21 cm Intensity Mapping: A New Cosmological Tool?

天籁实验阵列

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LBNL Research Progress Meeting
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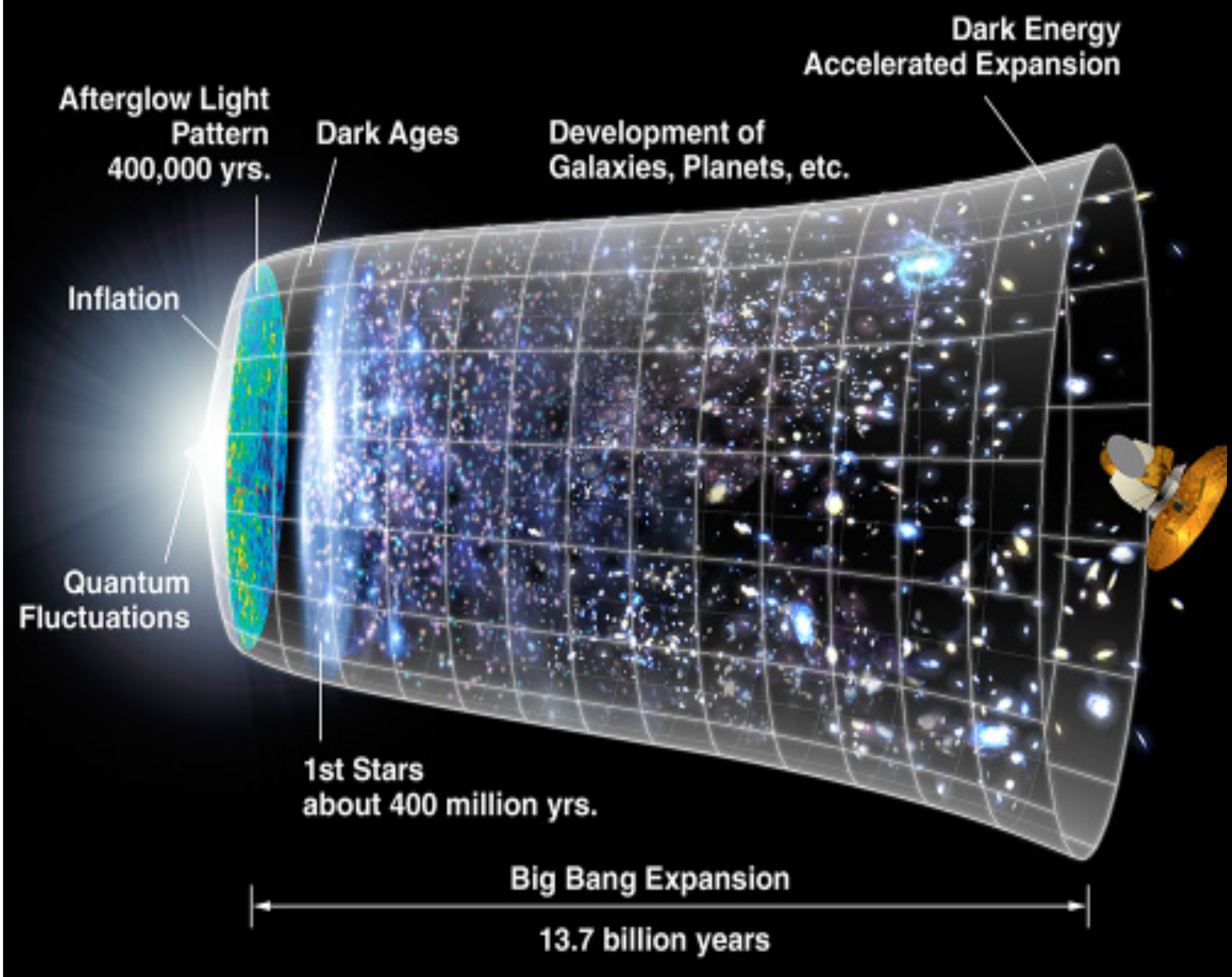
Cosmic Questions



Inflation?

Dark matter?

Dark energy?

Neutrino mass?

