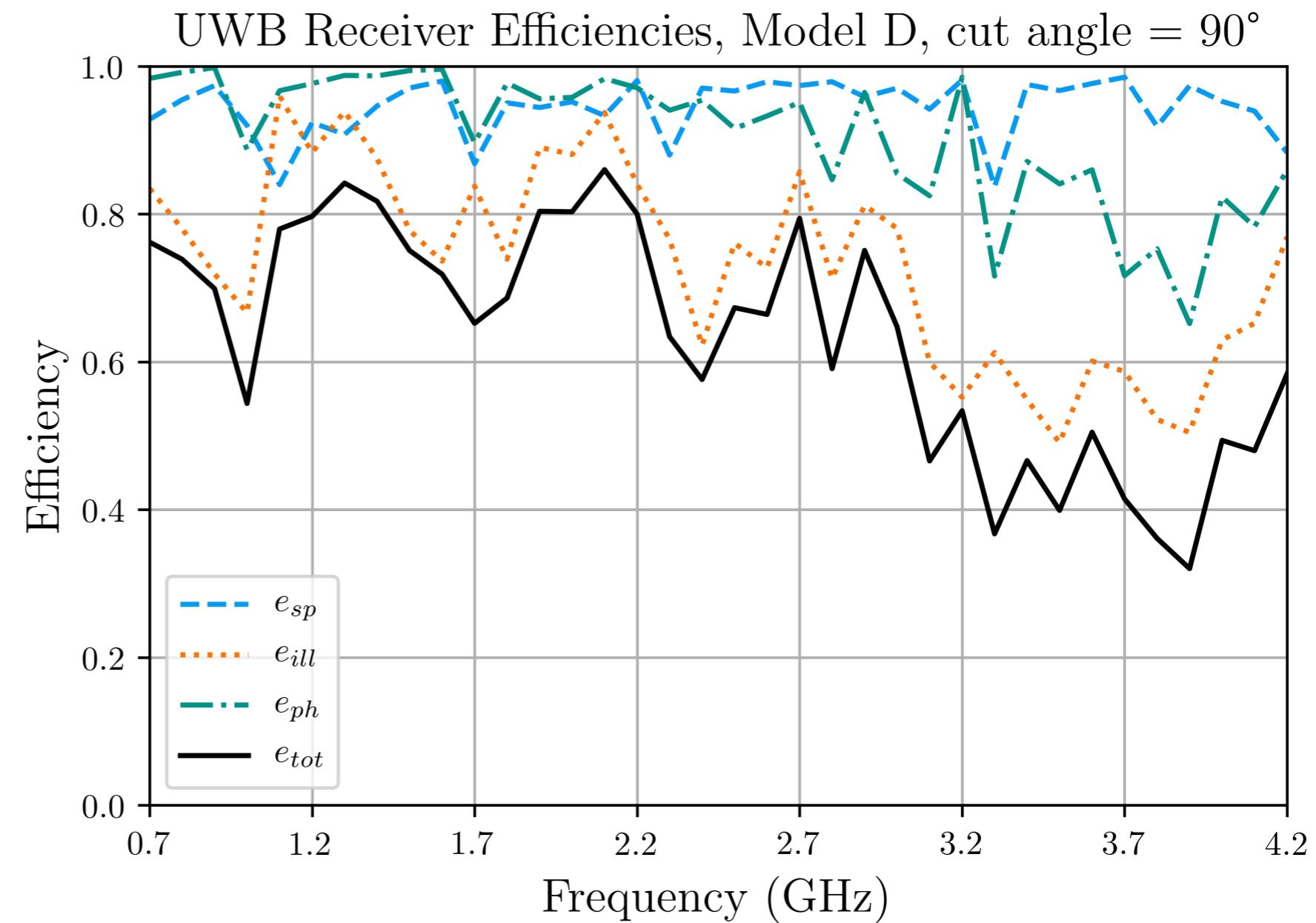
## EFFICIENCY ANALYSIS RESULTS

- **C: no Teflon**
- Including spear raises baseline efficiency at high freq.
- Detriment at 2.9 GHz still present



