# Instrumentation for Future radio intensity mapping surveys

Session #71

# Introduction

Organizers:

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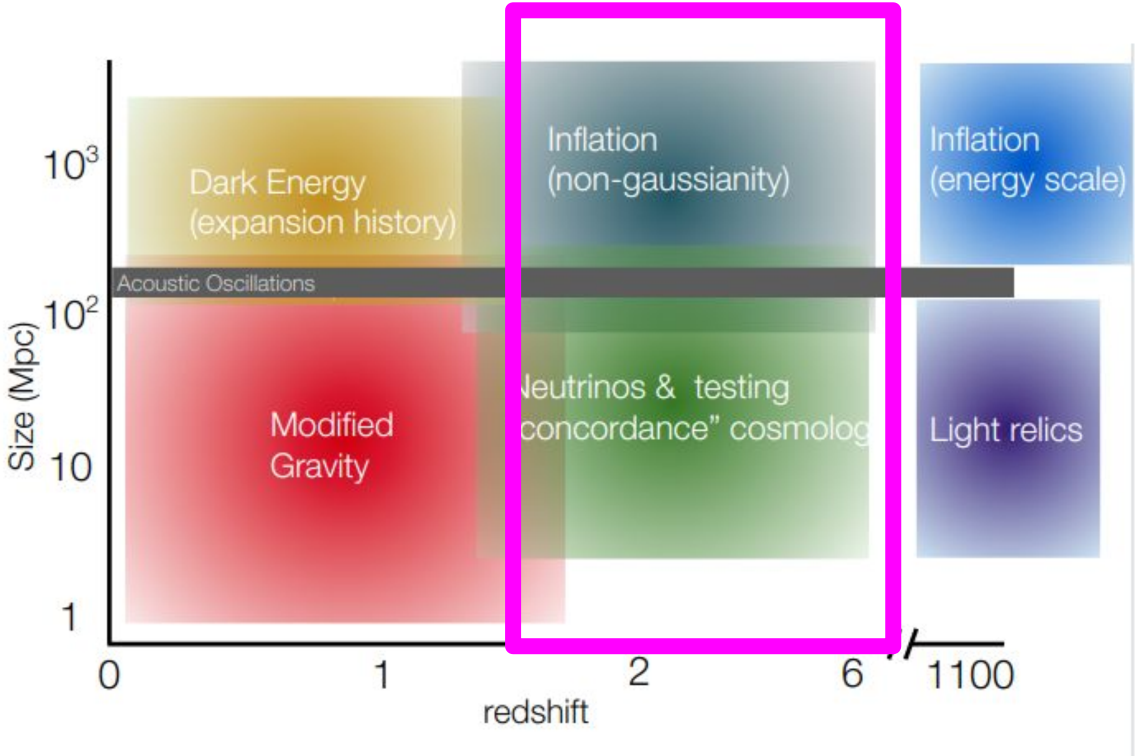
- John Parsons (Columbia University)
- Anže Slosar (BNL)

Goal:

- Give Instrumentation Frontier a taste for problems in 21cm intensity mapping

# Key cosmological science drivers as a function of redshift and the scale of clustering



# CF5 / IF7 overlap LOIs

General science cases referencing LIM/21cm IM

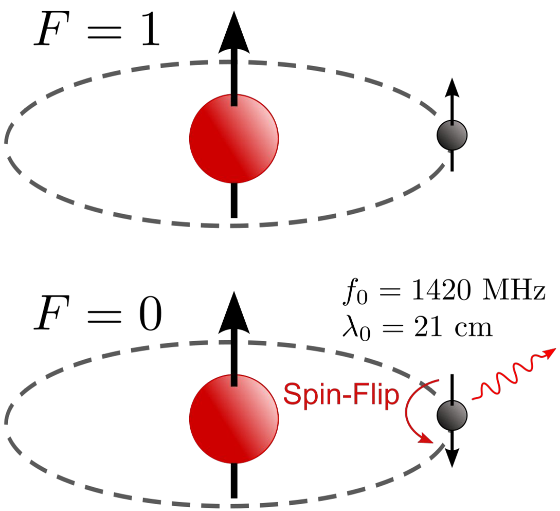
- 223 Probing Physics at the Highest Energy Scales with Primordial Features
- 64 Cosmological Collider: Precision calculation and probes of new physics