Outline

I. **Cosmic Questions**

II. 21 cm astrophysics

III. Current Measurements

IV. Future Opportunities

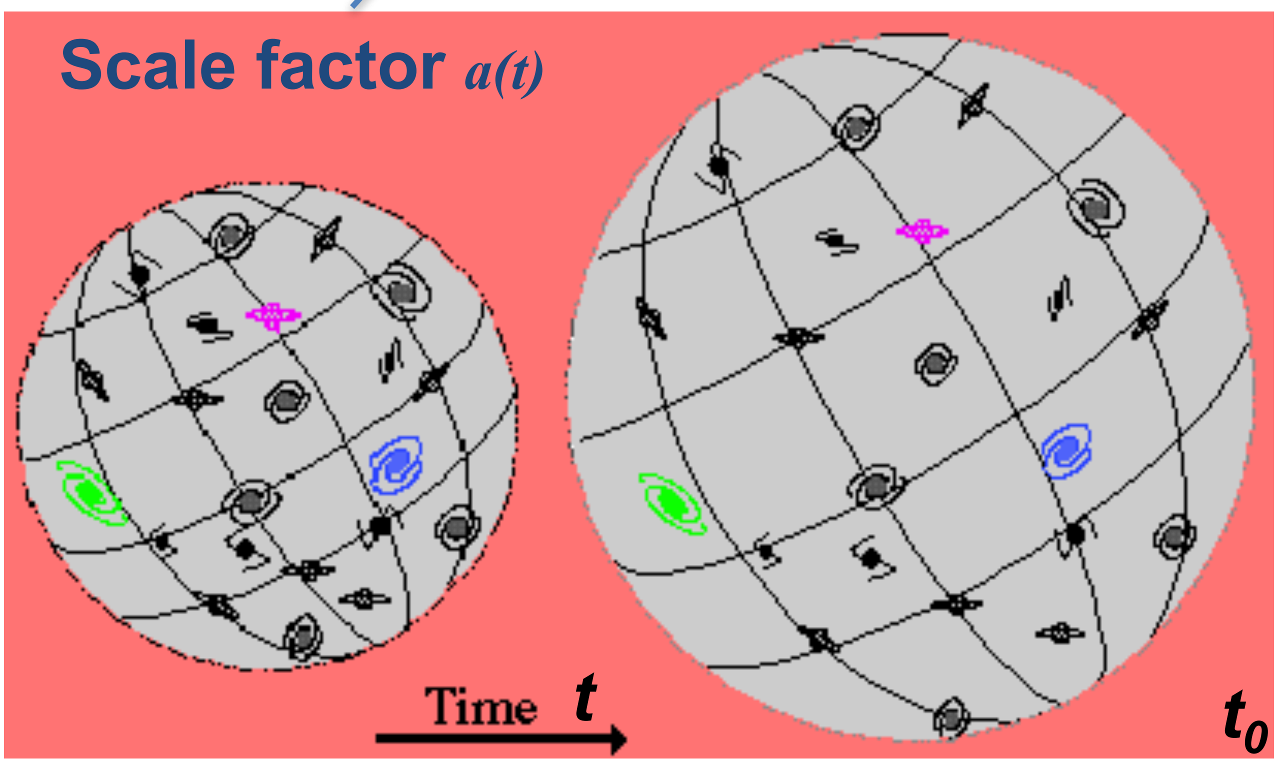
Cosmic Expansion

$$D(t) = a(t)r$$

Comoving distance

$$\frac{1}{1+z} = a(t)$$

Redshift



Hubble parameter

$$H(t) = \frac{\dot{a}}{a}$$

Friedmann Equation & Equation of State

Flat universe case

$$H(a) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\rho_{mat} + \rho_{rad} + \rho_{\Lambda} + \rho_{DE}\right)$$

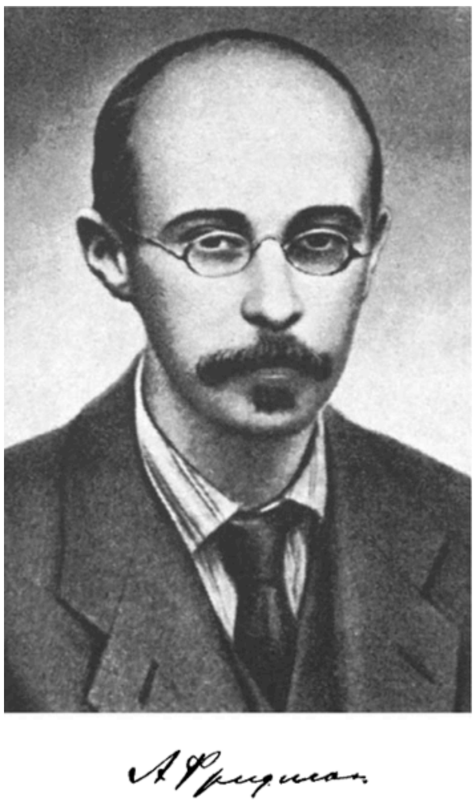
?

