THE GREEN BANK OBSERVATORY

ULTRA WIDEBAND RECEIVER

ALYSSA BULATEK

APRIL 2, 2020

Image credit: Greta Helmel

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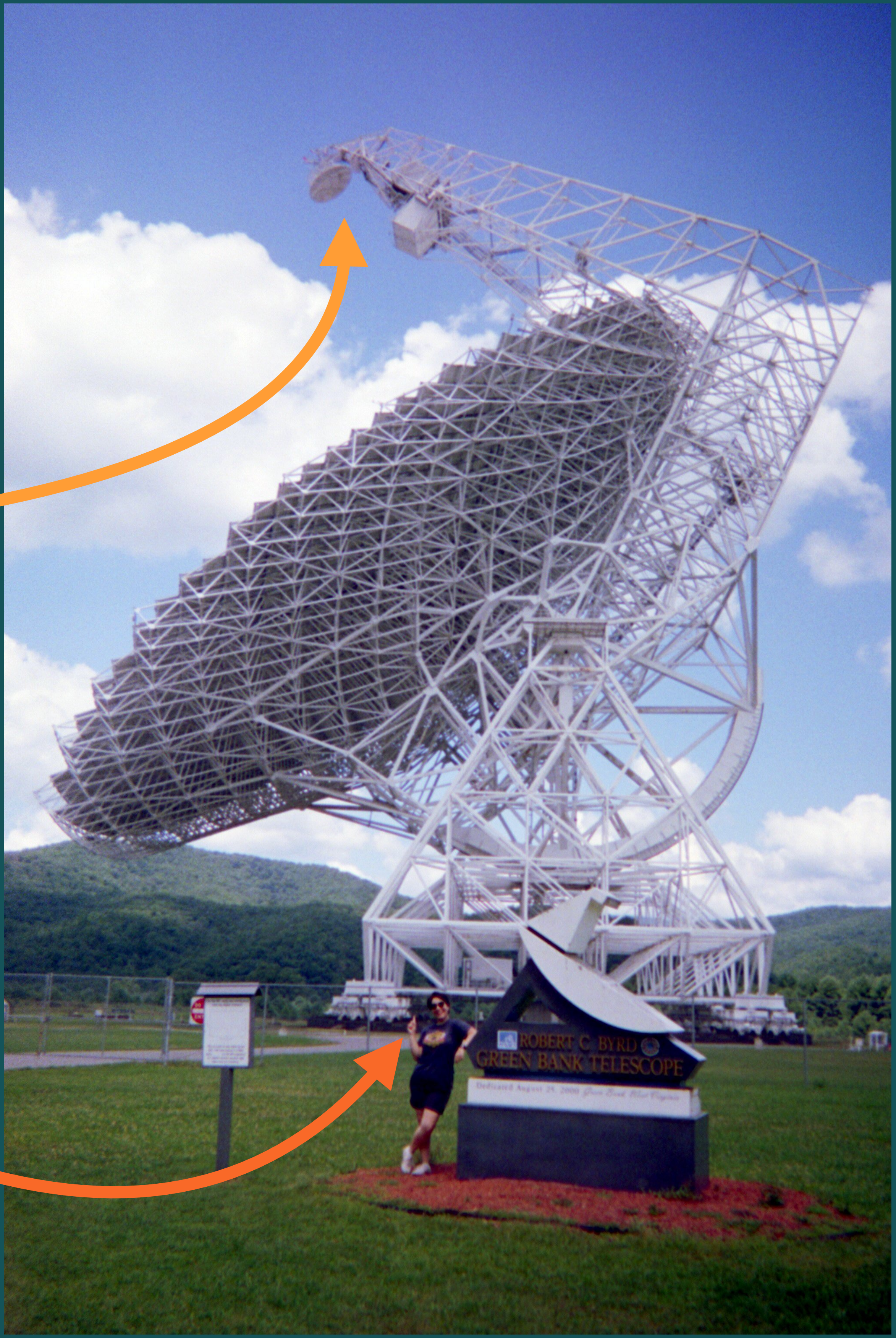

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APRIL 2, 2020

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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

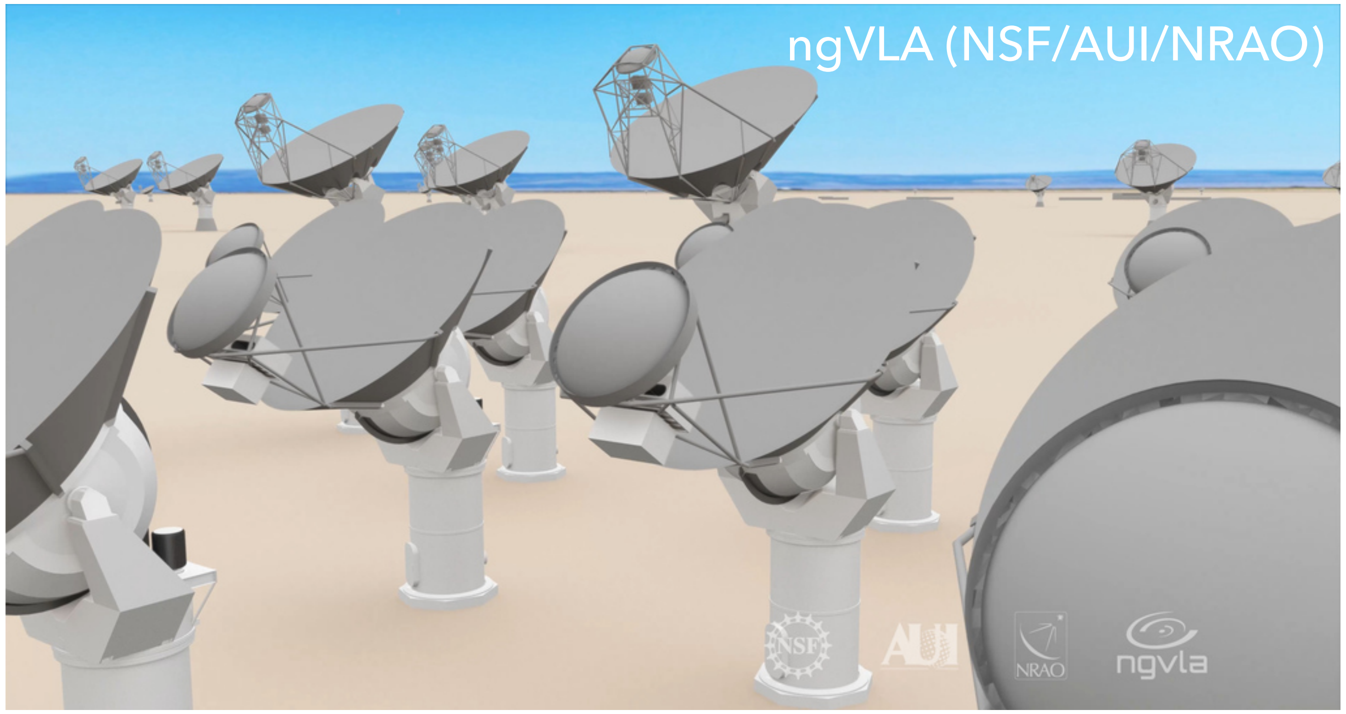
Troubleshooting a receiver in 3 easy steps

A waveguide mode breakdown tutorial

ACT I

THE FUTURE OF RADIO ASTRONOMY


FAST (Liu Xu/Xinhua/Getty Images)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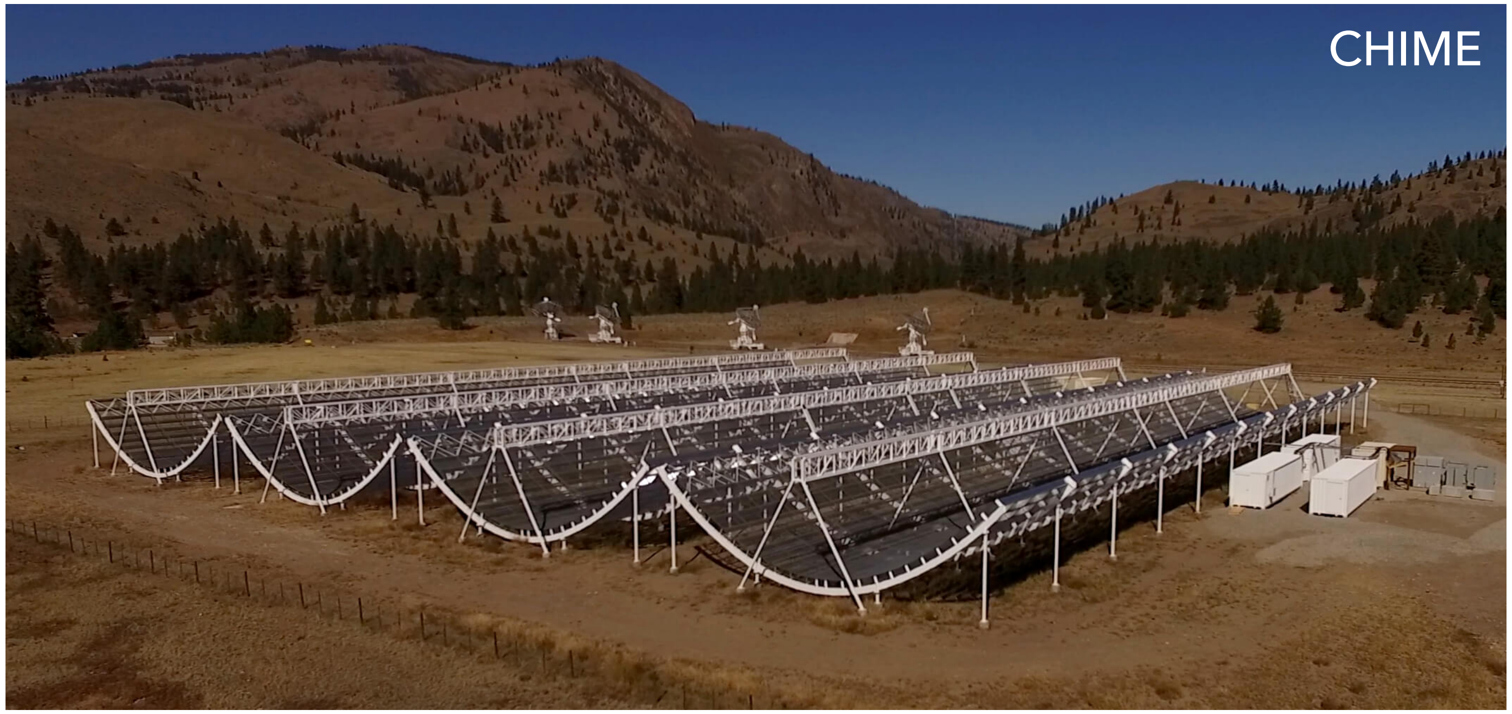
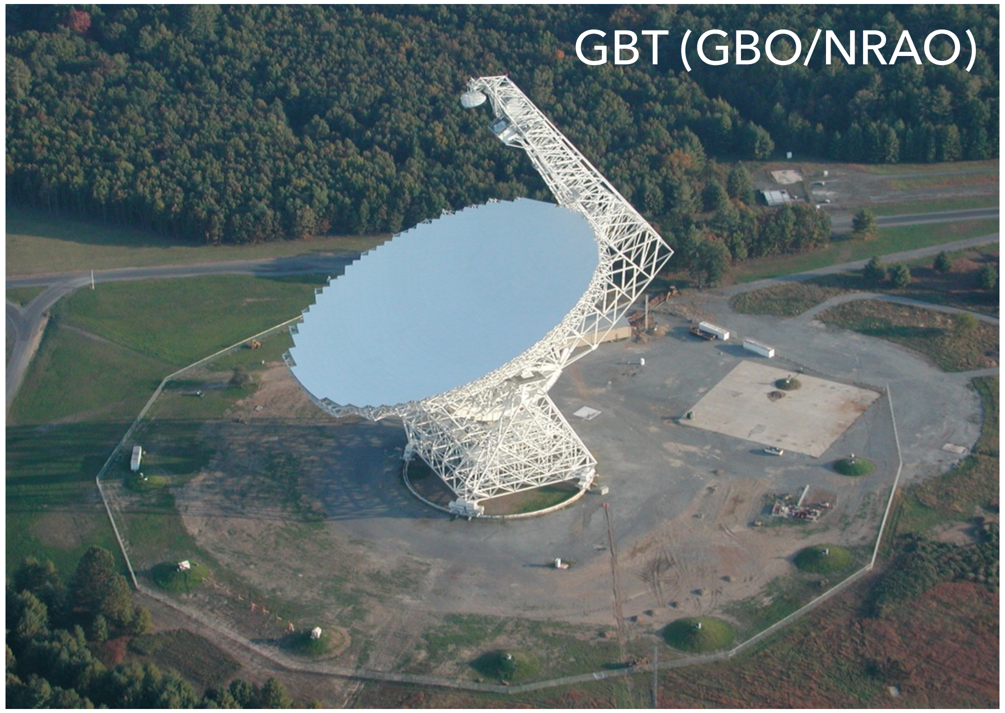

CHIME


GBT (GBO/NRAO)

THE FUTURE OF RADIO ASTRONOMY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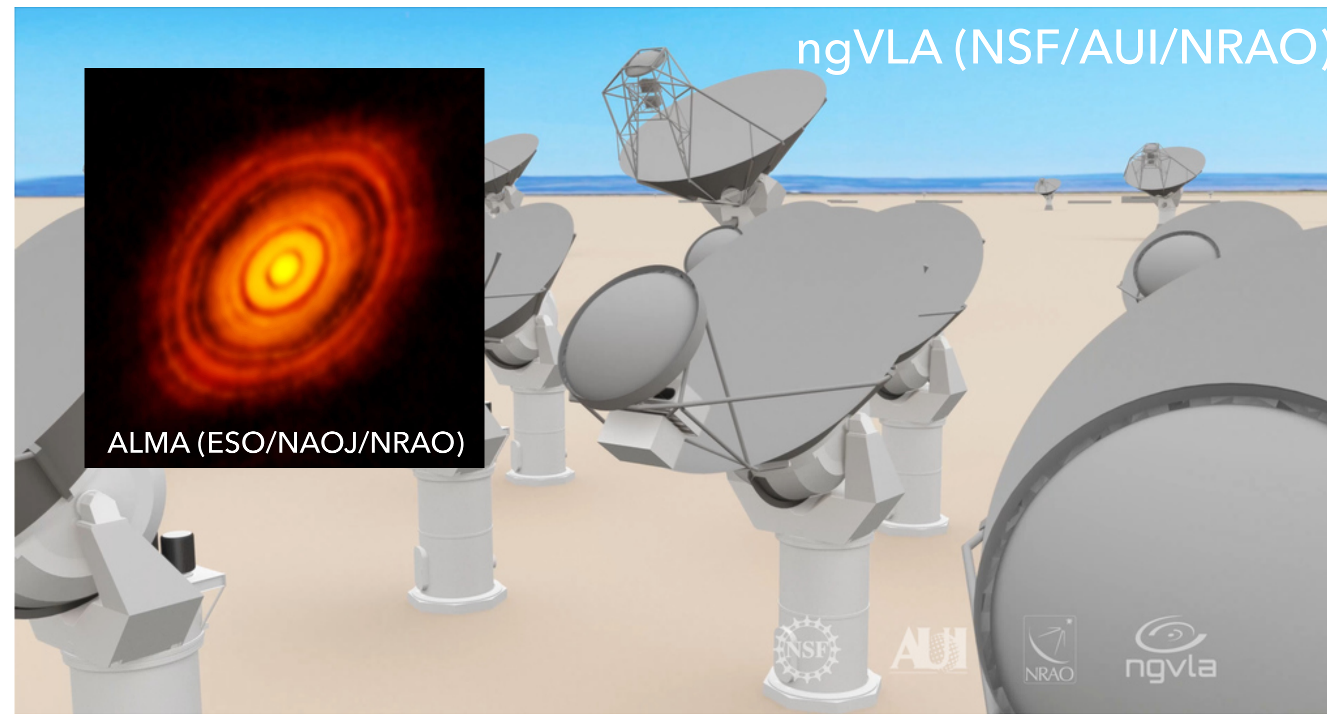
ngVLA (NSF/AUI/NRAO)

ALMA (ESO/NAOJ/NRAO)


CHIME


GBT (GBO/NRAO)

