CHORD and HIRAX Instrumentation & Calibration

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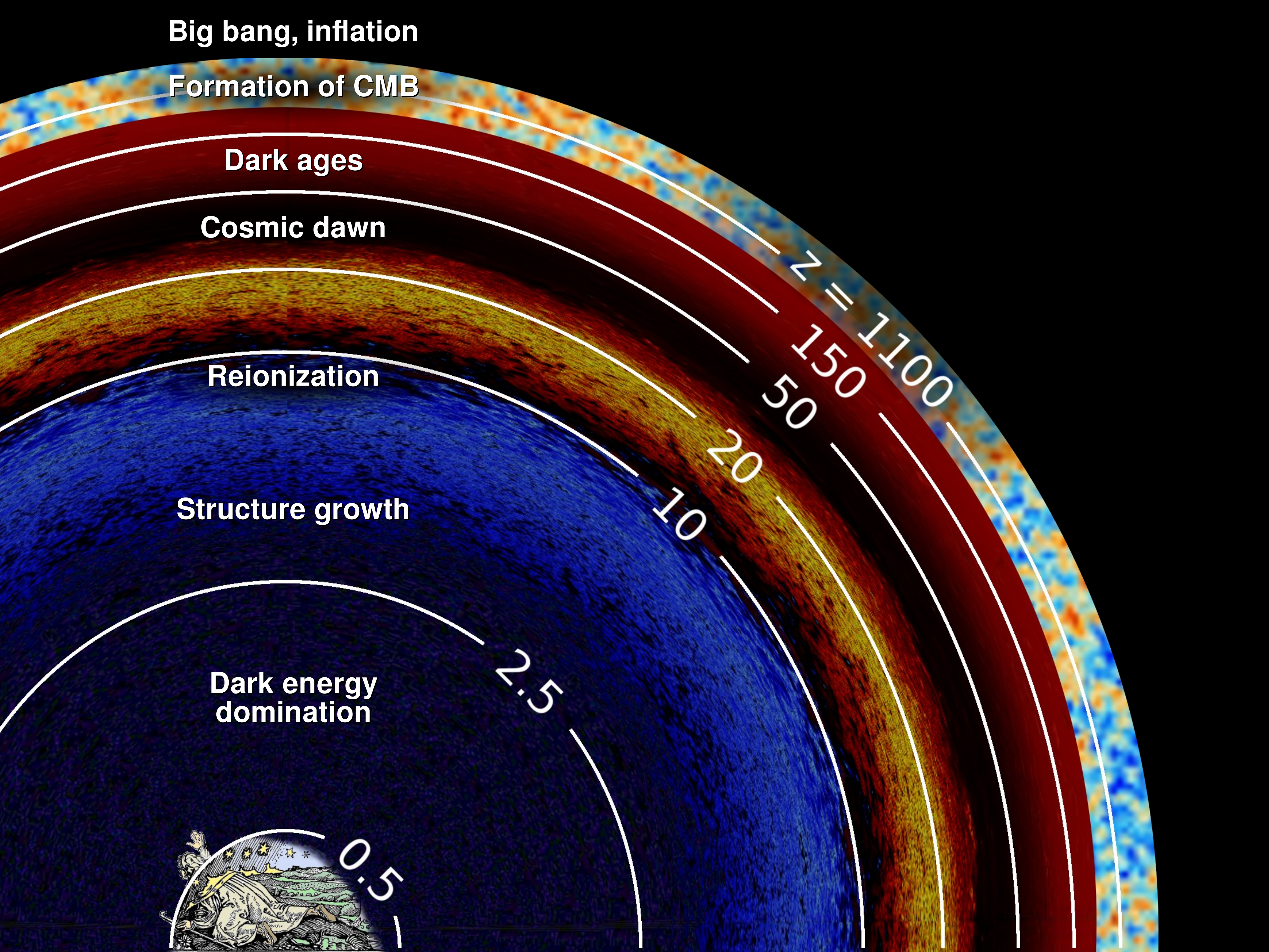
McGill University

Swiss SKA Days
6 September 2023


Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Structure growth
Dark energy domination
z = 1100
150
50
20
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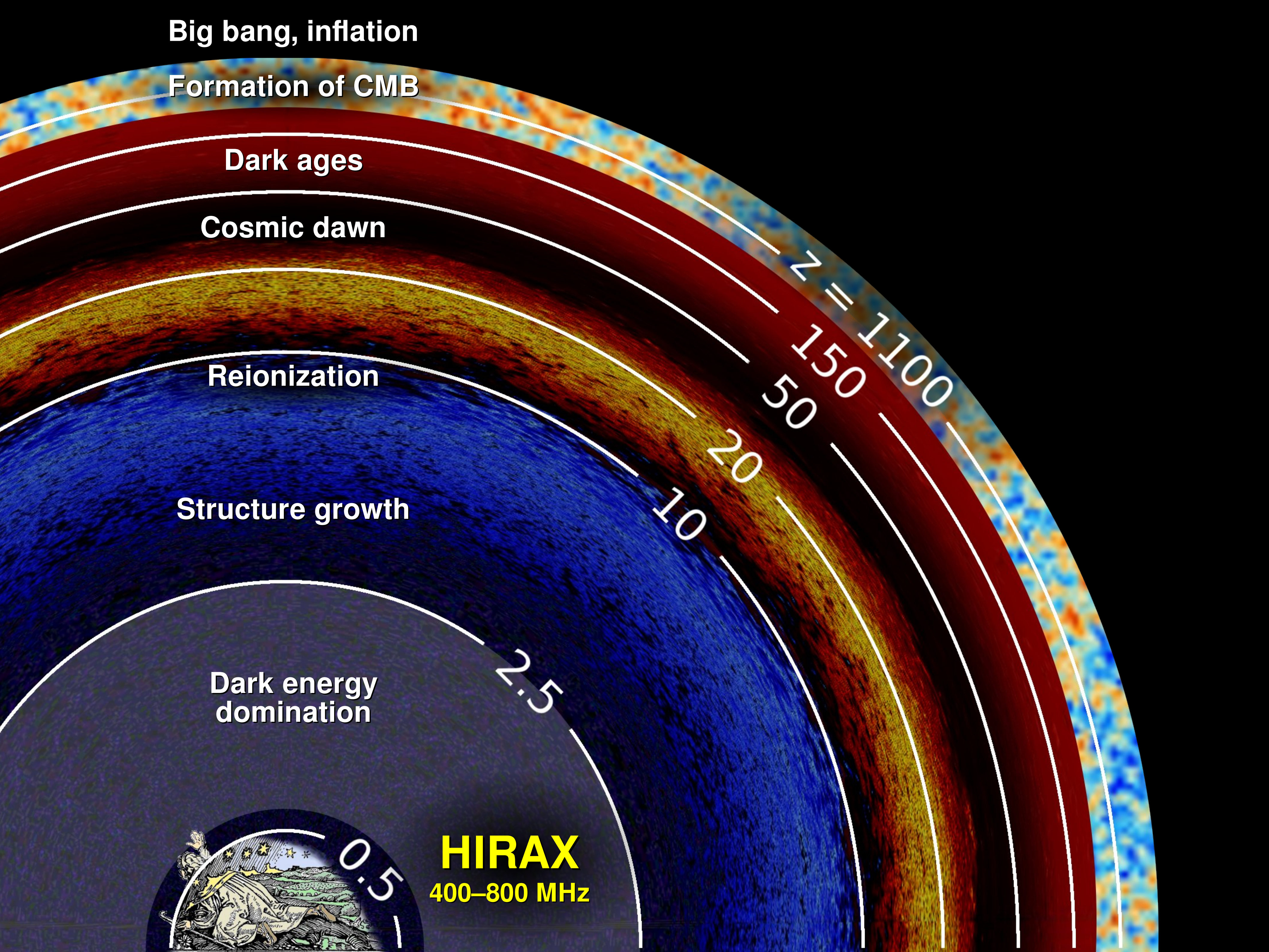
2.5
0.5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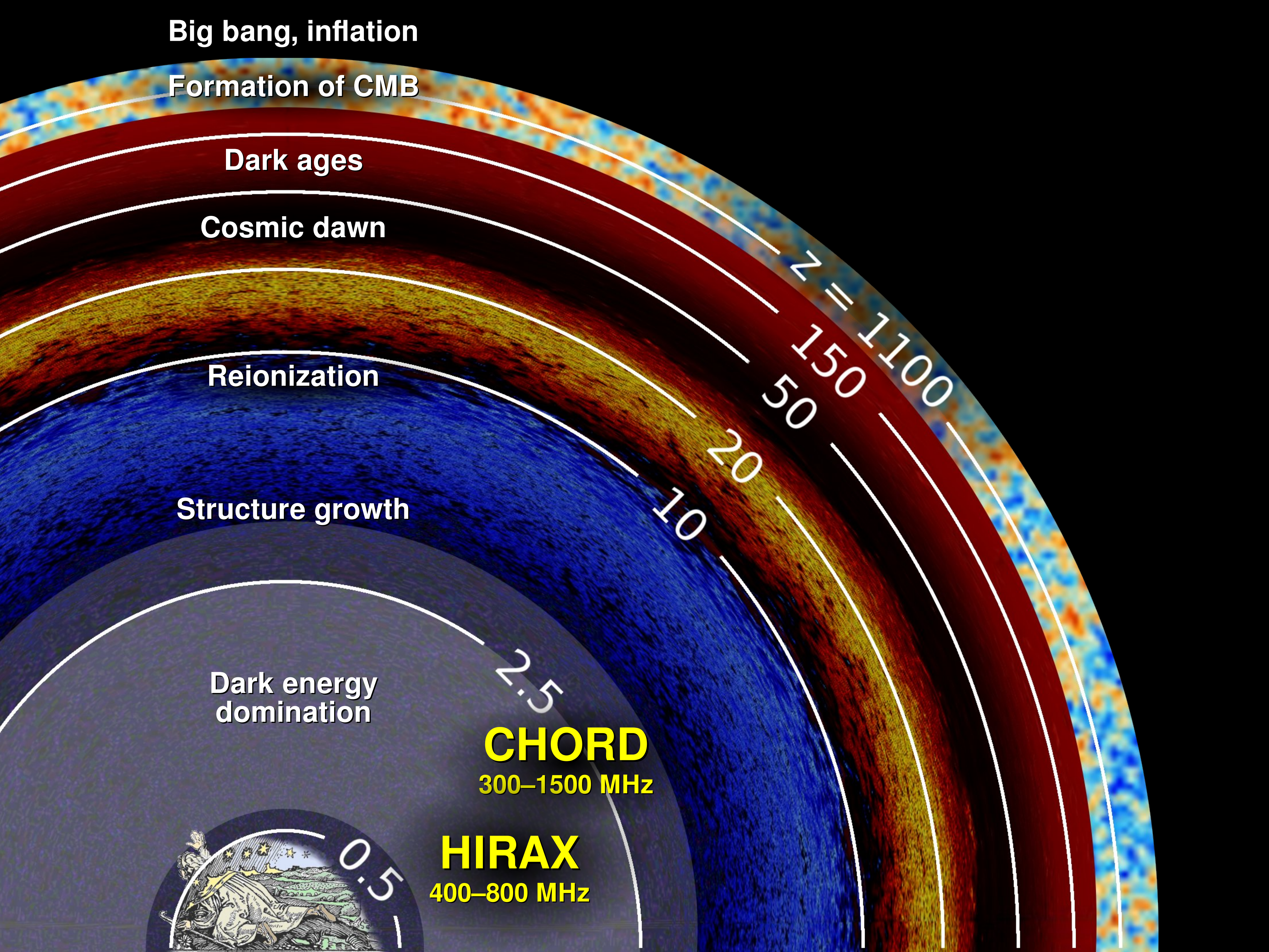
HIRAX
400–800 MHz