$\sim 1/a^3$, $w = 0$

$\sim 1/a^4$, $w = 1/3$

$const$, $w = -1$

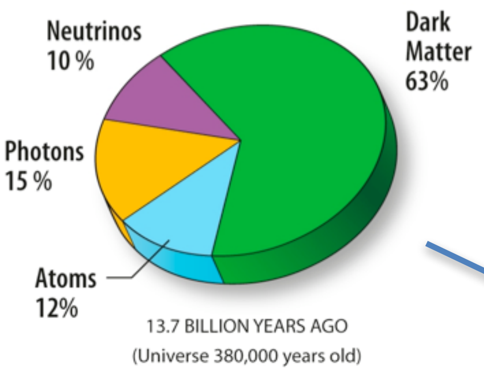
$w(a) = w_0 + (1-a)w_a$

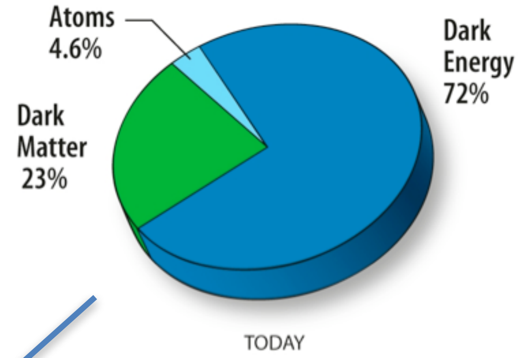


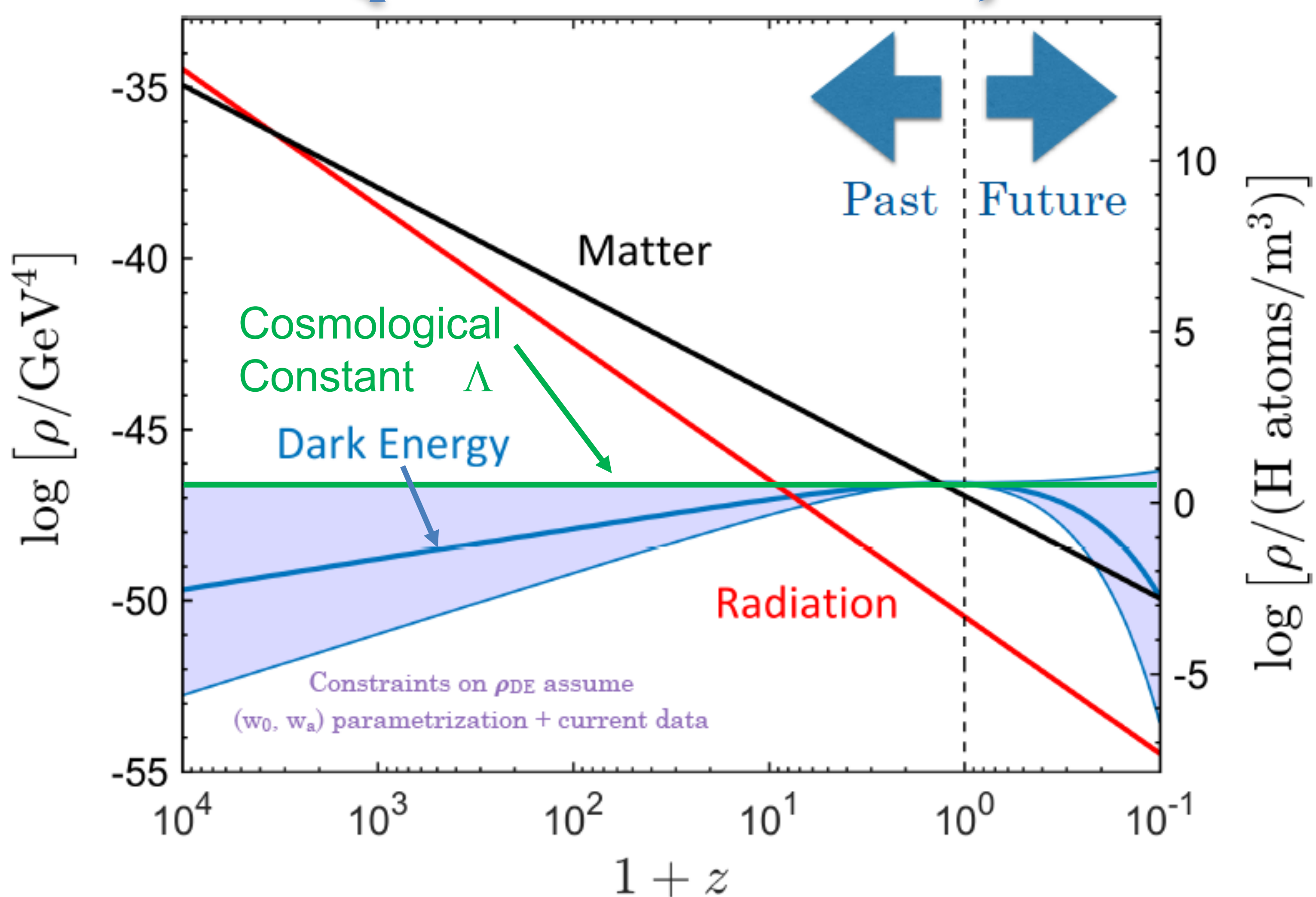
1888-1925

$$\frac{P}{\rho} = w$$

Cosmic Contents

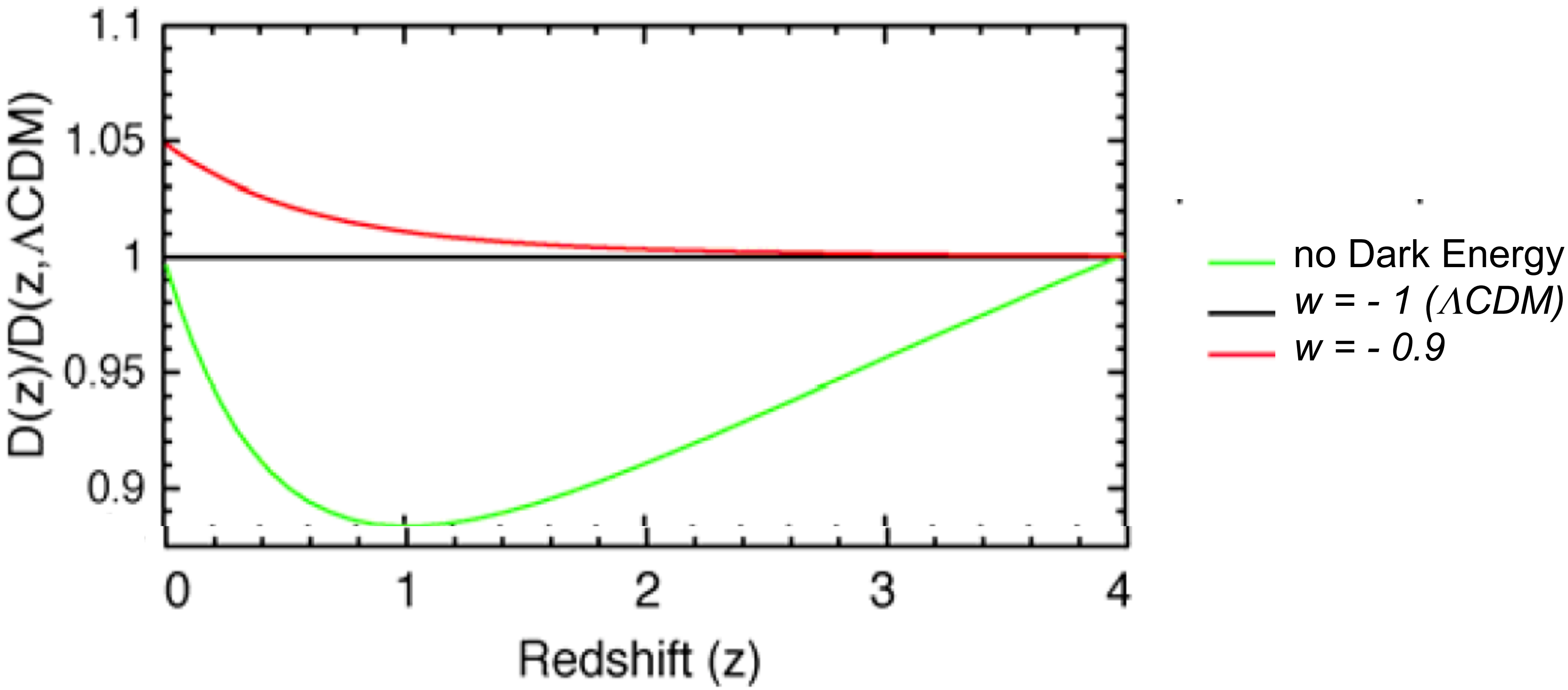






Huterer & Shafer Rep. Prog. Phys. 2018