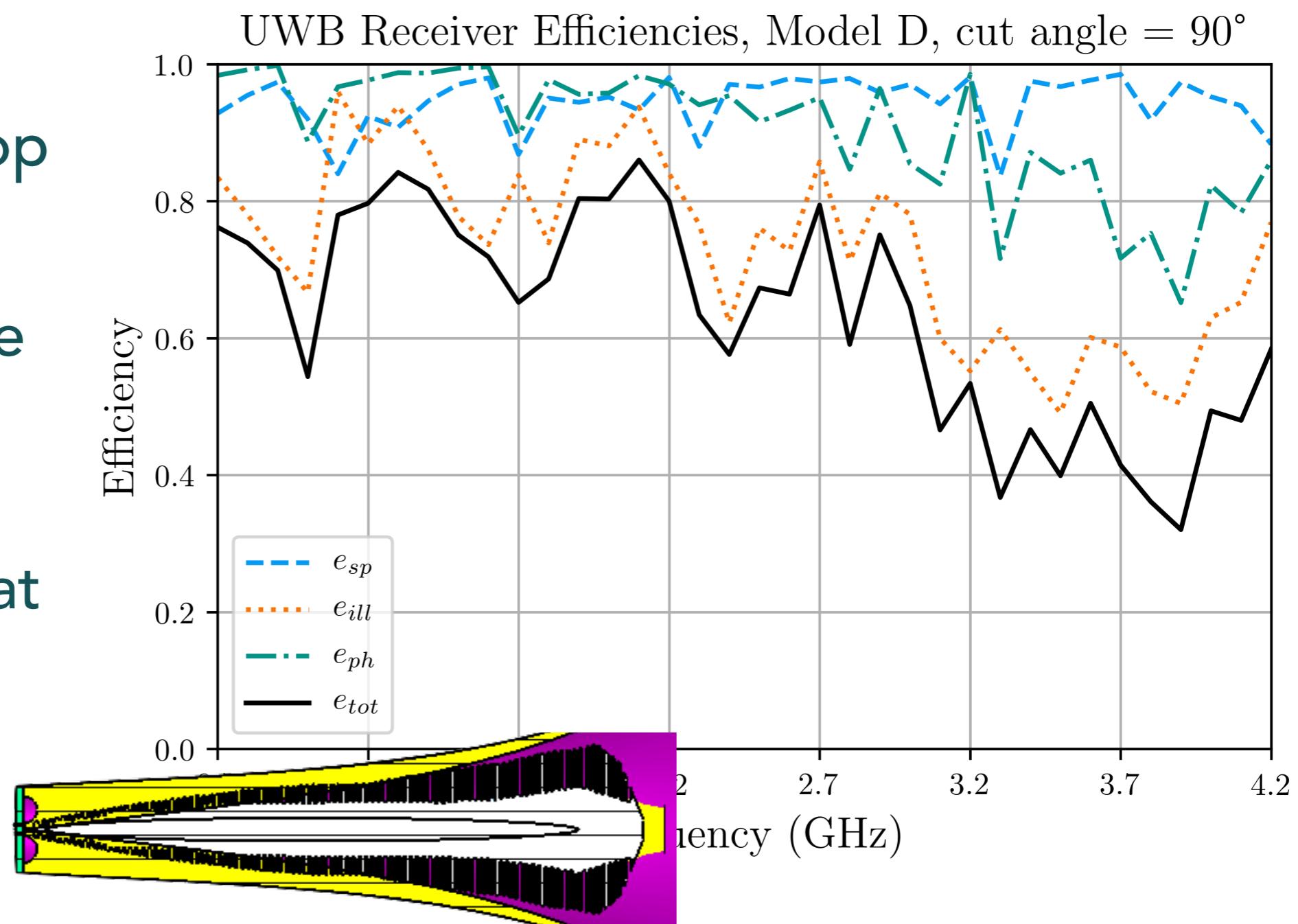
## EFFICIENCY ANALYSIS RESULTS

- **D: Teflon**
- Reduces drop at 2.9 GHz!
- Low baseline at high frequencies suggests that we need to optimize



