CHORD: The Canadian Hydrogen Observatory and Radio-transient Detector

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McGill

Queen's UNIVERSITY

CHORD

UNIVERSITY OF CALGARY

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TRUTH · DUTY · VALOUR

VÉRITÉ · DEVOIR · VAILLANCE

UBC THE UNIVERSITY OF BRITISH COLUMBIA

YORK UNIVERSITÉ UNIVERSITY

INAF ISTITUTO NAZIONALE DI ASTROFISICA

NRAO National Radio Astronomy Observatory

ASU Arizona State University

MIT Massachusetts Institute of Technology

WestVirginiaUniversity

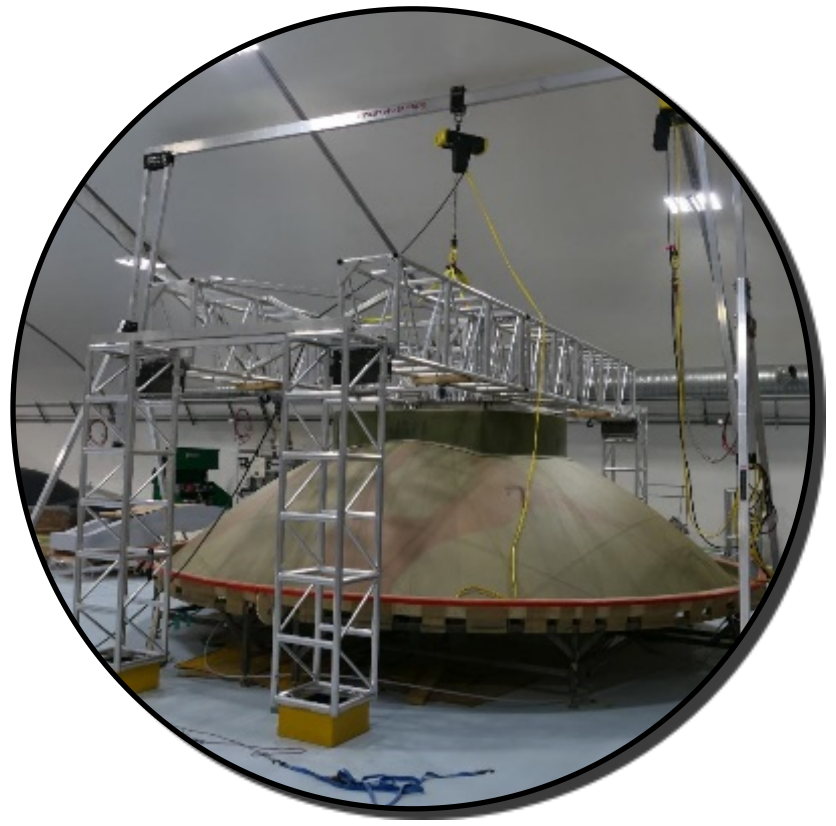
Outline

Outline

Instrument
Overview

Outline

Instrument
Overview



Key
Technologies

Outline

Instrument
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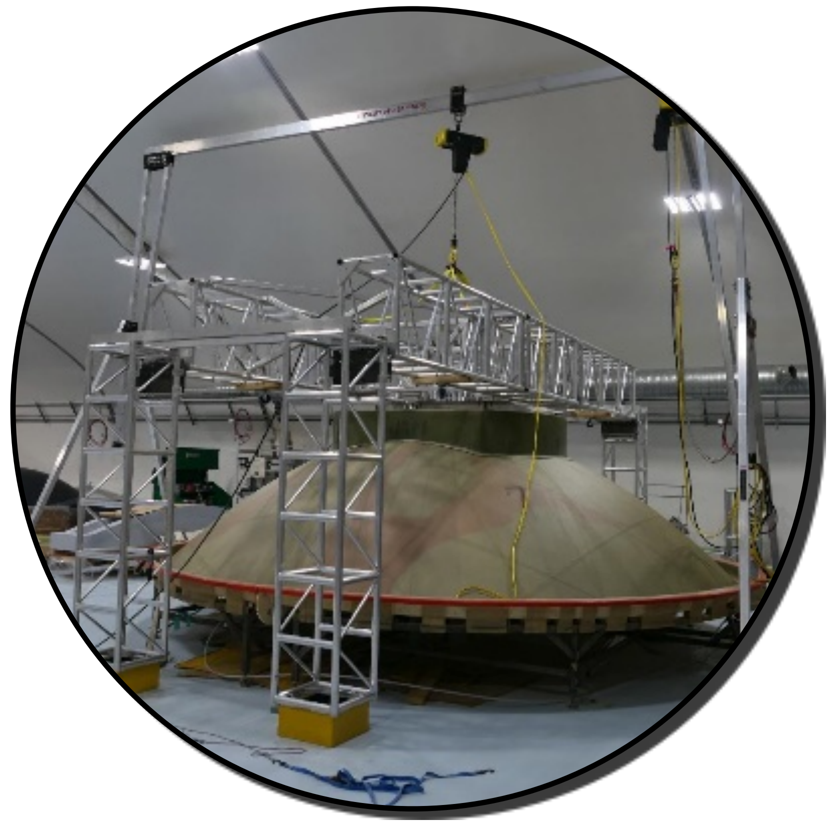

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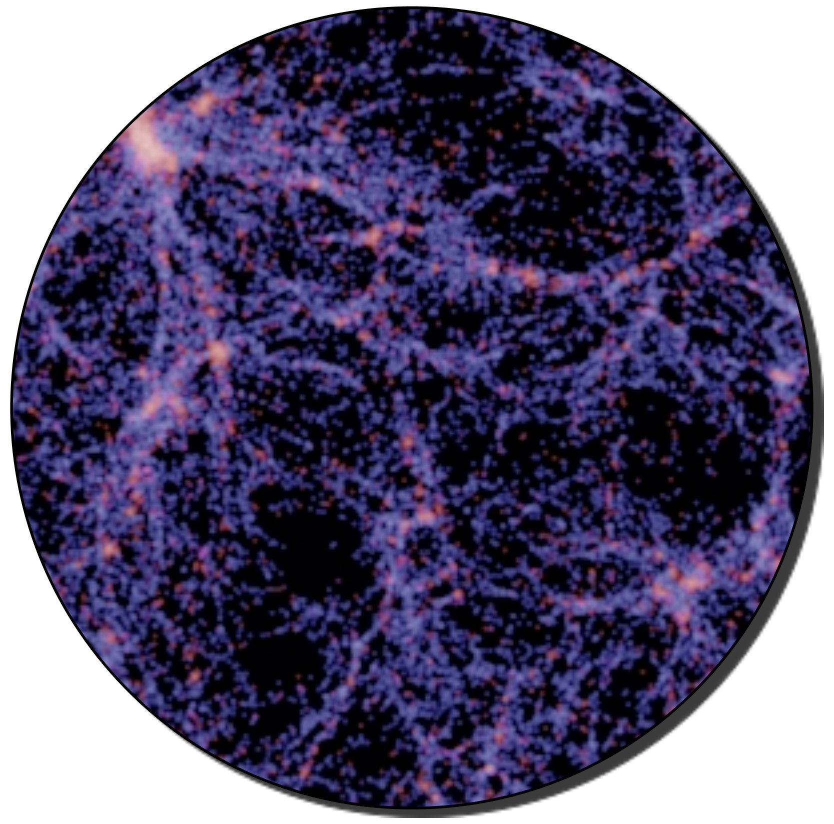

Forecasts

Instrument Overview

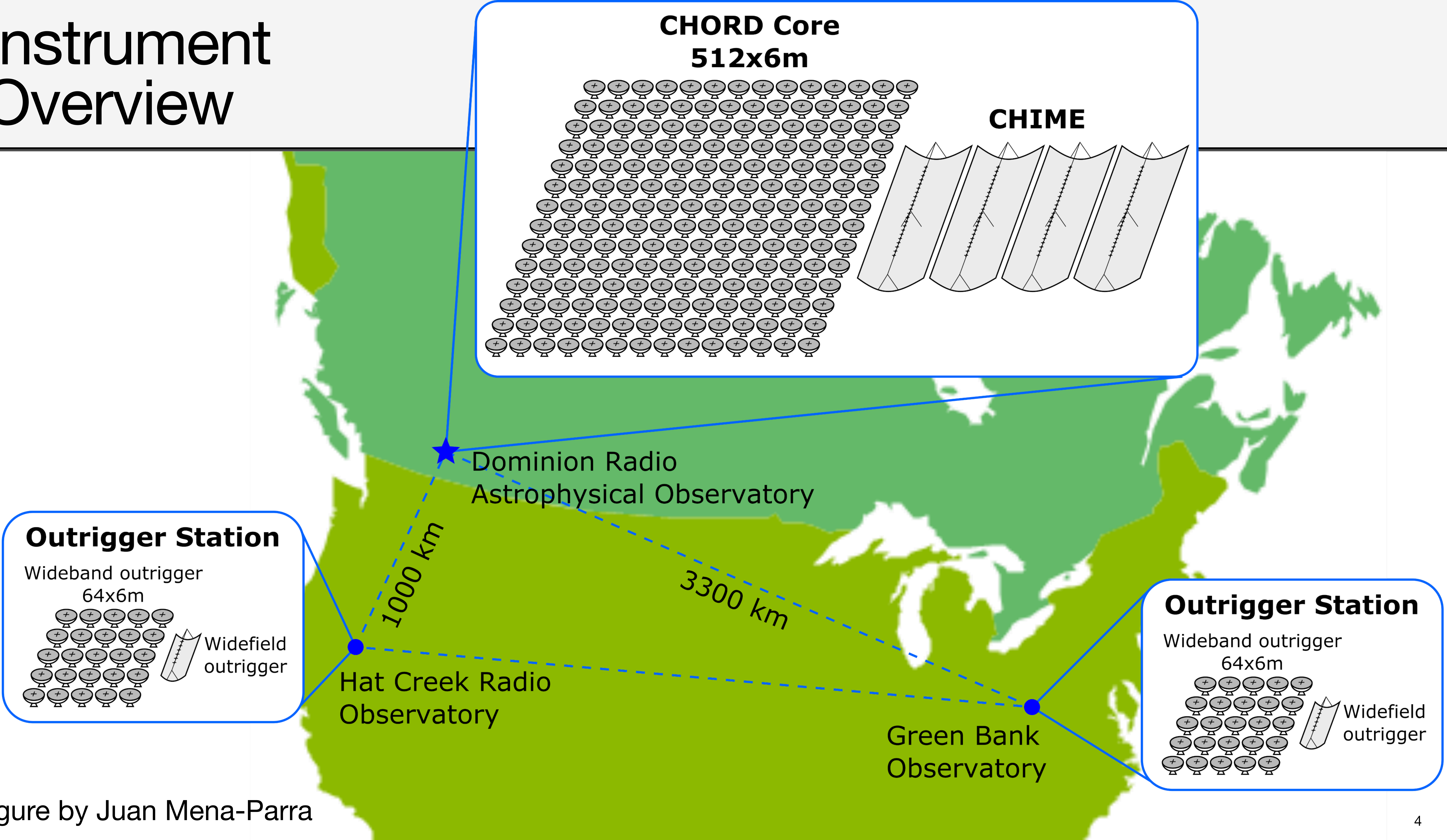

Figure by Juan Mena-Parra

Instrument Overview

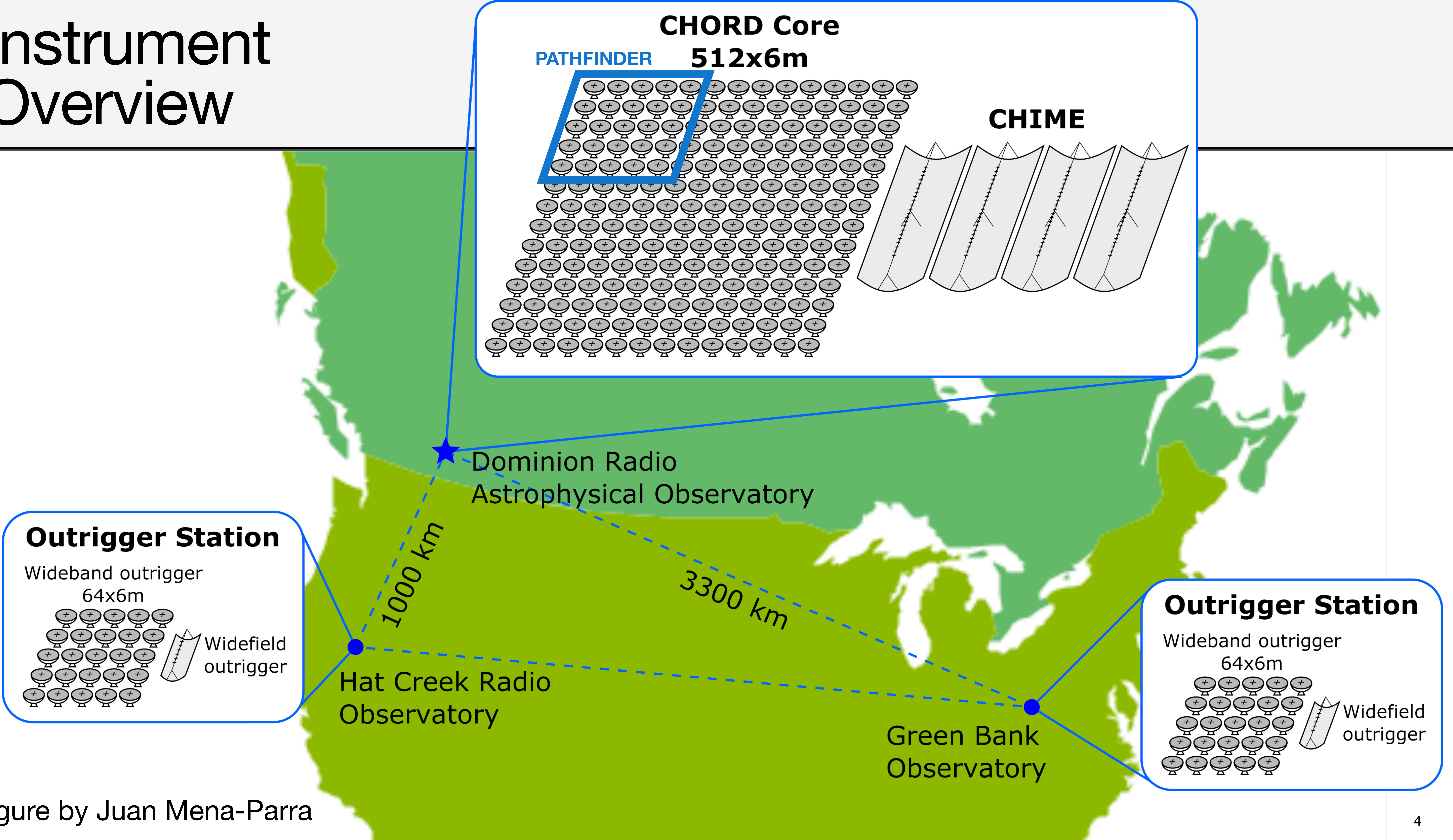

Figure by Juan Mena-Parra

Instrument Overview

N_{dish}	512	
Area	14,500 m^2	
T_{sys}	30 K + $T_{sky}(\nu)$	
Aperture Efficiency	50%	
SEFD	12 Jy + $SEFD_{sky}(\nu)$	
Transient Localization	< 50 milli-arcsec	
Bandpass	300 MHz	1500 MHz
PSF	17 arcmin	3.5 arcmin
Field of View	12 deg	2.5 deg
21 cm Redshift	3.7	0.0