Instruments, sorted by wavelength 5m to <1 mm

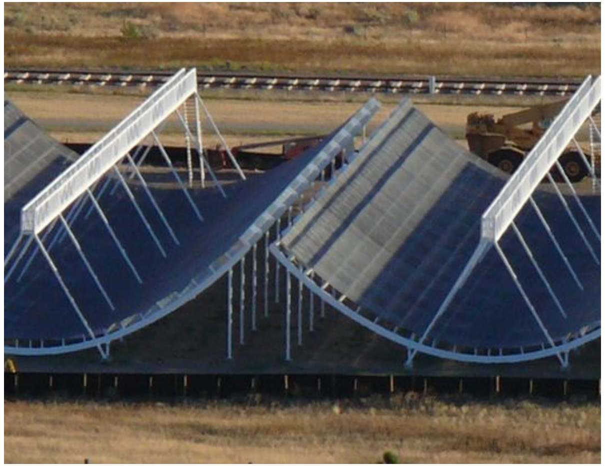
- 211 Cosmic dawn: A probe of dark matter at small scales
- 212 A 21-cm based standard ruler at z ~ 20
- 27 Packed Ultra-wideband Mapping Array (PUMA): Science Opportunities
- 242 Cosmology with Millimeter-Wave Line Intensity Mapping

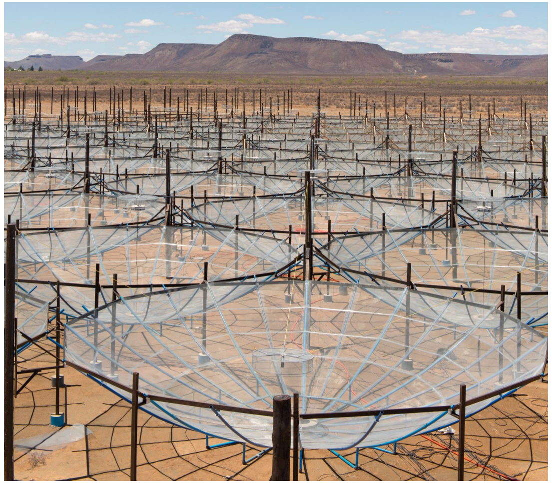
# 21cm emission

- Hyperfine transition in neutral hydrogen at $\nu$=1420MHz, λ=21.1cm;
- This is the **only** transition around -- if you see a line at 710MHz, it is a z=1 galaxy;
- (not true in optical)
- Universe is mostly hydrogen (75%), but at low redshift we are sensitive to pockets of neutral hydrogen in galaxies;
- **21cm surveys are galaxy surveys in radio frequencies**



We build **massive interferometric radio arrays**
Interferometers are combination **software/hardware telescopes that need to be thought of as an integrated system**



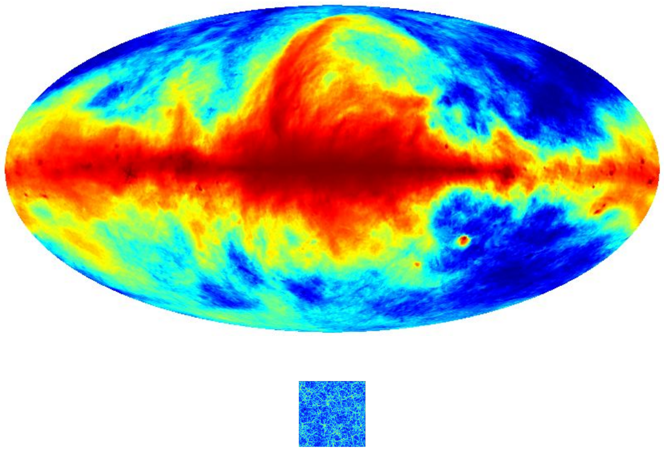


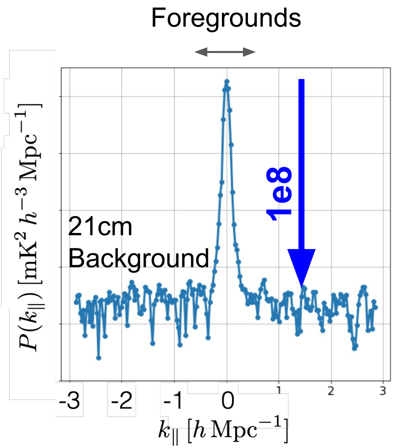
**CHIME (taking data): 1024 dual-pol feeds, 400-800MHz, (0.8<z<2.6)**