## EFFICIENCY ANALYSIS RESULTS

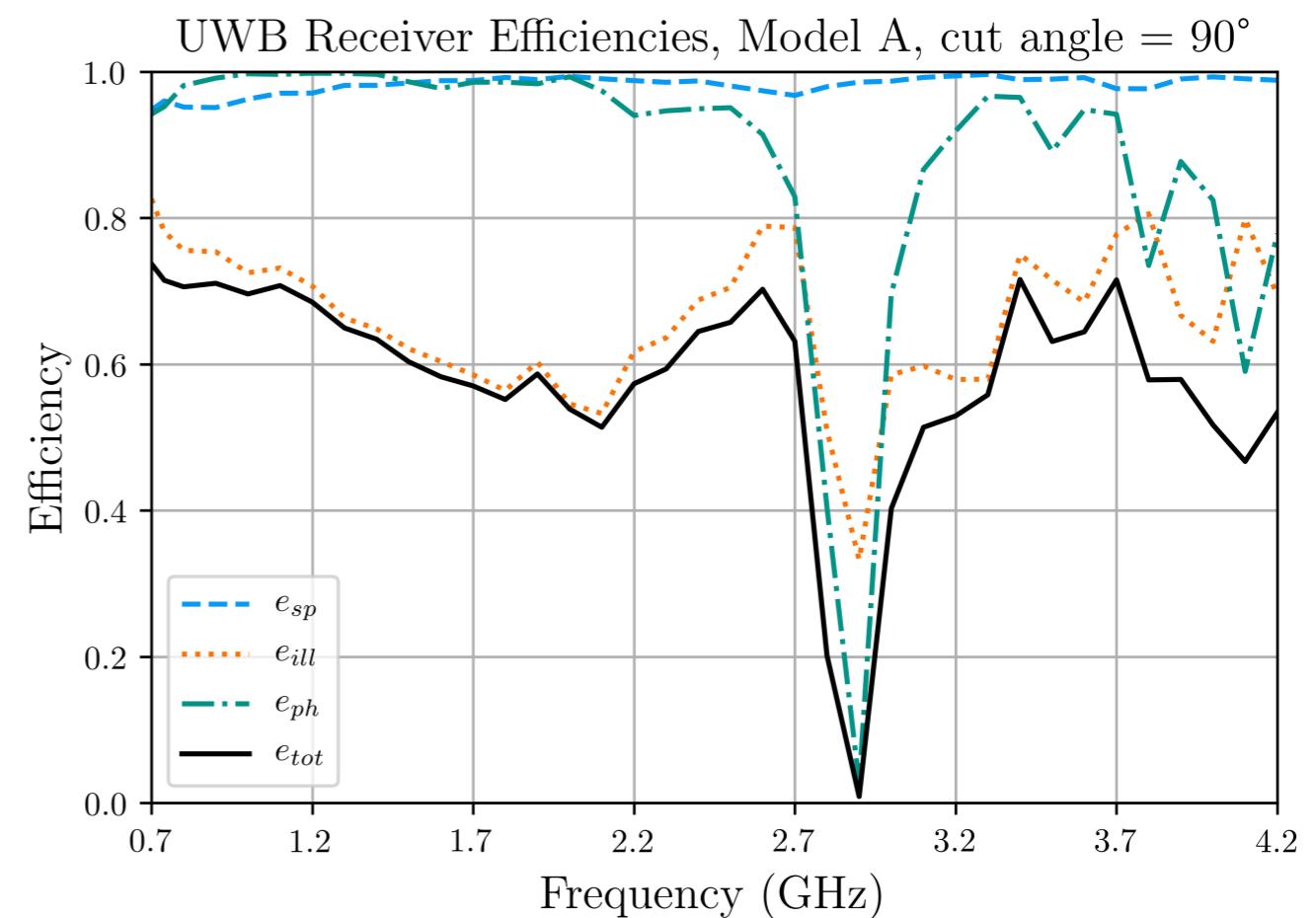
- **D: Teflon**
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# **ACT IV**

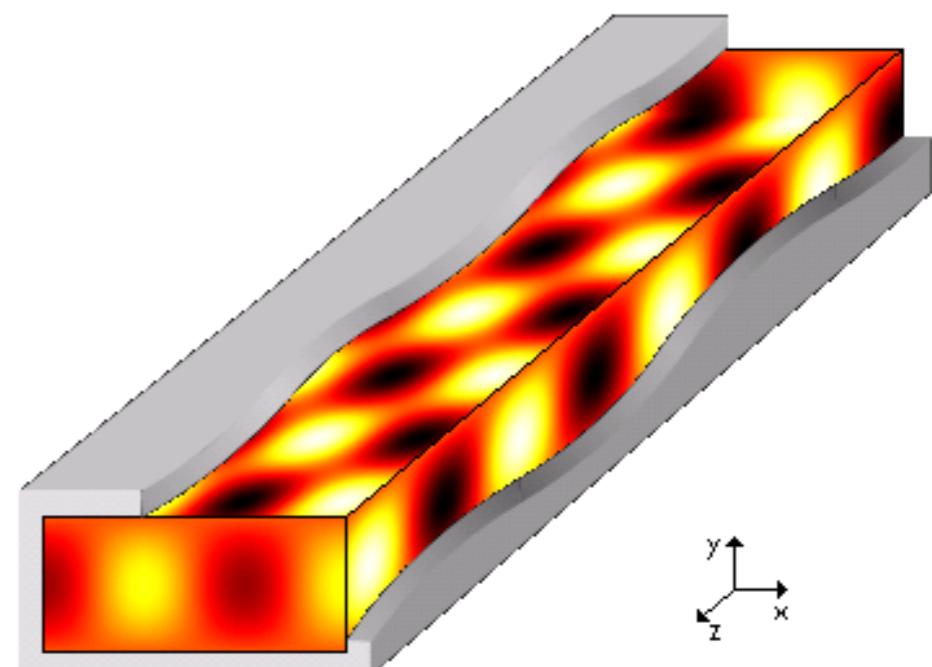
# MODAL EXCITATION

- Originally, detriment at 2.9 GHz was puzzling
- Beukman (2015) hypothesizes that reduced efficiency is caused by an imbalance in higher-order waveguide mode excitation in a receiver



## WAVEGUIDE MODES

- Recall that waveguides propagate radio waves in **quantized modes**
  - Have indices  $m$  and  $n$
- Transverse electric (TE) and transverse magnetic (TM)
- Lower-order modes generally preferred for Gaussian beam shape