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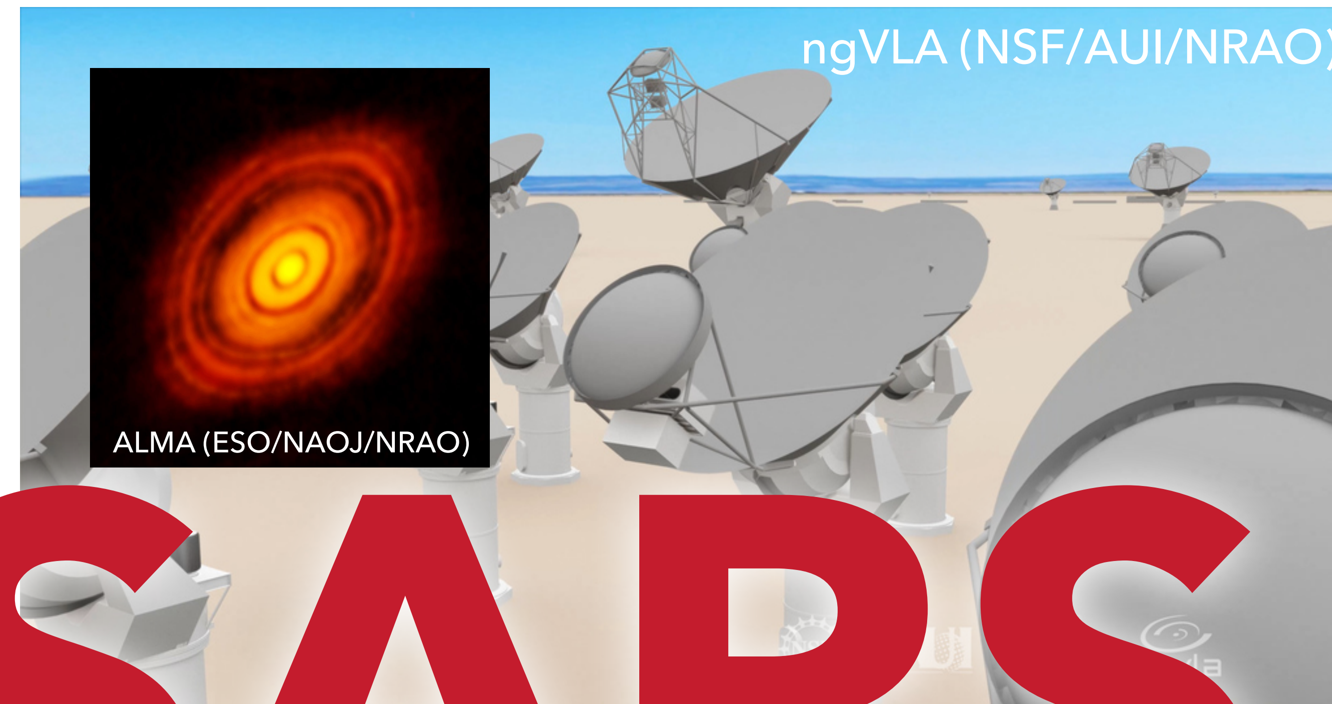
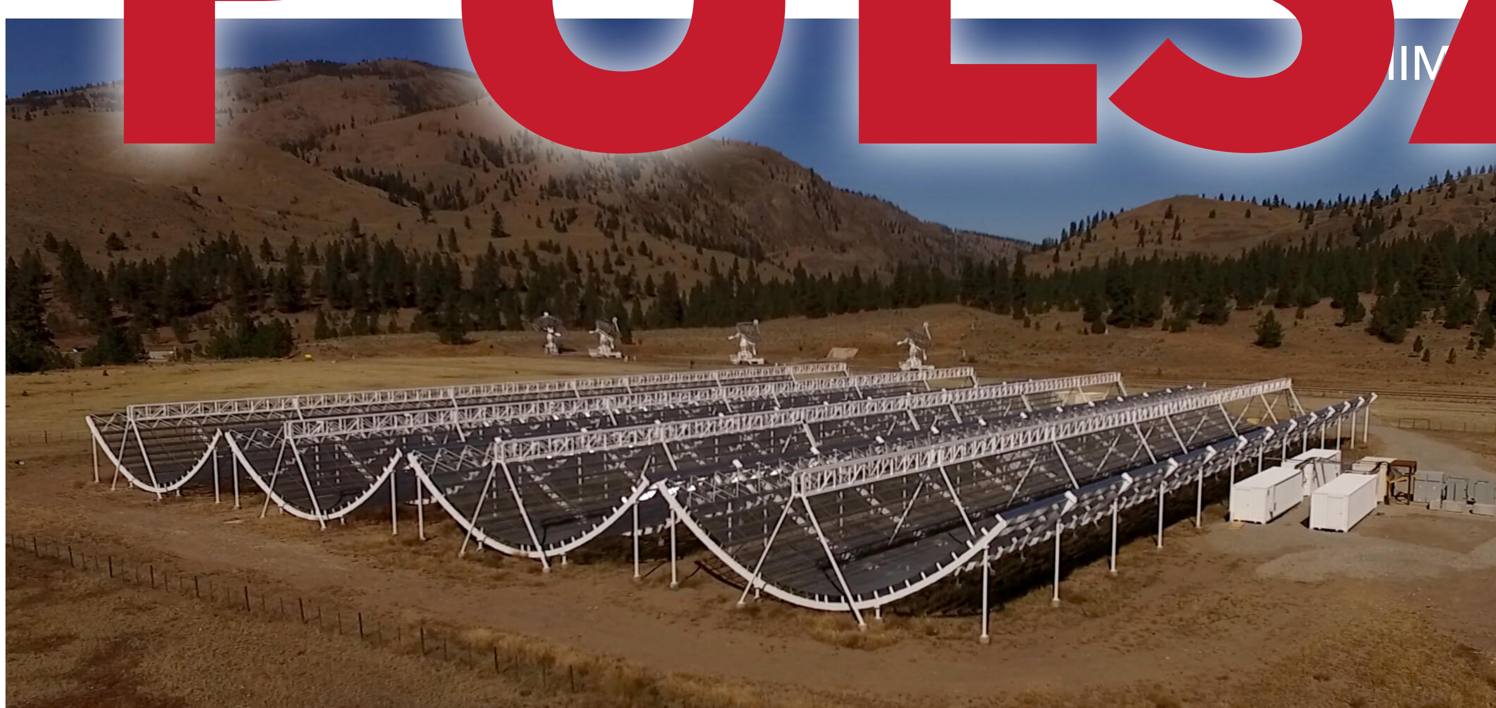


PULSARS



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)

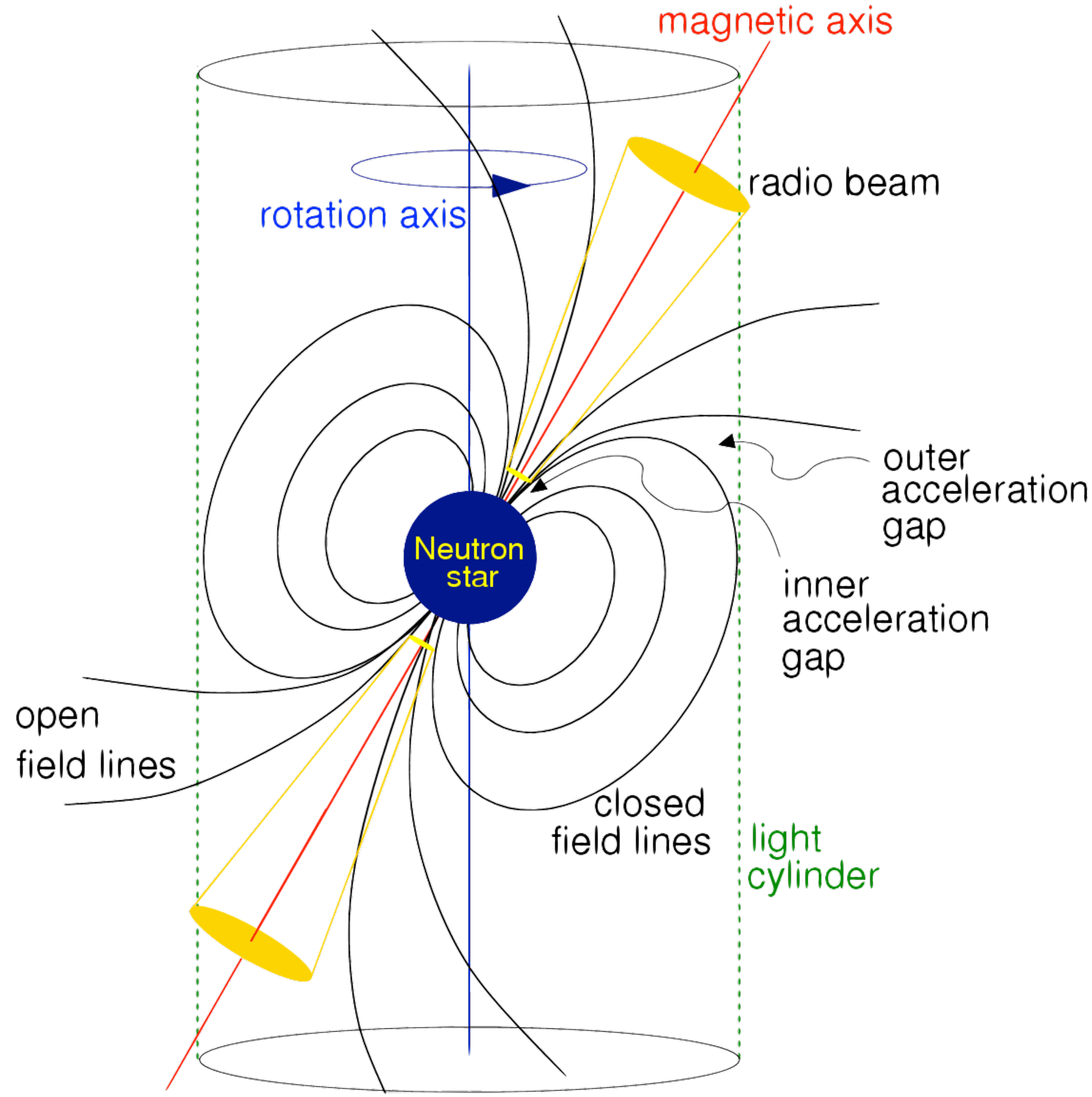


Image credit: Lorimer & Kramer (2005)

PULSAR TIMING

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

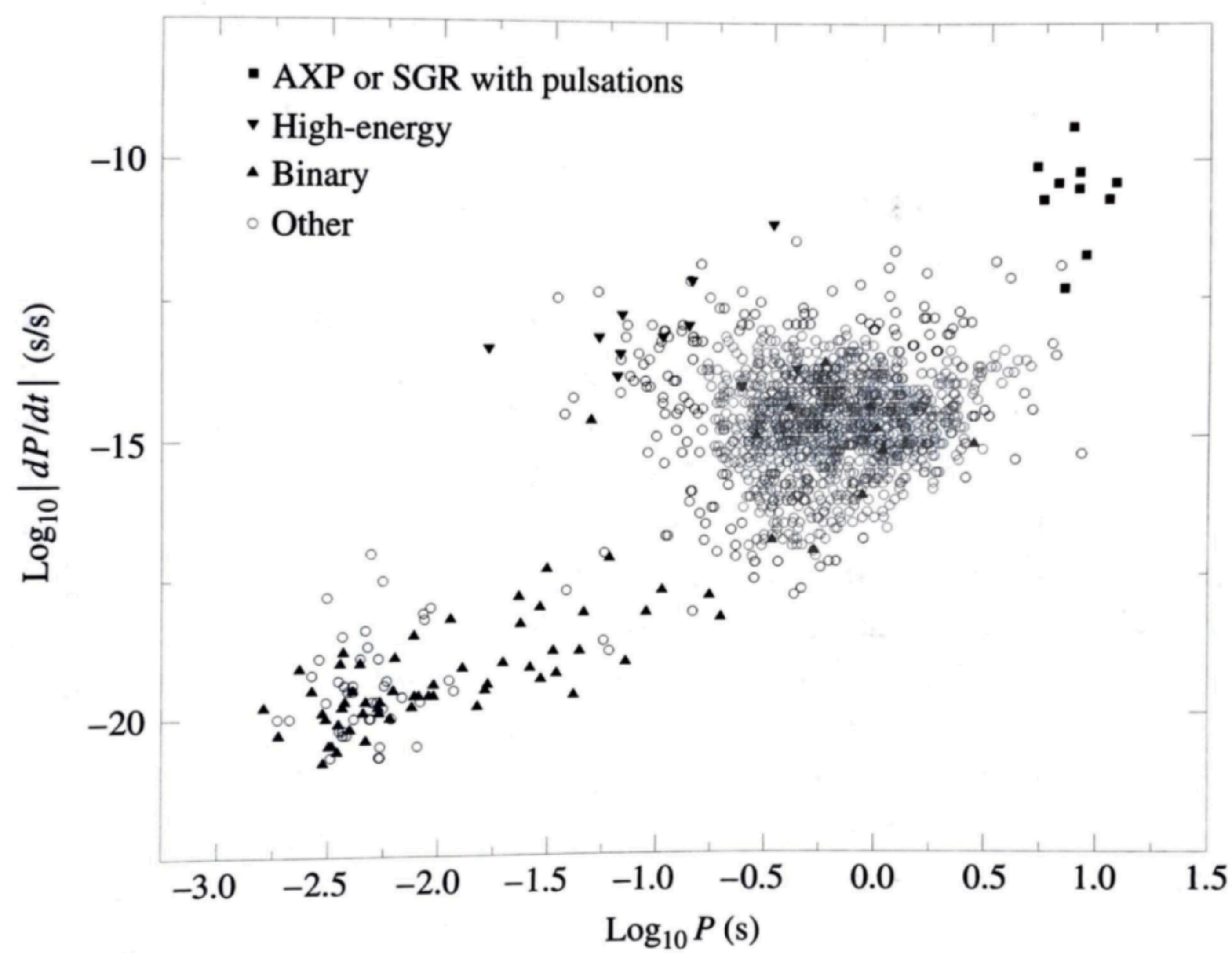


Image credit: Carroll & Ostlie (2017)