Kit Gerodias (McGill)

Compared to CHIME

Wider band (x3)

Finer angular resolution (x2)

Increased sensitivity (x4)

- x2 larger collecting area
- x2 lower system temperature

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Reduced instrument chromaticity

Deep-dish design to reduce
cross coupling and spill over

Improved redundancy

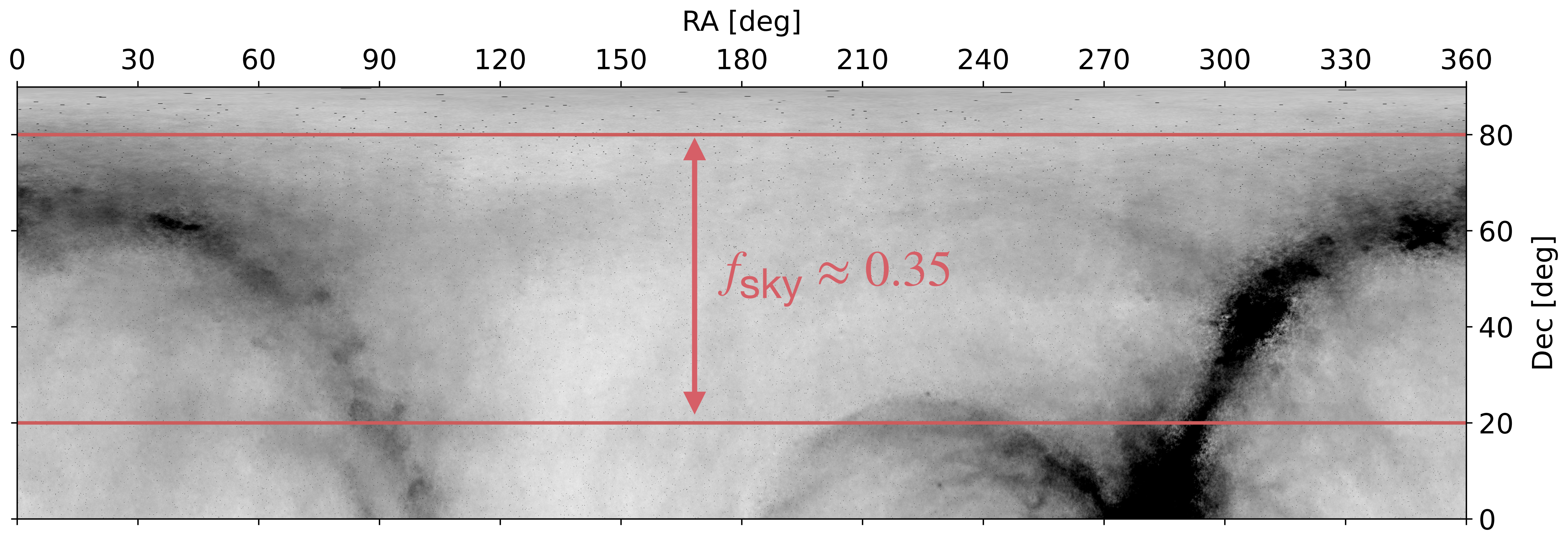
Repeatable, high-precision (sub-mm)
manufacturing & assembly processes

Observing Strategy

Drift scan

Azimuthal pointing: fixed to local meridian

Elevation pointing: manually adjusted between Dec $= 20° - 80°$



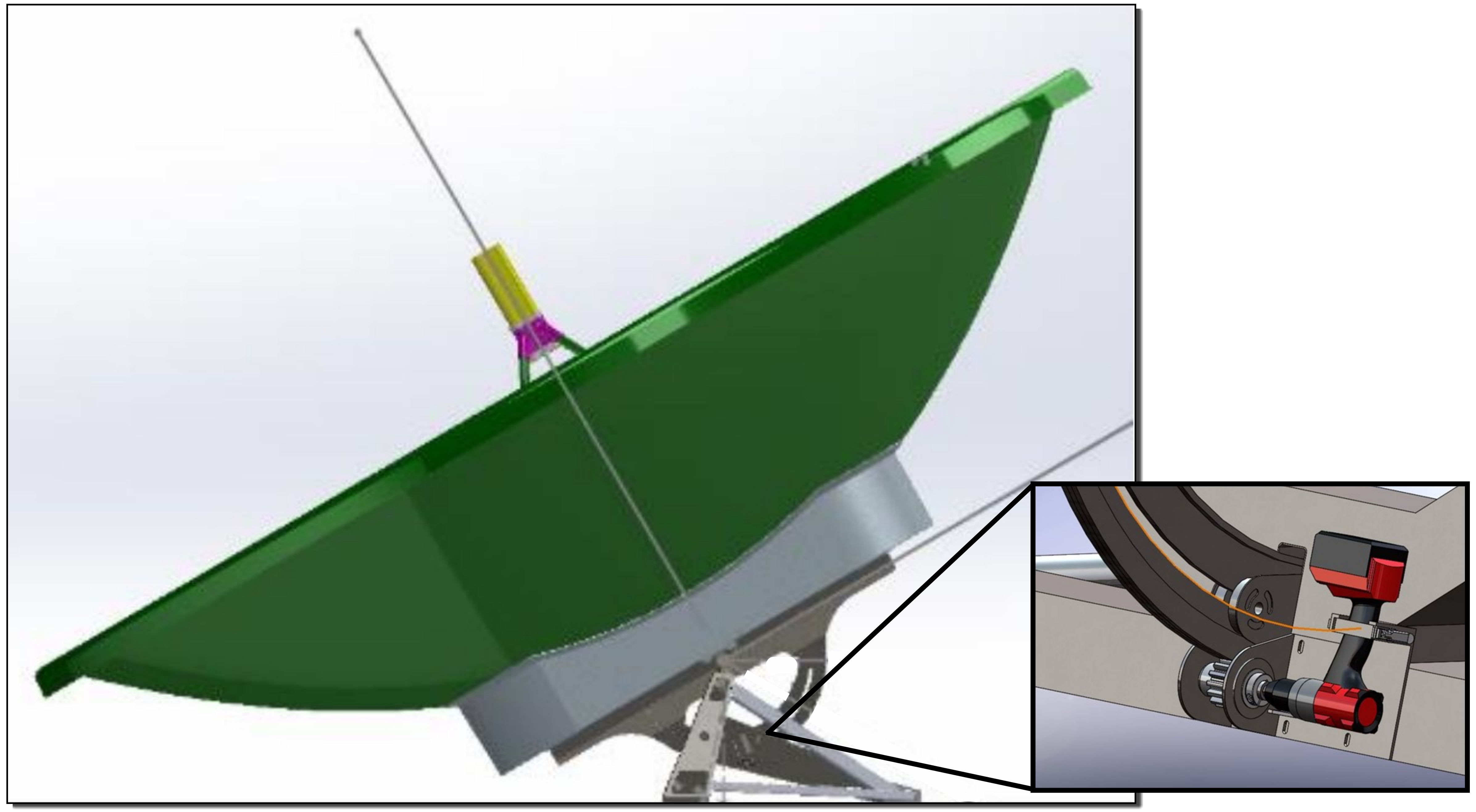


Image by Mohammad Islam (DRAO)

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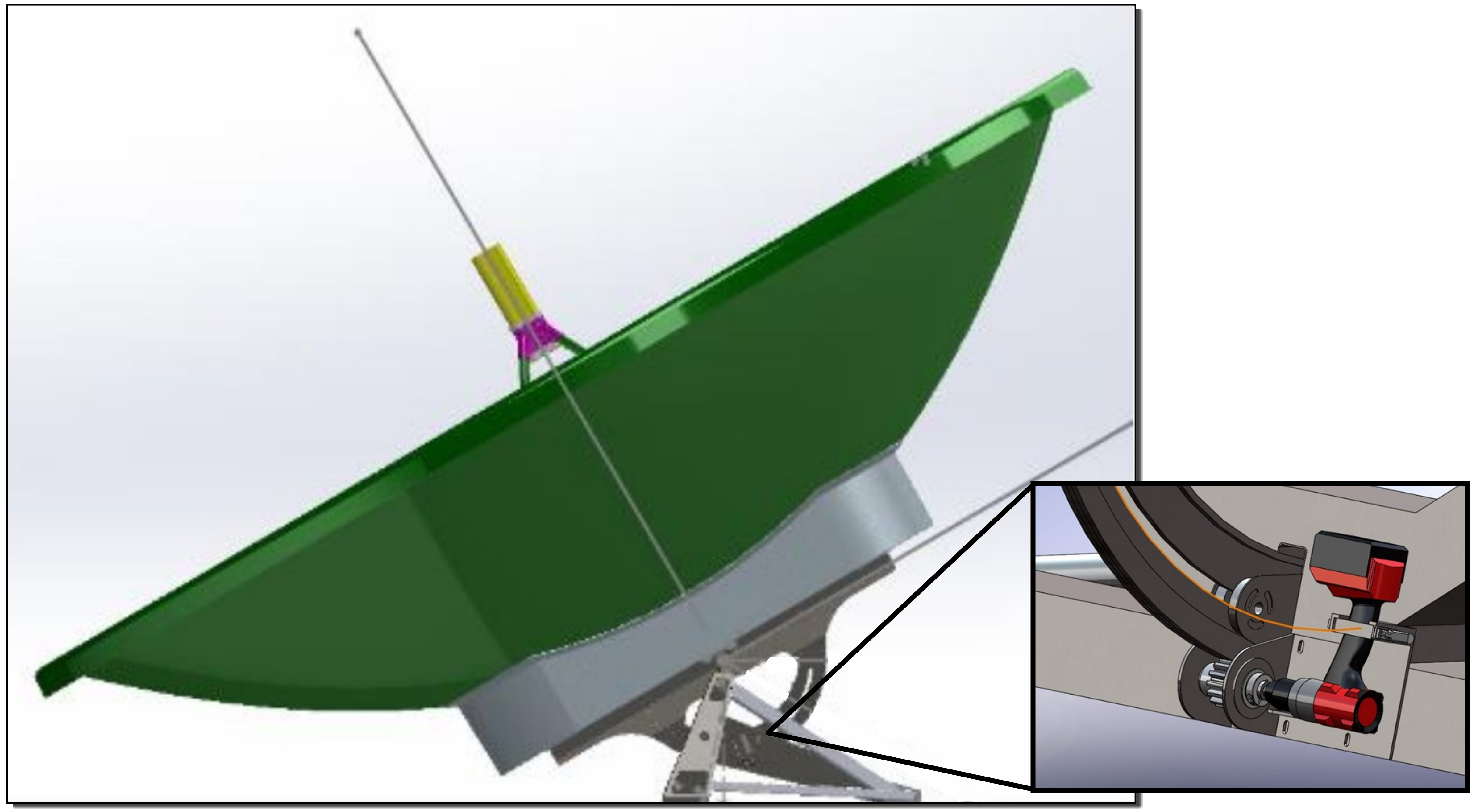