# TECHNIQUE

- At each frequency, calculate the percent contribution of each waveguide mode to the radiation pattern
  - Many, many exports
- Since Teflon matching layers reduced detriment, compare modal content with/without Teflon

The screenshot shows a Jupyter Notebook environment with the following components:

- Code Cell (In [428]):**

```
# Goes with Mode_calculations.
# Written by Alyssa Bulatek.
# Version 1.1

# Import necessary packages.
import numpy as np
import pandas as pd
from scipy.integrate import simps
from mpmath import besselj, besseljzero
import os

#####
# Note that this code does not work with the files exported by CST.
# I remove the line of dashes as well as the spaces between words in the
# .txt files manually. Some future work for this script would involve
# automating this as part of the script, as well as scripting this to
# run on each of the files in a directory so the filenames do not need
# to be entered manually.
#####

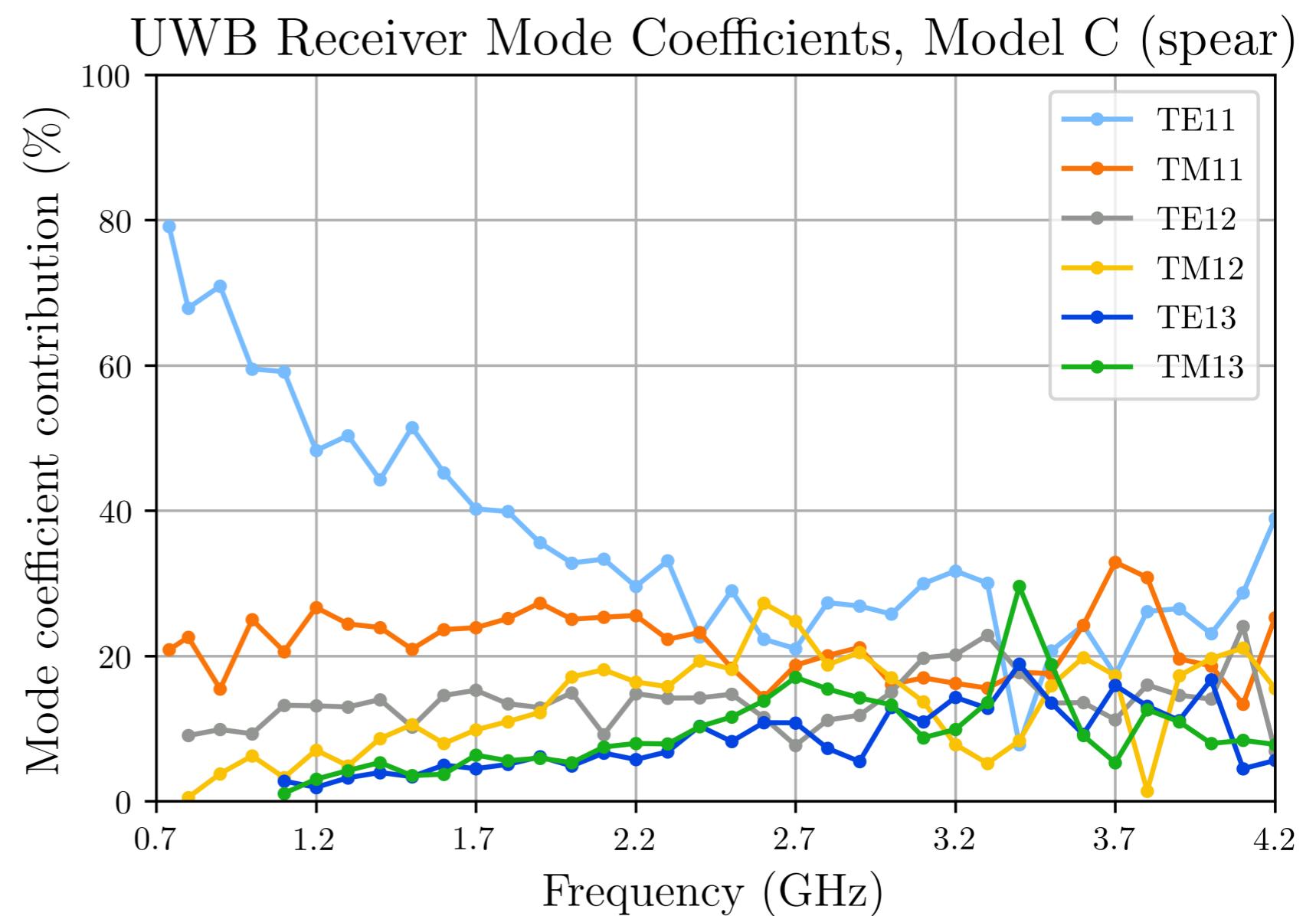
# Set user-specified parameters.
modeType = "TM" # Either TE or TM as a string.
m, n = 1, 3 # Set values for the desired mode.
path = "/Users/alyssabulatek/Desktop/Mode_calculations/Final_Tef/TM13_smWindow"
filename = "4200FF_E_14p88_p1and3.txt"
```
- Data Table (Top):**