**HERA (taking data with ~100 dishes now): 350 dual-pol dishes, 80-200MHz (6<z<17)**

**PUMA (proposed): 5000-32000 dual-pol dishes, 200-1100 MHz (0.3<z<6)**

Conventional techniques do not deliver the exquisite levels of systematics control (through the entire hardware/software pipeline) needed to overcome the high dynamic range necessary for precision constraints





# Highest priority Technology Challenges: **21-cm intensity mapping**

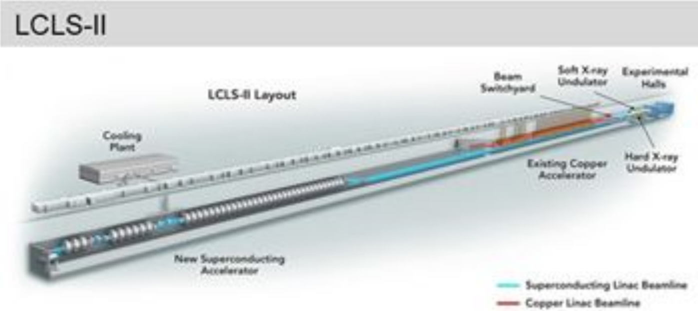
- Direct, sub-ps synchronized digitization at each of the ~1000 dishes separated by up to a km
- EM simulation and measurement to 1:1e5 and 2x fractional bandwidth
- New network technologies that can process tens of petabytes of raw data per second with modest power consumption, and lower development cost
  - ***Synergistic with streaming DAQ development for collider applications***
- Real-time calibration per dish: embedded noise calibrators, real-time correction
- Folding precise monitoring and systematics characterization through the analysis pipeline

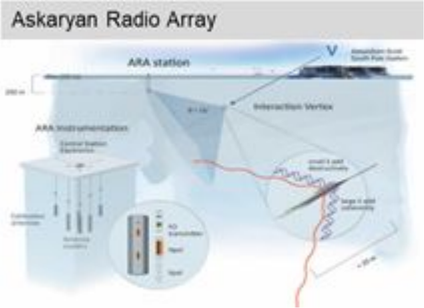
# Technical Challenge: integrated front-end

- Front-end amplifiers, digitizer, channelizer
- Current set-ups use individual components
- We want an integrated solution:
  - In: radio wave in air
  - Out: digital signal out on optical cable (waveform or channelized)
  - low power, low cost, must also be able to sing a song
- Solutions should be available with recent RFSoC advances
- Must integrate:
  - Broadband feed and OMT
  - Low-noise amplifiers
  - Multi-Gsample/s digitizer (with clock synchronization decoder)
  - (perhaps polyphase filterbank channelizer)
  - Formatting onto ethernet frames
  - Careful RFI mitigation

# Technical Challenge: clock distribution

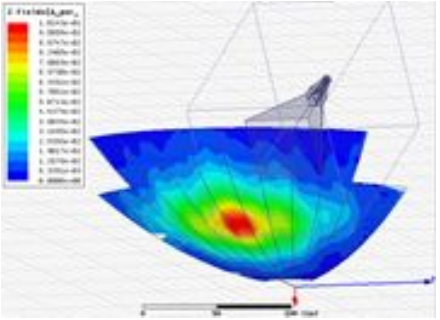
- Clock distribution across km with pico-second synchronization
- Synergies with other IF problems, BRN “breaking the pico-second barrier”
- Synergies beyond HEP:
    - LIDAR
    - Advanced light sources
    - Quantum key distribution




# Technical Challenge: Dish + feed construction / evaluation

- Dishes need to be cheap but very well understood. (Sometimes precision more important than accuracy)
- In dish arrays experience has shown significant amount of dish-dish coupling
- Due to high-dynamic range, the dish surface needs to be better than for usual applications, but how much better still unclear
- With thousands of dishes, a per-element cost must be in $1k range.
- Need for a comprehensive program of:
  - Dish construction techniques
  - EM modelling (including simulations of dishes embedded within a large array)
  - Quality assurance and repeatability monitoring