Big bang, inflation
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z = 1100
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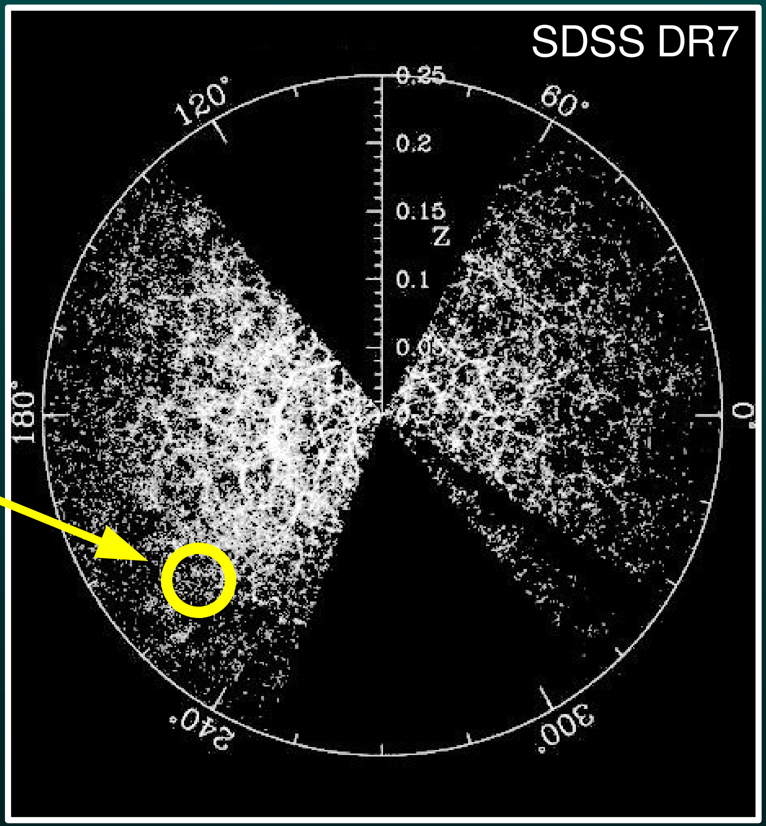
CHORD
300–1500 MHz
HIRAX
400–800 MHz

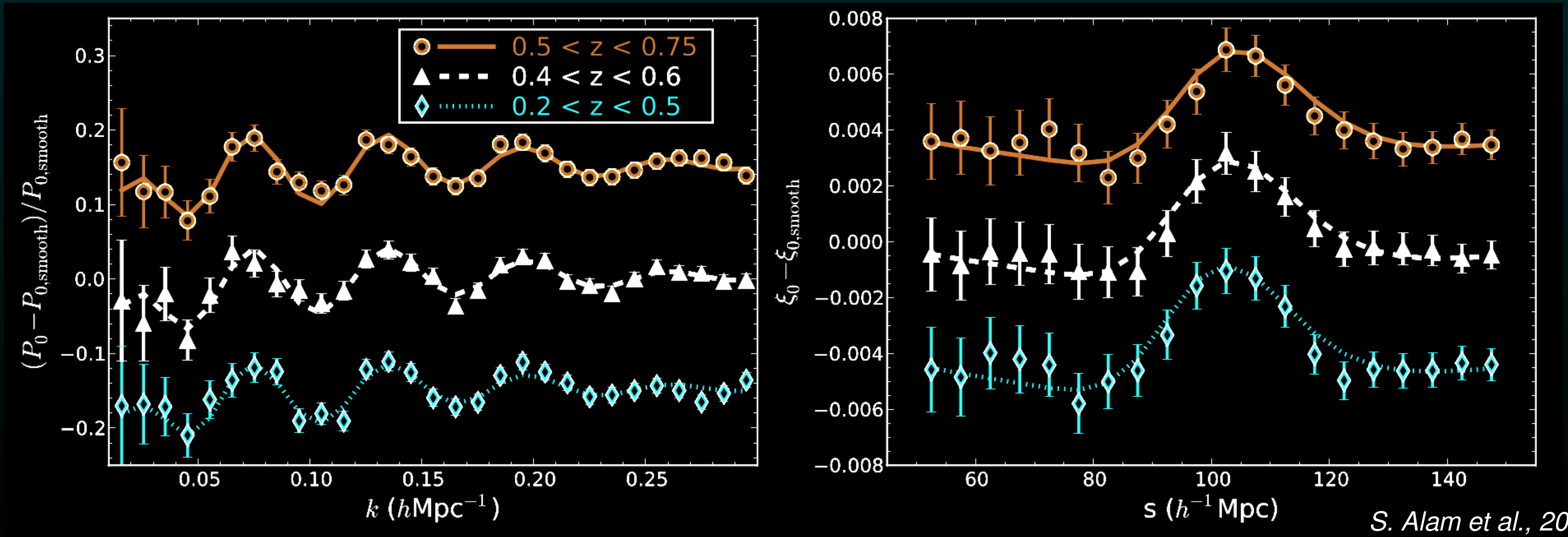
Baryon acoustic oscillations

Galaxy positions “remember” acoustic waves from the early universe

Sound horizon sets ~150 Mpc scale: use as a ruler for charting expansion rate and catching dark energy in the act

We need lots of volume for cosmology: use intensity mapping to measure aggregate line emission





S. Alam et al., 2016

Required specs for BAO intensity mapping

- Maximize sensitivity on scales of interest
  $\rightarrow$ Use compact array geometry
- Redshift range of interest: $0.8 < z < 2.5$ to capture dark energy domination at $z \sim 2$
  $\rightarrow$ Required frequencies: 400 – 800 MHz
- BAO 150 Mpc angular scale: 3 – 1.3 degrees at $0.8 < z < 2.5$
  $\rightarrow$ Required baseline lengths: 15 – 60 meters
- BAO scale along line of sight: 20 – 12 MHz at $0.8 < z < 2.5$
  $\rightarrow$ Required freq resolution: minimum ~100 channels, more for foregrounds and higher order peaks
- BAO signal level: ~0.1 mK
  $\rightarrow$ Low system temperature, large collecting area

CHORD and HIRAX

CHORD

Site: DRAO, Canada

Dishes: 512 core + 128 outriggers

Frequencies: 300 – 1500 MHz

HIRAX

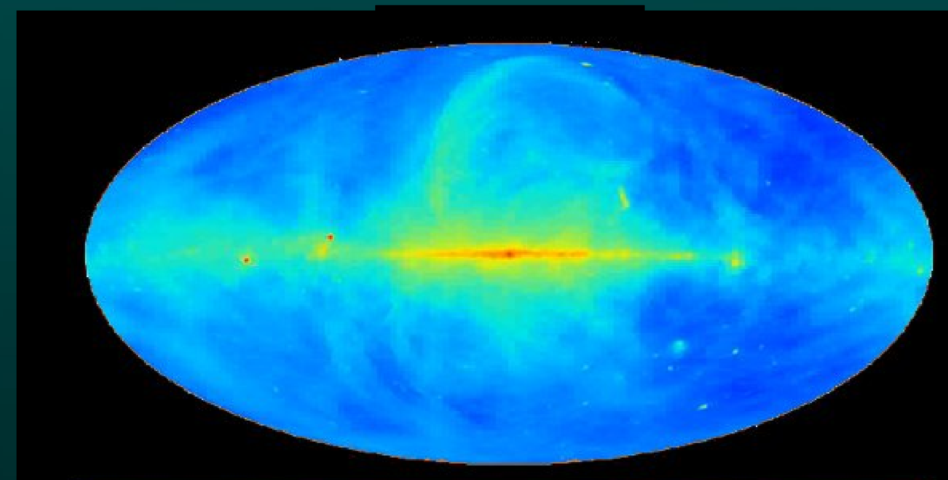
Site: Karoo desert,
South Africa

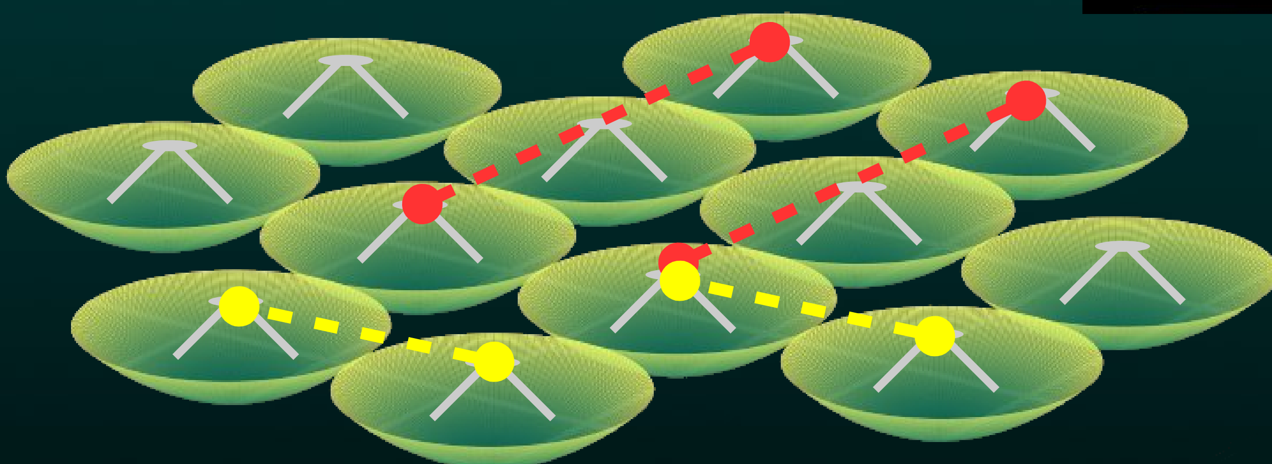
Dishes: 256 core +
TBD outriggers

Frequencies:
400 – 800 MHz

The need for "redundancy"

Milky Way is 1000 x brighter than BAO signal, and we don't have a model that's good to 1 part in 1000





Calibration depends on identical baselines seeing the same signal

Within a few days, need to average visibilities, otherwise we have 50-100 Tb/day data

Gain calibration: more instrumental imperfections mean solving/saving a more complicated sky model. Non-redundancies bleed foregrounds into visibility averages, corrupting data.