	Theta [deg.]	Phi [deg.]	Abs(E) [V/m]	Abs(Theta) [V/m]	Phase(Theta) [deg.]	Abs(Phi) [V/m]	Phase(Phi) [deg.]	Ax.Ratio[]
11.260	-180.000		3.852e+01	3.852e+01	335.778	8.448e-05	282.471	3.162e+02
11.260	-179.000		3.852e+01	3.851e+01	335.779	6.208e-01	147.748	3.162e+02
11.260	-178.000		3.851e+01	3.849e+01	335.780	1.241e+00	147.747	2.221e+02
11.260	-177.000		3.850e+01	3.846e+01	335.783	1.861e+00	147.748	1.482e+02
11.260	-176.000		3.849e+01	3.841e+01	335.786	2.480e+00	147.750	1.112e+02
11.260	-175.000		3.847e+01	3.835e+01	335.791	3.098e+00	147.753	8.909e+01
11.260	-174.000		3.845e+01	3.828e+01	335.796	3.715e+00	147.757	7.436e+01
11.260	-173.000		3.843e+01	3.819e+01	335.802	4.330e+00	147.762	6.385e+01
11.260	-172.000		3.840e+01	3.809e+01	335.809	4.942e+00	147.767	5.599e+01
- Data Table (Bottom):**

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Frequency (GHz)	TE11	TM11	TE12	TM12	TE13	TM13	%TE11	%TM11	%TE12	%TM12	%TE13	%TM12	%TM13	
2	0.74	48.4892	12.7610					79.1658	20.8342						
3	0.8	46.0457	15.3024	6.1206	0.3431			67.9022	22.5660	9.0258	0.5060				
4	0.9	48.9762	10.6689	6.8076	2.6084			70.9179	15.4485	9.8573	3.7769				
5	1.0	41.5995	17.4602	6.4816	4.3566			59.5147	24.9796	9.2729	6.2328				
6	1.1	42.4869	14.8078	9.4840	2.3251	1.9776	0.7687	59.1326	20.6993	13.1997	3.2360	2.7524	1.0699		
7	1.2	35.3450	19.5232	9.8069	5.1406	1.3926	2.2159	48.2695	26.6622	13.1198	7.0204	1.9018	3.0262		
8	1.3	37.3347	18.0968	9.8164	3.6073	2.3839	3.1264	50.3398	24.4005	12.9661	4.8638	3.2143	4.2154		
9	1.4	33.1058	17.8863	10.4643	6.4496	2.9501	3.9781	44.2389	23.9012	13.9833	8.6186	3.9422	5.3158		
10	1.5	38.6474	15.7090	7.6770	7.9031	2.5281	2.6360	51.4609	20.9173	10.2223	10.5233	3.3862	3.5100		
11	1.6	33.3355	17.5265	10.7927	5.8686	3.6777	2.7530	45.2131	23.2695	14.5508	7.9366	4.9583	3.7117		
12	1.7	29.5359	17.5279	11.2050	7.2057	3.2849	4.6522	40.2333	23.8762	15.2633	9.8155	4.4747	6.3371		
13	1.8	29.0645	18.3235	9.7742	7.9847	3.6884	4.0538	39.8750	25.1389	13.4097	10.9545	5.0603	5.5615		
14	1.9	24.7606	18.9891	9.8651	8.5019	4.2452	4.1204	35.5846	27.2901	12.8842	12.2185	6.1009	5.9216		
15	2.0	22.3467	17.0866	10.1675	11.6529	3.3062	3.6058	32.7915	25.0465	14.9198	17.0995	4.8515	5.2911		
16	2.1	22.5904	17.1716	6.2252	12.2631	4.4890	5.0551	33.3219	25.3290	9.1825	18.0887	6.6215	7.4565		
17	2.2	20.1712	17.4431	10.1074	11.1930	3.9127	5.4168	29.5574	25.5599	14.8106	16.4014	5.7334	7.9373		
18	2.3	22.6594	15.2570	9.7175	10.7965	4.6577	5.3957	33.0872	22.2783	14.1895	15.7650	6.8012	7.8788		
19	2.4	14.1903	14.5589	8.9090	12.0989	6.4793	6.4299	22.6443	23.2325	14.2165	19.3069	10.3393	10.2605		
20	2.5	18.7138	11.8451	9.5037	11.7282	5.3004	7.4819	28.9805	18.3438	14.7178	18.1627	8.2084	11.5867		
21	2.6	11.9141	7.6224	6.1593	14.5748	5.7725	7.3787	22.3019	14.2683	11.5296	27.2825	10.8055	13.8121		
22	2.7	10.1753	9.0682	3.7207	12.0145	5.2257	8.2609	20.9951	18.7107	7.6770	24.7899	10.7824	17.0449		
23	2.8	14.6868	10.7629	5.9895	10.0695	3.9000	6.2916	27.3249	20.0493	11.1574	18.7576	7.2651	15.4458		
24	2.9	12.6197	9.9349	5.5574	9.6165	2.5634	6.6771	26.8681	21.1520	11.8321	20.4742	5.4576	14.2159		
25	3.0	14.1625	8.8430	8.2633	9.3501	7.0919	7.2941	25.7477	16.0767	15.0229	16.9987	12.8932	13.2608		
26	3.1	17.5026	9.9179	11.5231	7.9966	6.3856	5.1106	29.9516	16.9721	19.7191	13.6843	10.9274	8.7455		
27	3.2	18.7185	9.5767	11.9012	4.5976	8.4390	5.8249	31.6952	16.2158	20.1517	7.7849	14.2893	9.8631		
28	3.3	14.8699	7.7110	11.3234	2.5766	6.3306	6.7307	30.0146	15.5645	22.8560	5.2008	12.7783	13.5858		
29	3.4	2.2611	5.1532	5.1527	2.4126	5.4773	8.5867	7.7852	17.7429	17.7429	8.3069	18.8588	29.5648		
30	3.5	8.5920	7.2954	5.6062	6.6058	5.6196	7.8256	20.6813	17.5605	13.4944	15.9005	13.5266	18.8367		
31	3.6	12.2709	12.2695	6.8776	10.0260	4.6619	4.5752	24.2120	24.2092	13.5703	19.7826	9.1985	9.0274		