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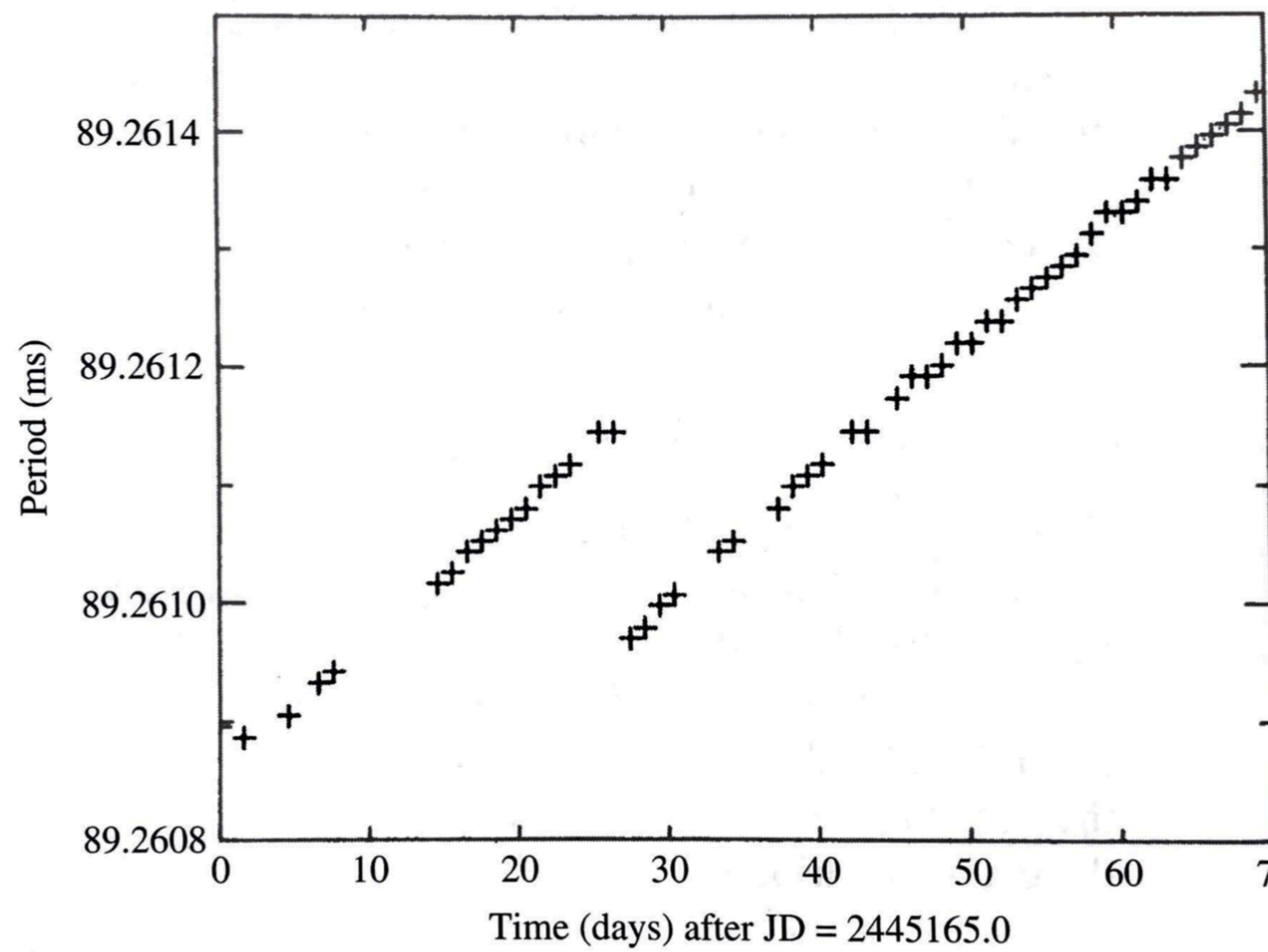
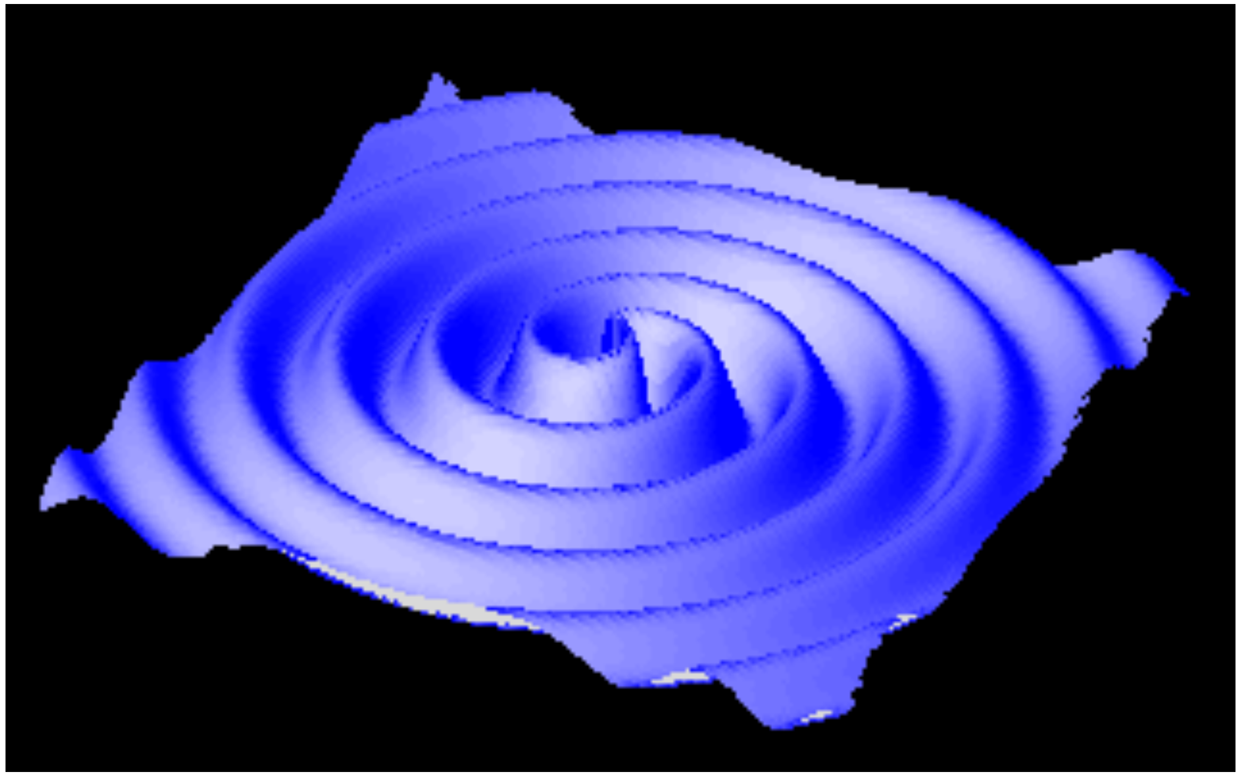


Image credit: Carroll & Ostlie (2017)

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)

GIF credit: NASA/JPL

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

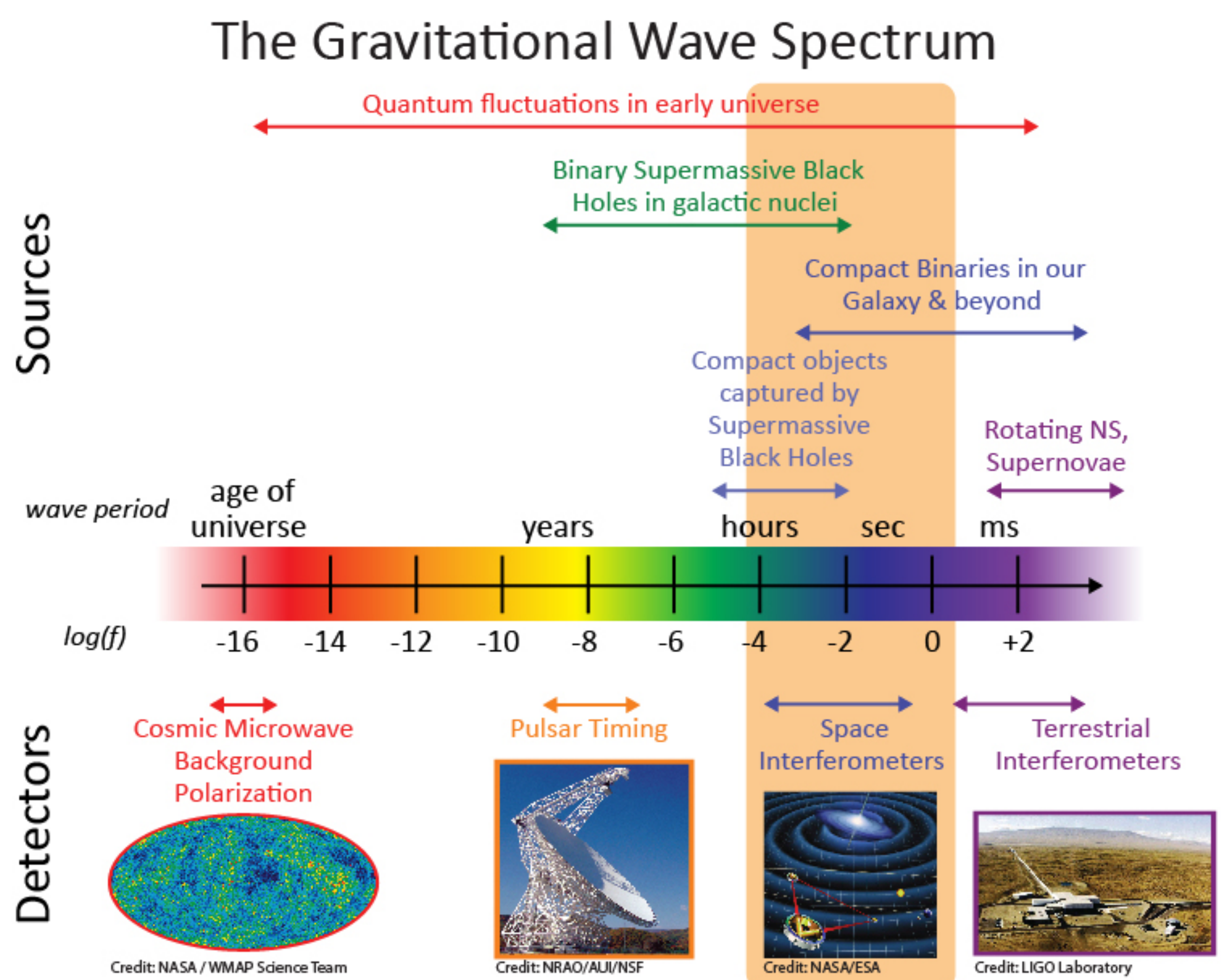


Image credit: NASA/ESA through LISA website

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!**

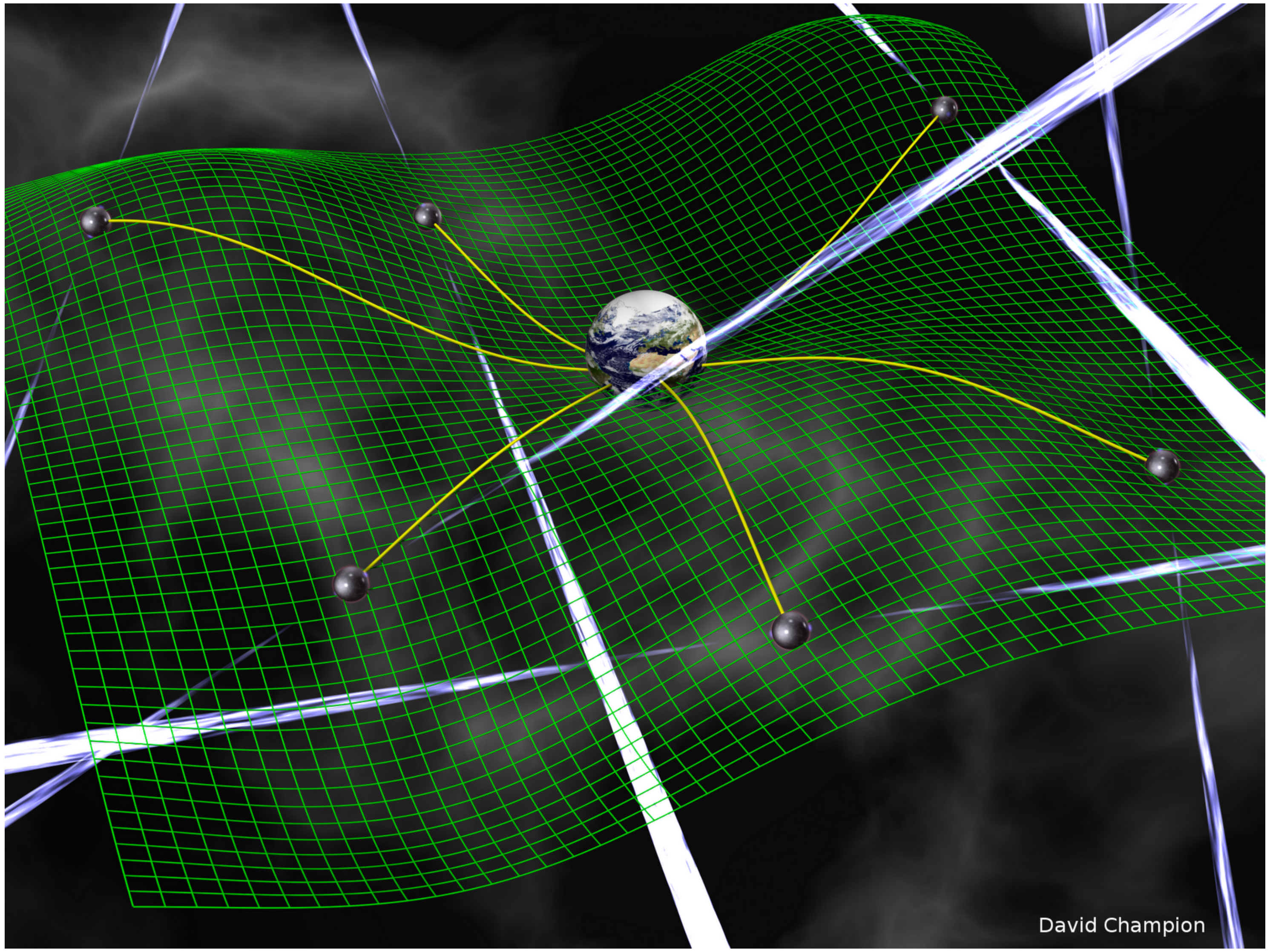


Image credit: David Champion

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

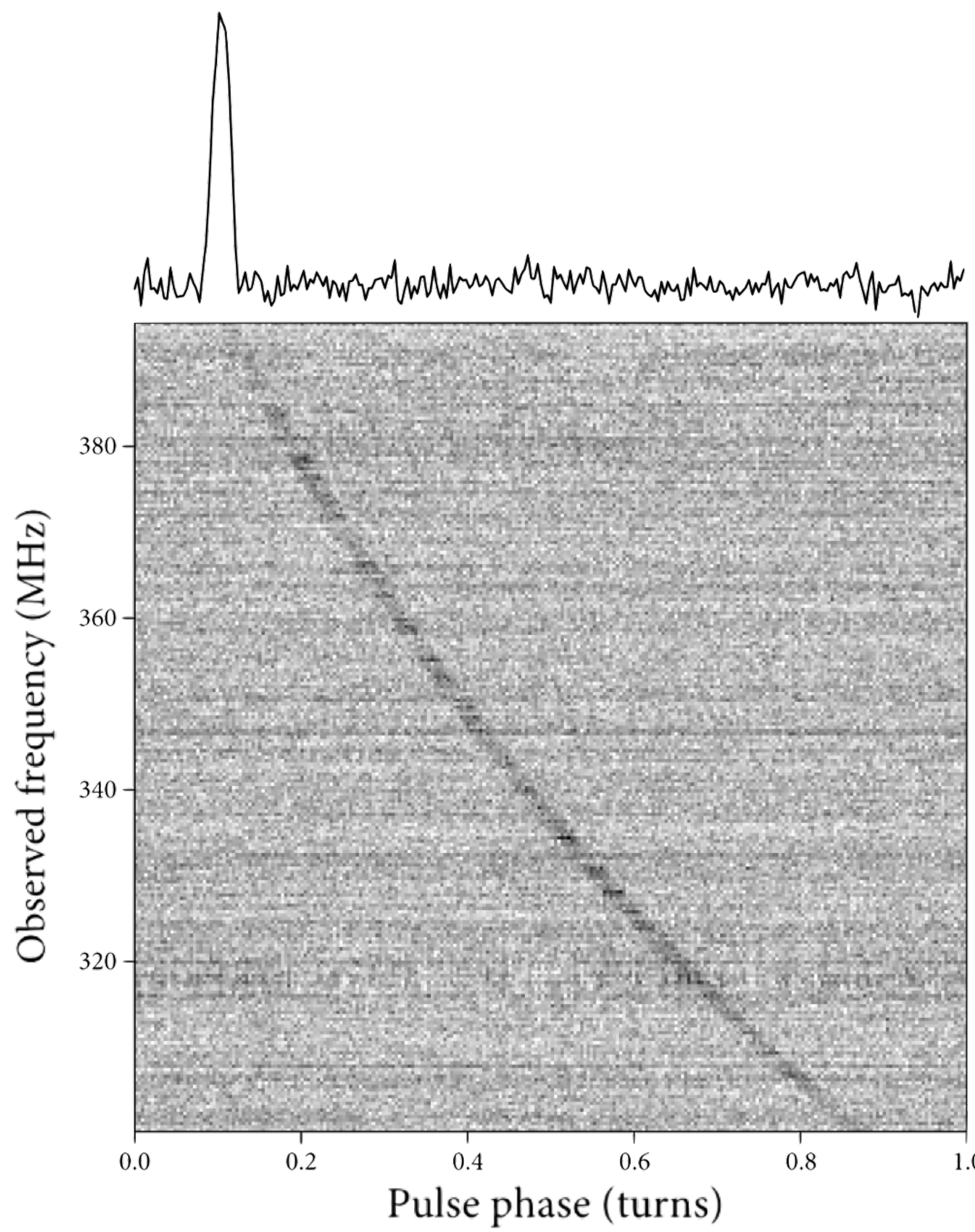


Image credit: Condon & Ransom (2016)