Post-calibration isn't good enough: we need up-front <u>control</u>

Achieving redundancy in 4 easy steps

1) Define specifications using cosmology forecasts and instrument sims

2) Build instrumentation that meets the required tolerances

3) Verify that the instrumentation meets the required tolerances

4) Rejoice in your experimental victory

Achieving redundancy in 4 easy steps

1) Define specifications using cosmology forecasts and instrument sims
   - Sliding scale in trading degraded redundancy for increased computation/data storage
   - Complex dependencies between top-level and downstream requirements
   - Mechanical realities may push back on top-level requirements

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- Ballpark tolerances are strict, set by foreground brightness relative to BAO signal
- Precision matters much more than accuracy
- Keeping costs down is important for large arrays

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- Verification is nontrivial for telescopes without active drive systems

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4) ~~Rejoice in your experimental victory~~ Lose sleep while repeating all the above

Defining specifications: HIRAX example

Cosmological forecasts: dark energy FOM target ~270–335, Bull et al. 2015 Fisher formalism + Shaw et al. 2015 foreground model, with Planck 2018 priors

- Range of $k_\perp$: 0.05–0.16 Mpc^{-1}
- Range of $k_\parallel$: 0.03–0.2 Mpc^{-1}
- 21-cm power spectrum relative sensitivity, median across scales: <0.8%
- Array level calibration target: <0.3%

Define system requirements

- Primary beam: consistent to a few parts in 1000 relative to the average integrated beam
- Pointing and positioning:
  - – Beam centroid pointing vectors must be parallel within 5 arcmin RMS
  - – Foci of all dishes must lie in a plane with 5 mm RMS deviation orthogonal to plane
  - – Foci must form a regularly spaced grid with separation distances precise to 2.5 mm RMS

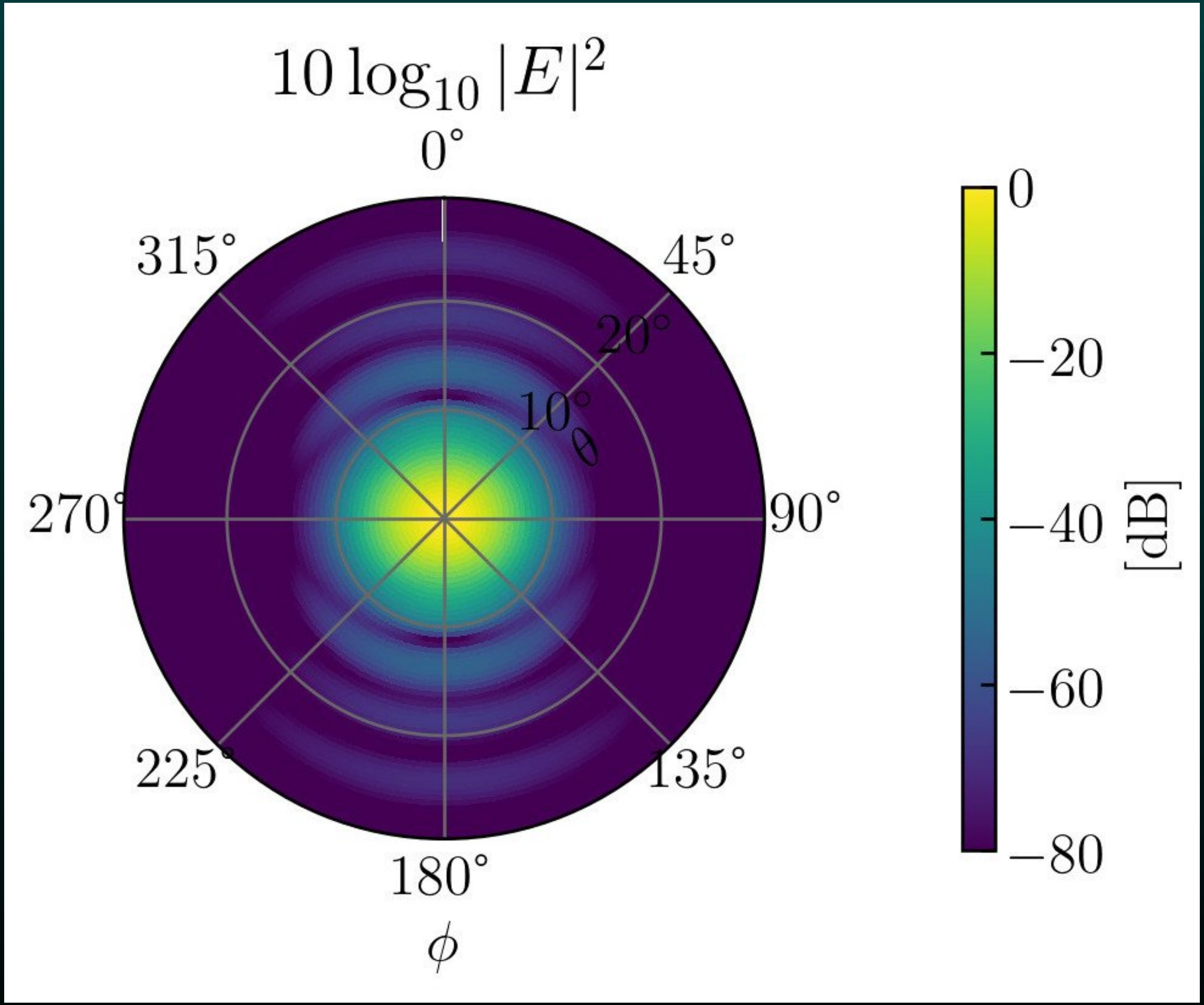
Telescope requirements

- Over 60 separate requirements for receiver support, dish, mount, foundation, etc.
- Pointing/positioning error analyzed with geometric model to compute error stackup
- Beam errors: CST simulations