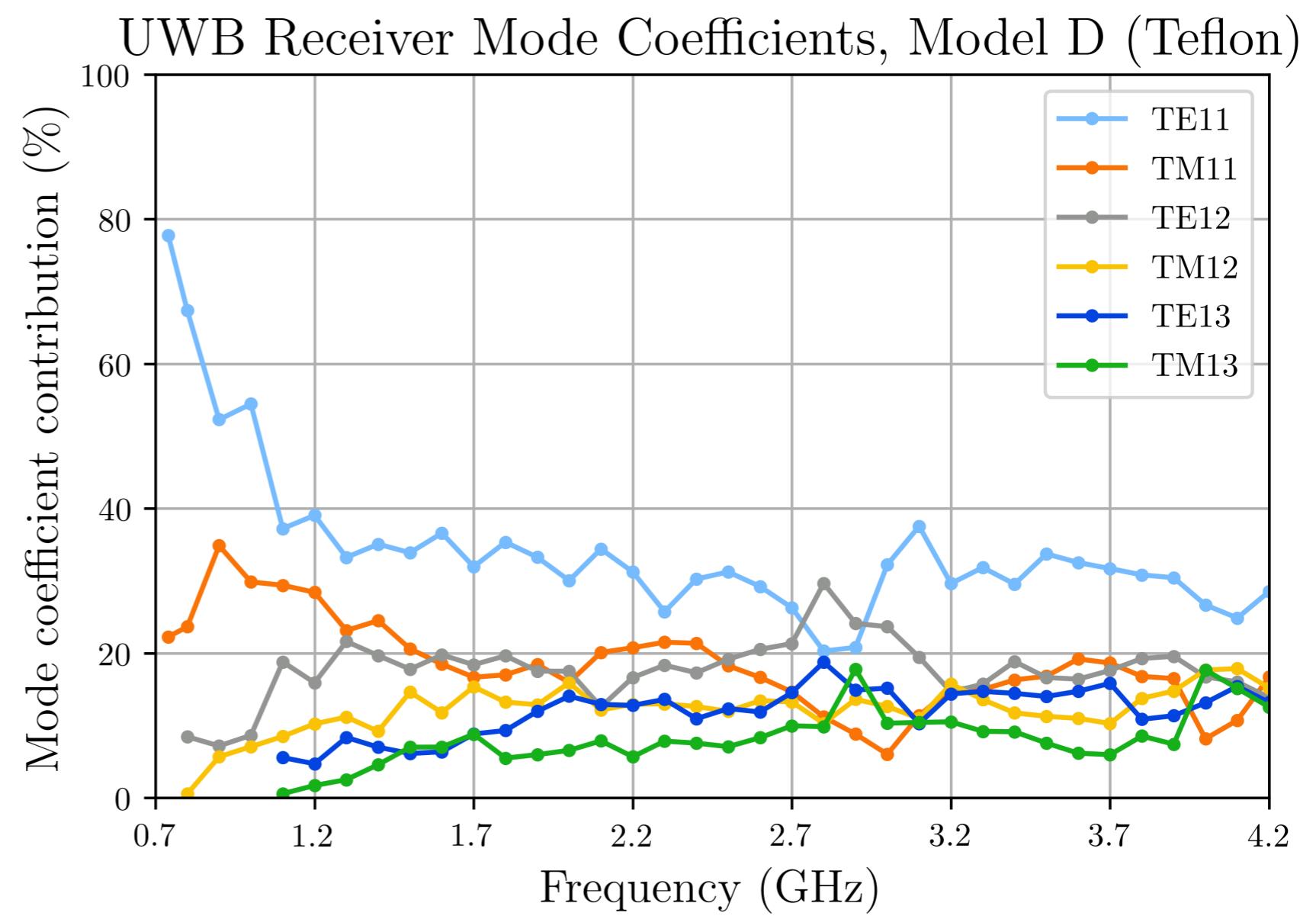
## MODAL EXCITATION RESULTS

- **C: no Teflon**
- As expected,  $TE_{11}$  dominant at lower freq.
- Higher-order modes (eg.  $TM_{13}$ ) gain power at higher freq.