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)!**

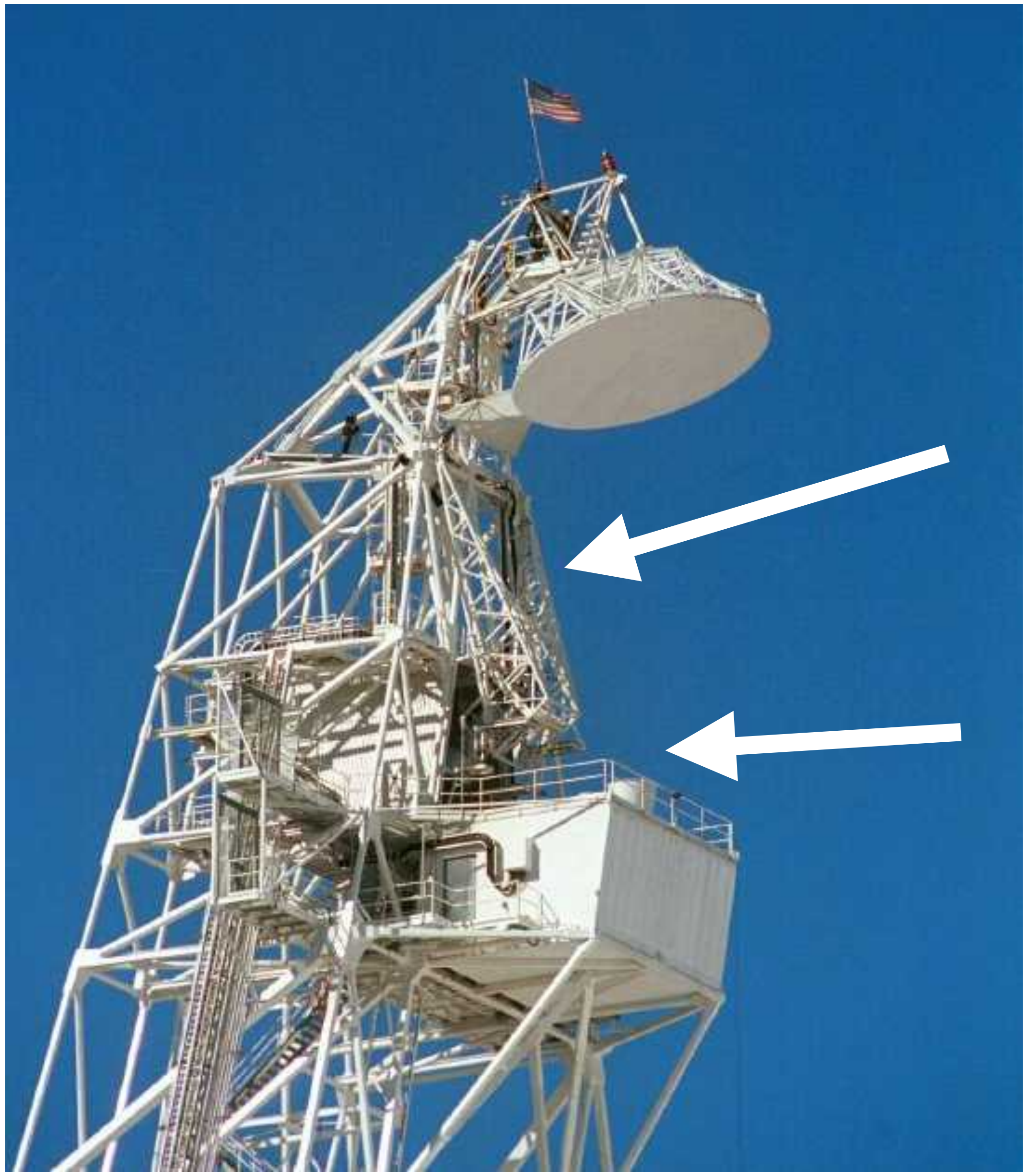


Image credit: NRAO

ACT II

WAVEGUIDES

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

Image credit: Surplus Sales of Nebraska; *Tele-Tech* magazine

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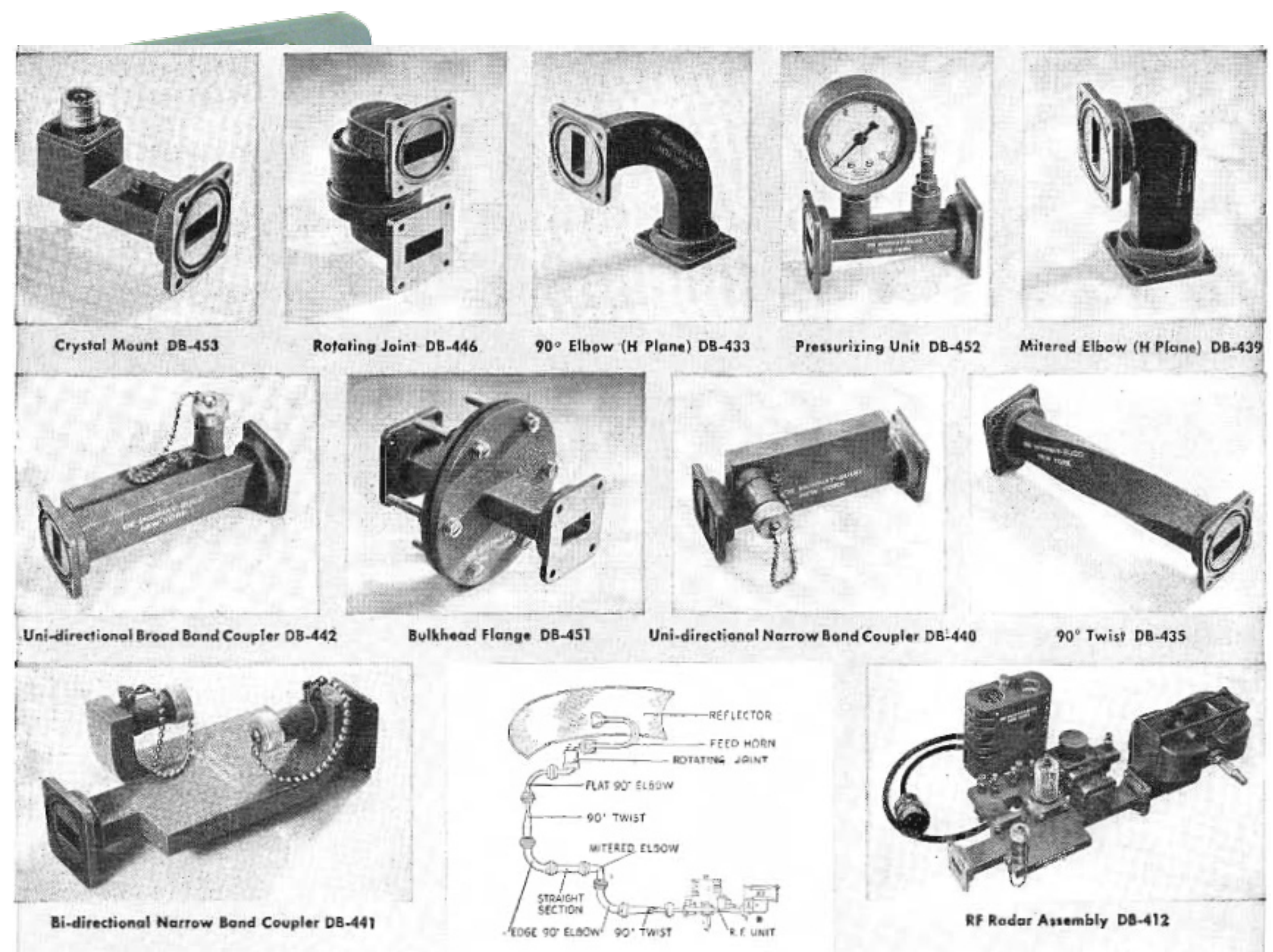

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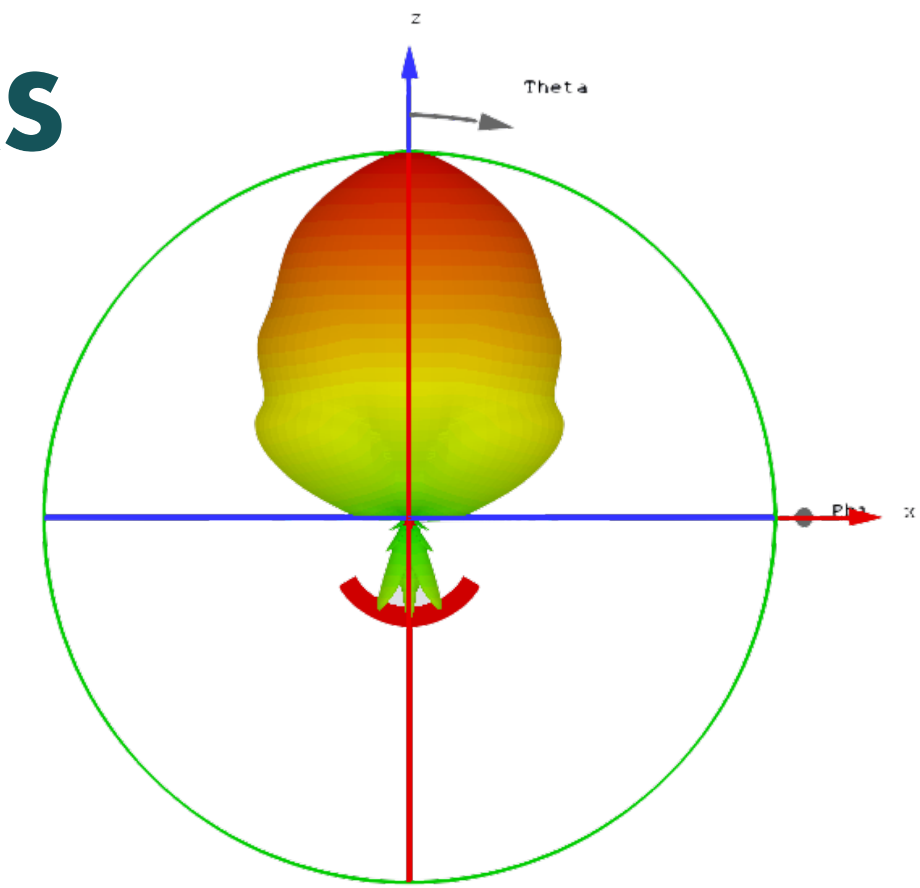
RADIO RECEIVERS



- 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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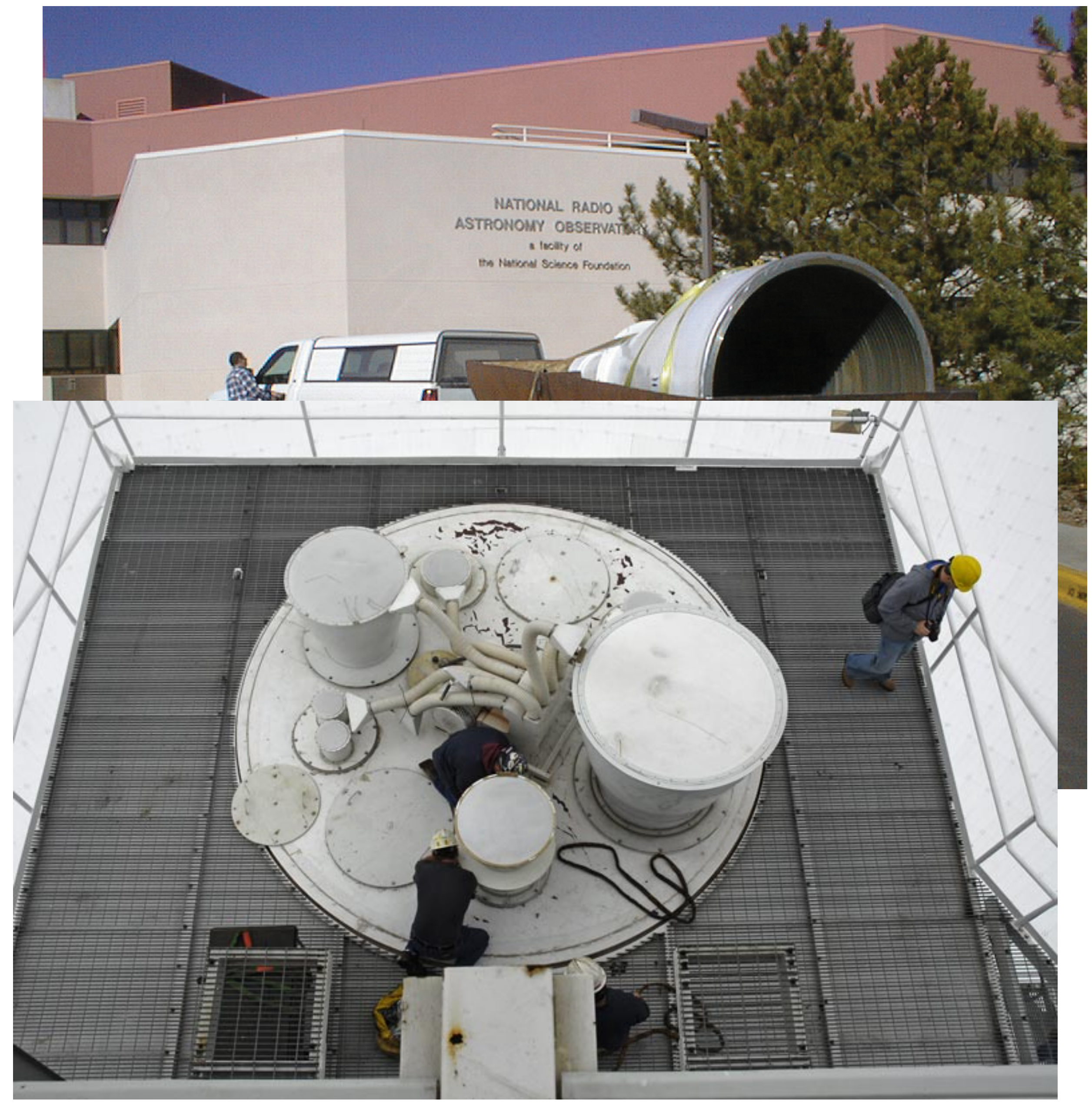