D. Crichton et al., arXiv:2109.13755

Defining specifications: HIRAX example

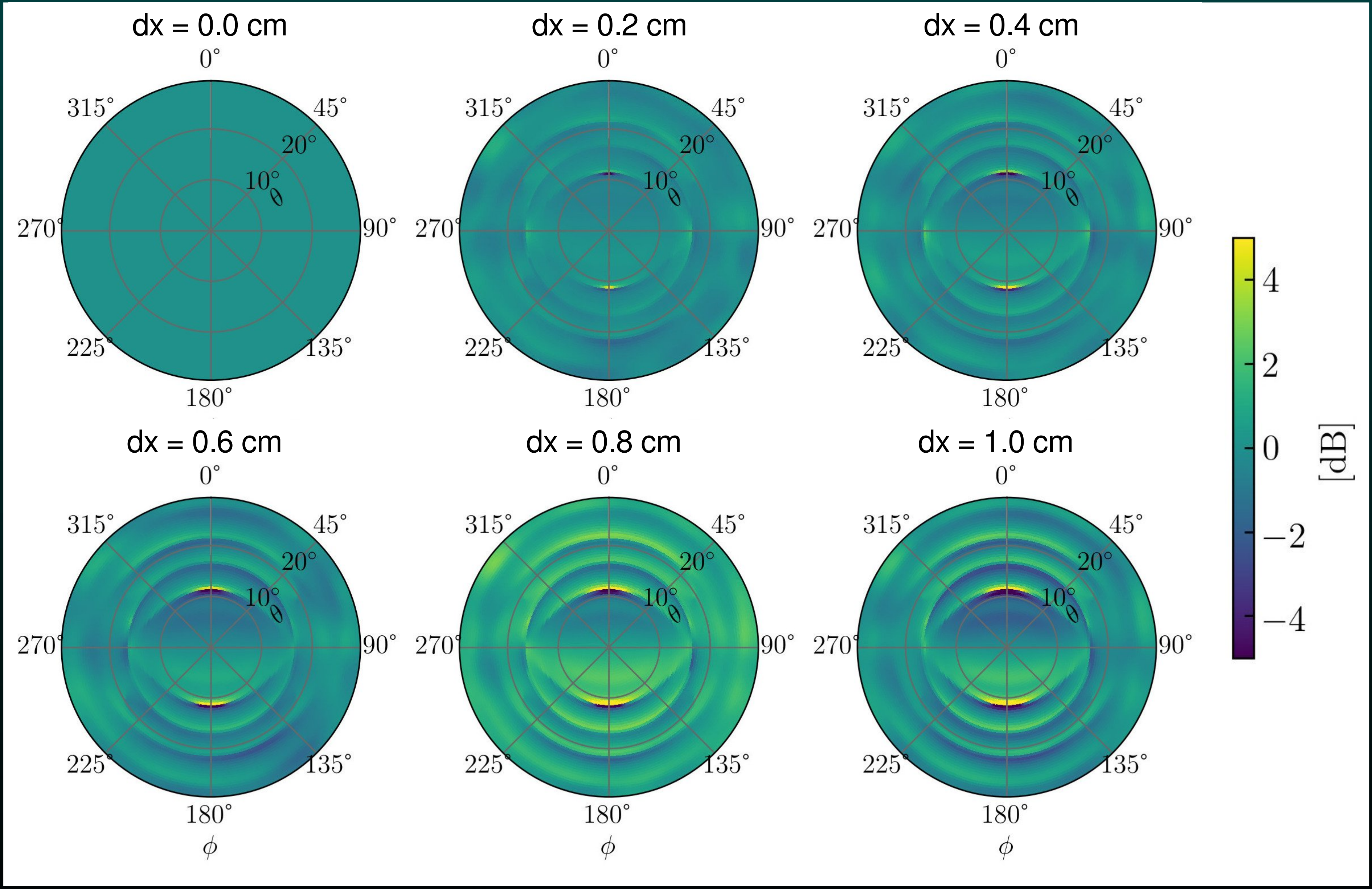
Fiducial beam with no systematics



Analysis: D. Crichton, K. Gerodias, E. Pieters, B. Saliwanchik

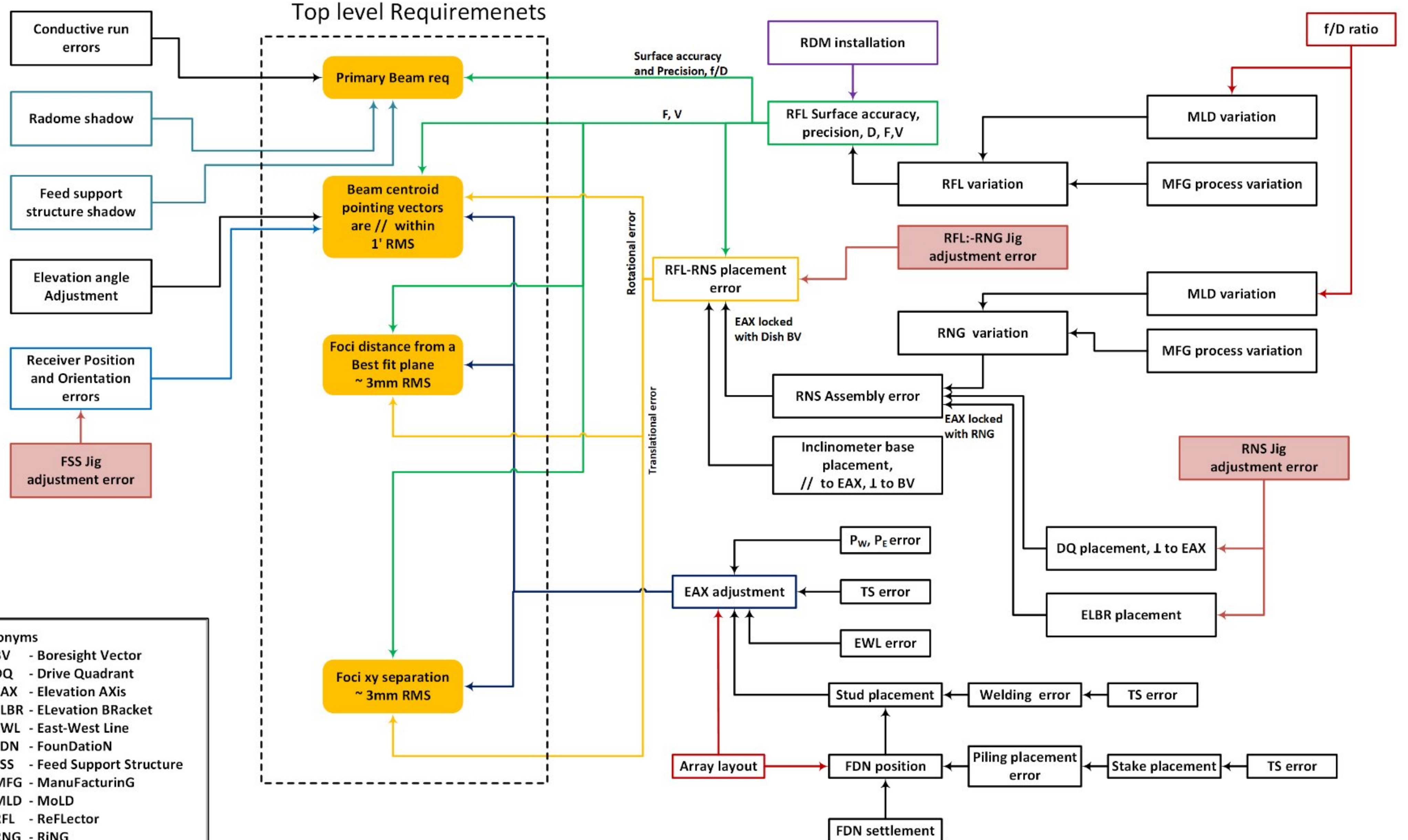
Defining specifications: HIRAX example

HIRAX feed position spec: 0.5 mm RMS



Analysis: D. Crichton, K. Gerodias, E. Pieters, B. Saliwanchik

Defining specifications: CHORD example



Acronyms

- BV - Boresight Vector
- DQ - Drive Quadrant
- EAX - Elevation AXis
- ELBR - ELevation BRacket
- EWL - East-West Line
- FDN - FounDatioN
- FSS - Feed Support Structure
- MFG - ManuFacturinG
- MLD - MoLD
- RFL - ReFLector
- RNG - RiNG
- RNS - RiNg Sub-assembly
- RDM - RaDoMe
- TS - Total Station

Image: M. Islam

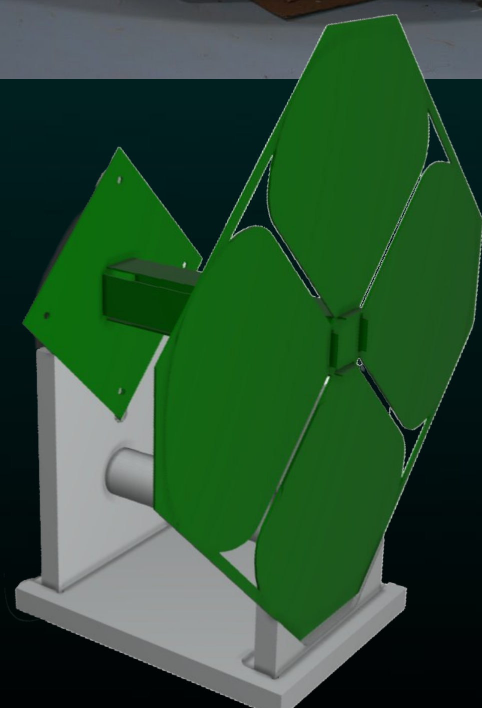
Building the hardware

Monolithic composite dishes

Laser-cut wideband feeds (CHORD)

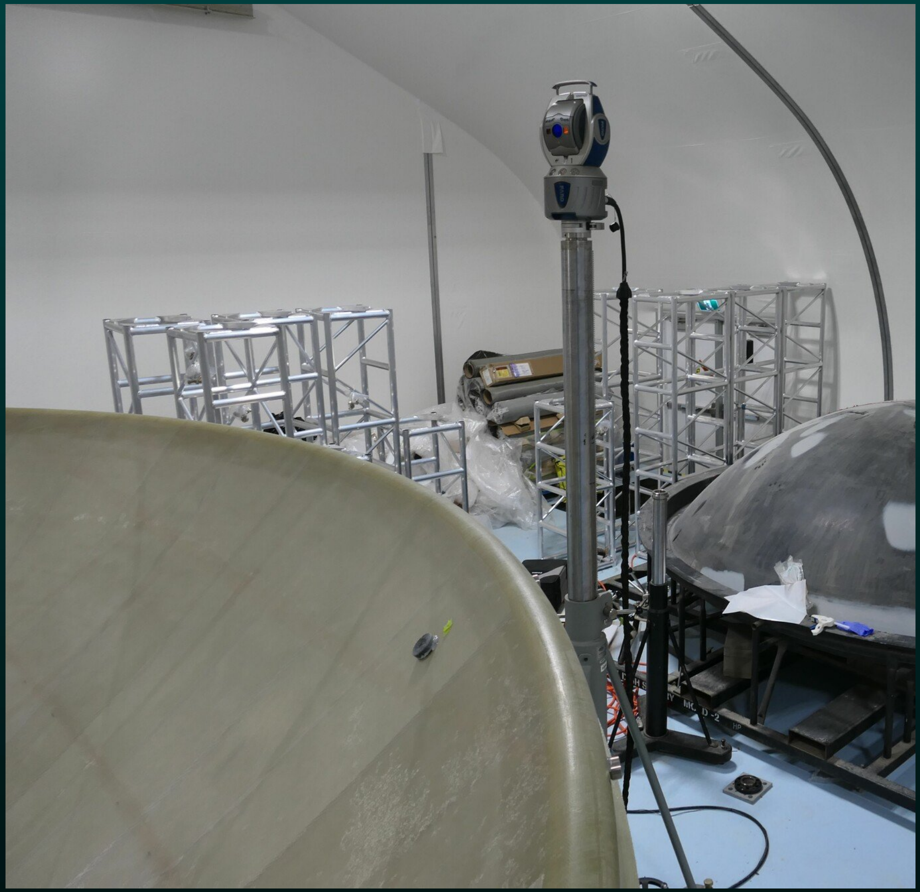
Feed assembly jigs (HIRAX)

...etc.



Instrument characterization and verification

Optical surface measurements

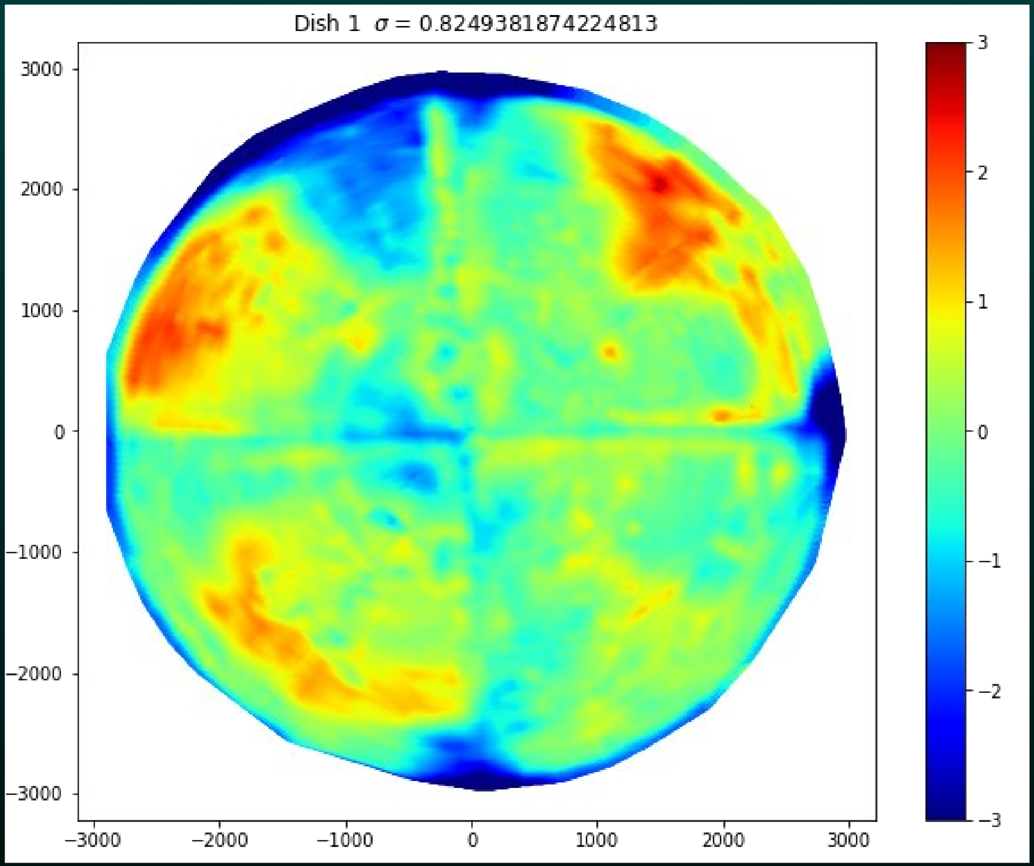


Laser tracker:
- High precision, ~tens of microns
- Measurement density limited only by patience
- Slow, and significant overhead

Photogrammetry:
- Precision somewhat worse than laser tracker
- Measurement density set by # of targets
- Comparatively fast and easy