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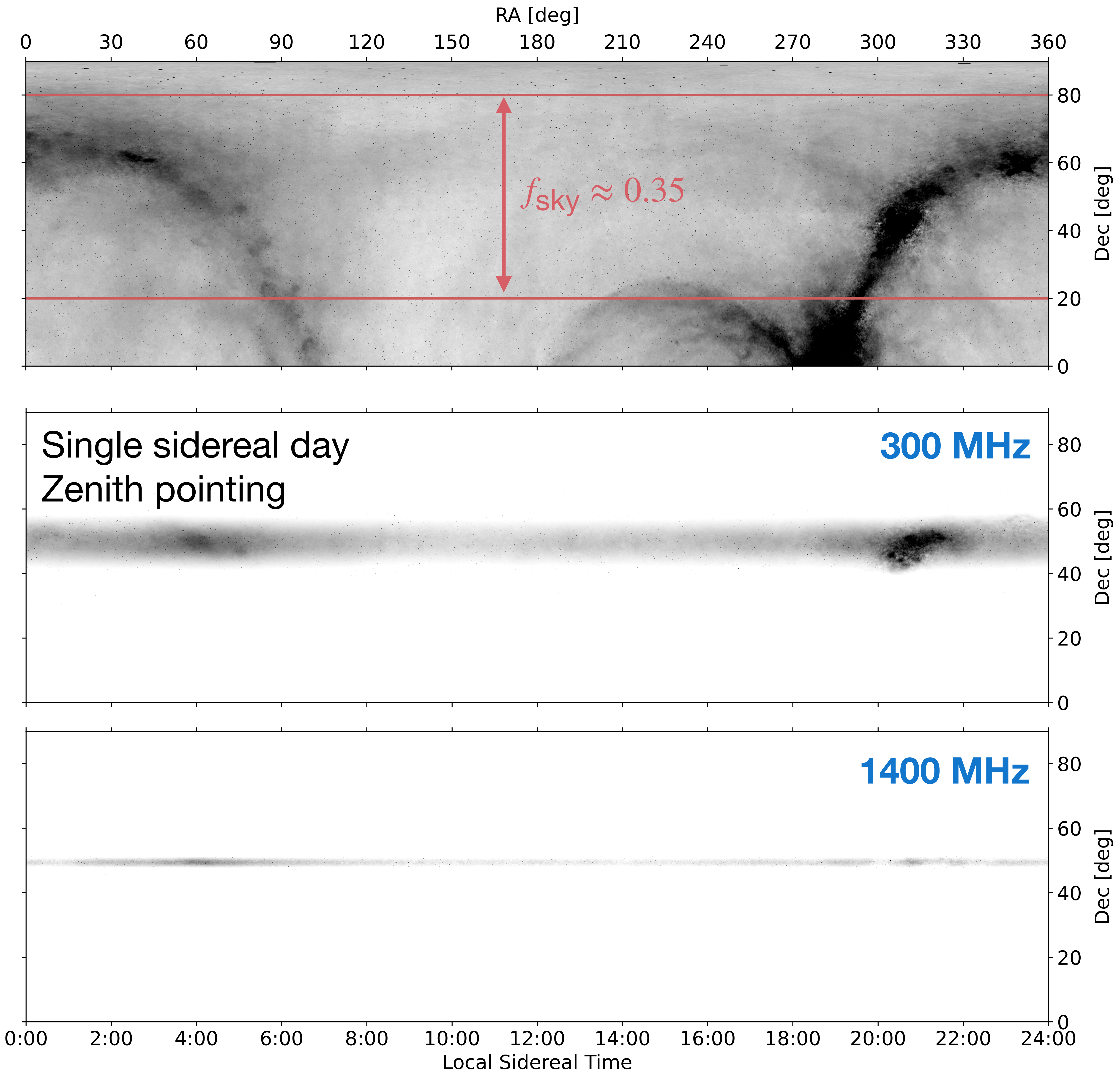
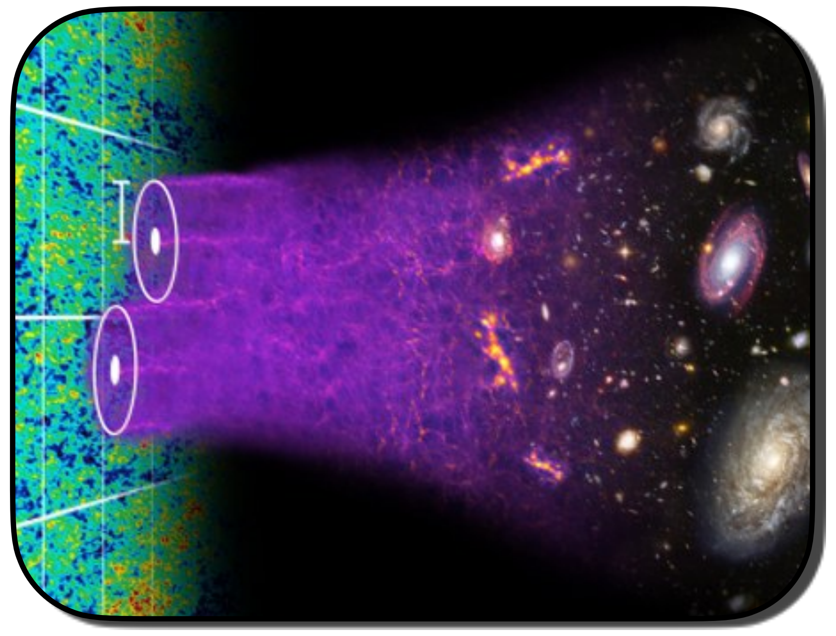
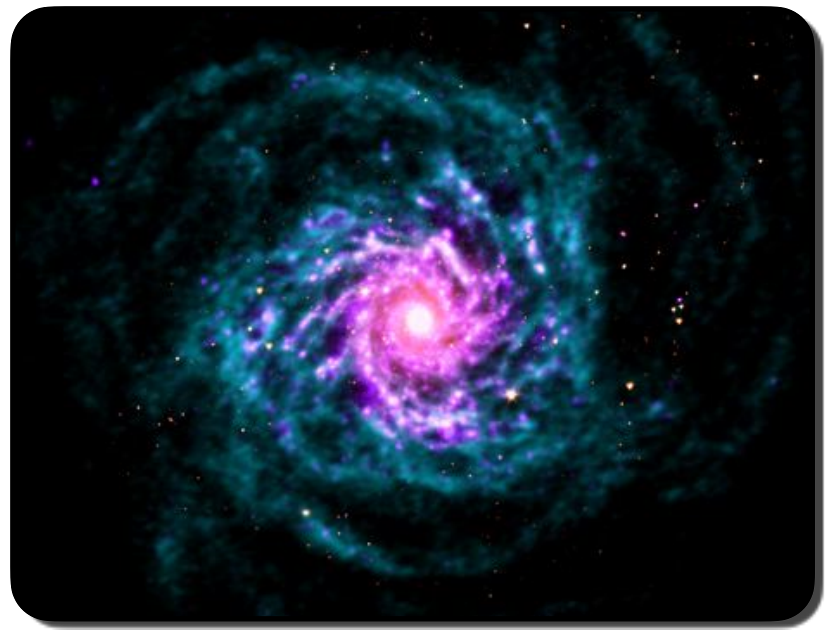


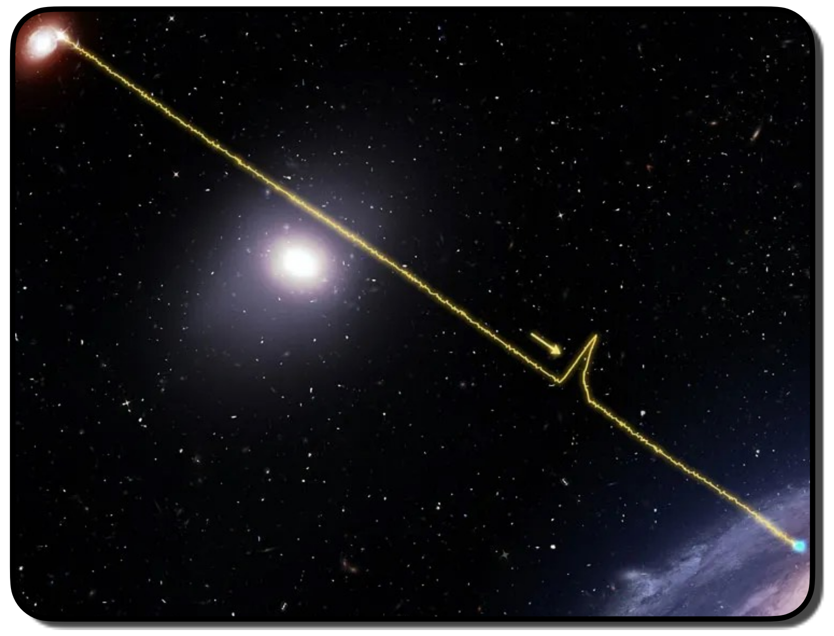
CHORD Science Objectives



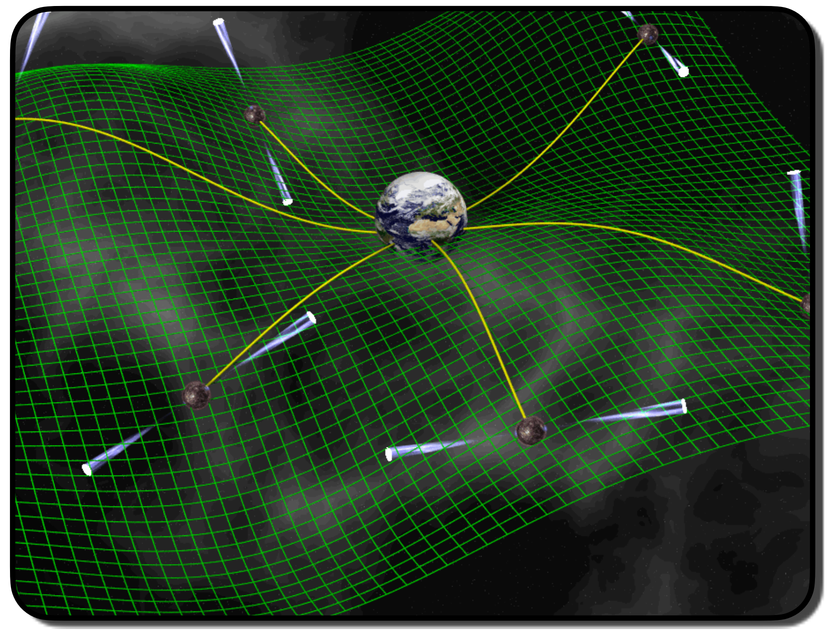
21 cm
Intensity Mapping



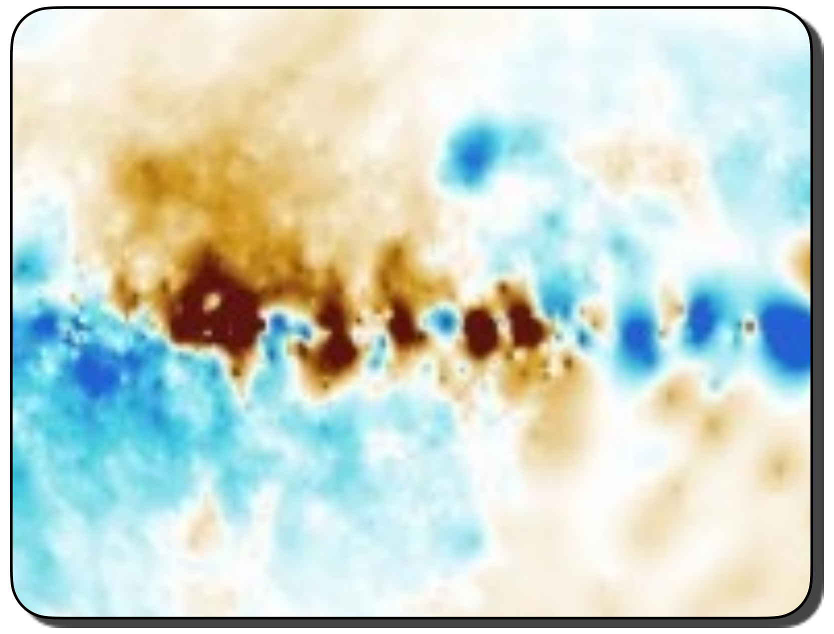
21 cm
Galaxy Search



Fast Radio Burst
Search & Localization



Pulsar Search
& Timing



Galactic & Cosmic
Magnetism

Images by C. Blake and S. Moorfield; Walter et al. 2008; M. Kornmesser; D. Champion; Opperman et al. 2012

Timeline

Jan 2020: CHORD proposed to Canada Foundation for Innovation (CFI).

Mid 2021: CHORD fully funded by CFI with matching contributions from provincial partners.

Late 2021: First end-to-end prototype dishes constructed at DRAO.

Late 2022: Break ground on dish production facility.

Early 2024: Begin construction of core array.

Late 2024: Begin commissioning with first 64 dishes.

2026: Complete construction of core array and outriggers.

2026 - 2031: Dedicated science observing period.