Image credit: NRAO

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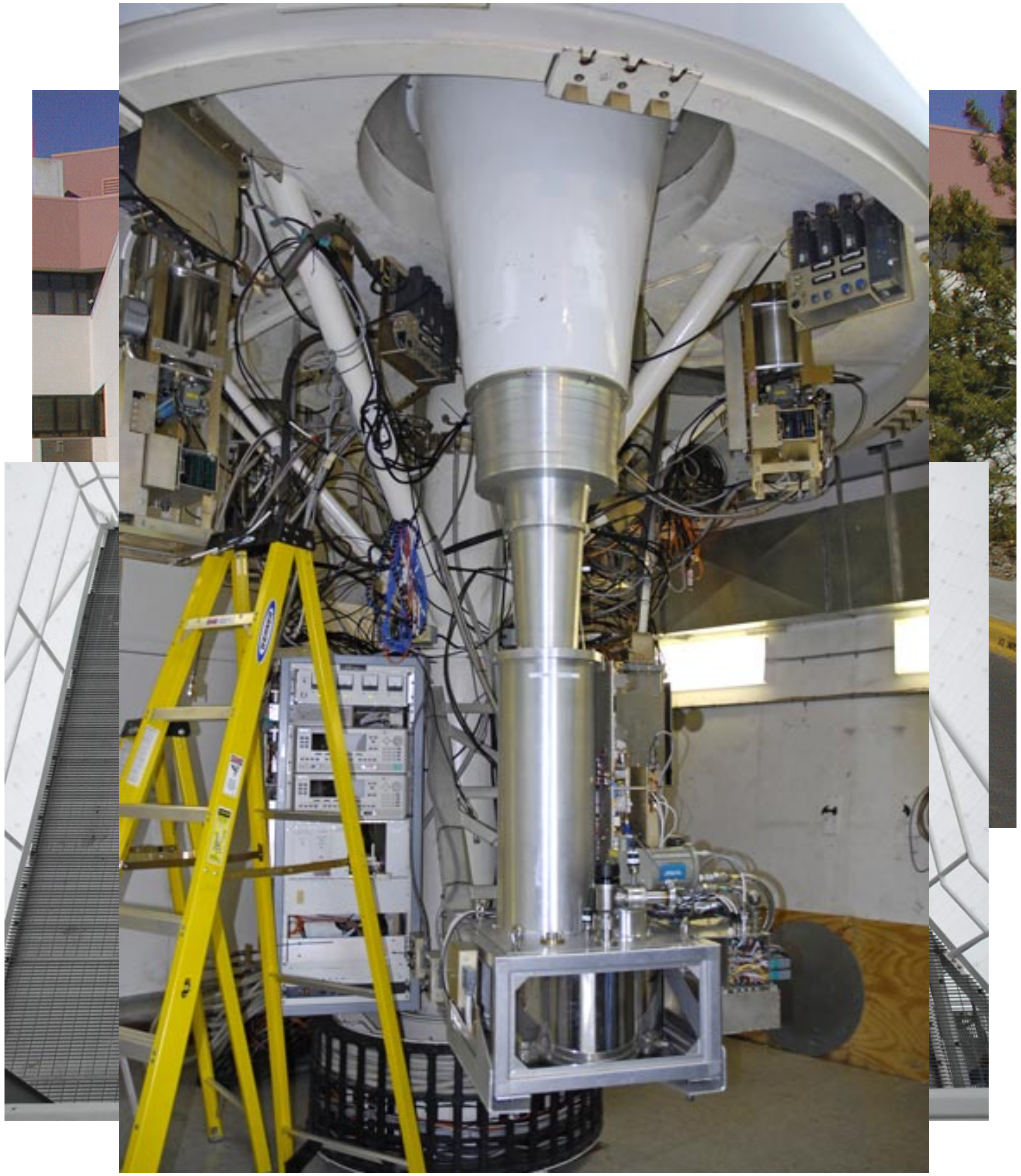
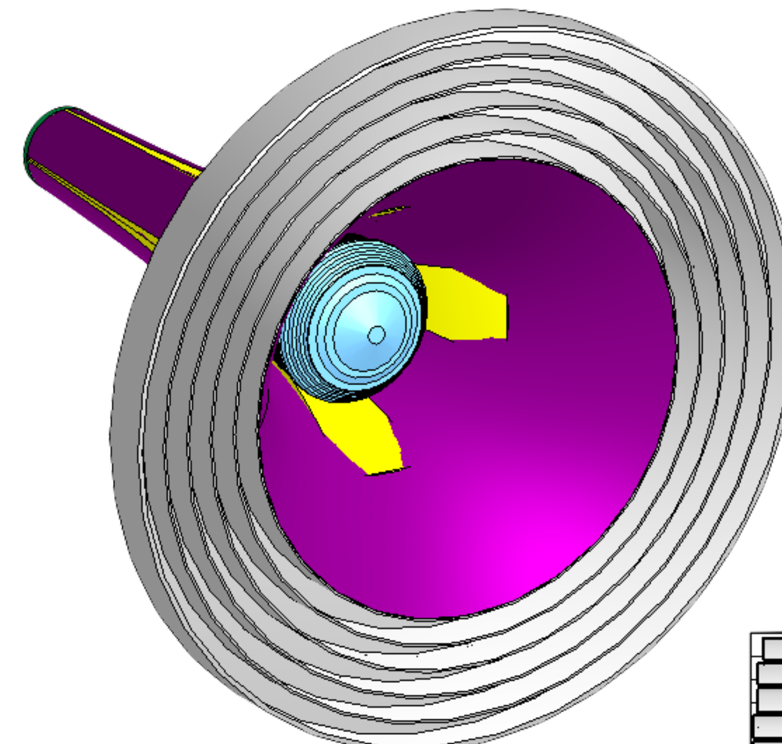
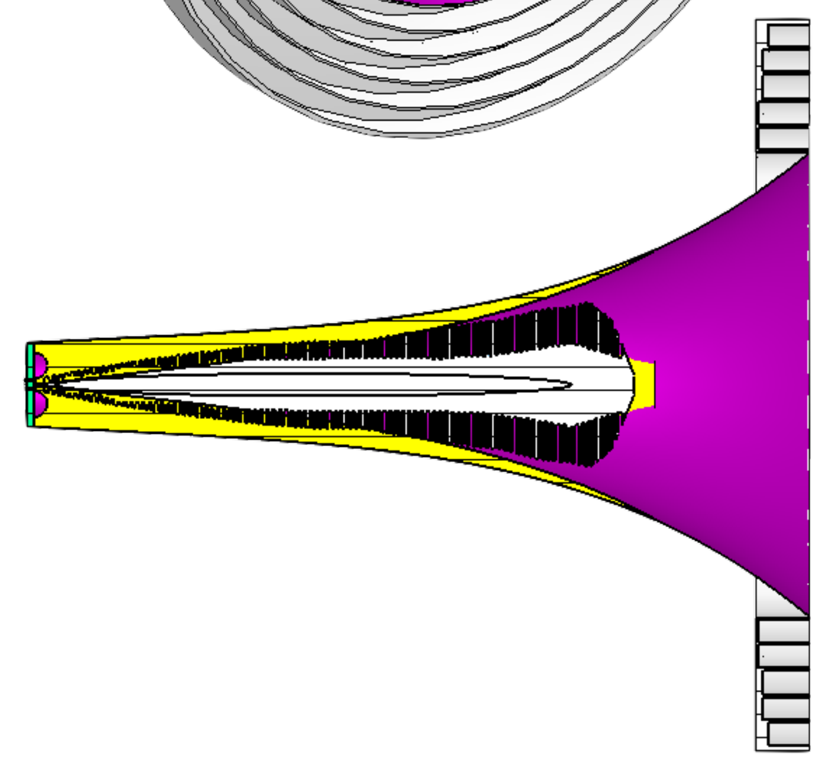


Image credit: NRAO

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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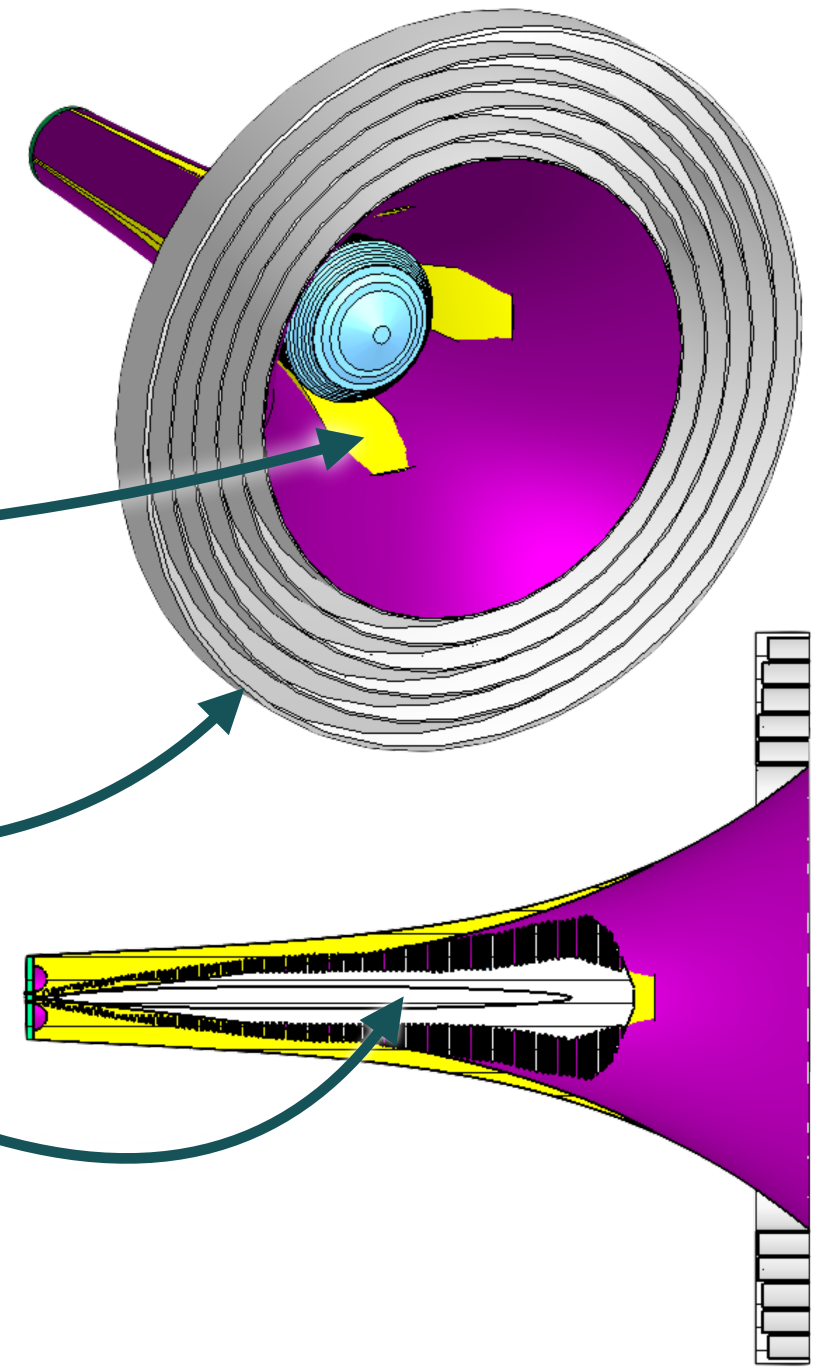
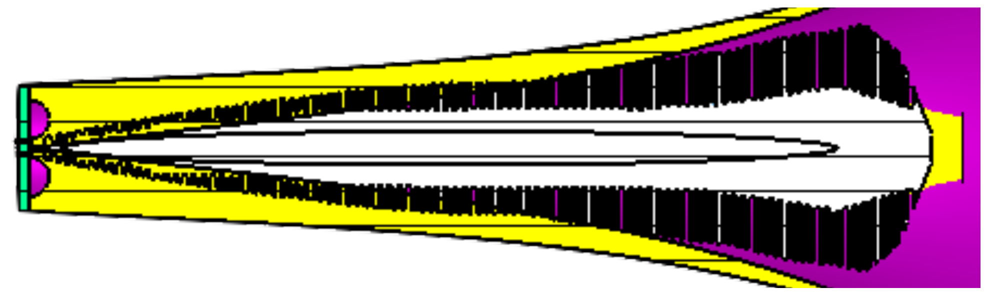
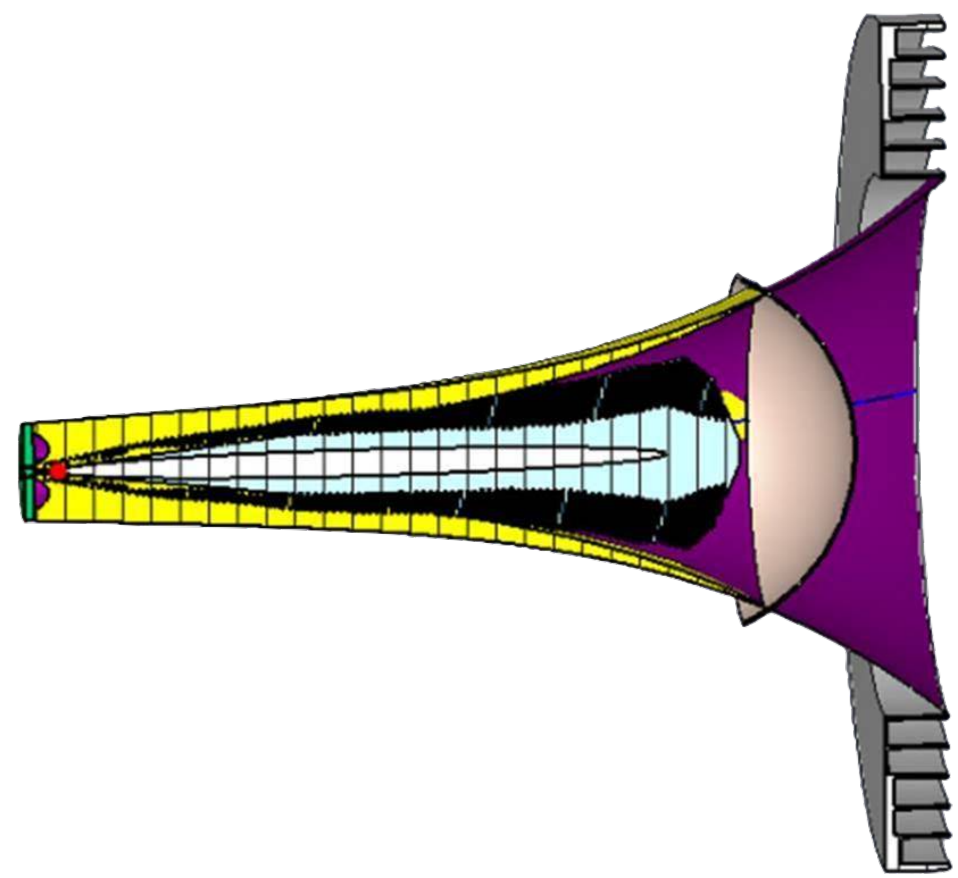
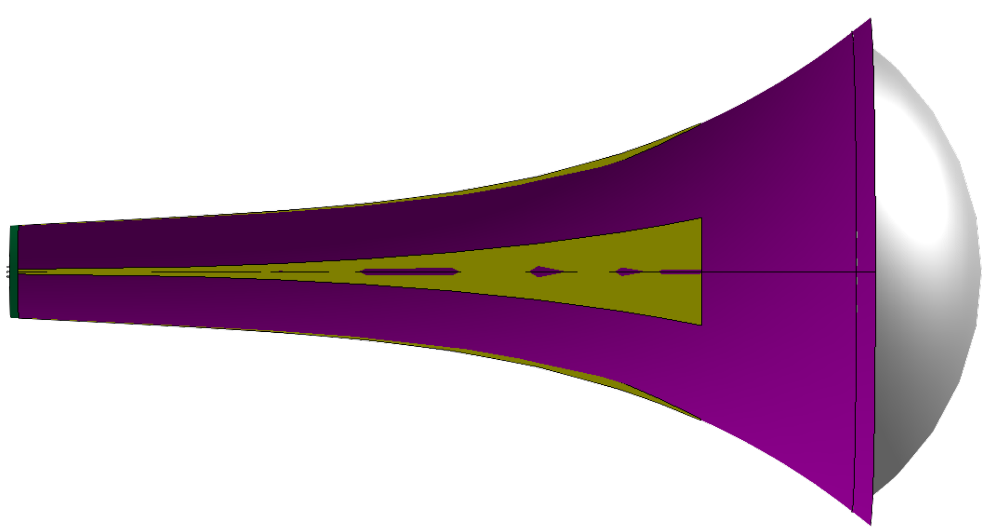


ULTRA-WIDEBAND RECEIVER

- **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

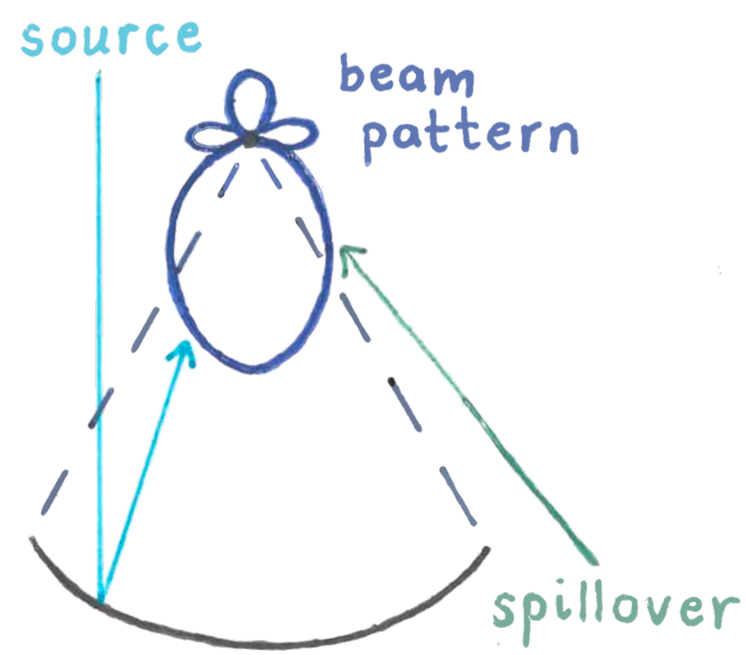
- Total feed efficiency, e_{tot}
  - Amount of light that hits the dish which actually gets received
  - Depends on shape of radiation pattern **(frequency-dependent)**
- Design goal: 60–70% at lower frequencies, above 50% at higher frequencies
- Can be divided into **sub-efficiencies:**

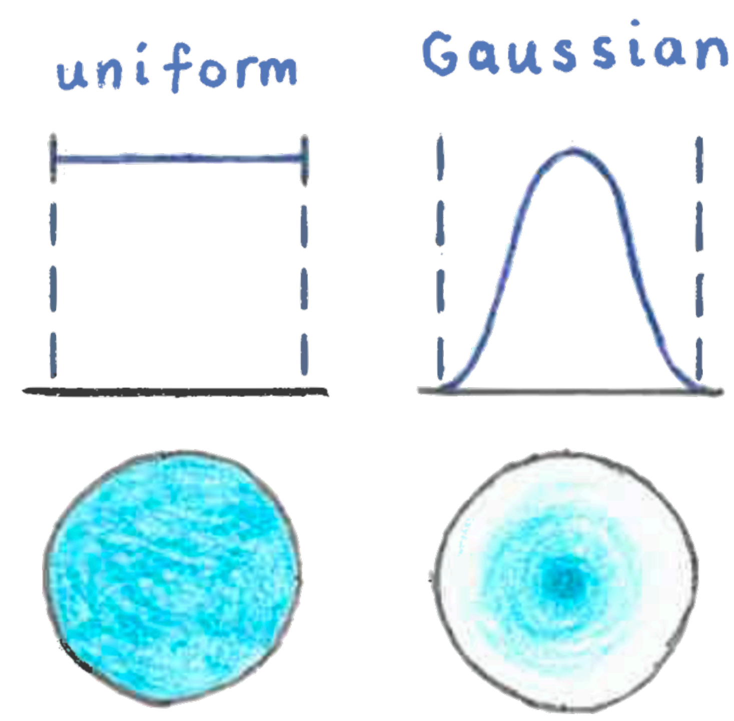
$$e_{tot} = e_{sp} \cdot e_{ill} \cdot e_{xp} \cdot e_{ph}$$