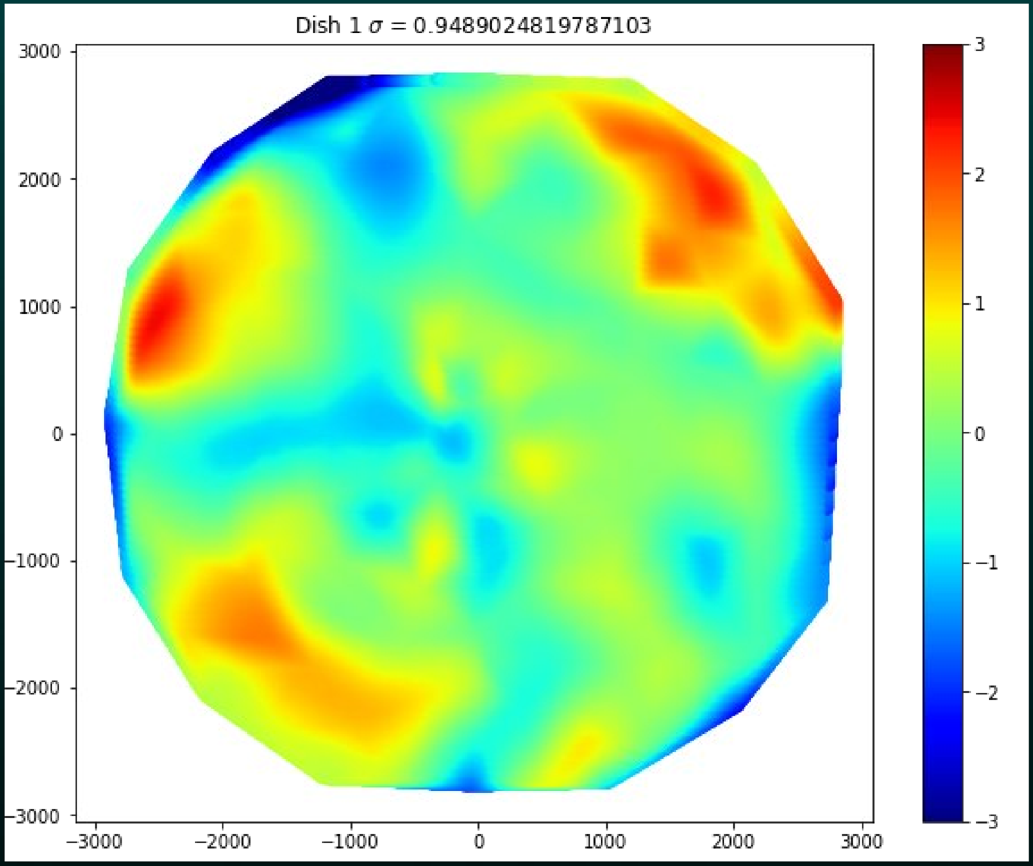
Instrument characterization and verification
Optical surface measurements

RMS error: 0.825 mm



Laser tracker:
– High precision, ~tens of microns
– Measurement density limited only by patience
– Slow, and significant overhead

RMS error: 0.949 mm



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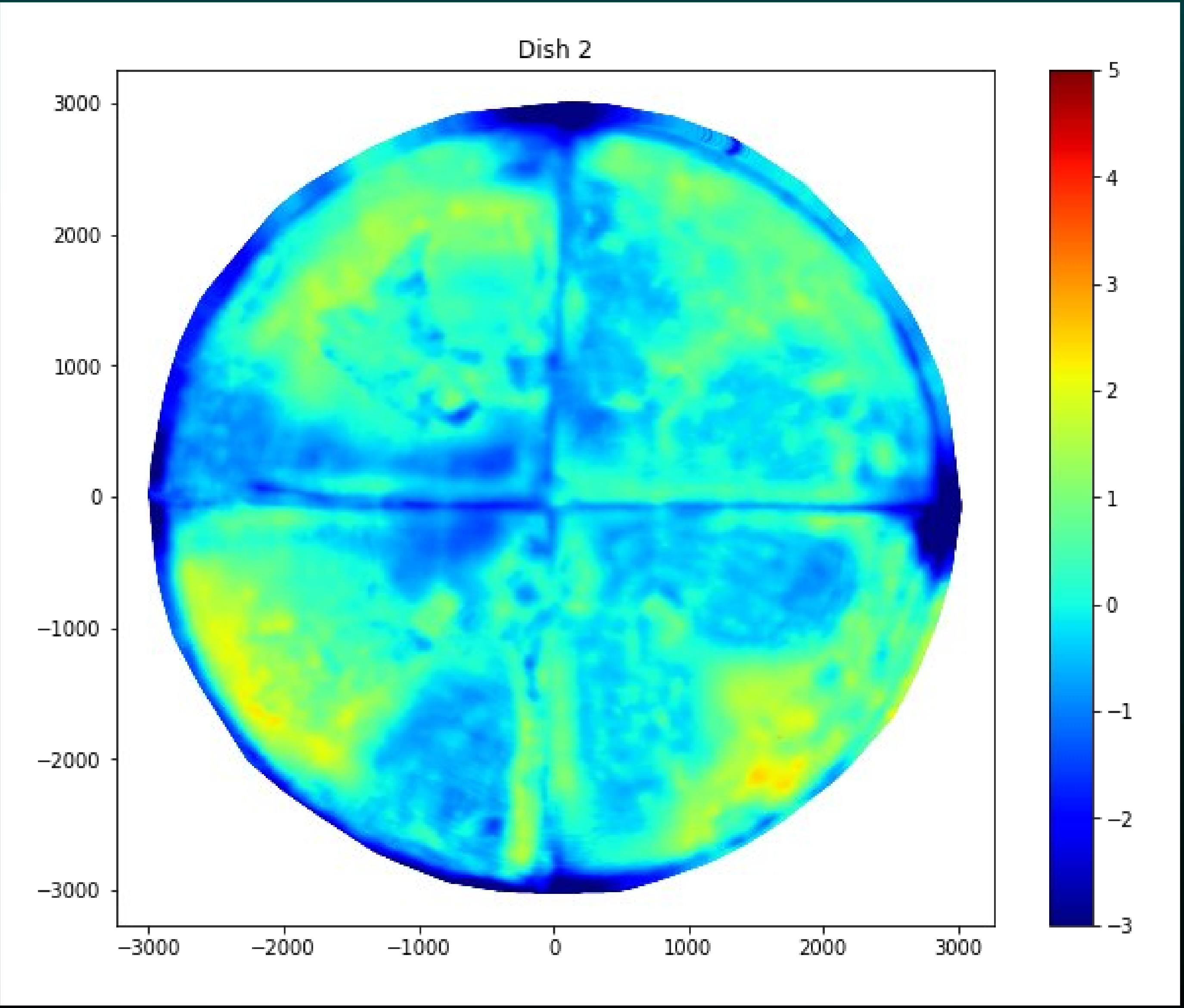
Analysis: A. Karigiri, M. Islam

Instrument characterization and verification

Optical surface measurements



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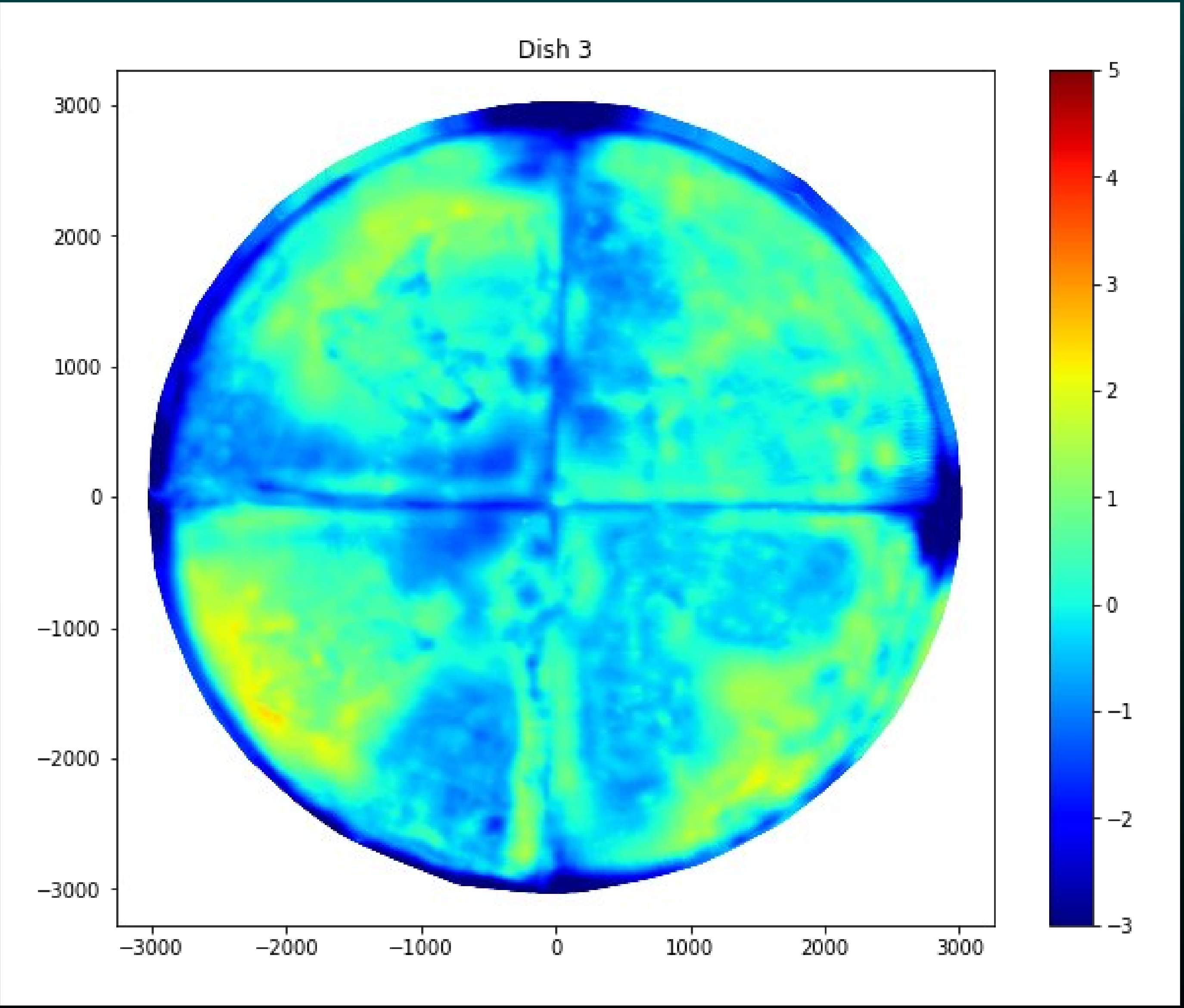
Instrument characterization and verification
Optical surface measurements