## MODAL EXCITATION RESULTS

- **D: Teflon**
- Not much change in modal content when Teflon is added
- Instead, Teflon alters phase velocities of modes



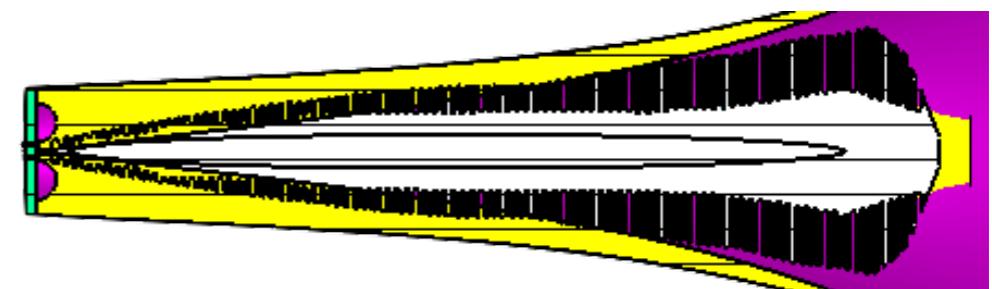
# **ACT IV+1**

## CONCLUSIONS

- UWB receiver meets efficiency design goals, with some additional optimization of Teflon layers necessary
- Cannot conclude that higher-order mode excitation caused the efficiency dip at 2.9 GHz
  - Teflon matching layers seem to mitigate the dip without changing the modal content in the receiver significantly

## FUTURE WORK

- Optimization of Teflon matching layer shapes, groove depth/thickness
- Calculation of even higher order mode coefficients (e.g.  $TE_{31}$  and  $TE_{32}$ ) to satisfy intellectual curiosity
- Fabrication!
  - One ridge is done, flared horn is next



## THE BIG PICTURE

- UWB receiver will ensure that the GBT remains a premier instrument for pulsar timing
- Detection of nHz GWs will mark a significant improvement in sensitivity
  - Opens doors for many, many other scientific pursuits
- Pulsars were discovered only ~50 years ago
  - Building a sensitive enough receiver to observe them carefully is just one piece in the greater astronomical puzzle