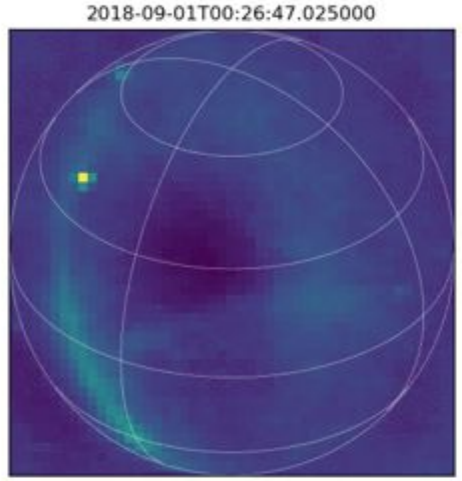
# Technical Challenge: in-situ primary beam calibration

- Various schemes with UAV with emitters have been tried:
  - Typical quadcopters, but also fixed-wing
  - Pulsar gating with large dish also a possibility
- No one has managed to make these systems operate at desired accuracy
- Known issues:
  - Positioning with differential GPS
  - Calibration signal drifts, emitting antenna position
  - Data reduction with fast-changing signals
- All surmountable and interesting technical problems

External and internal calibration sources are both necessary to measure electromagnetic response to 1e5. Pictured here is the ECHO drone mapping Long Wavelength Array in NM.

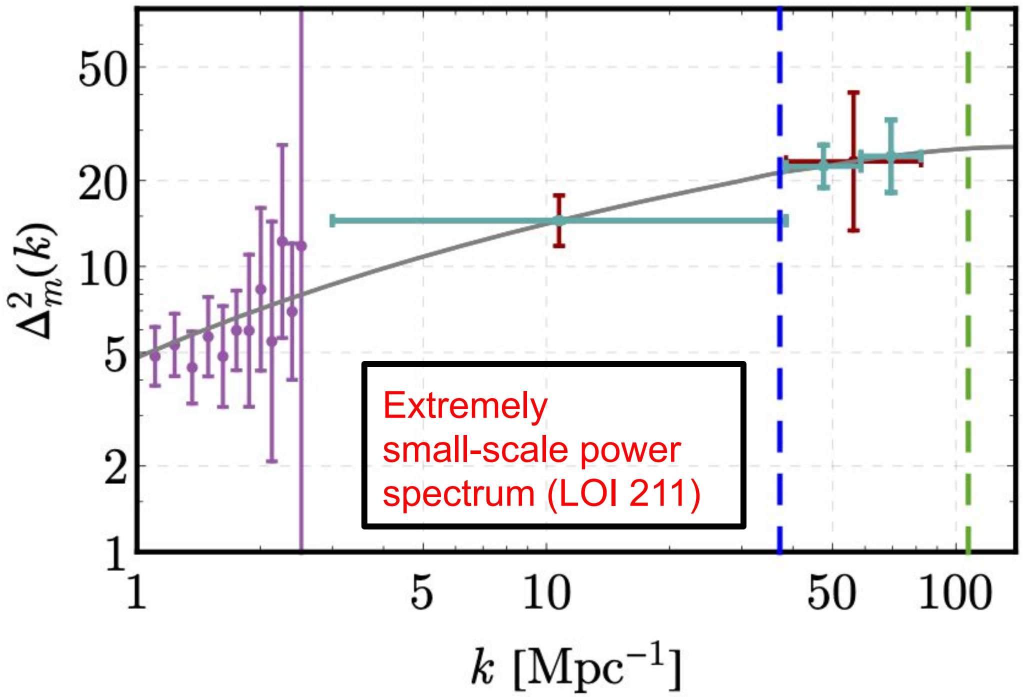
# Technical Challenge: Real-Time signal processing

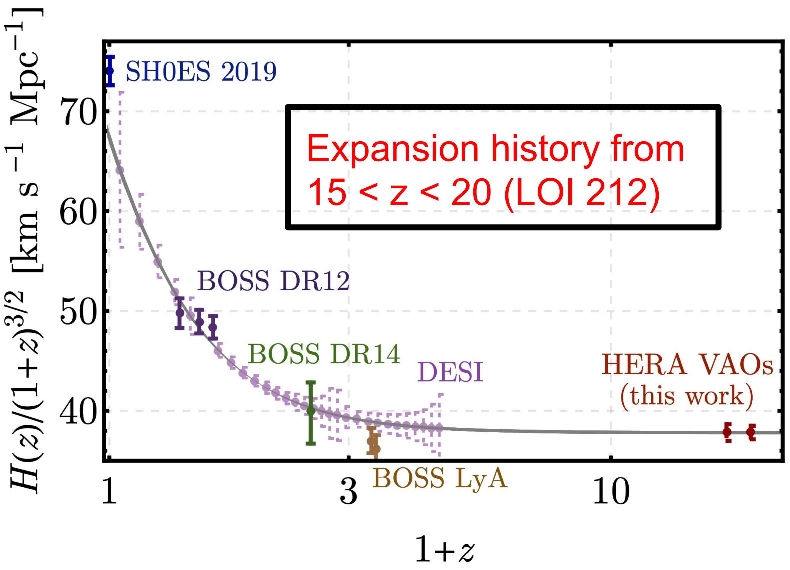
- The primary throughput of these systems is truly enormous:
  - 2Gs/s x 5000 antennas at 8 bit sampling = 10 TB/s
  - This is controlled by a massive real-time data reduction (correlator and post processor)
- Real time data compression requires:
  - real-time calibration: all the complex gains must be correct
  - exquisite system phase stability
  - computational power to perform calibration
- Design and operation of such self-calibrating FFT correlator is part of active research