- There are other factors, but not for the GBT

EFFICIENCY ANALYSIS

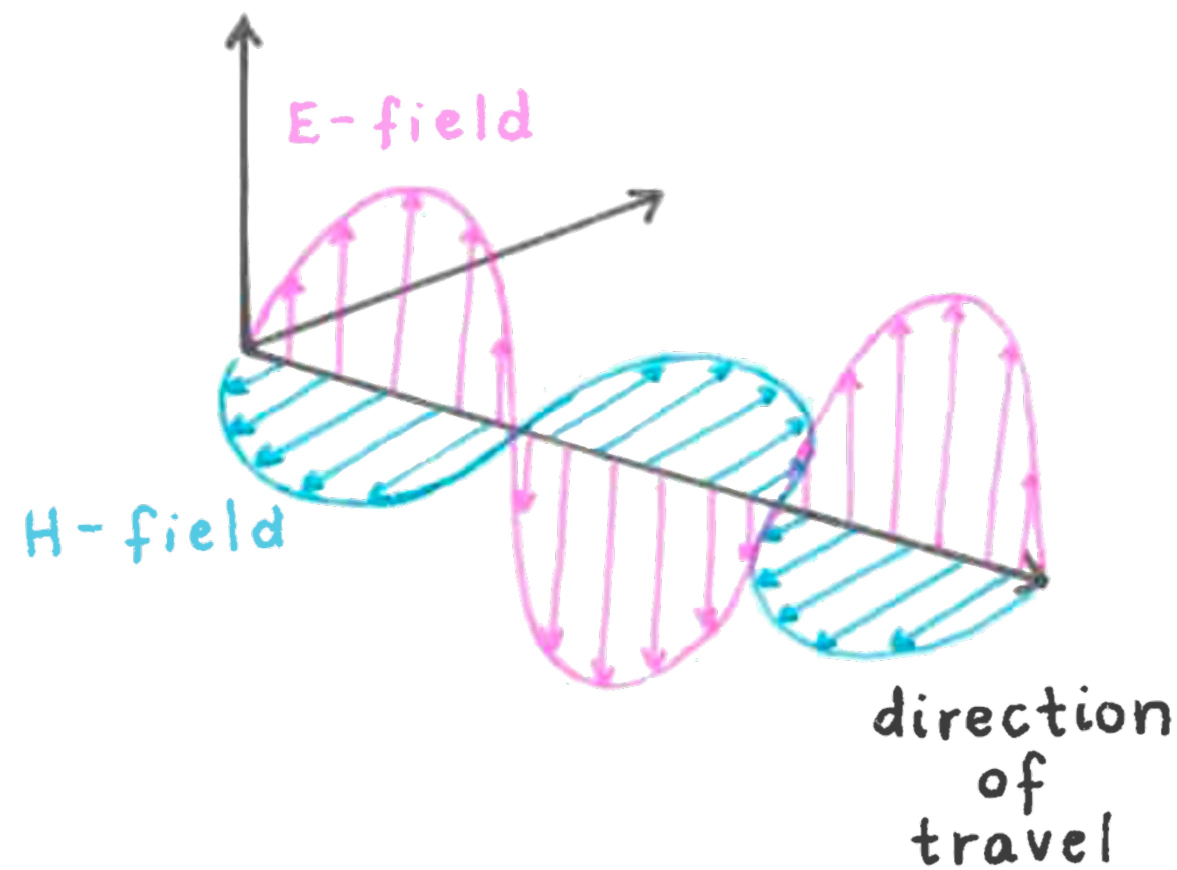
- Spillover efficiency, e_{sp}
  - Radiation that "spills over" the edge of the dish (or is accepted from beyond the edge of the dish)
- Illumination efficiency, e_{ill}
  - Measure of how much radiation pattern deviates from uniform across aperture > zero outside dish
- **Balance** between spillover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