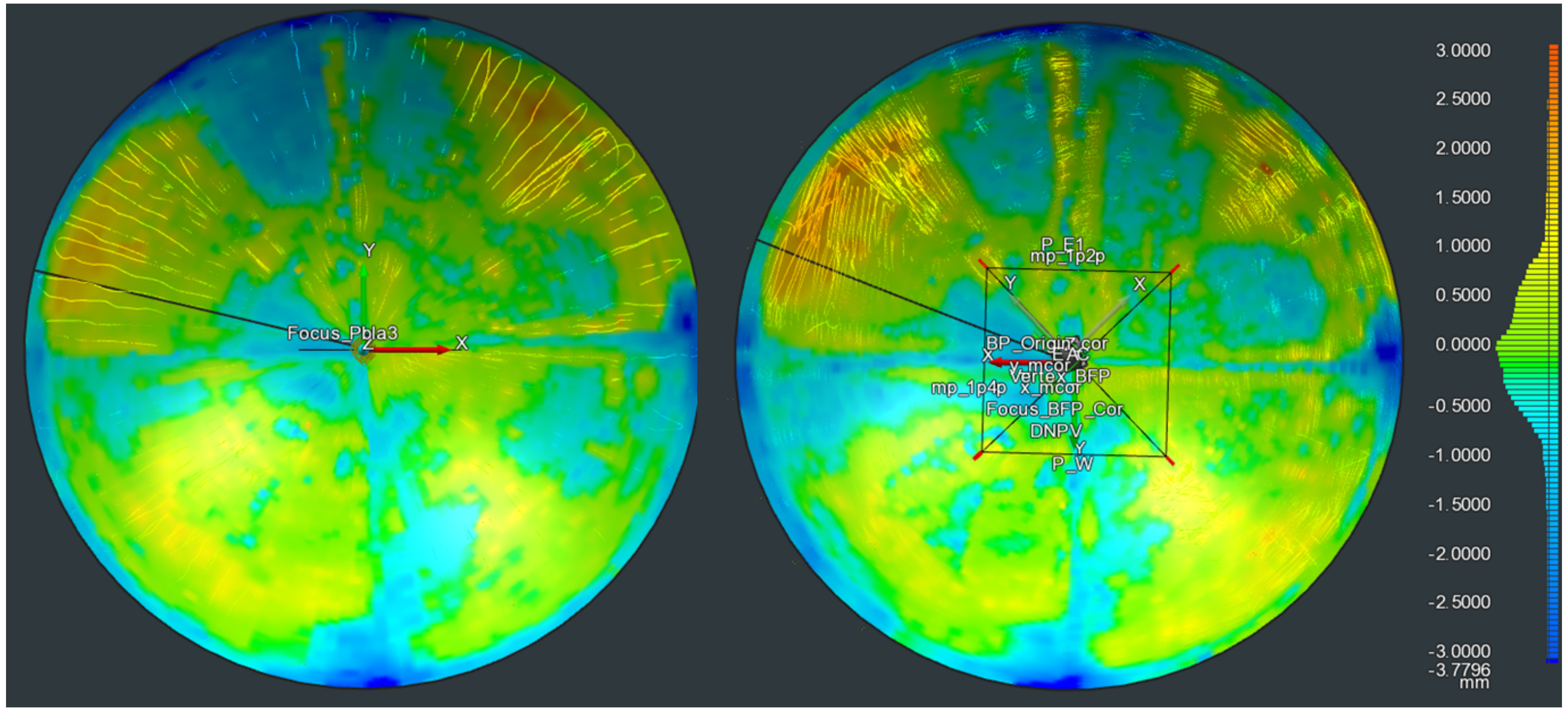
Key Technologies

Deep Dish Development Array (D3A)

CHORD Receiver

6m-diameter composite dishes

- Fabricated on site
- Low focal ratio (f/D = 0.21)
- Sub-mm surface precision



Laser metrology measurements
from Islam et al. 2022

CHORD Receiver

Ultra-wideband feed (5:1)

- Aperture efficiency 45-55%
- Side lobes < -20 dB

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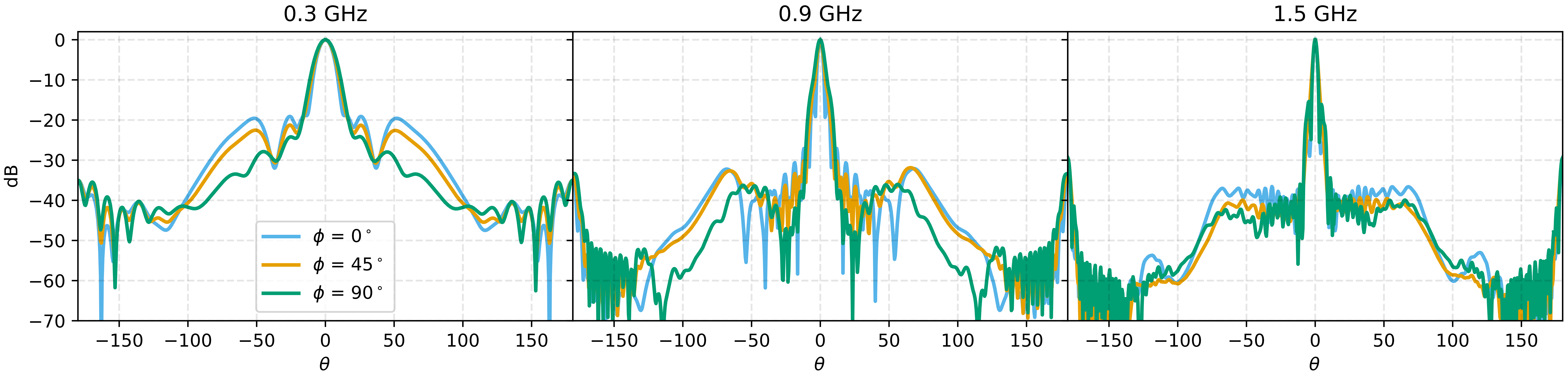
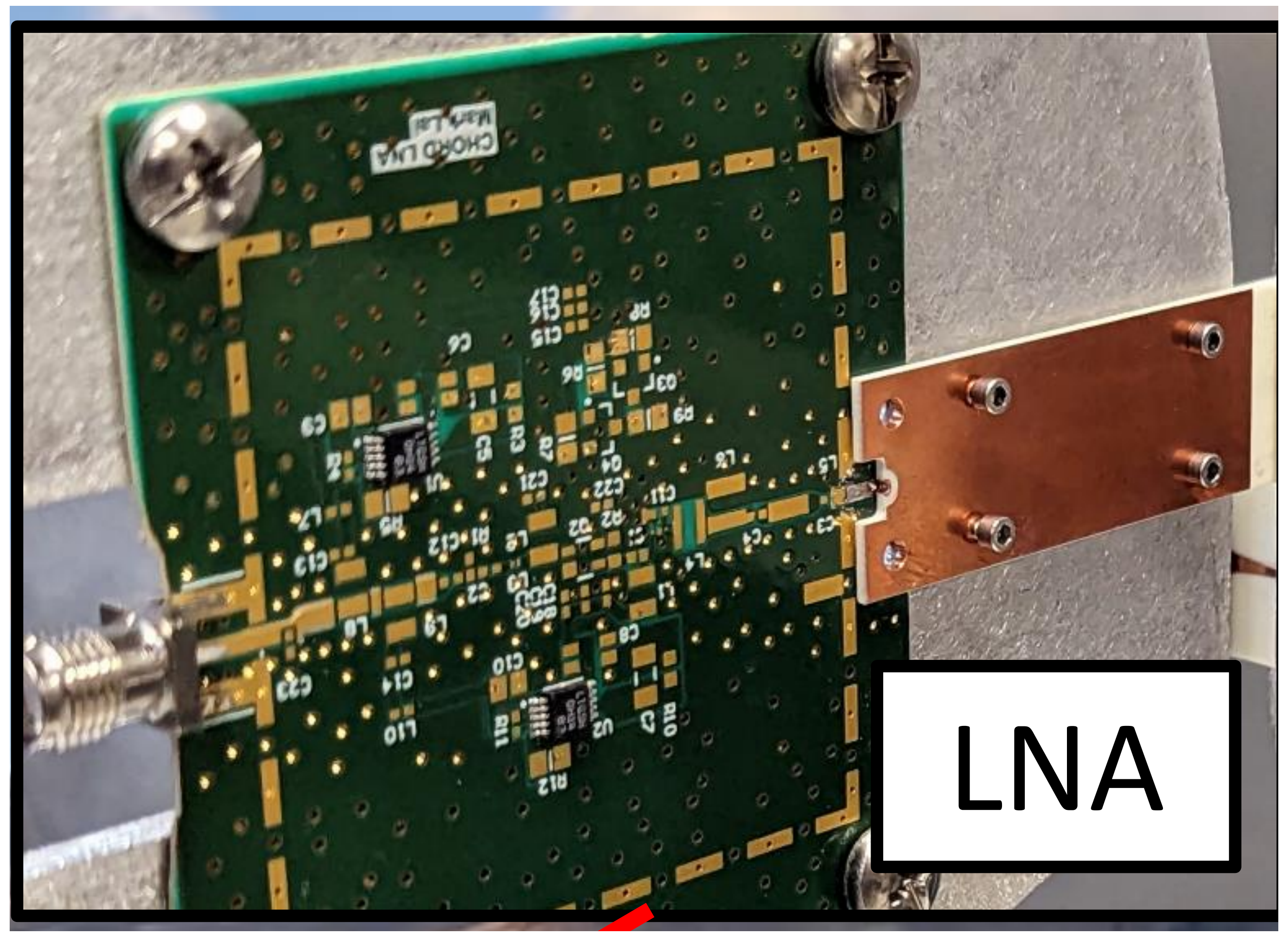


Primary beam of feed+dish based on E&M simulations (MacKay et al. 2023)

CHORD Receiver

LNA with Wideband Noise and Power Matching

Described in Lai et al. 2023



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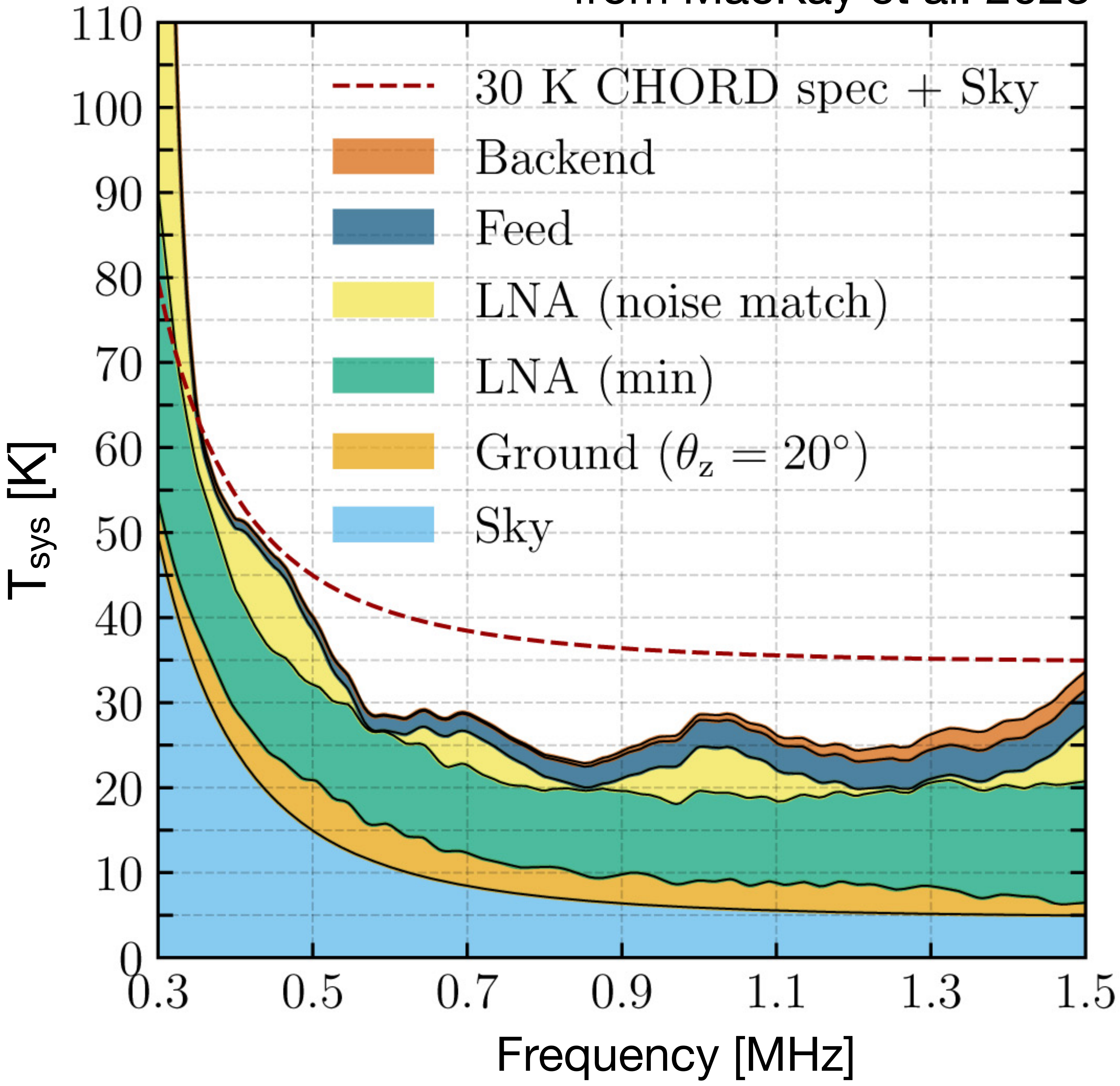
from MacKay et al. 2023