Distance – Redshift relation depends on Λ or DE



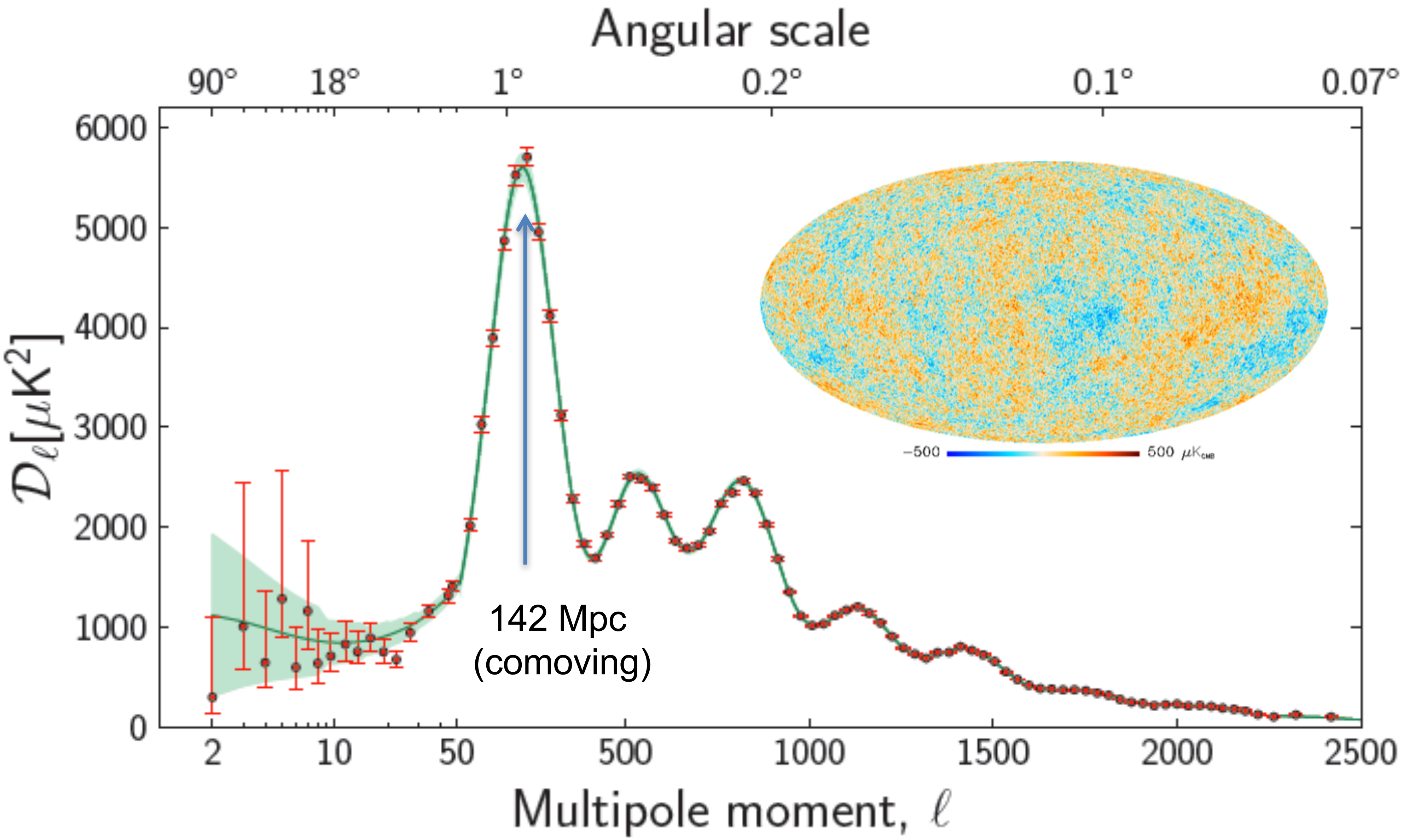
$$P/\rho = w(a) = w_0 + (1-a)w_a$$

Dark Energy Task Force 2006

How to measure effect of dark energy on expansion?

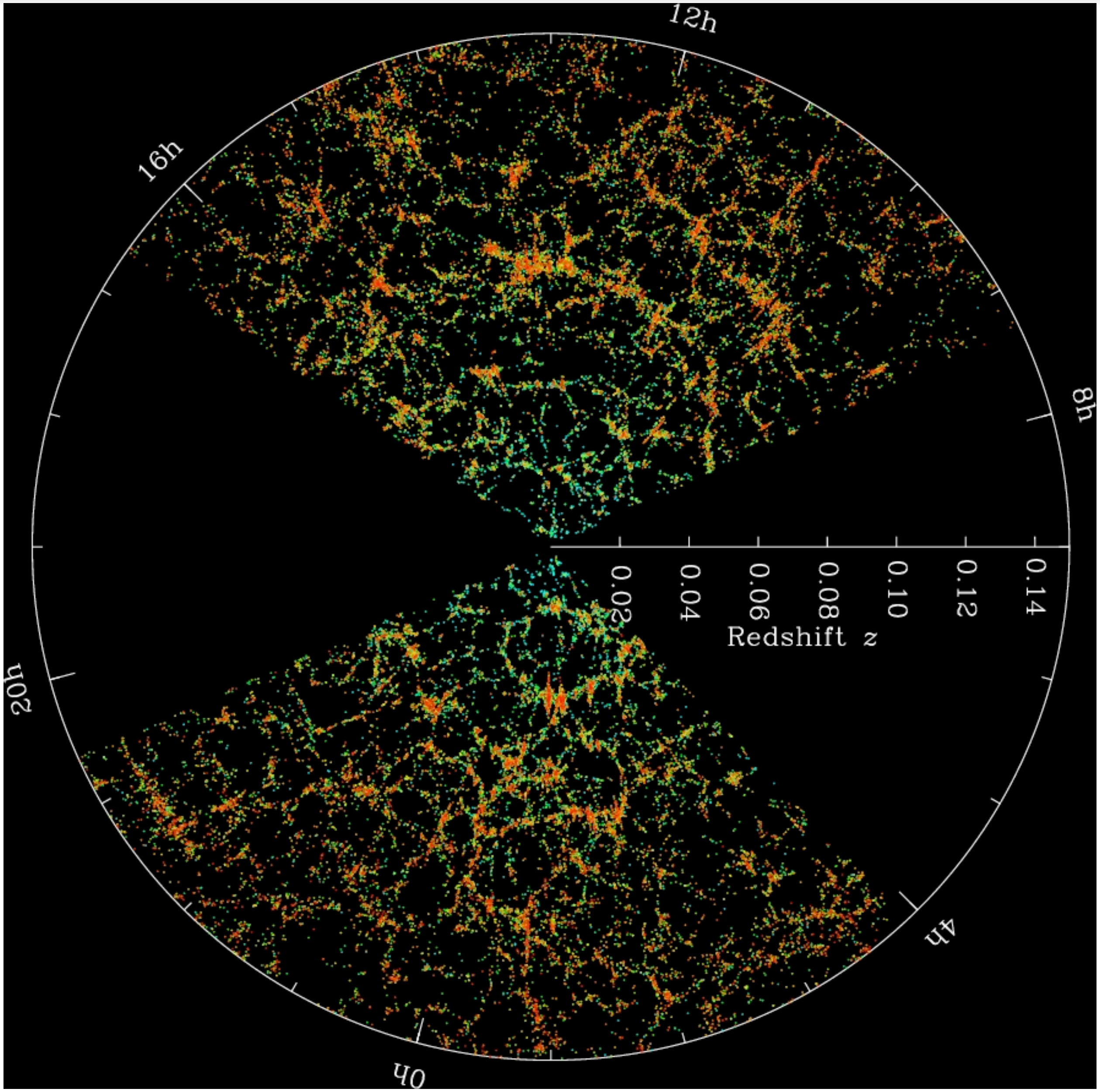
- Measure D vs z with *standard candles* (supernovae)
- Measure D vs z with *standard rulers*
- Measure *growth* of structure vs z
- All of the above!