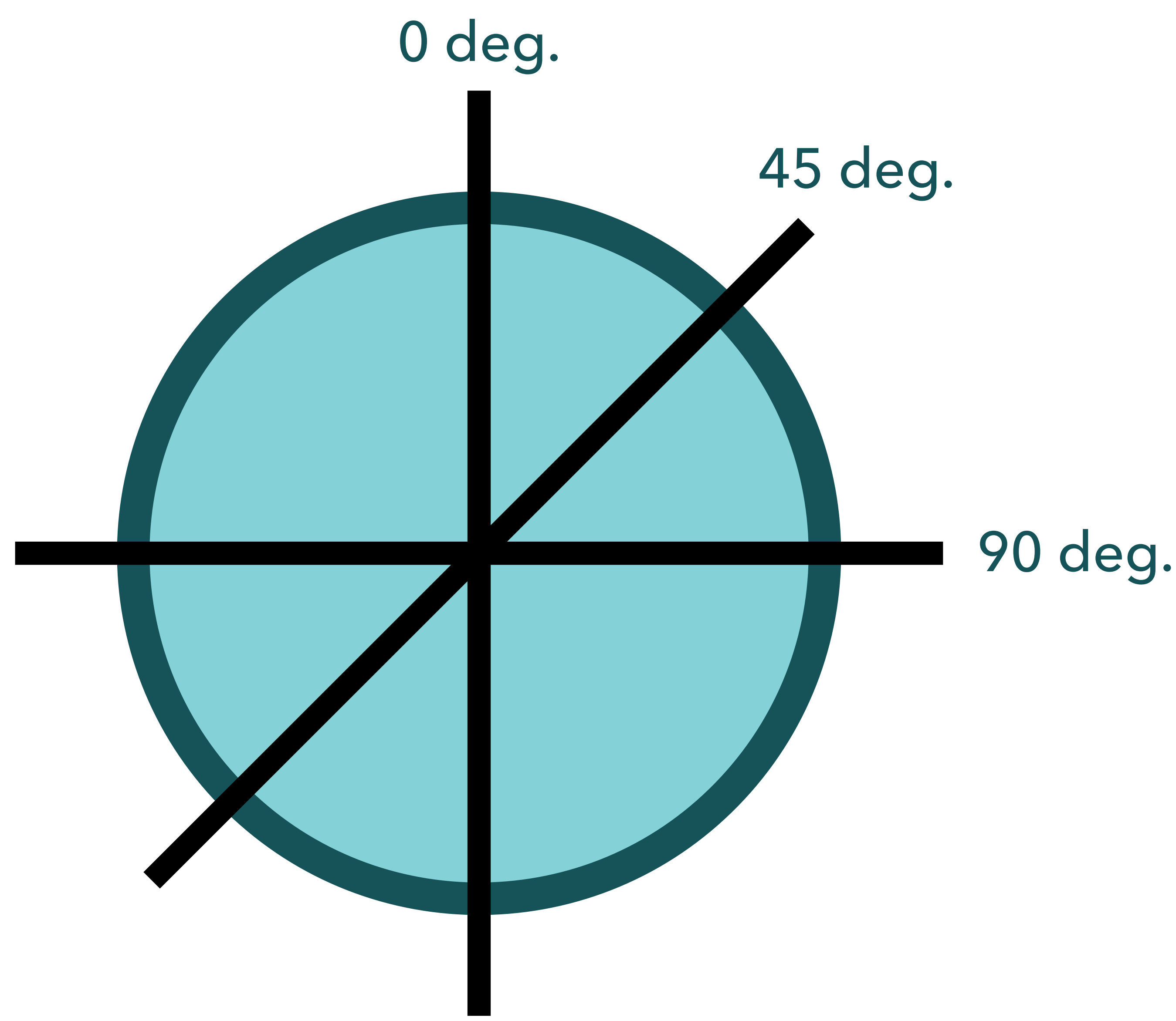
EFFICIENCY ANALYSIS

- **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



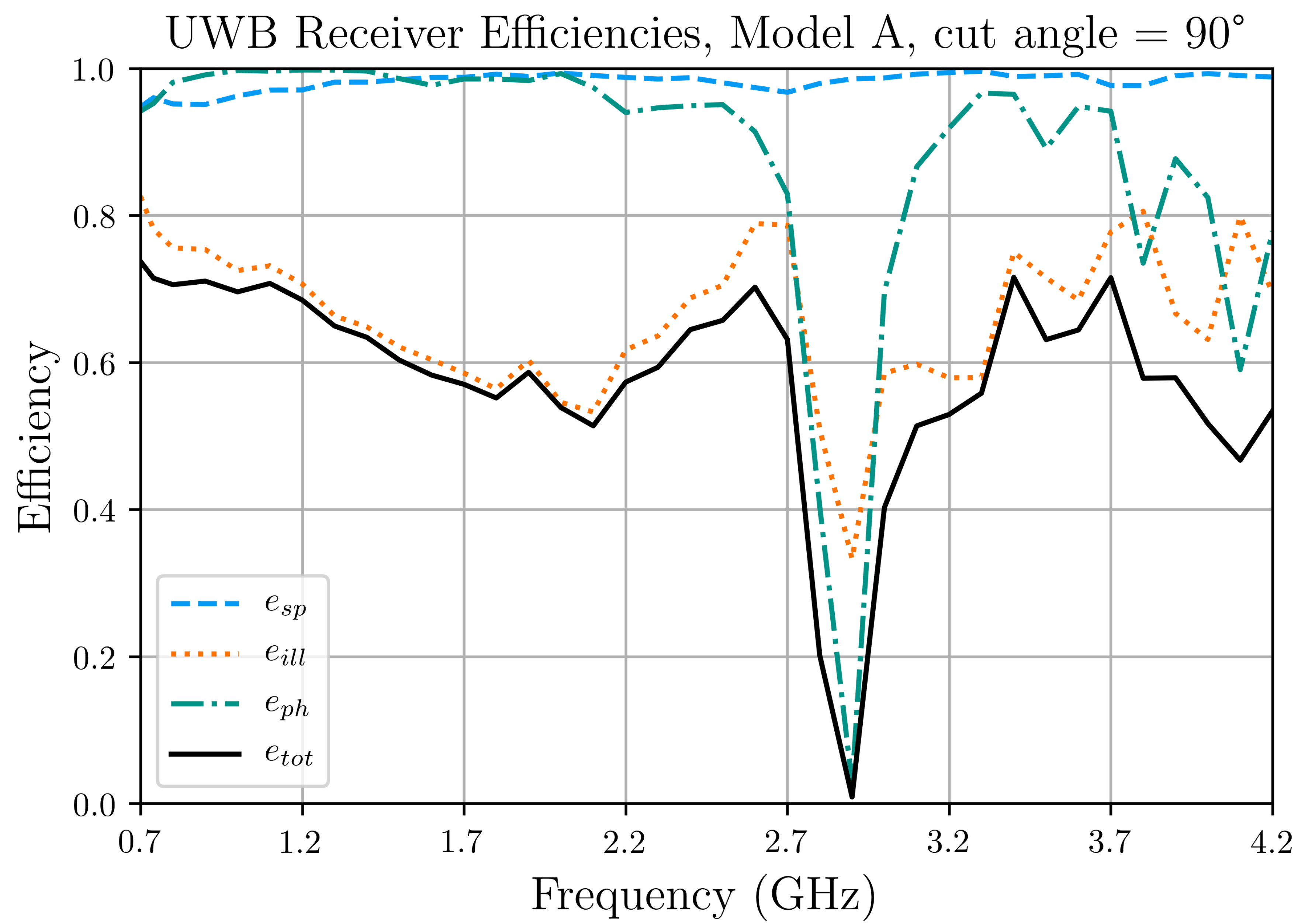
EFFICIENCY ANALYSIS

- 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



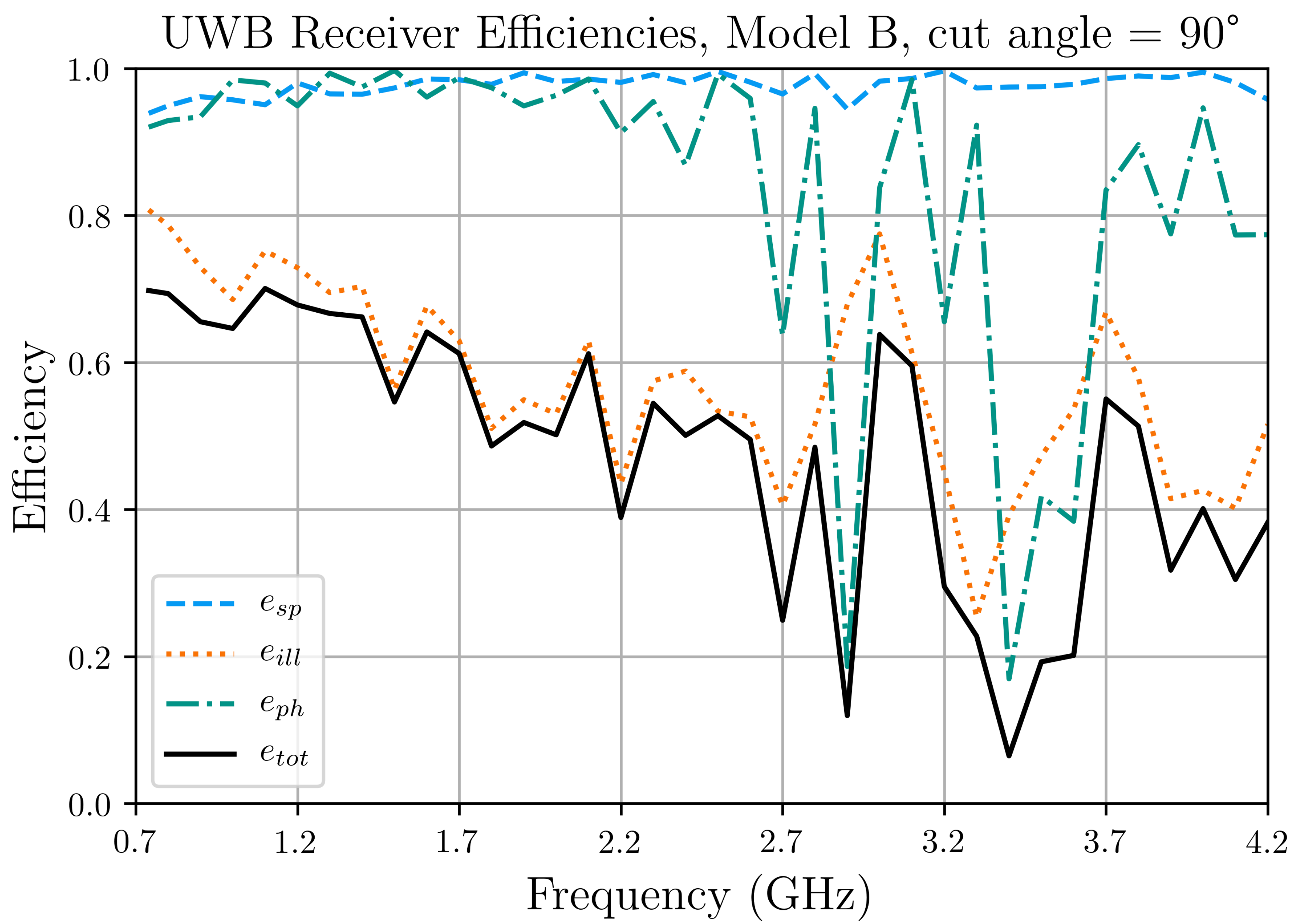
EFFICIENCY ANALYSIS RESULTS

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



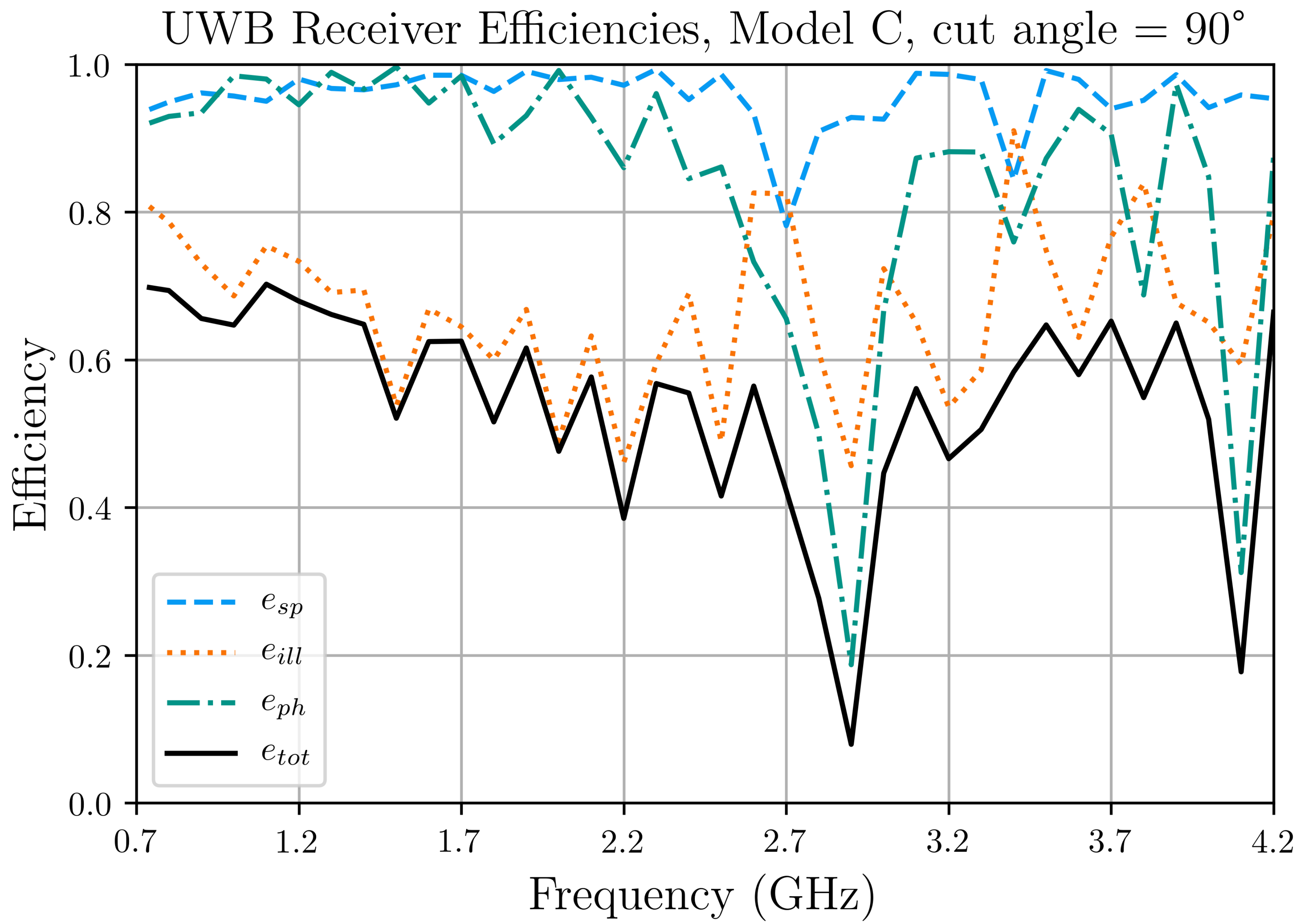
EFFICIENCY ANALYSIS RESULTS

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



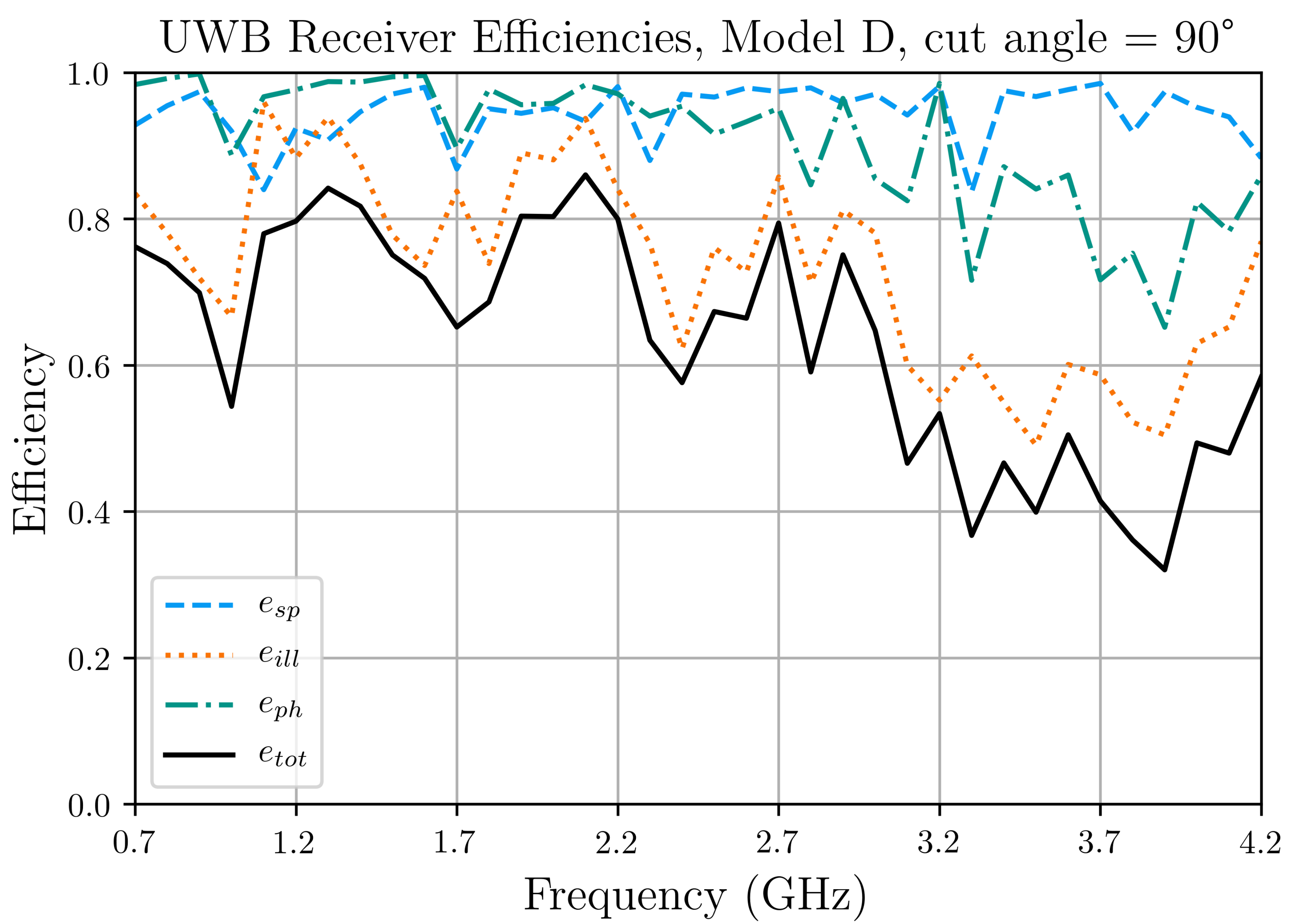
EFFICIENCY ANALYSIS RESULTS

- **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



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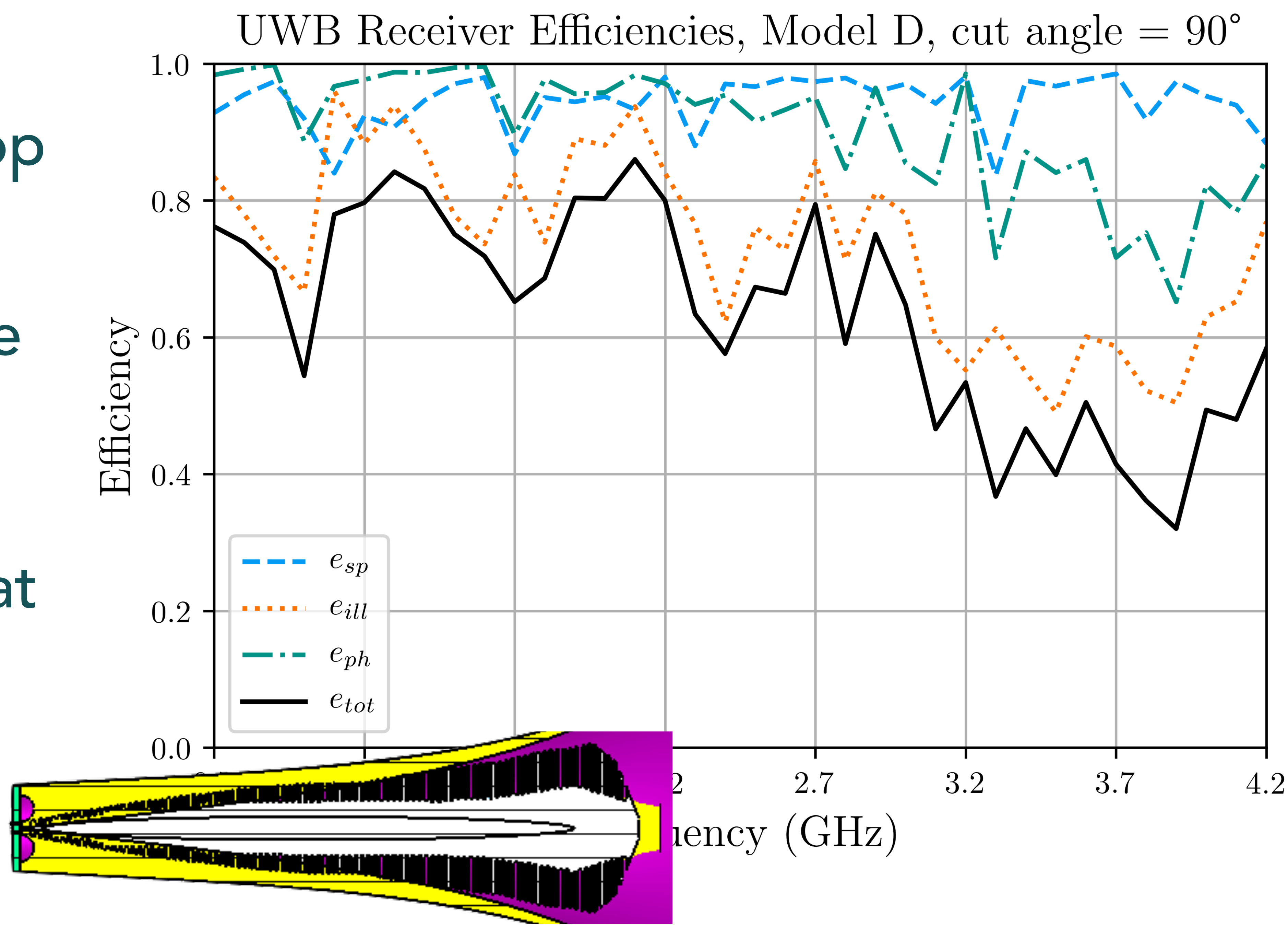
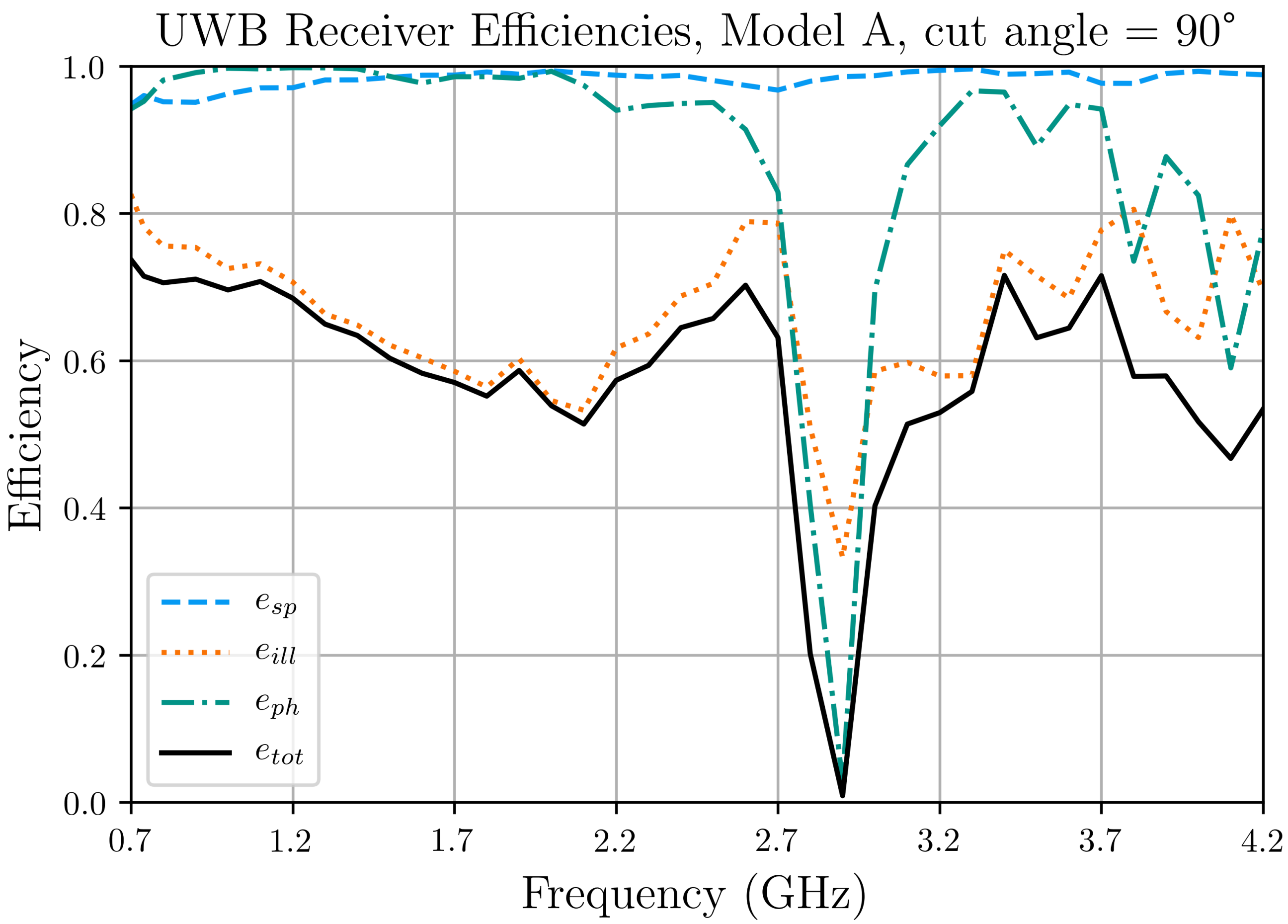