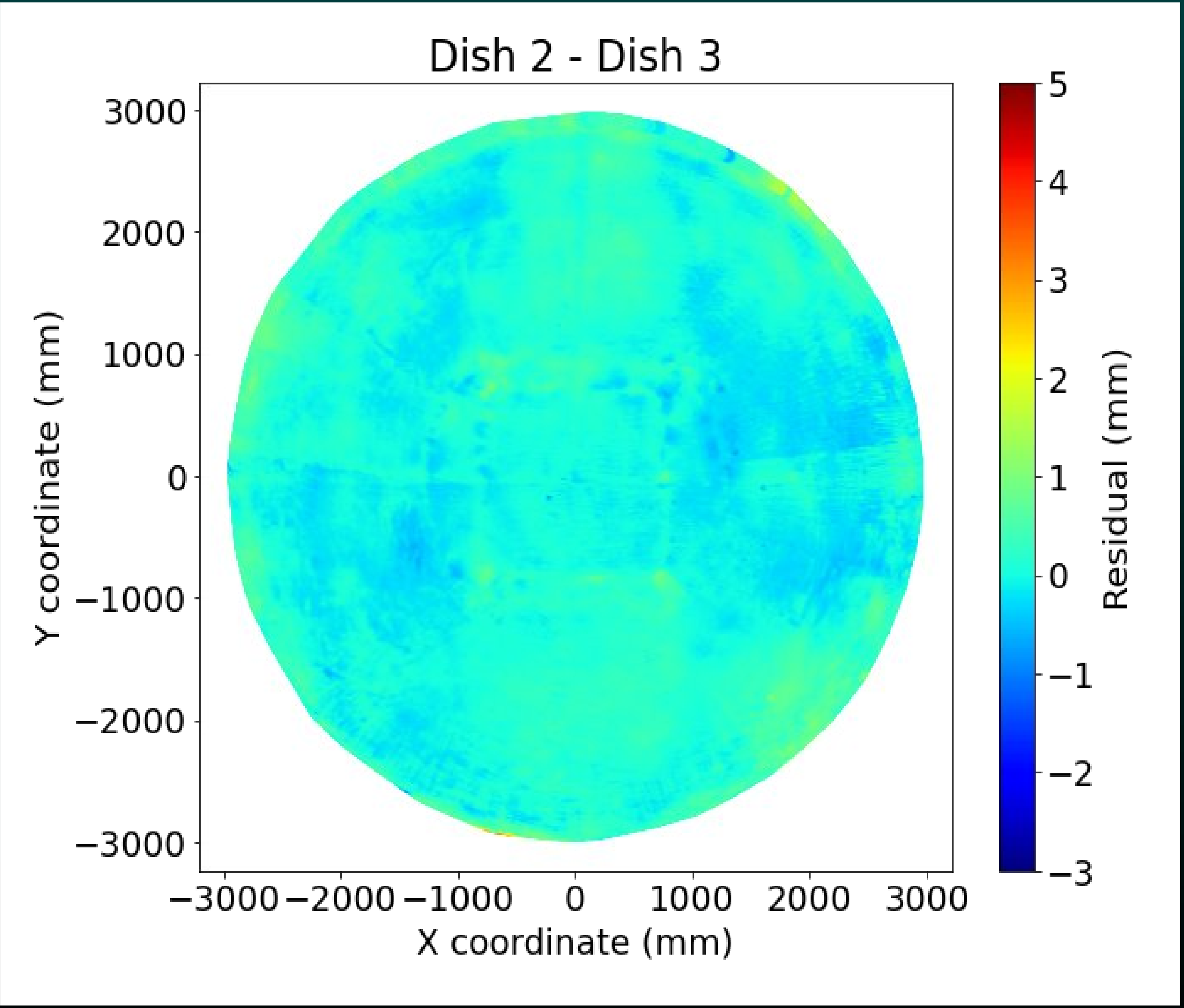


Analysis: A. Karigiri, M. Islam

Instrument characterization and verification

Optical surface measurements

RMS of difference: 0.210 mm!



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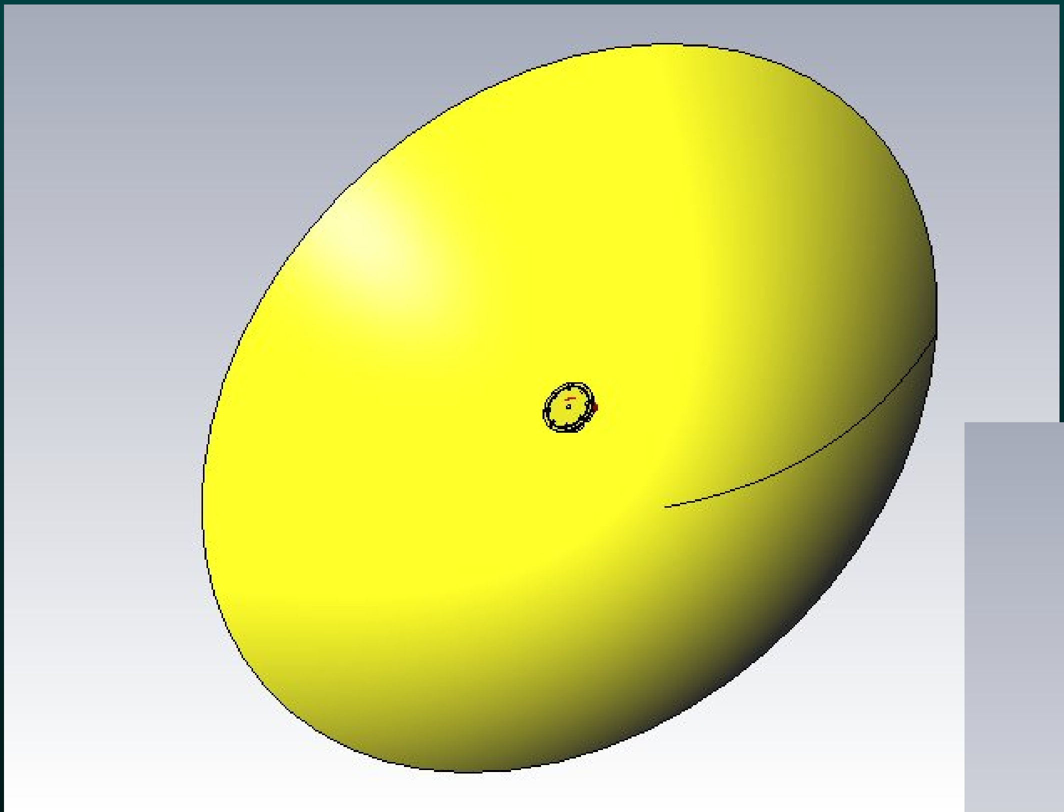
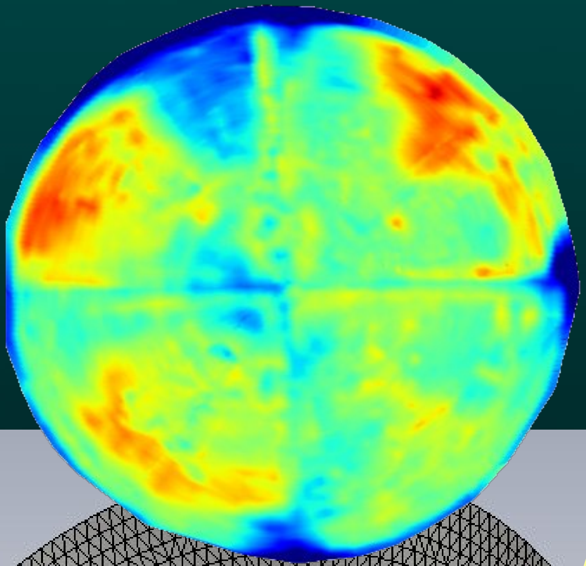
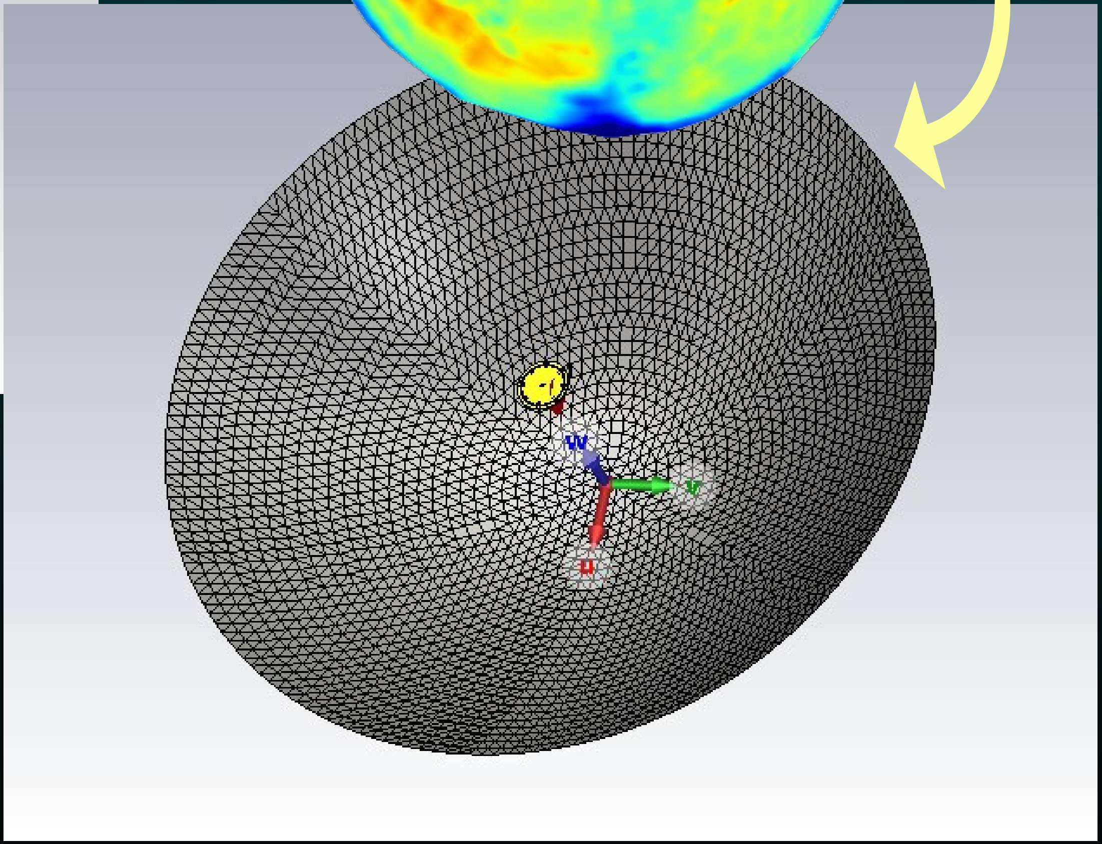
Instrument characterization and verification
Linking to EM sims