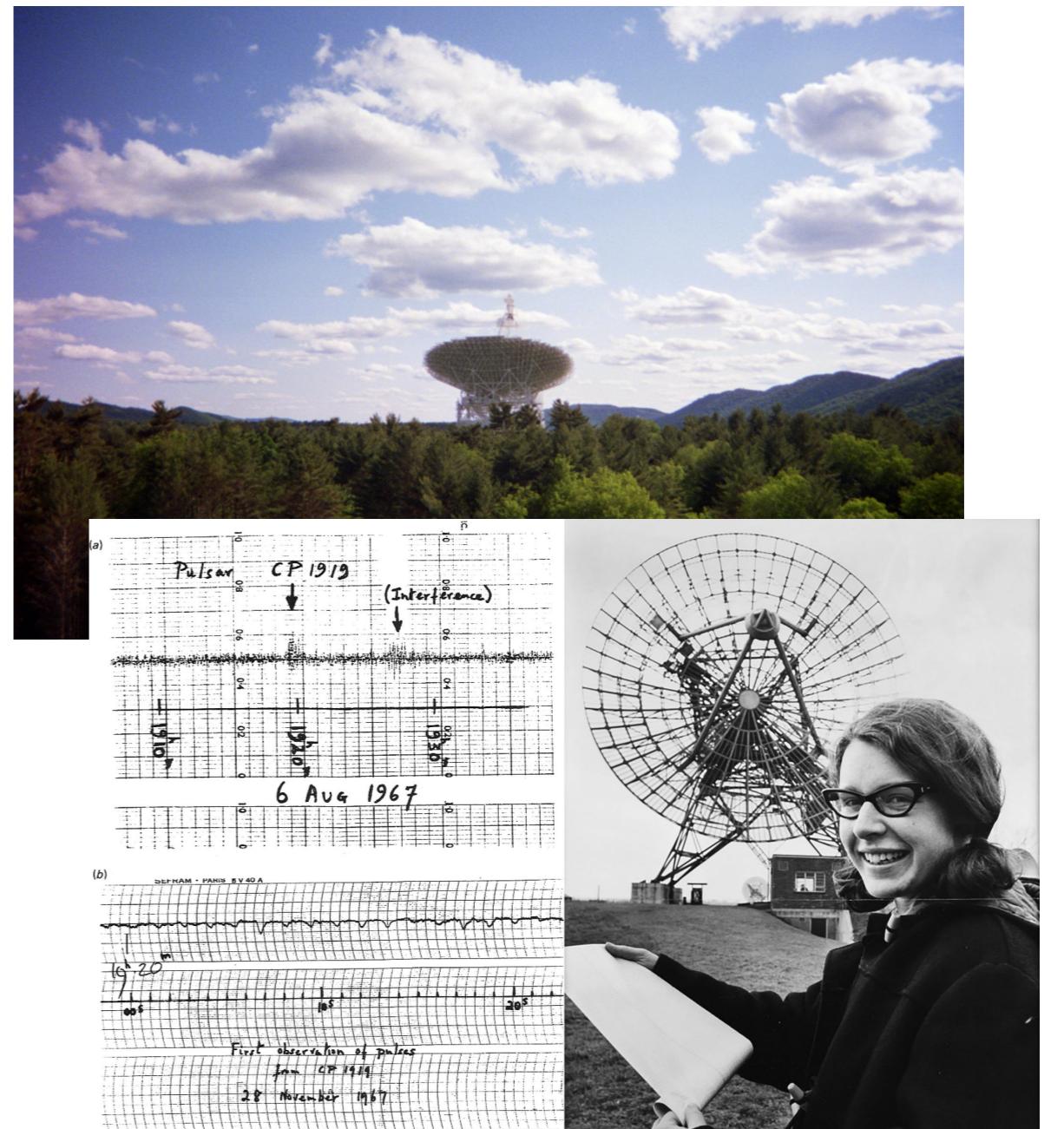


Image credit: me, CSIRO

**Thank you for listening to my talk!**

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- Sivasankaran Srikanth (CDL), Lisa Locke (JPL)
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- Everyone in PHYS 440
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## REFERENCES

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- Akgiray, A. H. 2013, California Institute of Technology, doi:10.7907/TYX5-2C48
- Beukman, T. S. 2015, Stellenbosch University
- Beukman, T. S., Meyer, P., Ivashina, M., & Maaskant, R. 2016, IEEE Transactions on Antennas and Propagation, 64, doi:10.1109/TAP.2016.2537363
- Carroll, B. W., & Ostlie, D. A. 2017, An Introduction to Modern Astrophysics (Cambridge University Press)
- Condon, J. J., & Ransom, S. M. 2016, Essential Radio Astronomy (Princeton University Press)
- Dunning, A., Bowen, M., Bourne, M., Hayman, D., & Smith, S. L. 2015, in 2015 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), 787-790
- Griffiths, D. J. 2013, Introduction to Electrodynamics, 4th edn. (Pearson Education, Inc.)
- Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., & Collins, R. A. 1968, Nature, 217, 709
- Kildal, P.-S. 1985, IEEE Transactions on Antennas and Propagation, 33, 903
- Lorimer, D. R., & Kramer, M. 2005, Handbook of Pulsar Astronomy (Cambridge University Press)
- Simon, R. J. 2005, NRAO Electronics Division Internal Report 315
  
- FAST radio telescope: <https://www.wired.com/story/china-fast-worlds-largest-telescope-tourists/>
- CHIME: <https://chime-experiment.ca/>
- ngVLA: <https://ngvla.nrao.edu/images>
- GBT: <https://arstechnica.com/information-technology/2015/01/electrosensitives-seek-haven-in-wi-fi-quiet-zone-as-teens-set-up-hotspots/>
- HL Tau: <https://www.eso.org/public/images/eso1436a/>
- GW gif: <http://lisa.jpl.nasa.gov/popups/ripples.html>
- GW spectrum: <https://lisa.nasa.gov/>
- Pulsar timing array: <https://sites.google.com/site/djchampion/research>
  
- GBT feed arm: <https://www.cv.nrao.edu/course/astr534/RadioTelescopes.html>
- Waveguide: <https://www.surplussales.com/RF/RFWaveG-4.html>
- Waveguides: [https://en.wikipedia.org/wiki/Waveguide\\_\(radio\\_frequency\)#/media/File:Waveguide\\_collection.jpg](https://en.wikipedia.org/wiki/Waveguide_(radio_frequency)#/media/File:Waveguide_collection.jpg)
- W band receiver: <https://ngvla.nrao.edu/page/technology>
- L band receiver on truck: <https://public.nrao.edu/gallery/trucking-a-giant-feed-horn/>
- GBT turret: <https://public.nrao.edu/gallery/looking-down-the-revolver/>
- L band inside turret: <https://www.cv.nrao.edu/course/astr534/RadioTelescopes.html>
- Waveguide mode gif: <https://workshopwaveguides.wordpress.com/>
- JBB: <https://blog.csiro.au/pioneer-pulsars-pops-into-parkes/>