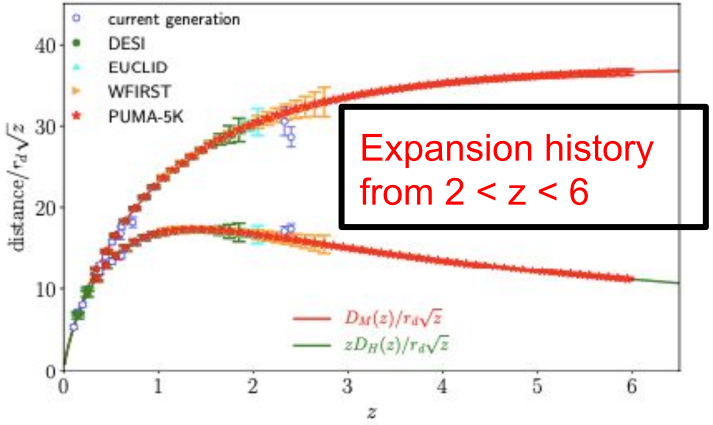


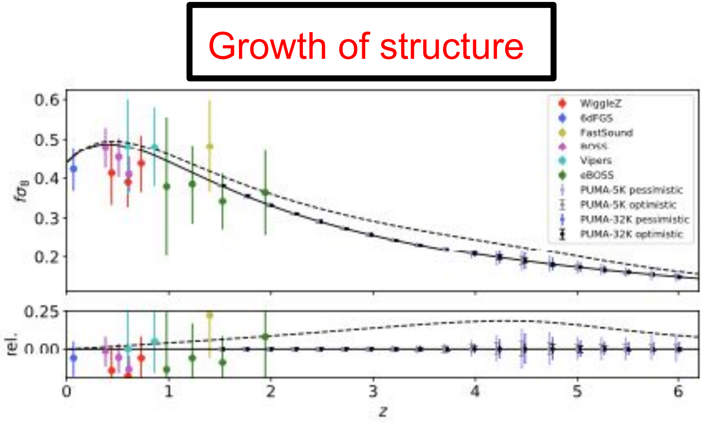

Example of output from the EPIC FFT imager on the LWA.
This is an all sky image of a single voltage sample from 256 antennas, computed in real time.

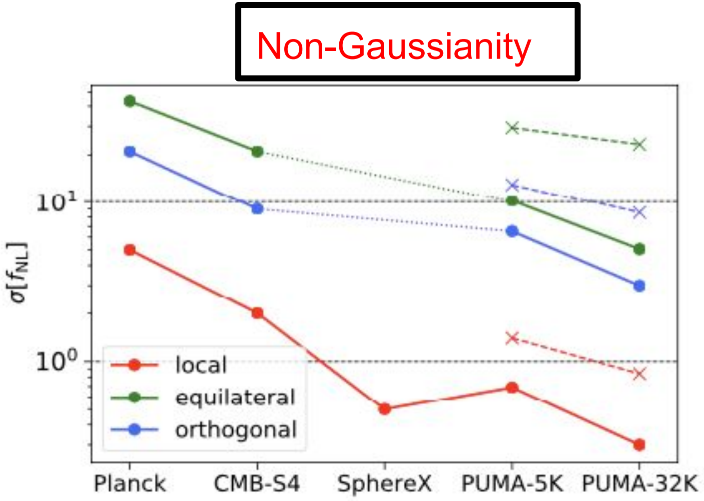
# Everything is challenging, but this is an opportunity to achieve compelling science and push radio instrumentation to new frontiers