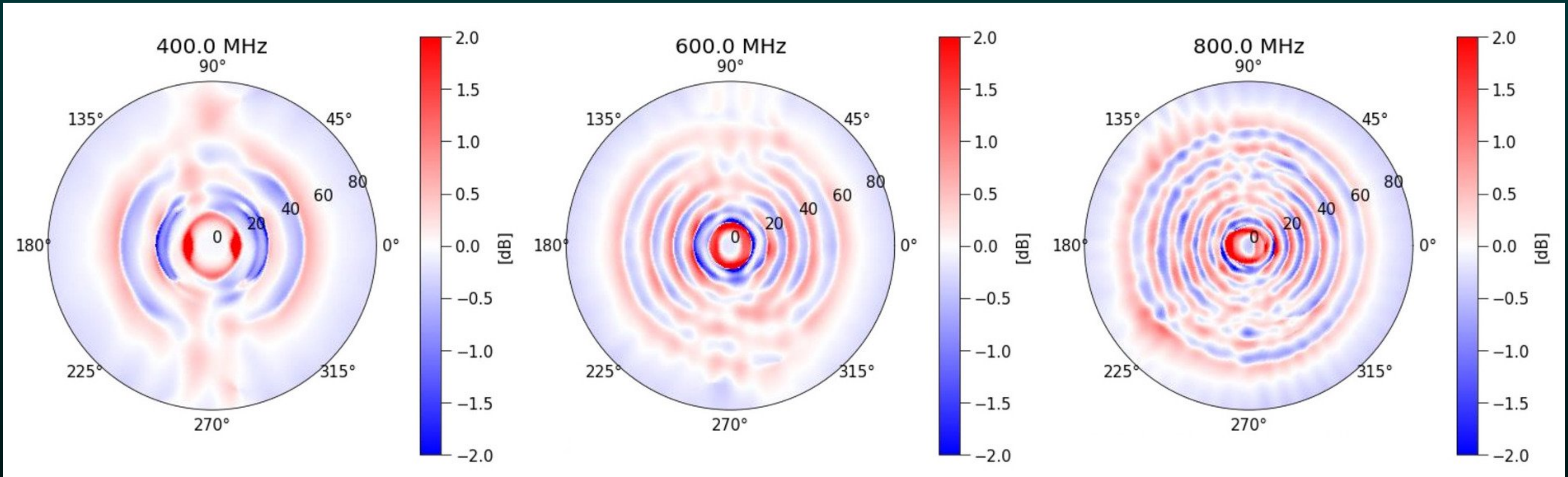
Model discretized dish surface in CST
and apply surface variations

Analysis: K. Gerodias

Instrument characterization and verification

Linking to EM sims

Beam difference between perturbed and perfect (but discretized) dish surface

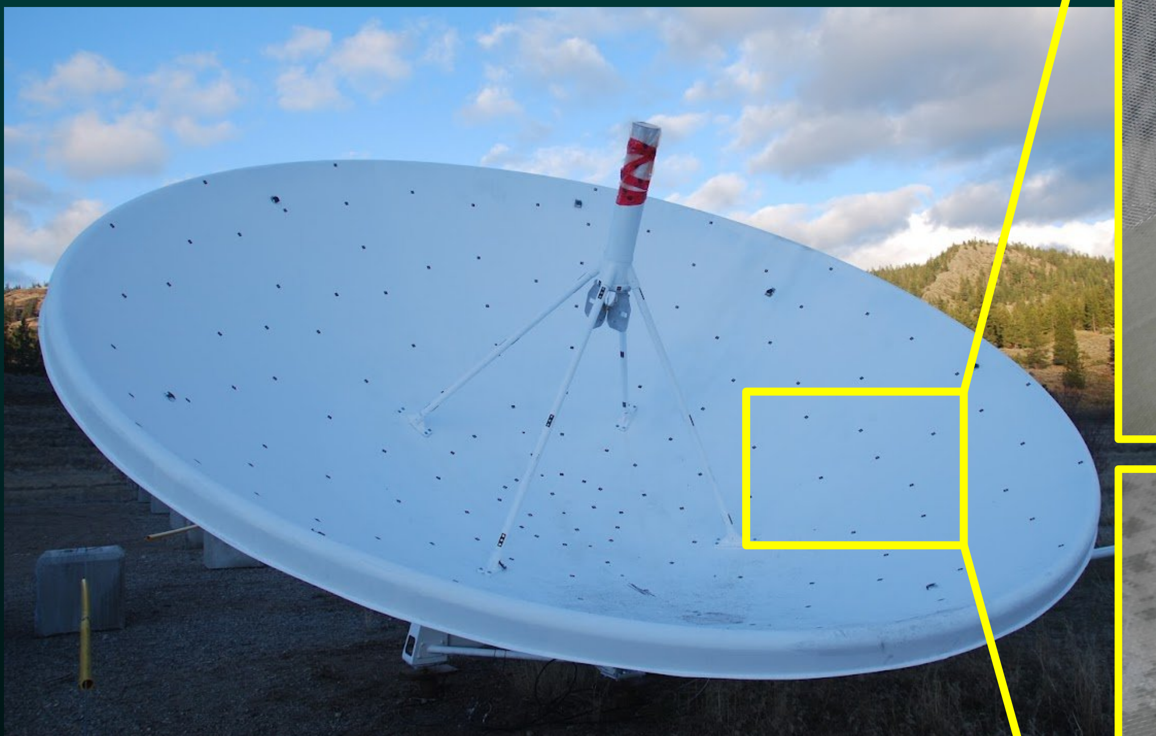


- We see some systematics from discretization, but they're mostly subdominant
- Some of the structure comes from defocusing
- Next steps: pushing simulated beams through cosmological simulations

Analysis: A. Karigiri, K. Gerodias

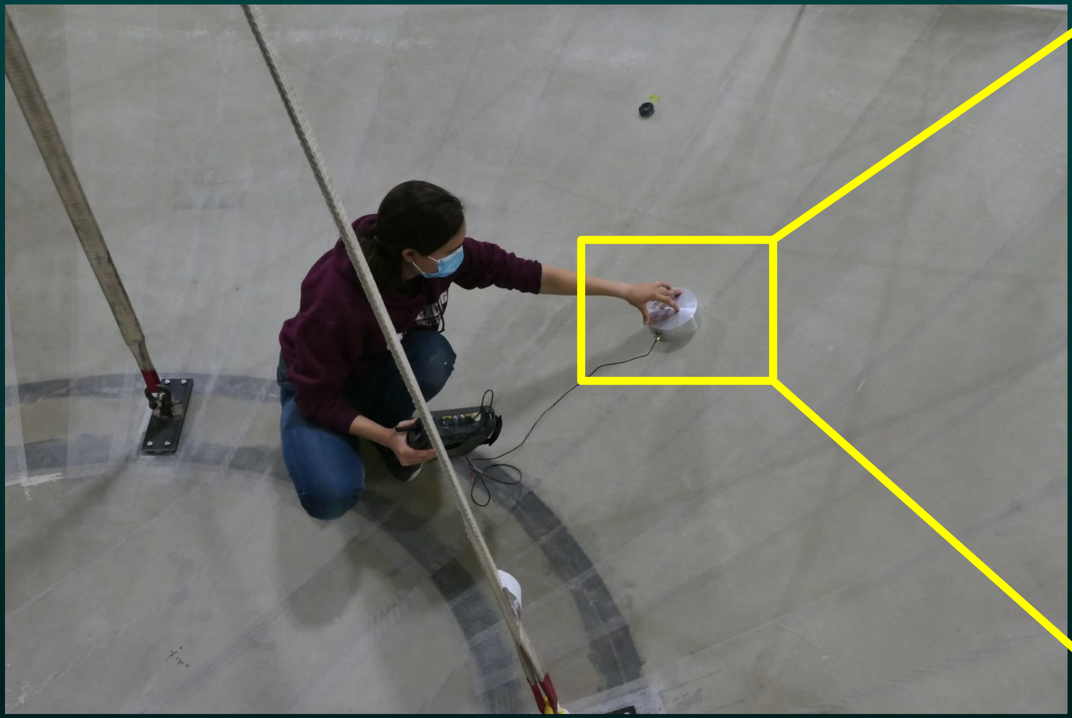
Instrument characterization and verification