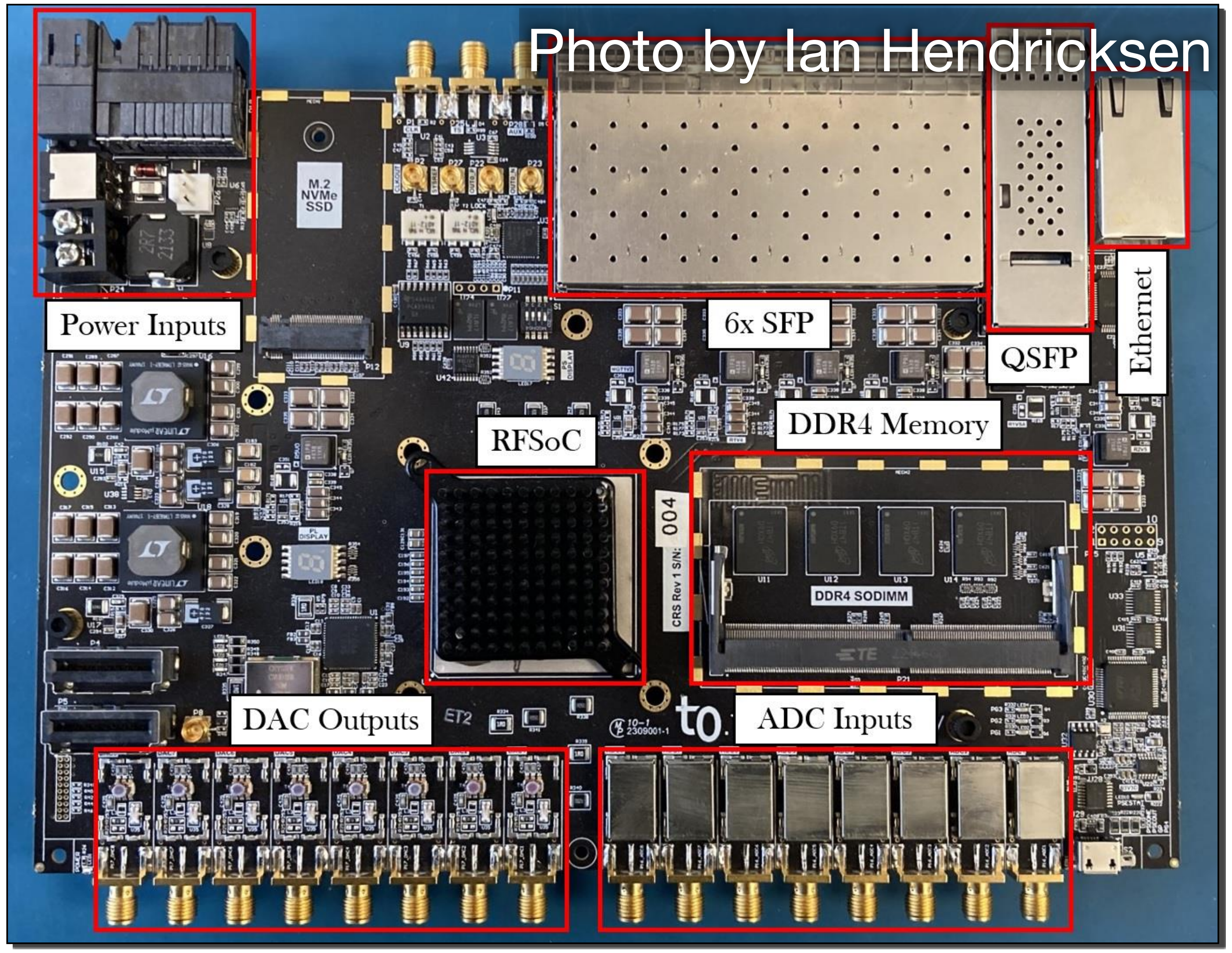
CHORD Correlator

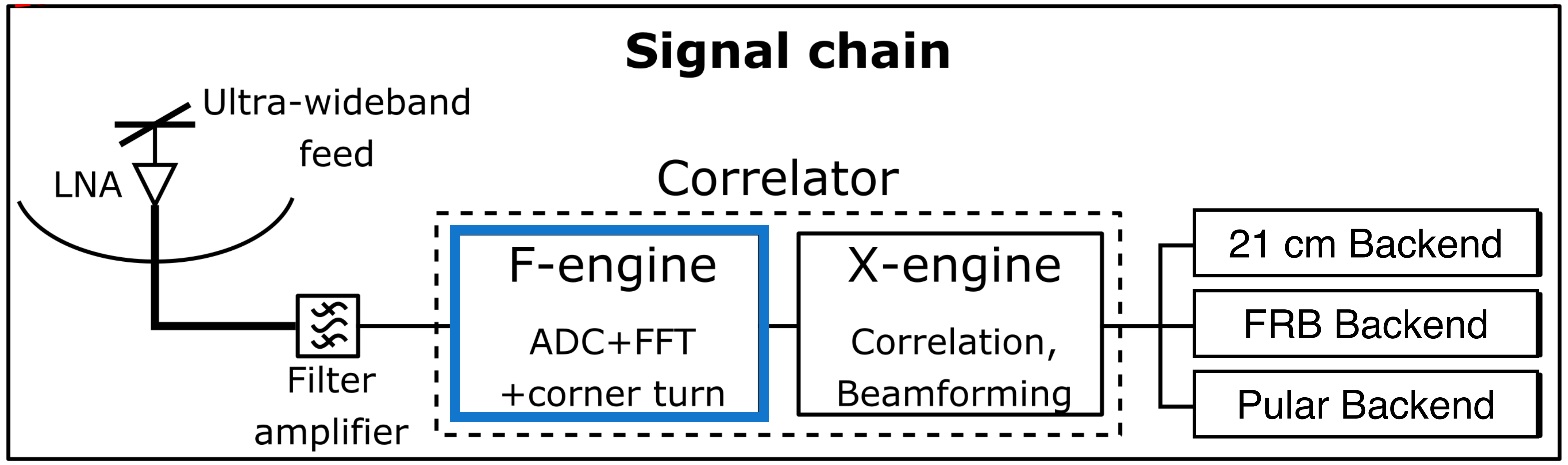
FPGA-based digitizer/channelizer

x128 AMD Zynq Ultrascale+ RF System-on-Chip (RFSoC)

- 14-bit, 3 Gsps ADC
- 4-tap polyphase-filter-bank, $\Delta\nu$ = 360 kHz (or 180 kHz)

McGill





CHORD Correlator

GPU-based correlator/beamformer

x128 Nvidia A40

- Built on `kotekan` software framework
- Processes 9.6 Tb/sec
- 100 sec baseband buffer
- Fast-cadence (~msec) RFI excision

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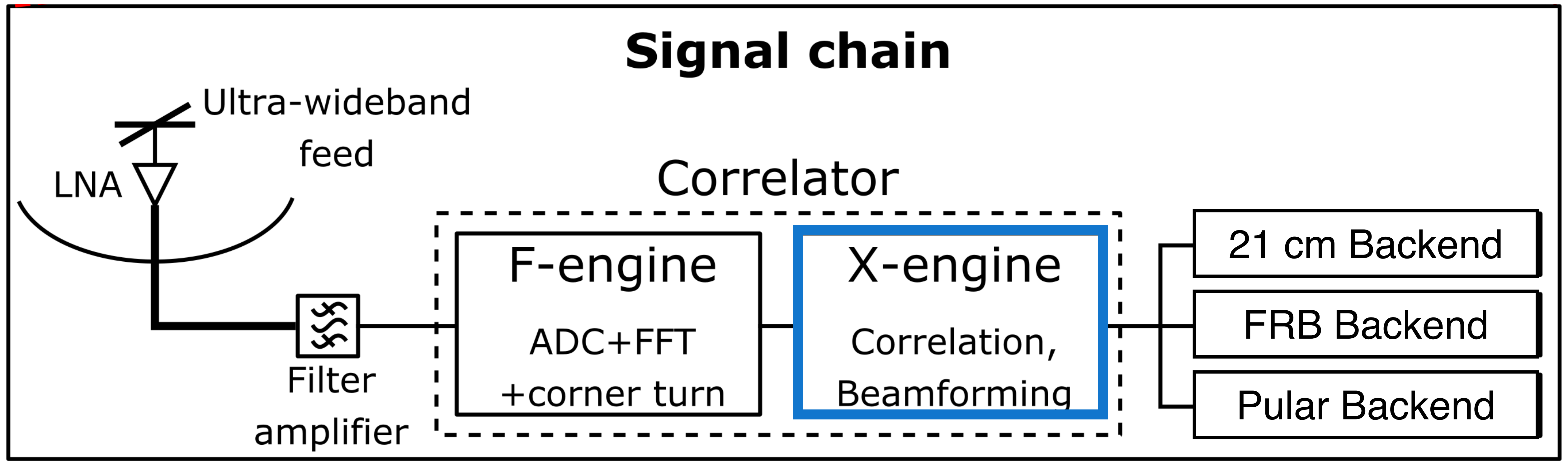
National Radio Astronomy Observatory



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- Support for multiple backends:
  - N^2 visibilities at ~1 sec (21cm IM+galaxies)
  - 48 full-Stokes, baseband beams (pulsar search+timing)
  - 5000 intensity beams at ~1 msec (FRB search)

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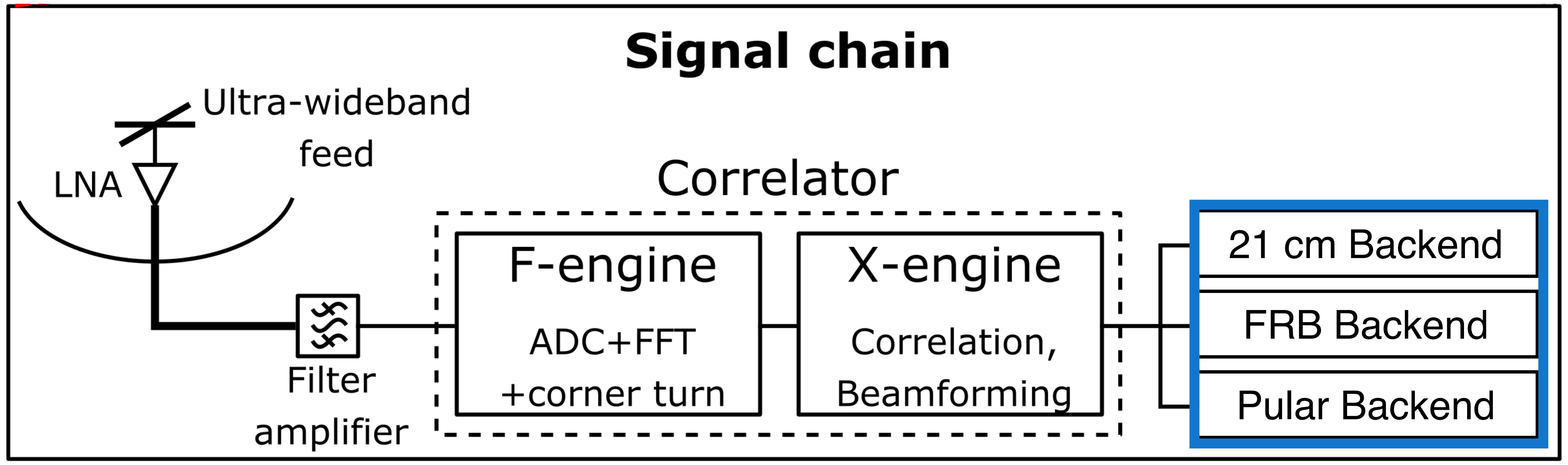

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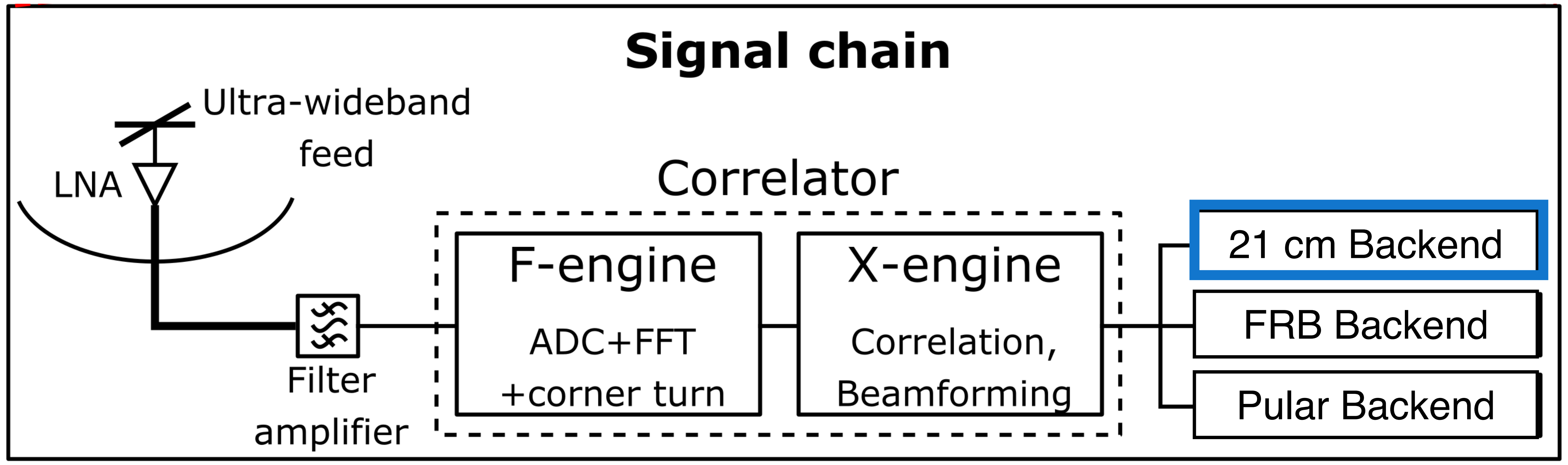
University of Toronto · Perimeter Institute · National Radio Astronomy Observatory (NRAO)

21 cm Backend

Receives 150 Gb/sec. Applies:

- RFI excision, fringestoping, time integration (to 30 sec)
- Relative gain calibration using `CorrCal`, redundant baseline averaging



FRB Search Backend

New GPU-based FRB search algorithm
in development at PERIMETER INSTITUTE

Computational cost roughly proportional to "data rate": $N_{beam} \times N_{freq} / t_{sample}$