CMB fluctuations are a standard ruler: Baryon Acoustic Oscillations



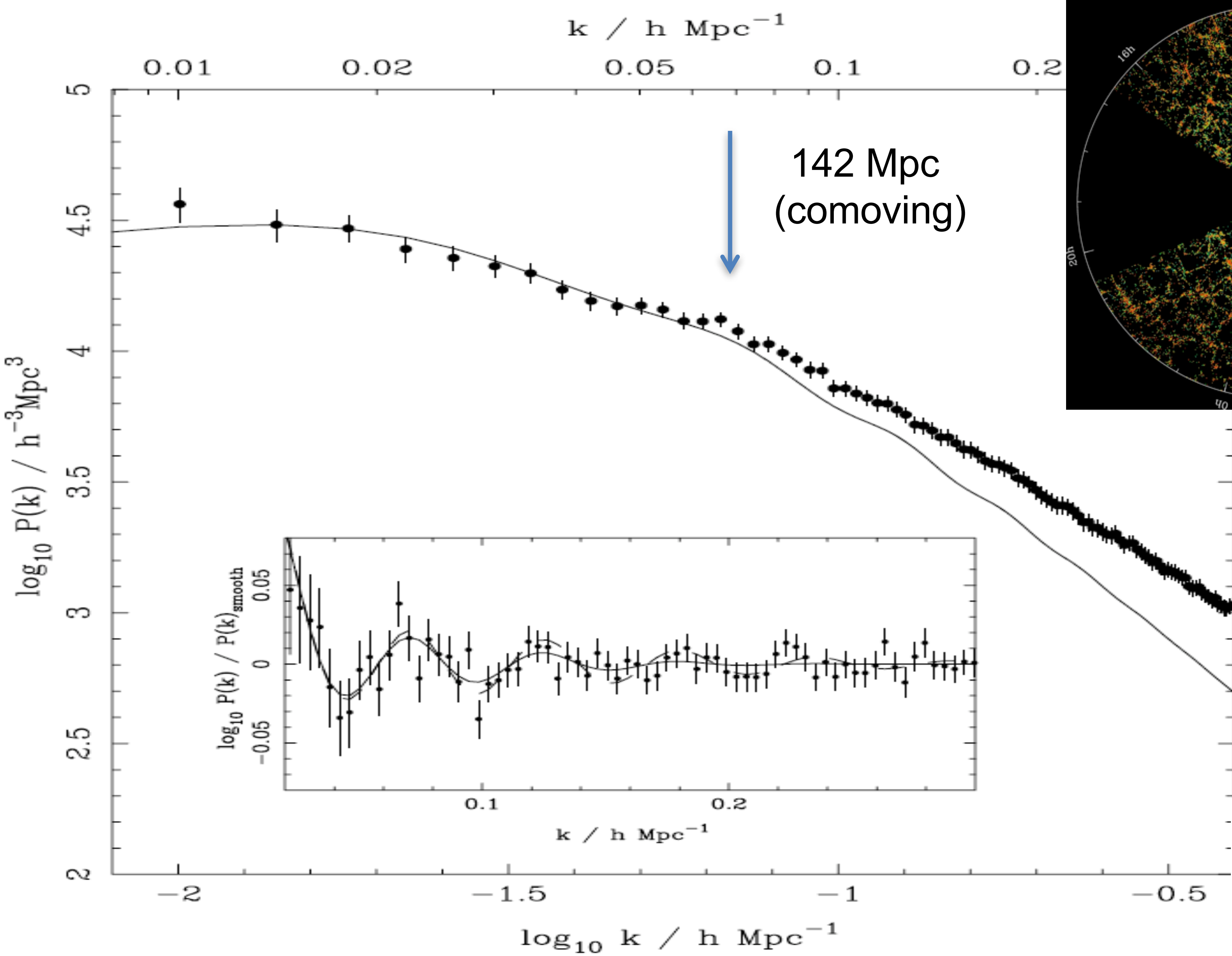
Planck Collaboration

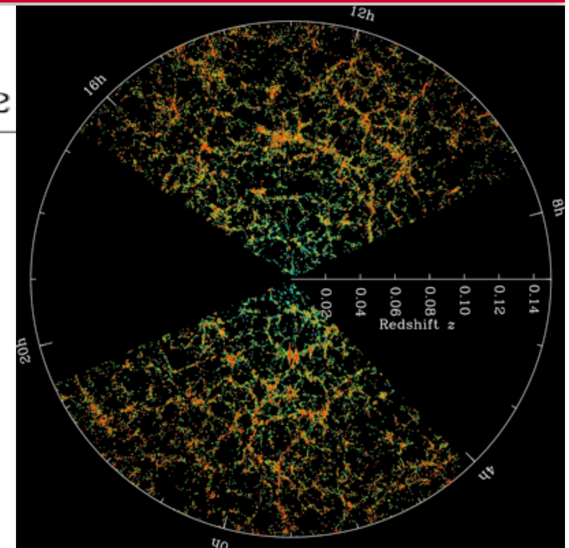
Galaxy surveys show similar structure in 3D



Sloan Digital Sky Survey

Galaxy surveys see similar structures in 3D





Sloan
Digital Sky
Survey

How to observe BAO standard ruler vs redshift?

- Galaxy redshift surveys
  - Sloan Digital Sky Survey (SDSS)
  - Large Synoptic Survey Telescope (LSST)
  - Dark Energy Spectroscopic Instrument (DESI)
  - Euclid
  - Etc.
- 21 cm intensity mapping