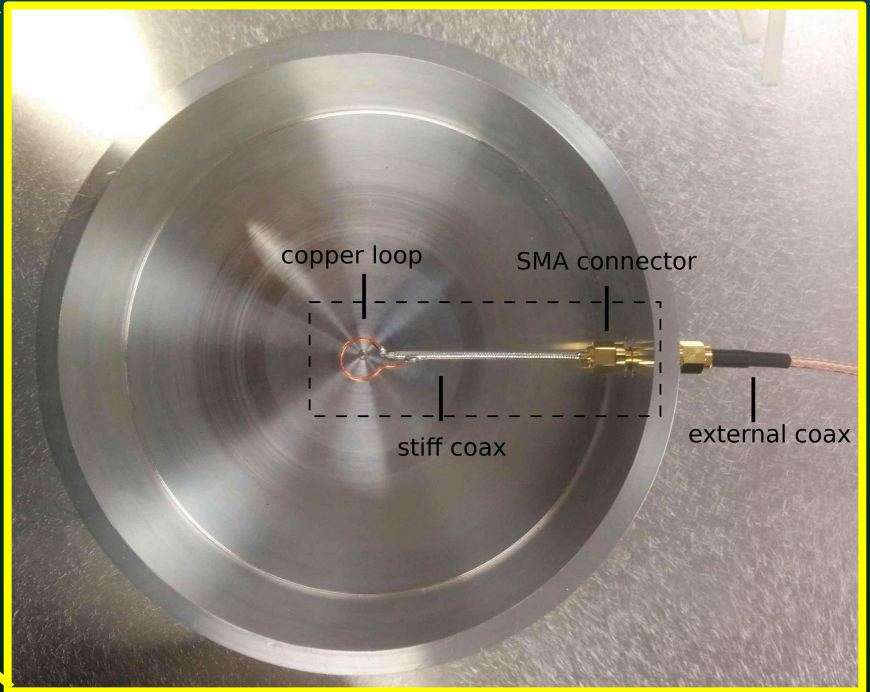
RF surface measurements

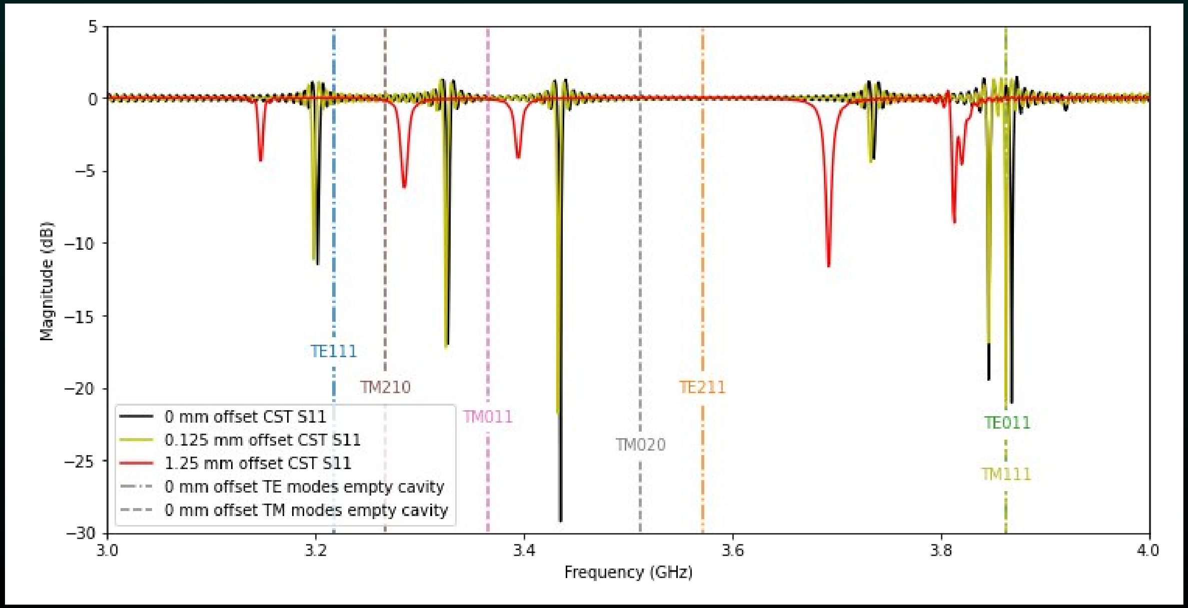


Reflective surface lies underneath and differs from optical surface measurements

Instrument characterization and verification
RF surface measurements







Reflectometer: open cylinder plus test surface forms a resonant cavity

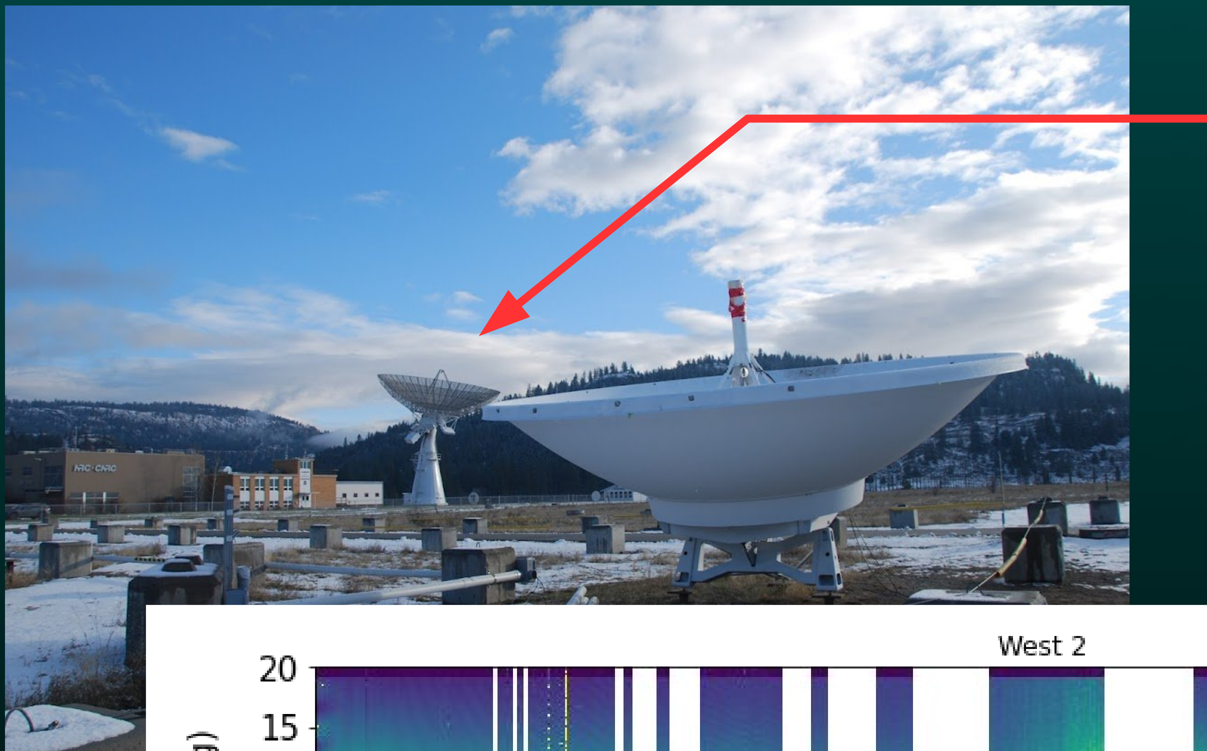
Use TE011 mode

~0.1mm depth precision
Qualitative sensitivity to resistivity

Analysis: E. Pieters, A. Di Nitto, L. Gonzalez Escudero

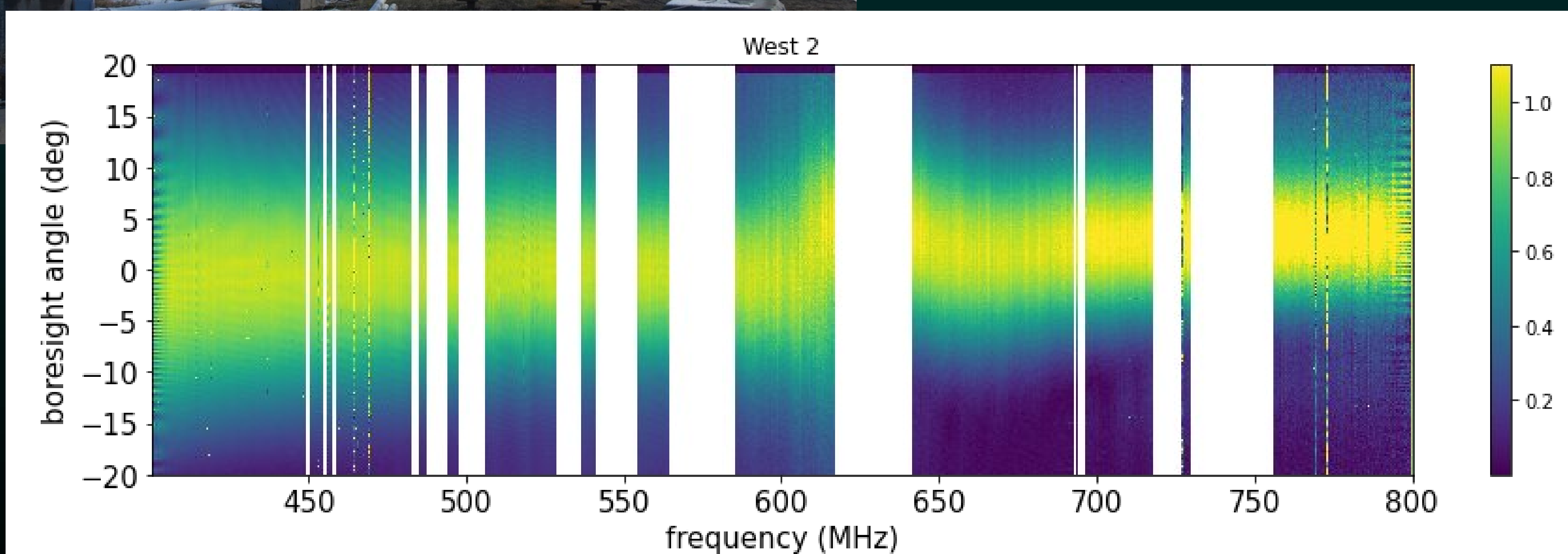
Instrument characterization and verification

Beam holography



DRAO Galt telescope:
our 26-m diameter friend

Track transiting sources and xcorr with CHORD to get 1D beam slices



Analysis: D. Wulf, K. Gerodias

Instrument characterization and verification

Drone beam mapping

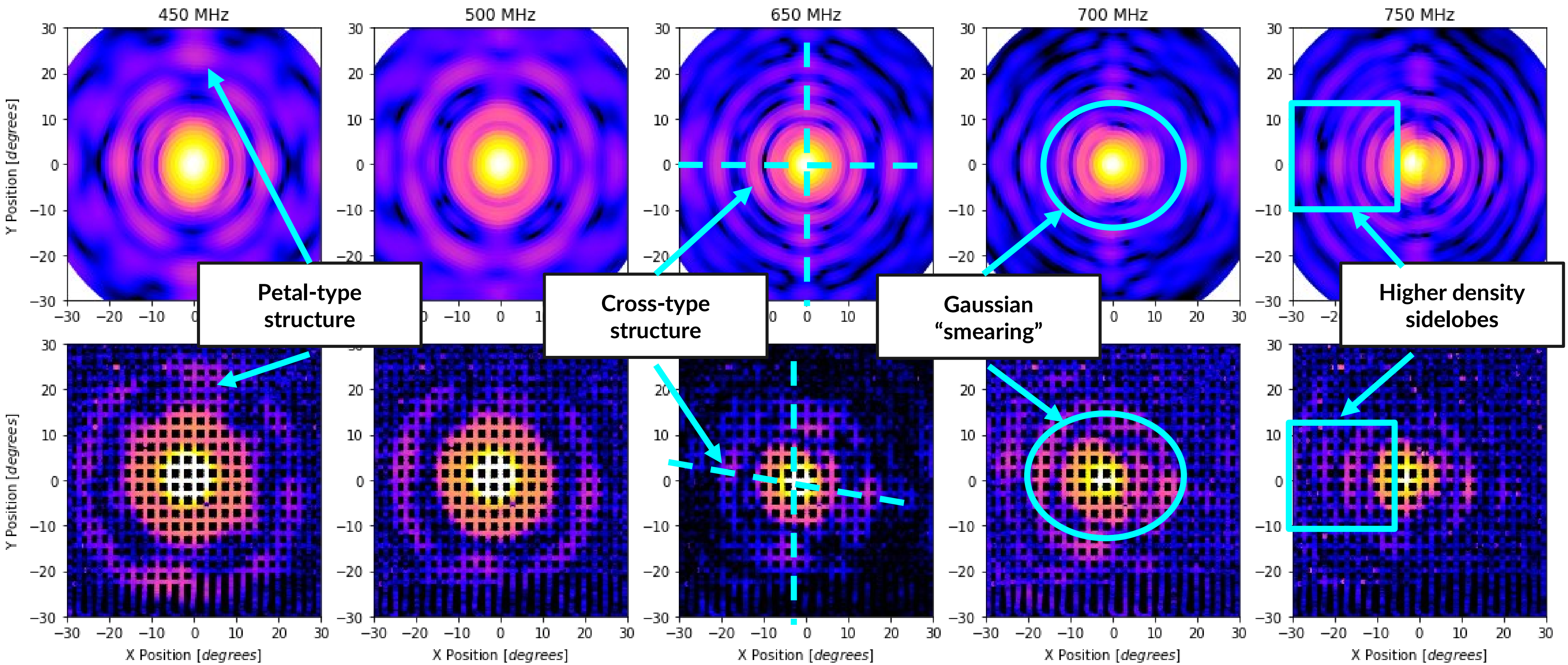
Image: E. Kuhn

If you can't scan your telescope,
then scan your source

K. Gerodias, L. Herman

Instrument characterization and verification

Drone beam mapping



Analysis: E. Kuhn
Simulations: B. Saliwanchik

Instrument characterization and verification

The ultimate smackdown

	Laser tracker	Photogrammetry	Reflectometer	Holography	Drone
Distance from dish	0m*	0m*	0m*	Far field	~100m
Meas. time	~Hrs/dish	<Hr/dish	~Hrs/dish	~Hrs/array	~Hrs/array
Cost	$$$$	$$$	$	$$ / $$$$$$	$$
1D or 2D	2D	2D	2D	1D (-ish)	2D
Density of points	High	Medium	Low	High (1D)	High
Measurement systematics					

** Need to combine with EM sims*

(This table is of course incomplete, and the fun is just starting...)