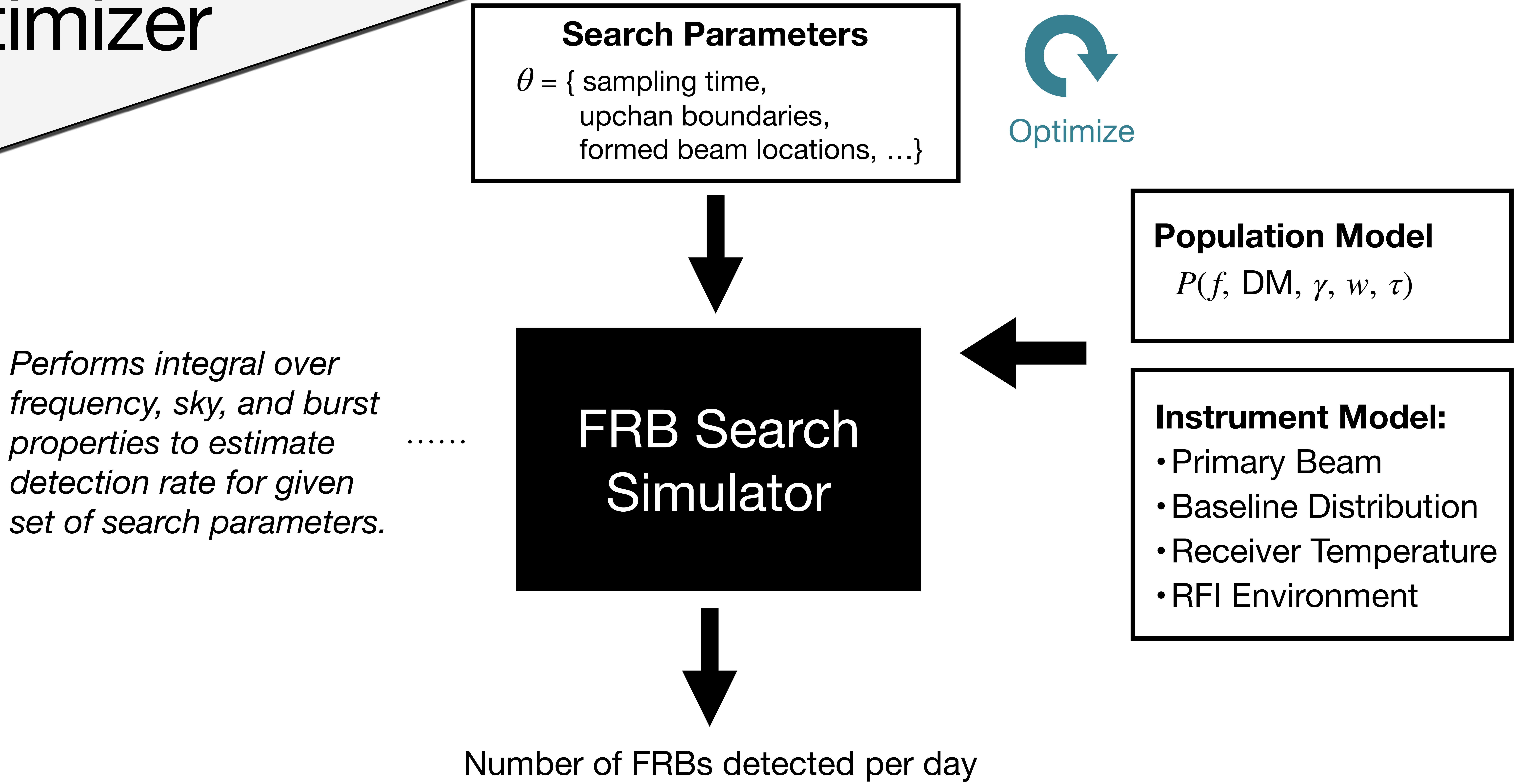
Expect to process 10 Gsps per GPU.

Comparison of Different FRB Searches				
	N_{beam}	**N_{freq}**	**t_{sample}**	**Data Rate**
CHIME	1000	16,000	1 msec	16 Gsps
CHORD	5000	32,000	1 msec	160 Gsps
SKA-low	500	8000	0.8 msec	5 Gsps
SKA-mid	1500	4000	0.08 msec	75 Gsps

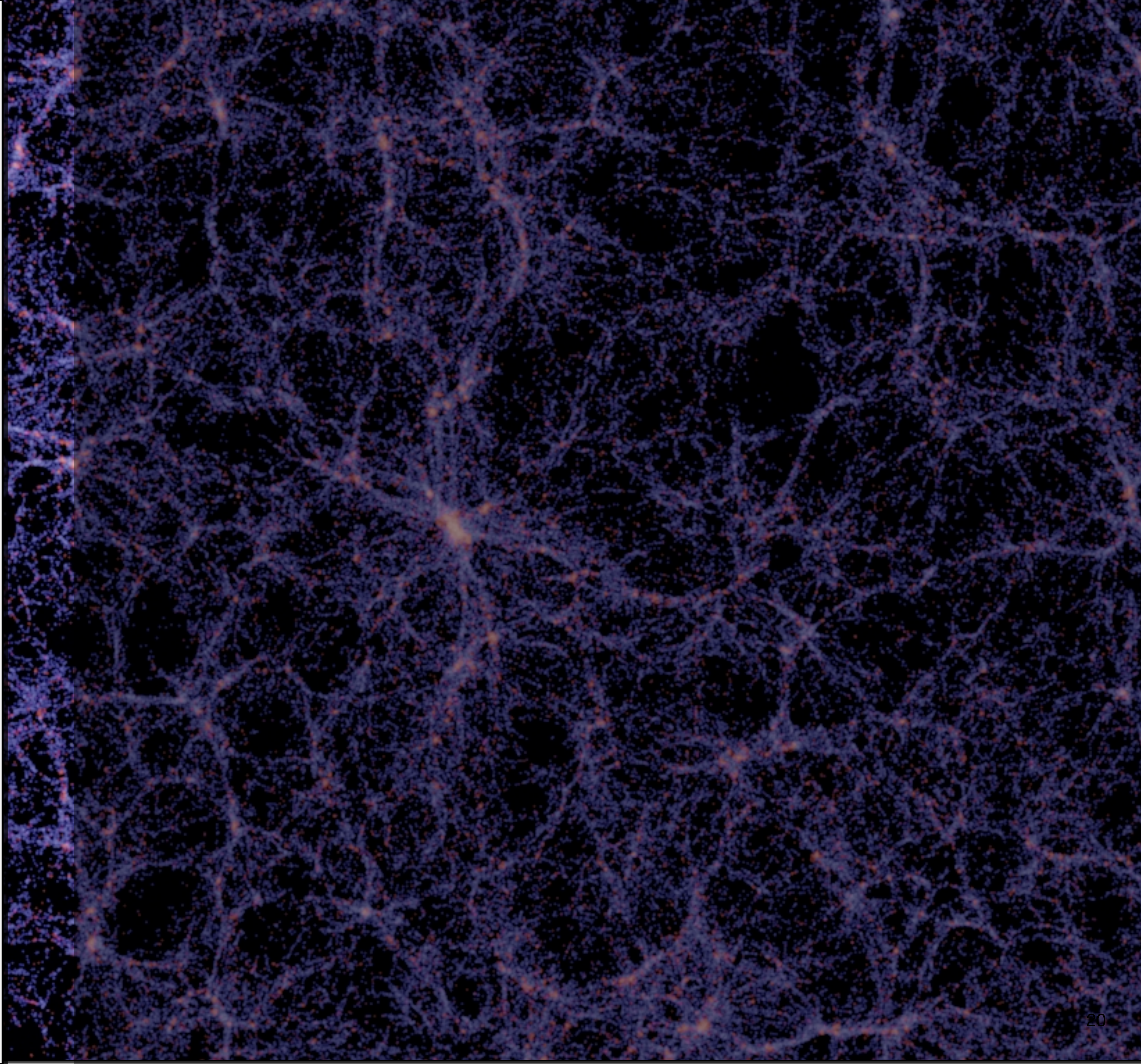
Table by
Kendrick Smith

Features: frequency-dependent upchannelization, arbitrary formed beam locations,
multiple sub-band searches, 100 sec baseband buffer, and early baseband triggers!

FRB Search Optimizer



Forecasts



HI Power Spectrum

CHORD will carry out a **5 year survey** to measure the HI power spectrum between **0 < z < 3.7**

Predicted thermal noise power spectrum (**orange**) compared to HI power spectrum (**black**).

Use formalism and software described in Salier et al. 2021.

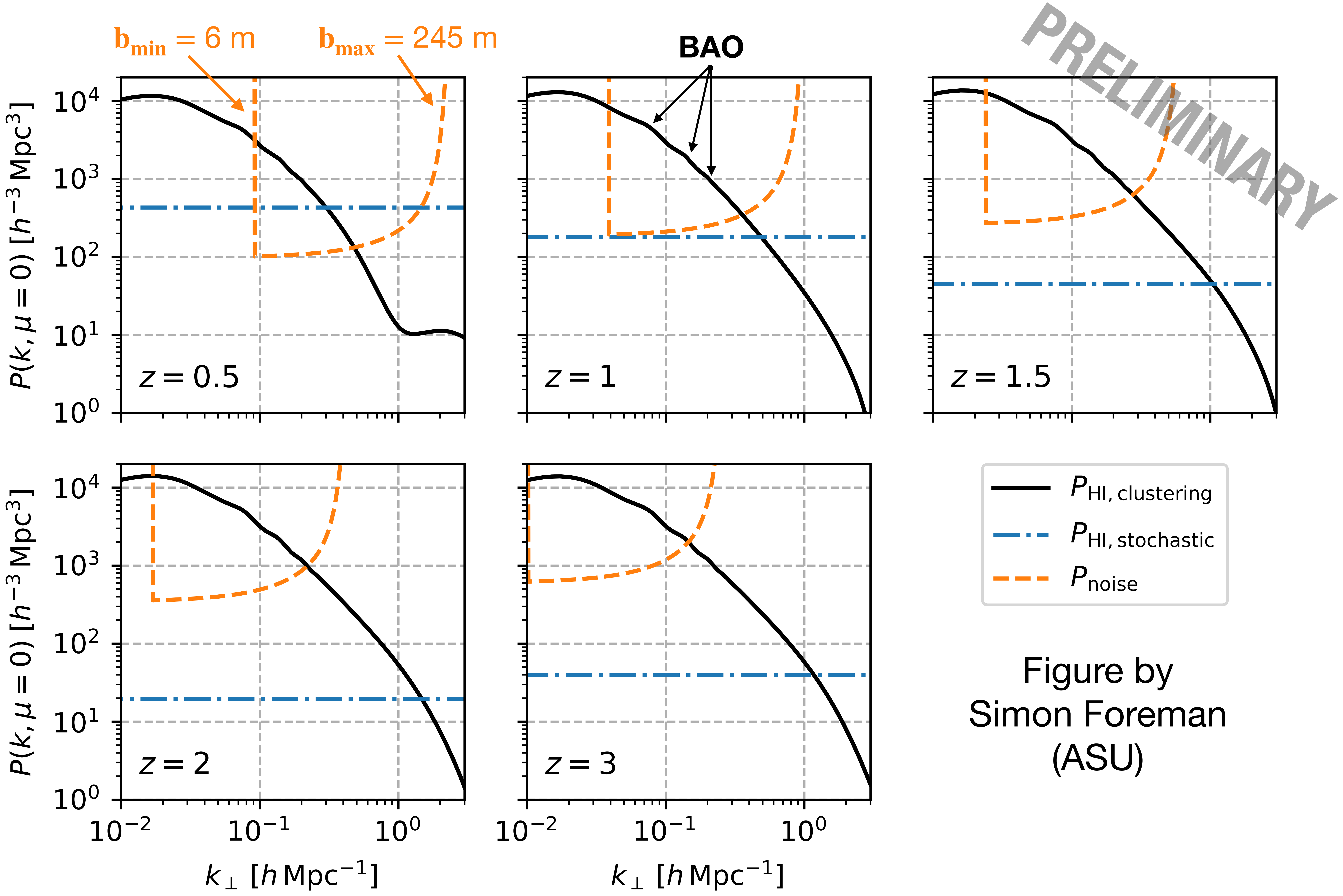


Figure by Simon Foreman (ASU)

Distance Measures

Figure by
Simon Foreman (ASU)

Relative errors on $\alpha_{\|}(z) \propto r_d\ H(z)$ and $\alpha_{\perp}(z) \propto D_A(z)\ /\ r_d$

Optimistic: excludes modes with $k_{\|} < 0.01\ h$ Mpc^{-1}
and modes within foreground wedge defined by primary beam width

Pessimistic: excludes modes with $k_{\|} < 0.1\ h$ Mpc^{-1}
and modes within foreground wedge defined by 3 x primary beam width

Cosmological Parameters

When combined with next-gen CMB measurements (Planck + Simons Observatory), CHORD significantly reduces uncertainties on standard ΛCDM parameters:

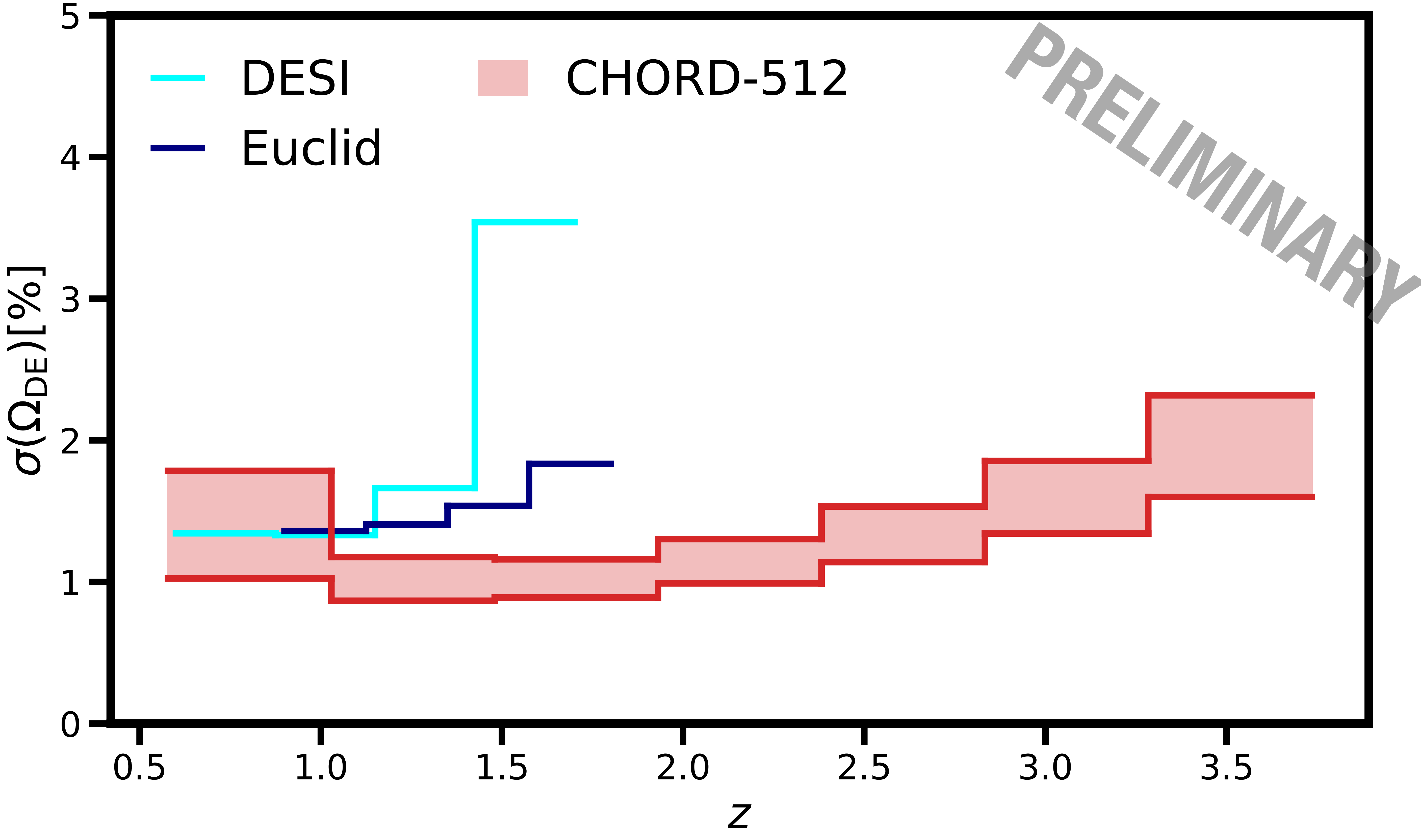
H_0 (20-60%) and Ω_{cdm} (15-50%)

and single-parameter extensions:

M_ν (50-80%) and Ω_k (35-45%)

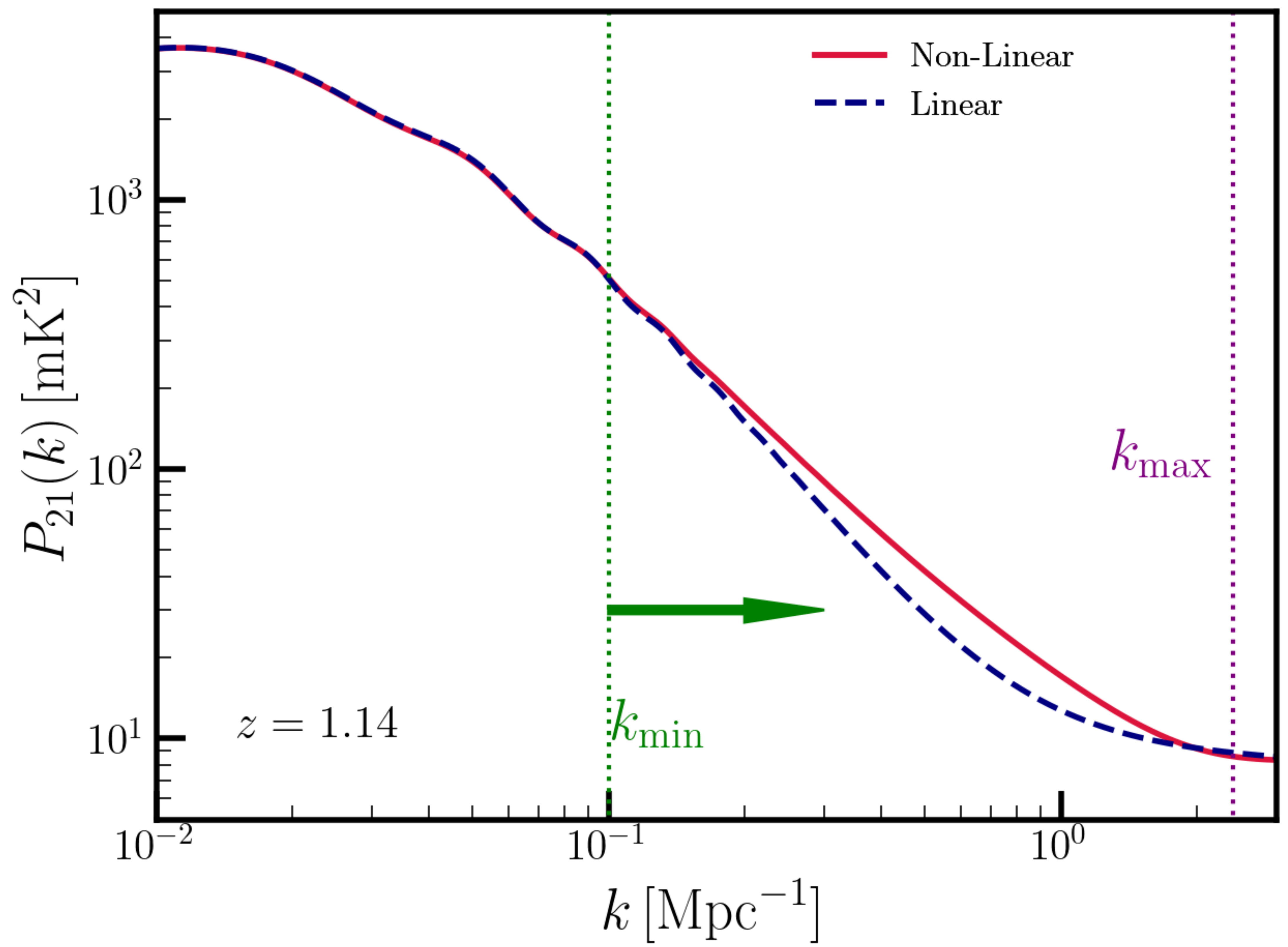
Also yields percent-level measurements of Ω_{DE} over a wide redshift range, enabling sensitive tests of dynamical models for dark energy.

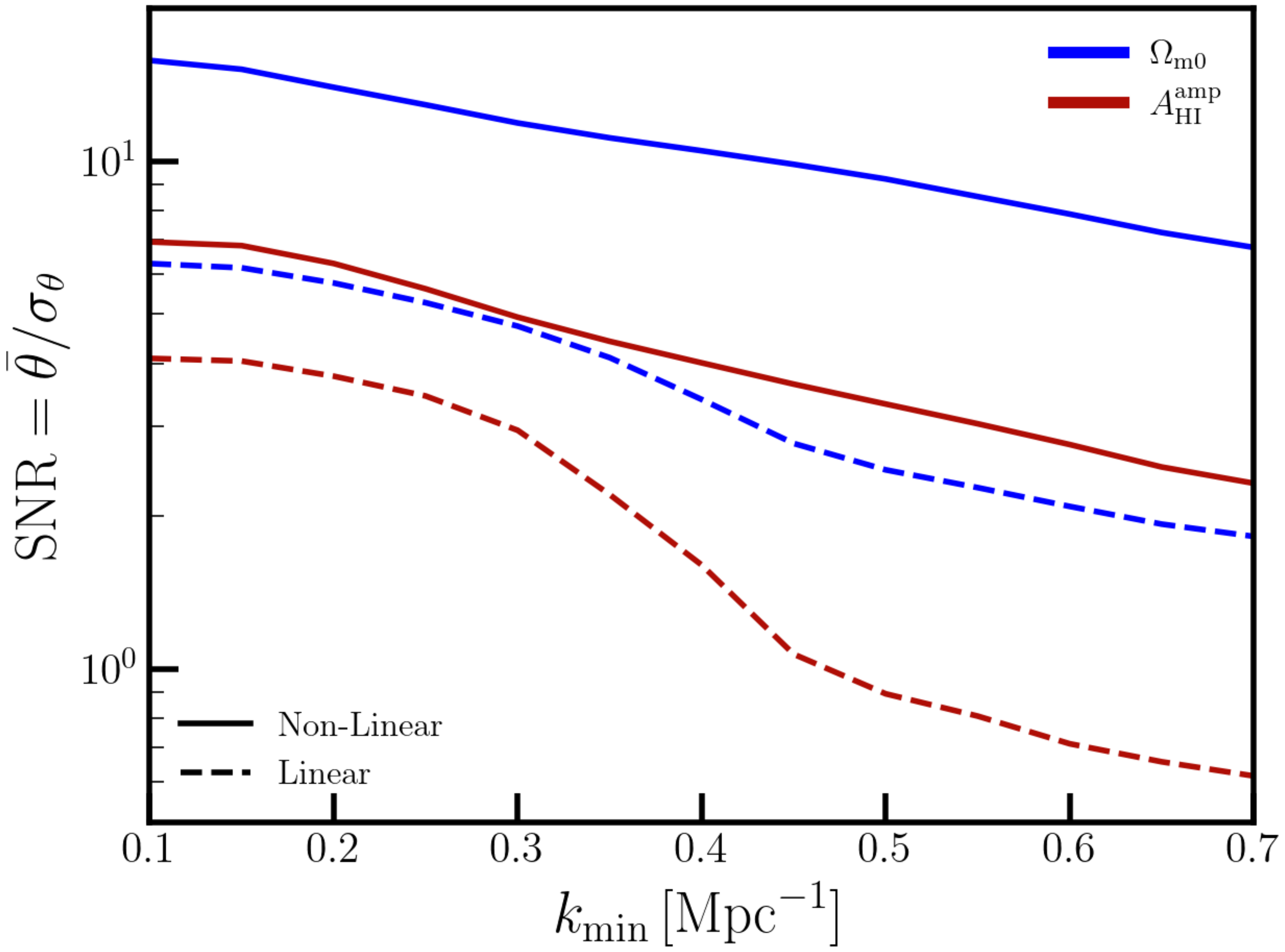
Figure by Arnab Chakraborty (McGill)



Halo Model Analysis Framework

Figure by Debanjan Sarkar (McGill)





Developing halo model framework for CHORD forecasting and analysis.

Above figure assumes 2 months of **64-dish pathfinder** data.

Exploring joint analysis of the 21 cm intensity mapping and 21 cm galaxy surveys.

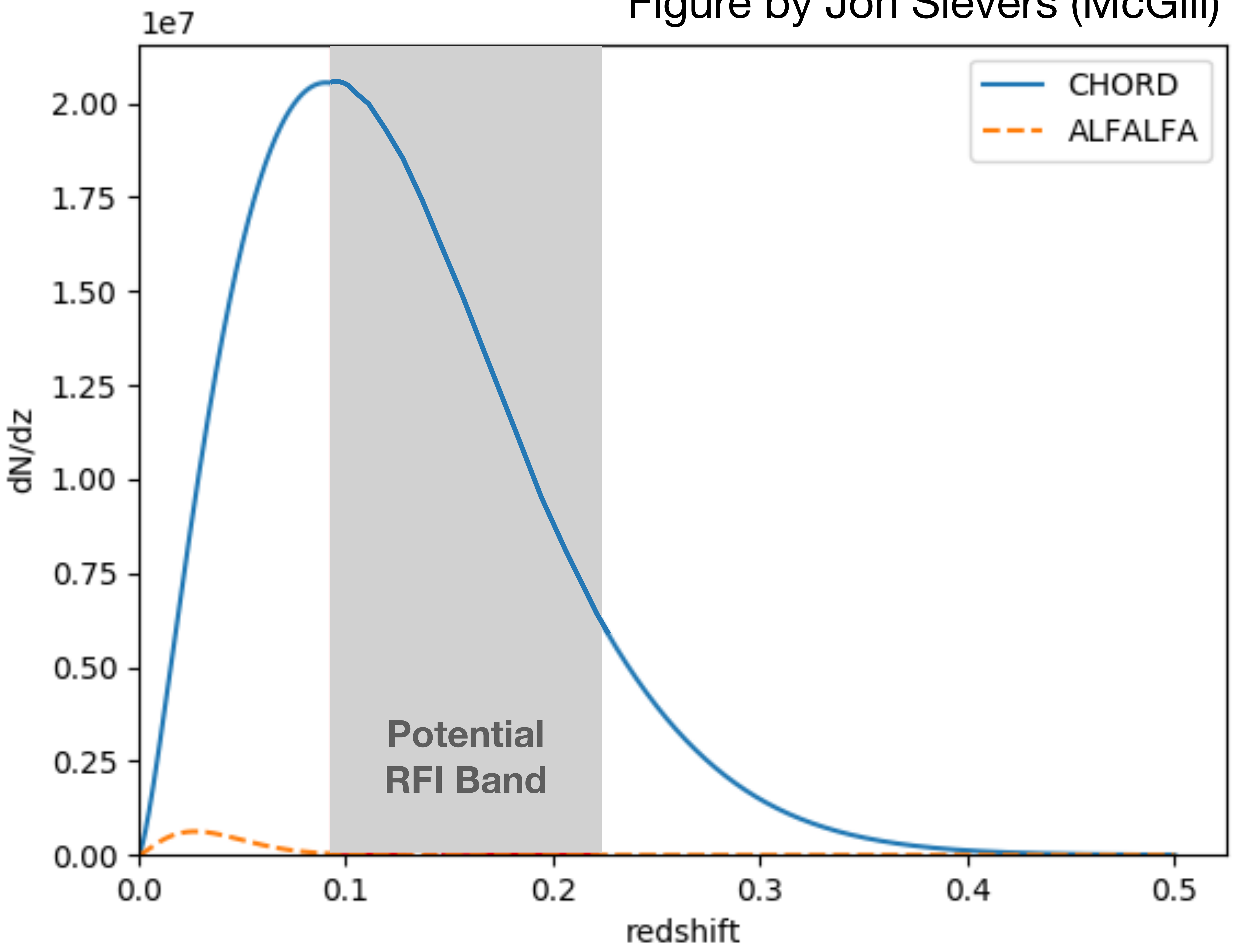
21 cm Galaxy Search

At low redshift, CHORD will detect the 21 cm emission from individual galaxies.