ACT IV

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

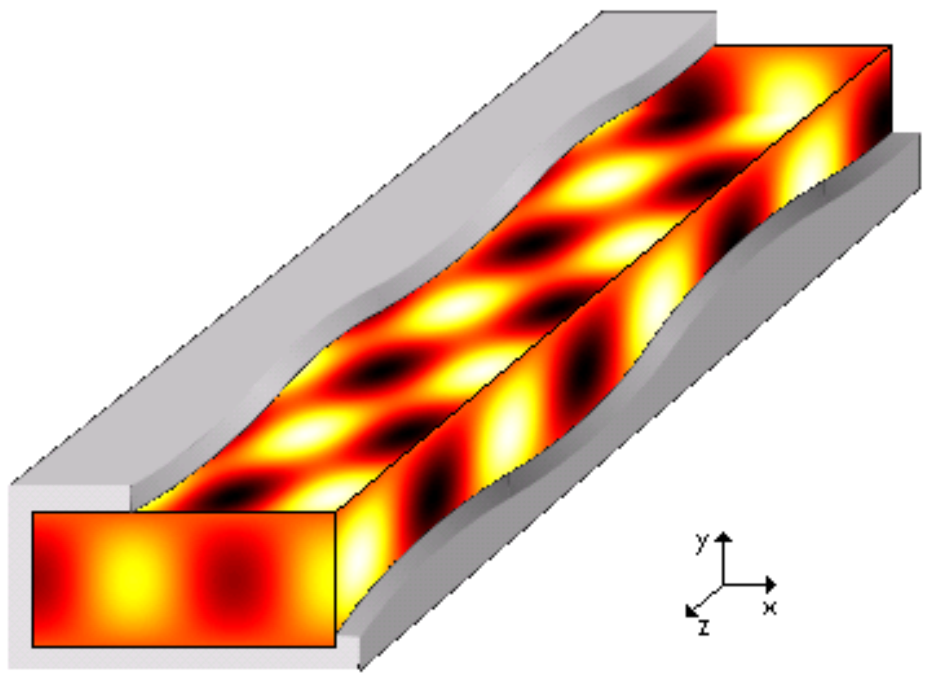
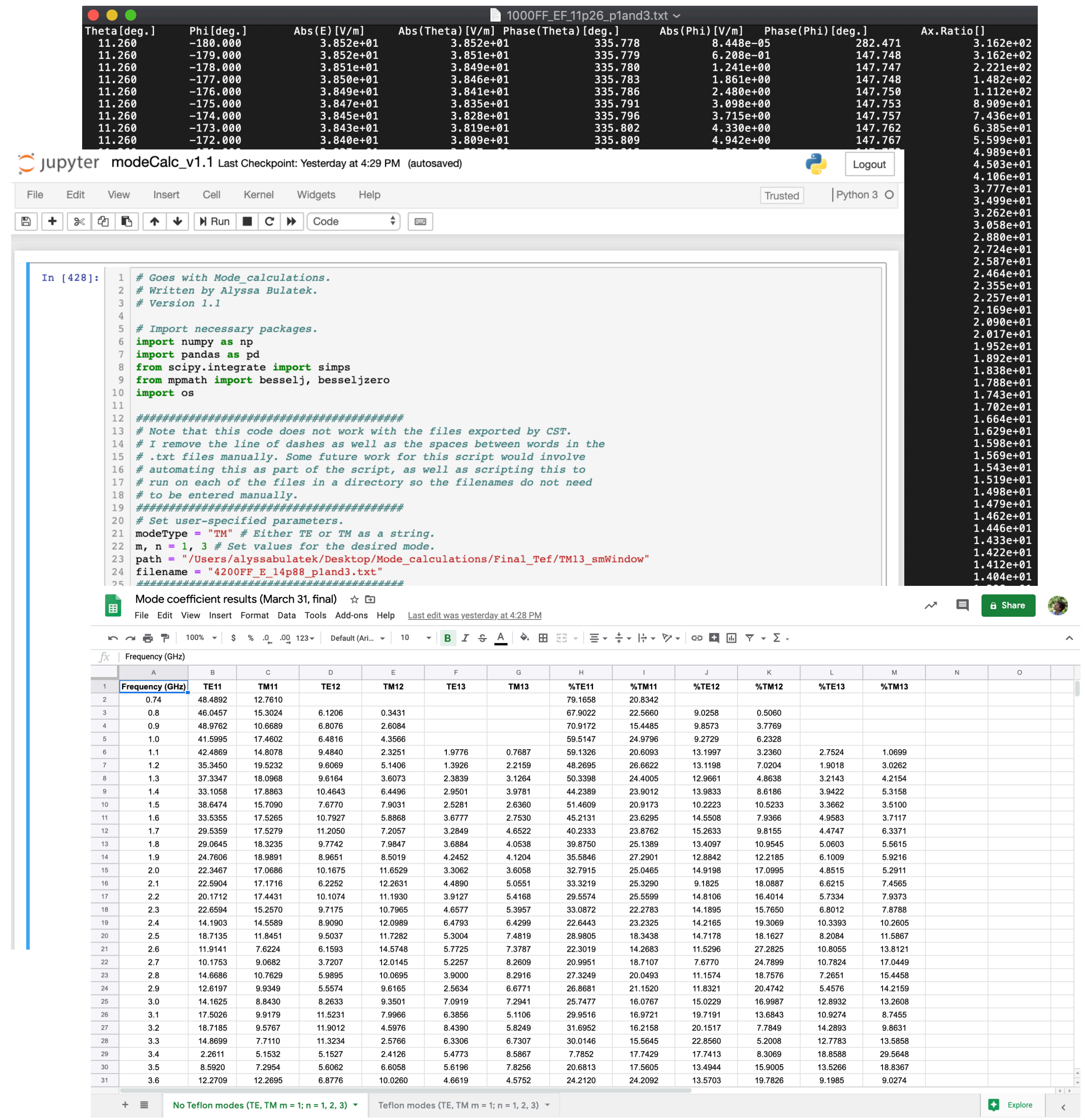


Image credit: Waveguides Workshop

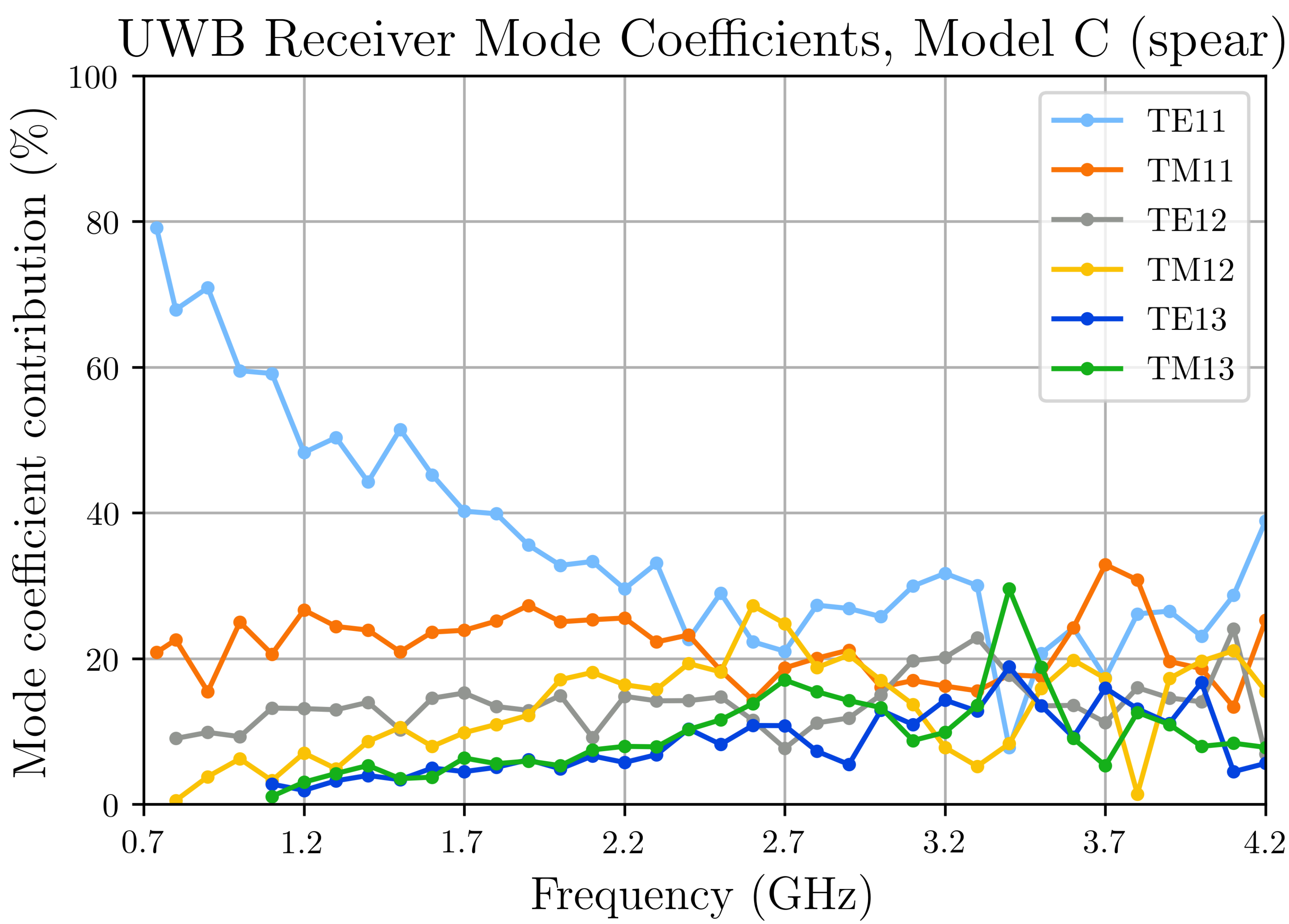
TECHNIQUE

- 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



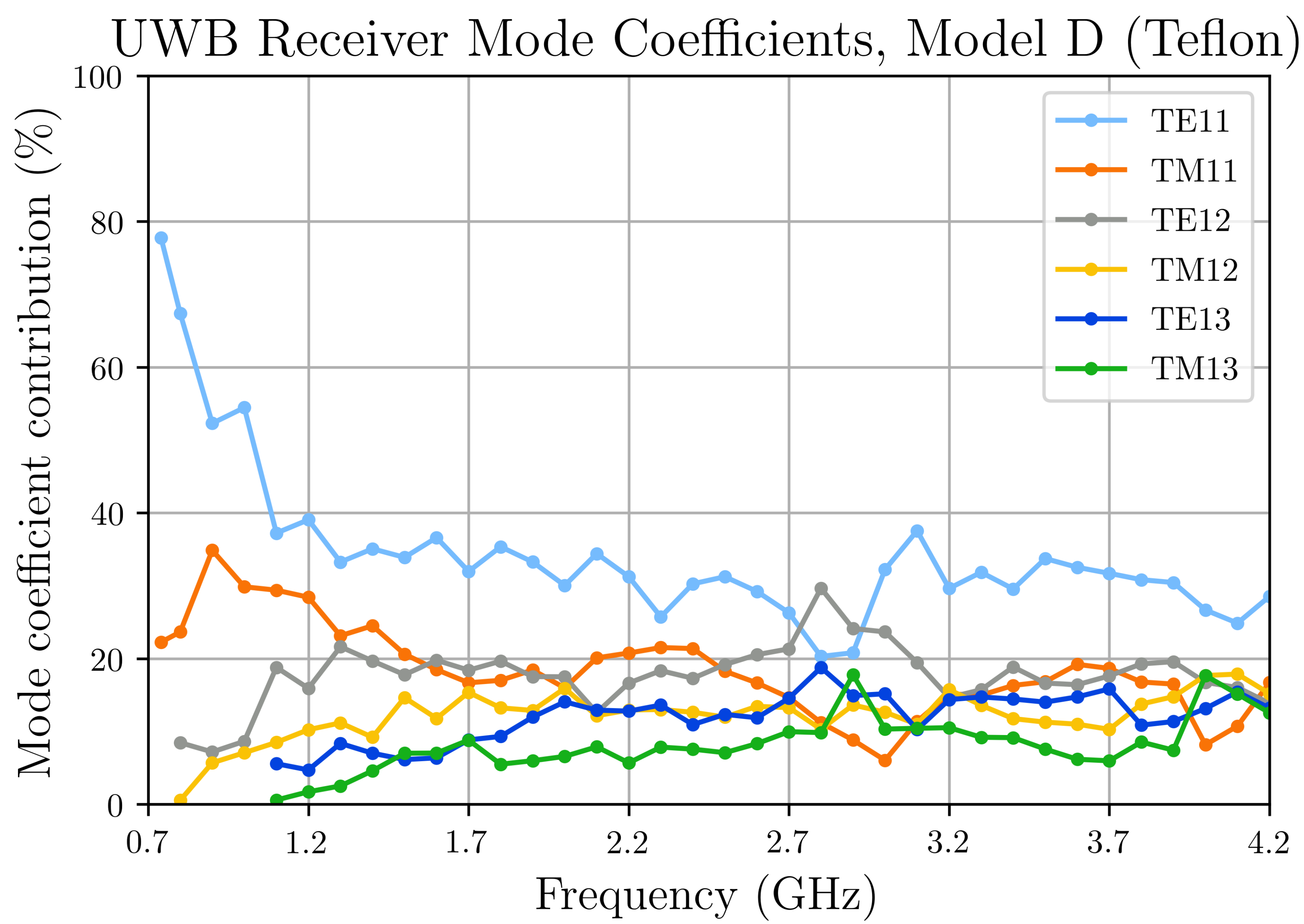
MODAL EXCITATION RESULTS

- **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



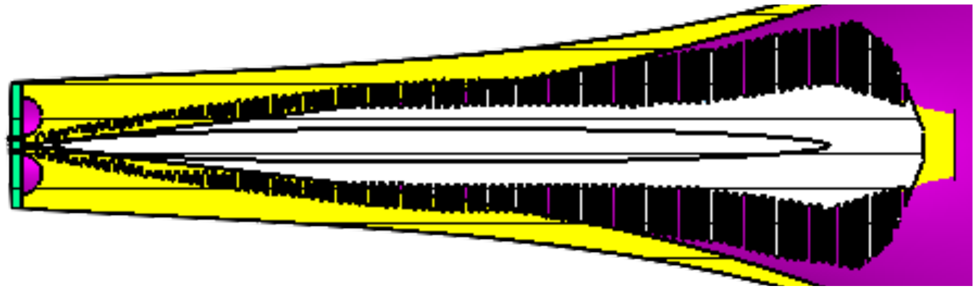
ACT IV+1

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

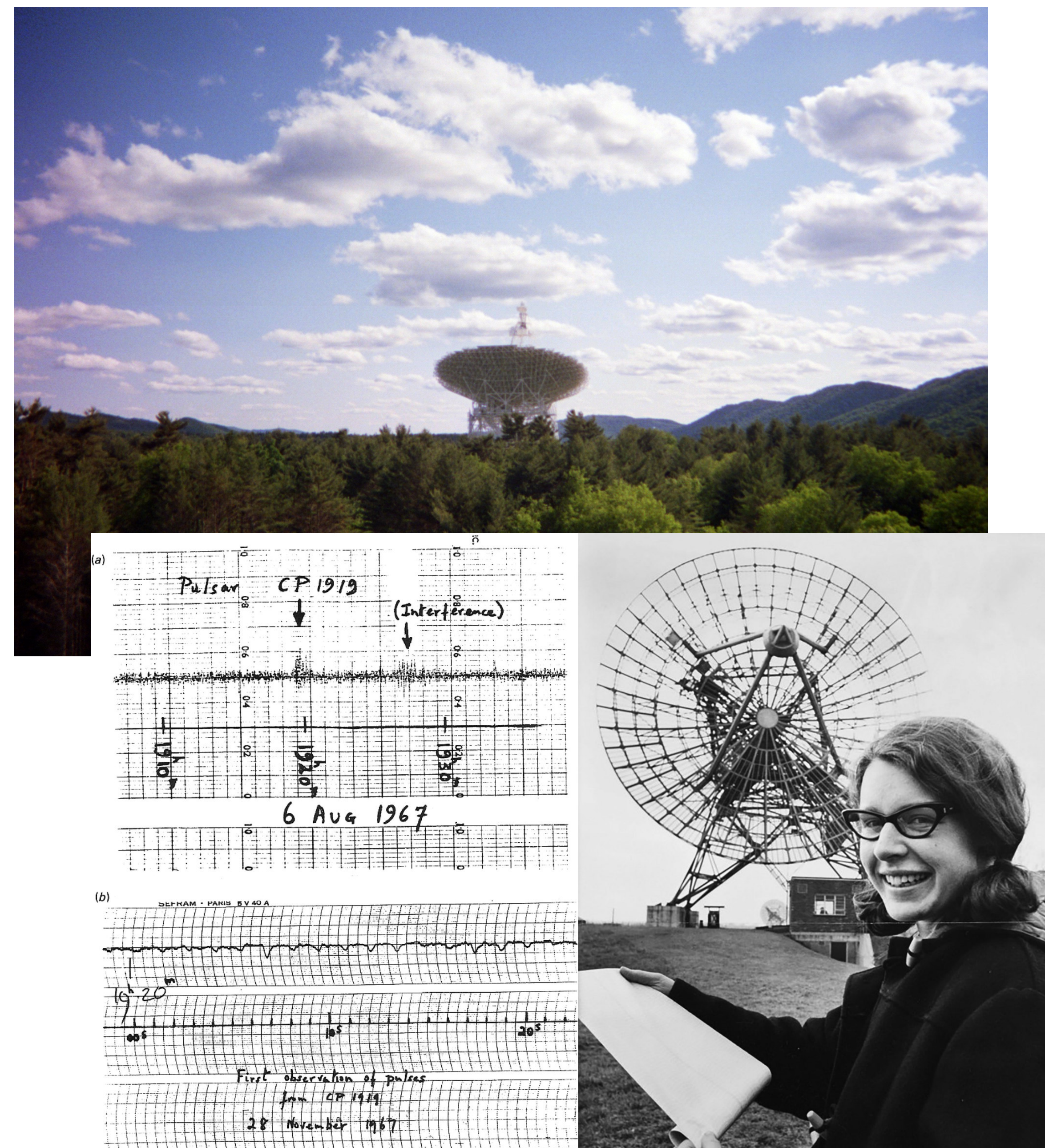


Image credit: me, CSIRO

Thank you for listening to my talk!

- Steve White, John Cannon, and James Heyman
- Bob Simon and Ryan Lynch (GBO)
- Sivasankaran Srikanth (CDL), Lisa Locke (JPL)
- The Physics and Astronomy faculty and students
- Lilly, James, and Greta
- Physics and Astronomy seniors
- Everyone in PHYS 440
- Craig McMurtry and Judy Pipher (UR); Kevin Flaherty (Williams)
- GBO summer students (2019)
- My mom and dad

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- 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
- 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/