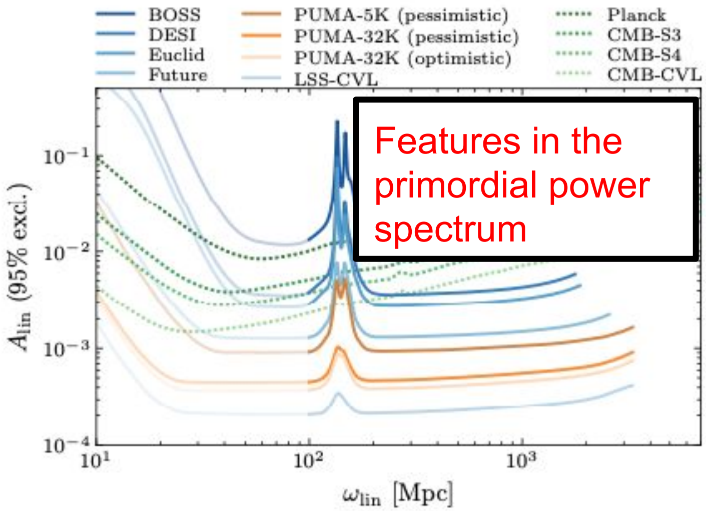



Expansion history from 2 < z < 6
current generation
DESI
EUCLID
WFIRST
PUMA-5K
$D_M(z)/r_d\sqrt{z}$
$zD_H(z)/r_d\sqrt{z}$
distance/$r_d\sqrt{z}$
$z$

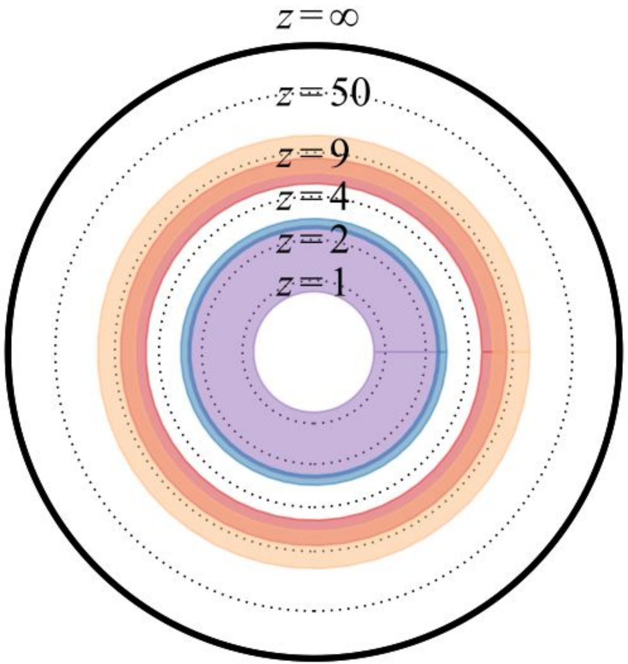

Growth of structure
WiggleZ
6dFGS
FastSound
Vipers
eBOSS
PUMA-5K pessimistic
PUMA-5K optimistic
PUMA-32K pessimistic
PUMA-32K optimistic
$f\sigma_8$
rel.
$z$


Non-Gaussianity
local
equilateral
orthogonal
$\sigma[f_{NL}]$
Planck
CMB-S4
SphereX
PUMA-5K
PUMA-32K


Features in the primordial power spectrum
BOSS
DESI
Euclid
Future
PUMA-5K (pessimistic)
PUMA-32K (pessimistic)
PUMA-32K (optimistic)
LSS-CVL
Planck
CMB-S3
CMB-S4
CMB-CVL
$A_{\rm lin}$ (95% excl.)
$\omega_{\rm lin}$ [Mpc]