Forecasted to detect more than **1 million galaxies.**

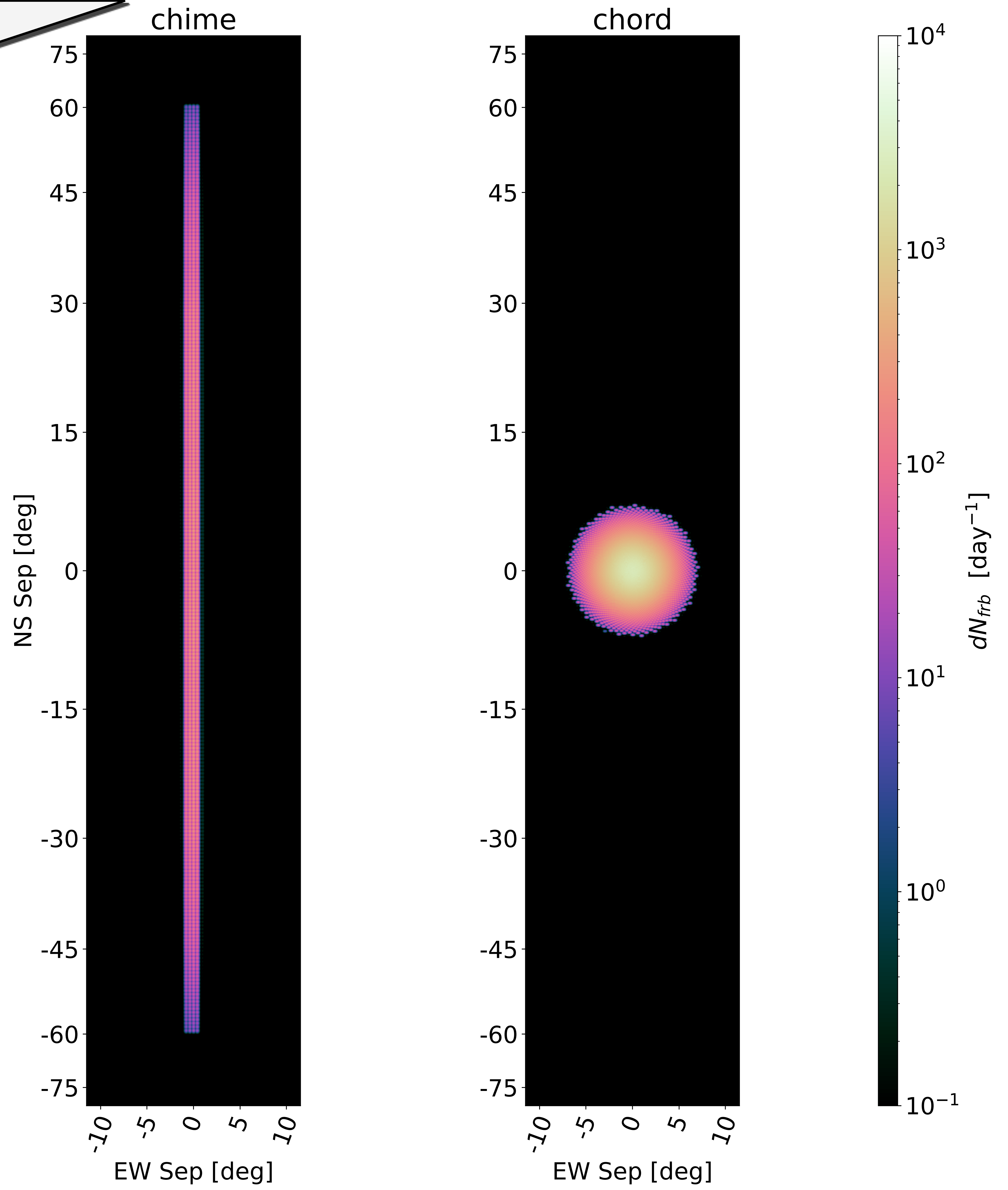
100x improvement over current state-of-the-art survey (ALFALFA).

Figure by Jon Sievers (McGill)



Fast Radio Bursts

CHORD is forecasted to detect **10-20 FRBs per day** with better than **50 milli-arcsec** localization.



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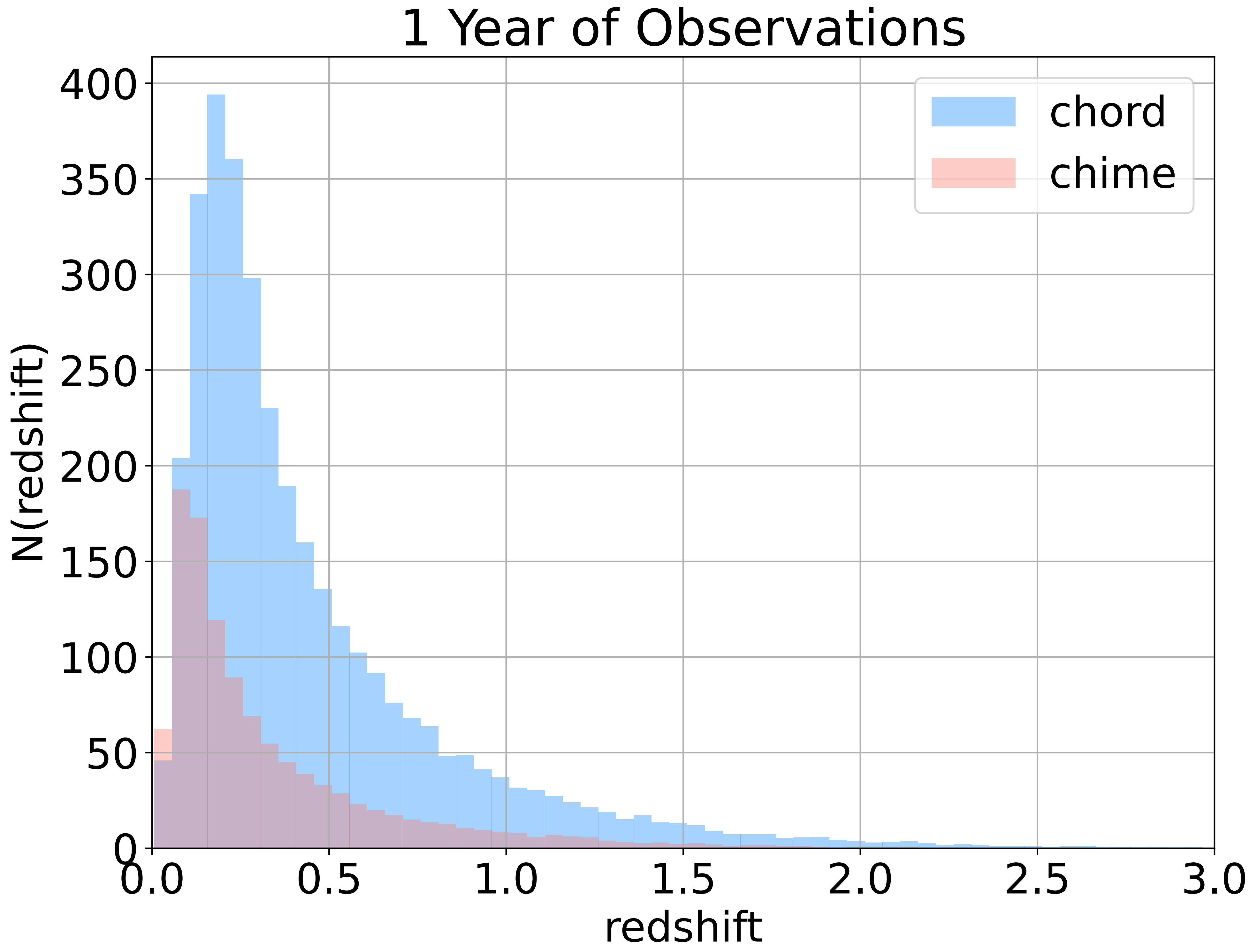
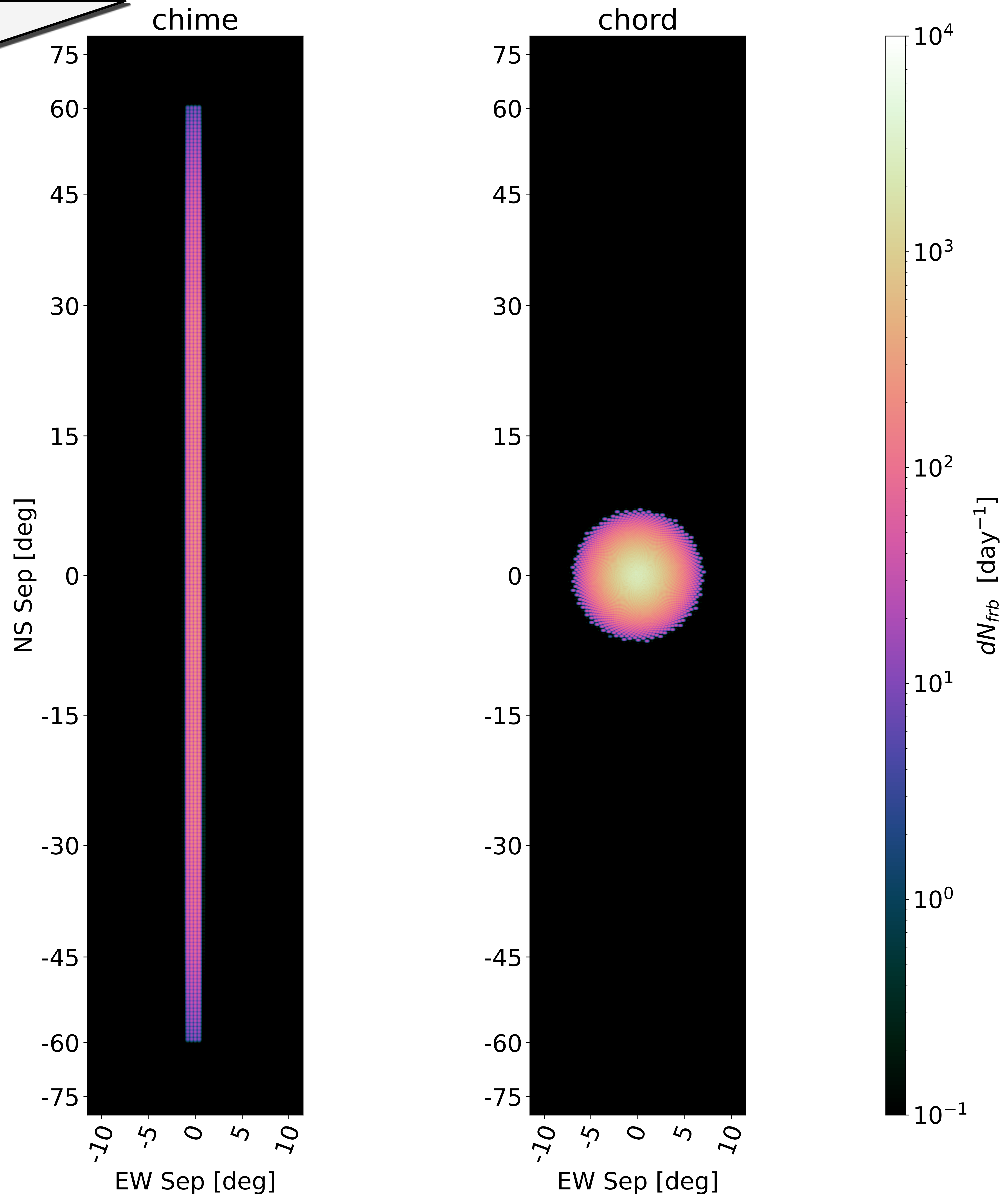
Assuming FRBs trace star formation rate, CHORD will detect FRBs out to redshift 3 to 4.





Summary

CHORD is a next-generation large-N, small-D radio observatory with
a compact core array and very long baseline outriggers sensitive to an ultrawide band (300-1500 MHz).

CHORD has the sensitivity and bandwidth required to

- Make a sub-percent level measurement of the expansion history between redshift 0 — 3.7
- Construct the largest catalog to date of HI galaxies
- Detect and precisely localize tens of thousands of FRBs
- Detect new pulsars and provide timing/polarimetry of known northern hemisphere pulsars
- Probe the magneto-ionic environment of the ISM and CGM via Faraday tomography

We are building CHORD with a focus on systematic errors. Specifically:

- Reducing its intrinsic chromaticity
- Improving the redundancy of the array elements to enable precise calibration

The 64-dish pathfinder will be operational late this year.
The full 512-dish core and two 64-dish outriggers are expected to come online in 2026.

For more information, see chord-observatory.ca