Outline

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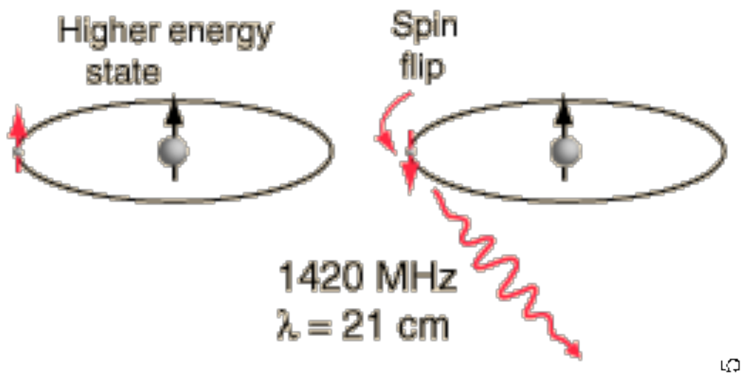
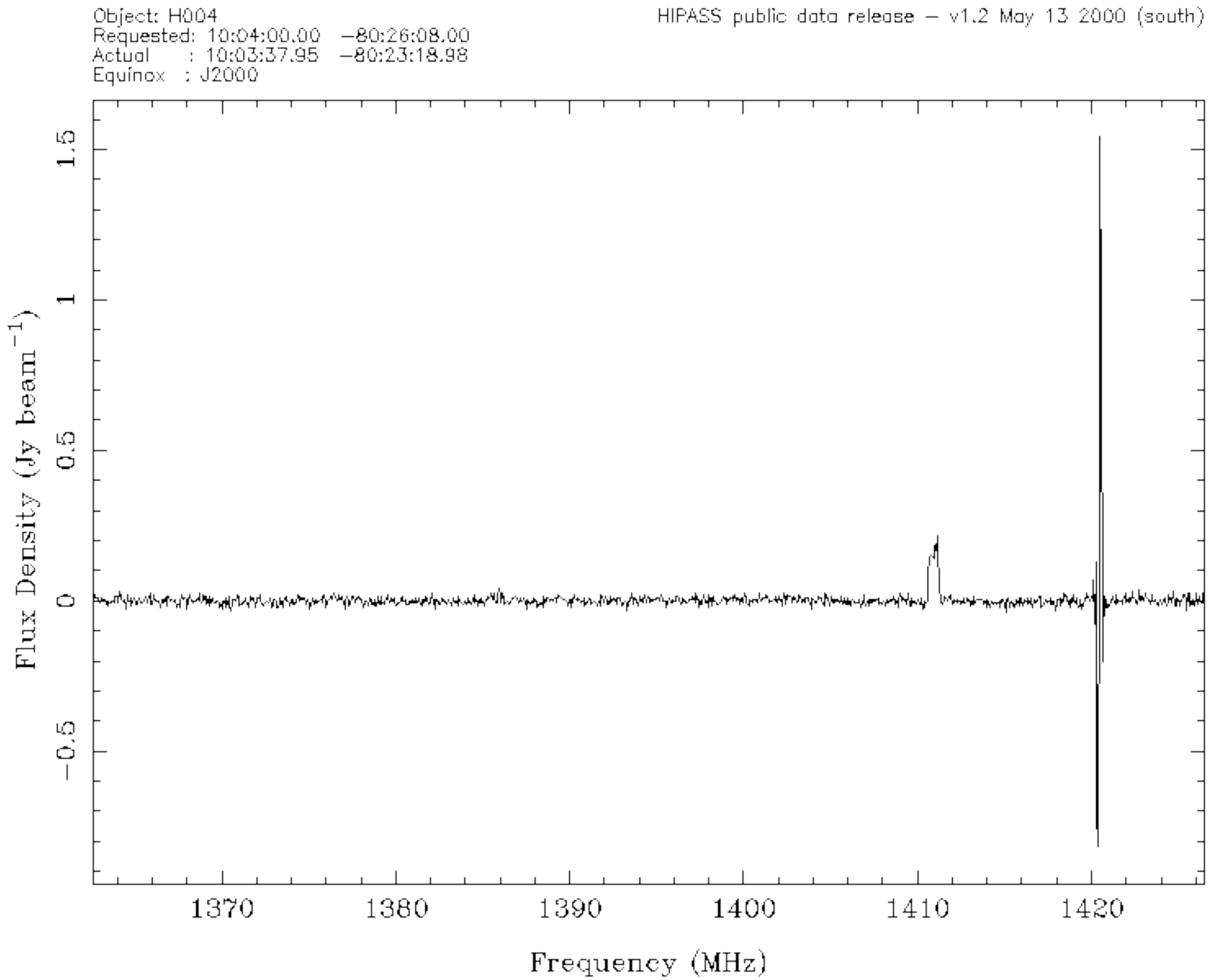
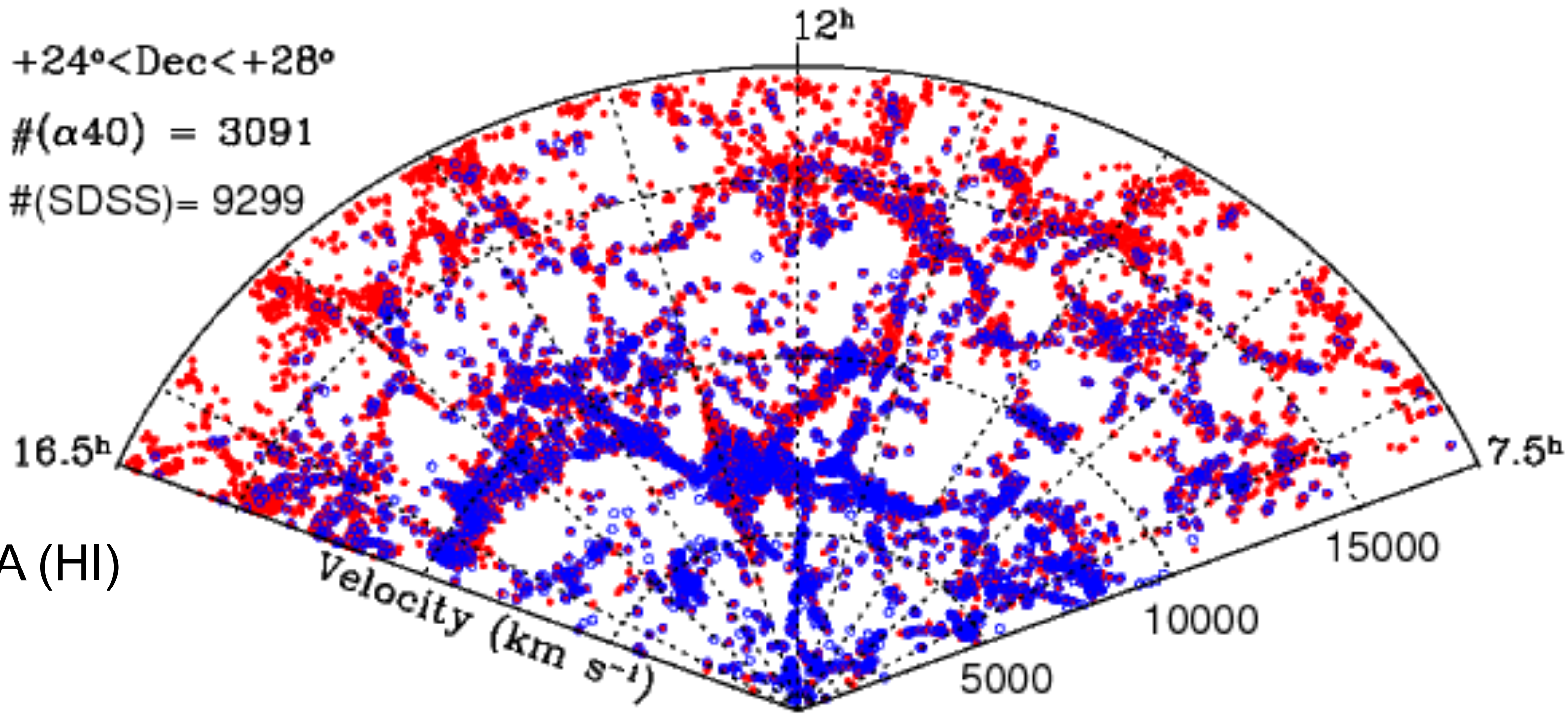
Radio astronomy with the hydrogen 21 cm line (HI)