LOI 27

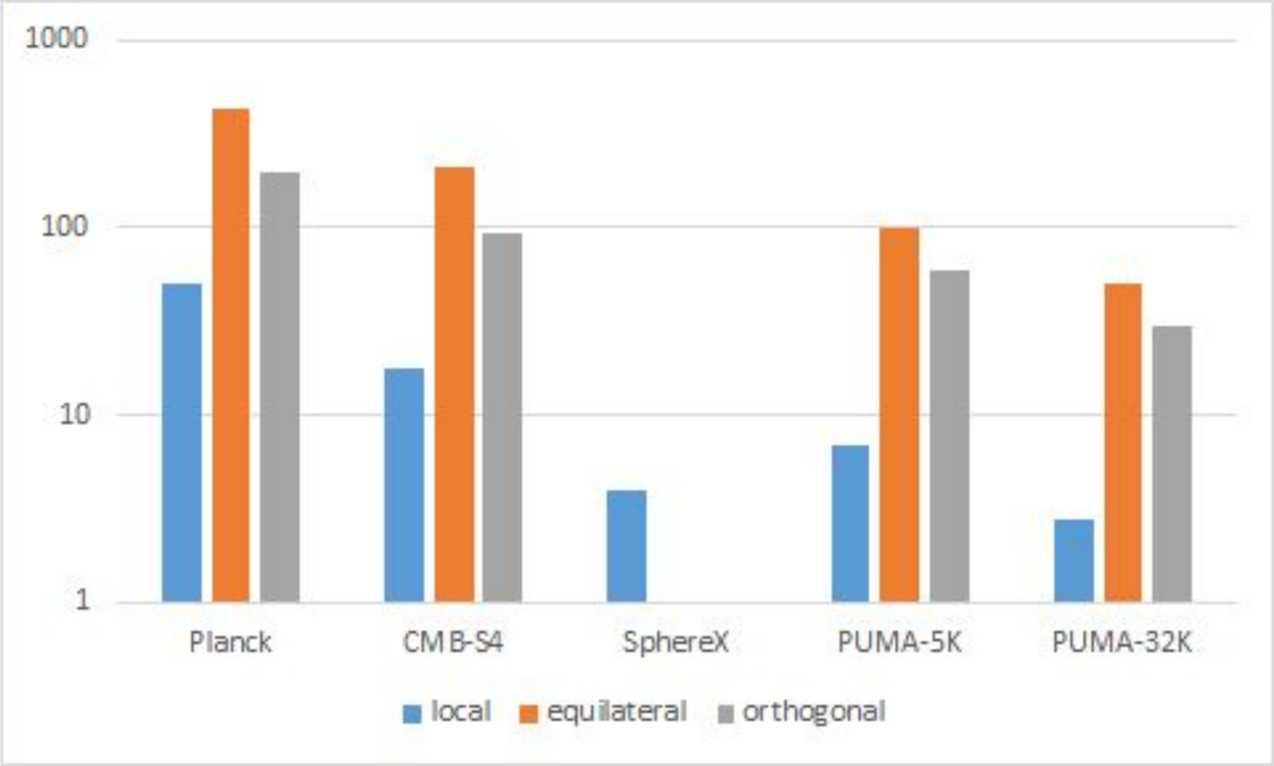
# This is one of many crucial probes in the spirit of "cross-correlate everything with everything else"




HI, [CII] (e.g., LOI 242), CO, hydrogen lines, galaxy surveys, CMB...

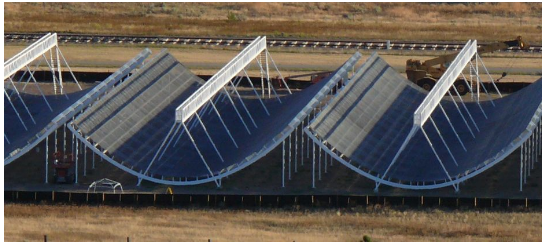
# More modes gets us better constraints on nonGaussianity = better probe of inflation