Parkes Radio Telescope

HI and Optical Surveys Detect Similar Structure to z ~ 0.07

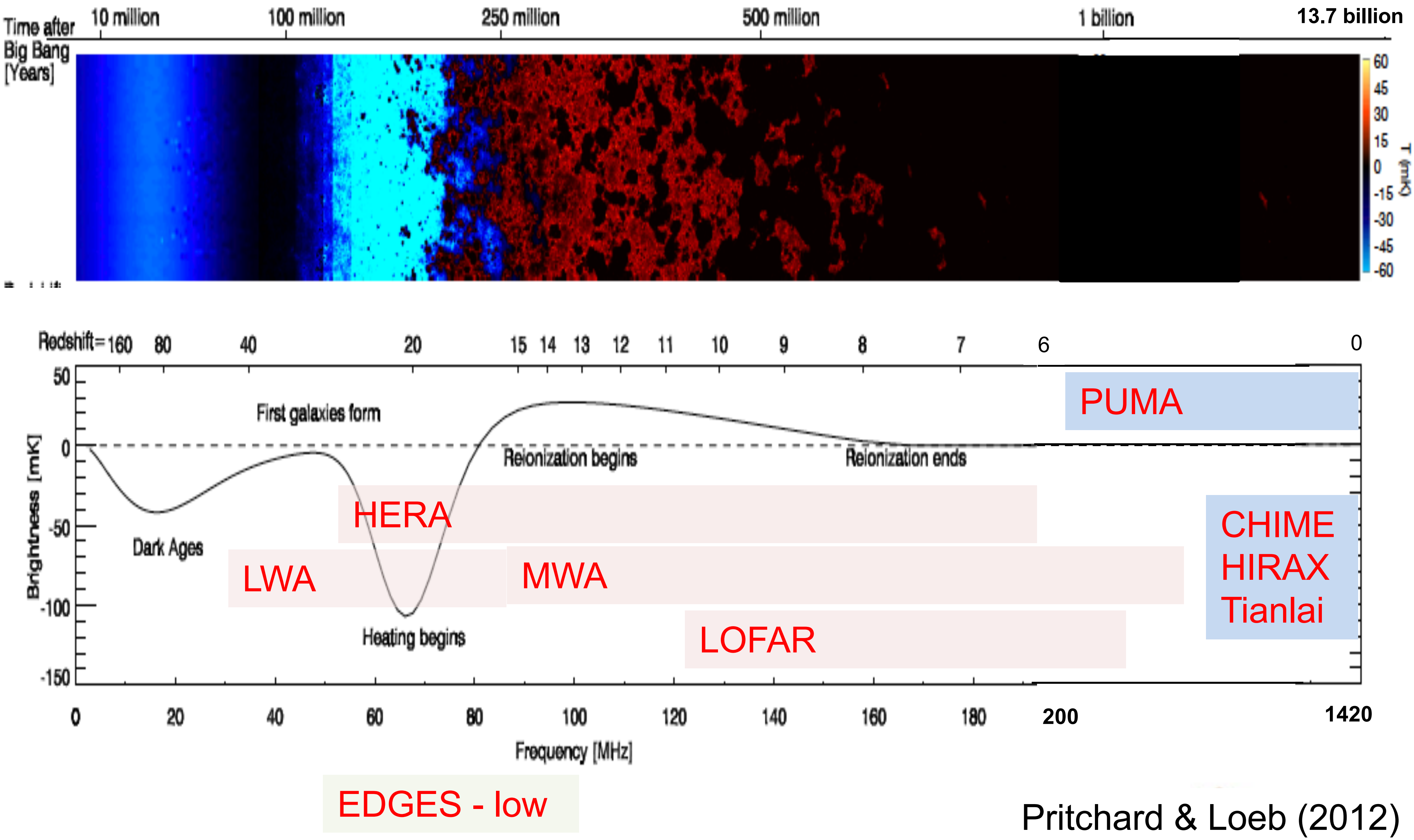


● ALFALFA (HI)