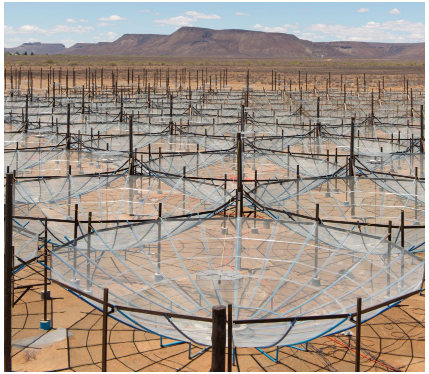
Tighter error bars



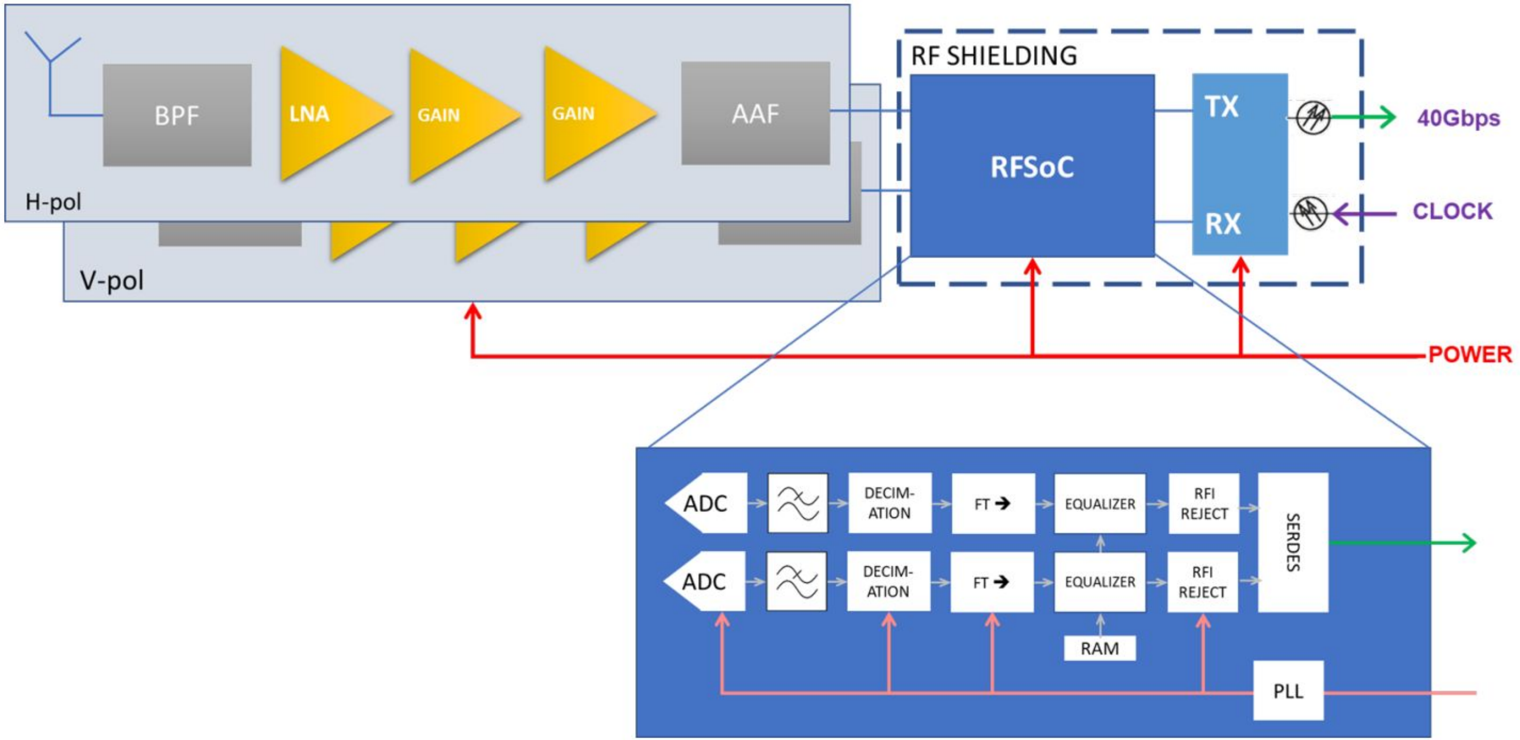
# Summary

- Science from next-generation 21cm interferometers is in-line with DOE CF science goals, and has access to:
    - More modes, and hence better measurements, of inflation in the form of non-Gaussianity
    - New probes like VAOs and Dark Matter in the early Universe
    - Combinations of cosmo probes (optical, other lines, CMB) to map full 3D history of the Universe
- Instrumentation challenges for next-generation 21cm interferometers:
    - Synergistic with other frontiers: ps timing, fast digitization, networking, and signal processing with real-time correction
    - Potential areas of overlap for radio feed/dish development at large scales with high precision and repeatability
    - Related: we need full simulated systematics pipeline to further develop requirements, understand how we know we achieved them, and ideally be used in the science analysis





# BACKUP 1



BPF
LNA
GAIN
GAIN
AAF
H-pol
V-pol
RF SHIELDING
RFSoC
TX
RX
40Gbps
CLOCK
POWER
ADC
DECIM-
ATION
FT →
EQUALIZER
RFI
REJECT
ADC
DECIM-
ATION
FT →
EQUALIZER
RFI
REJECT
SERDES
RAM
PLL