● SDSS

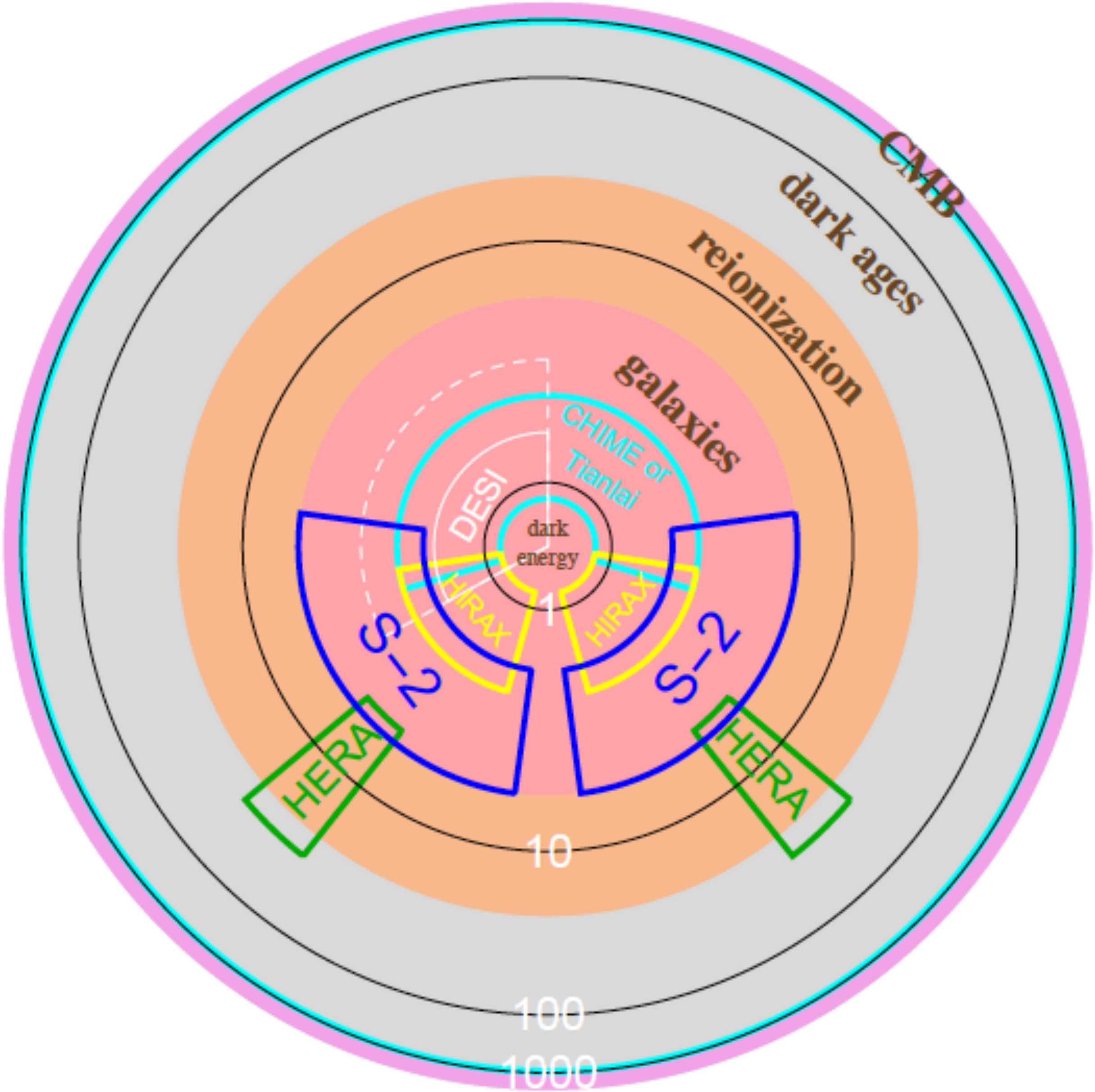
Haynes et al. (2011)

21 cm timeline



Pritchard & Loeb (2012)

21 cm surveys could probe huge cosmic volume



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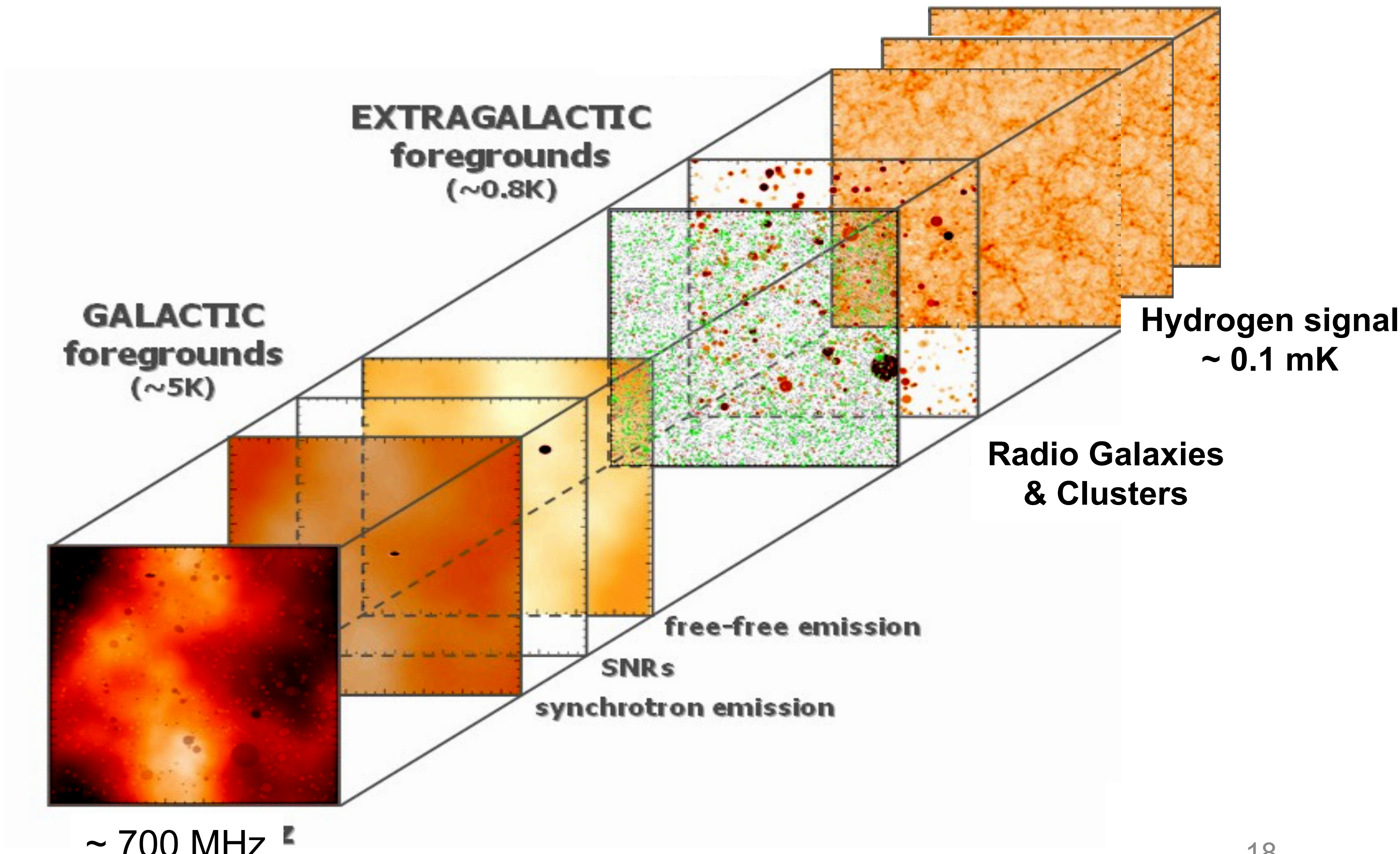
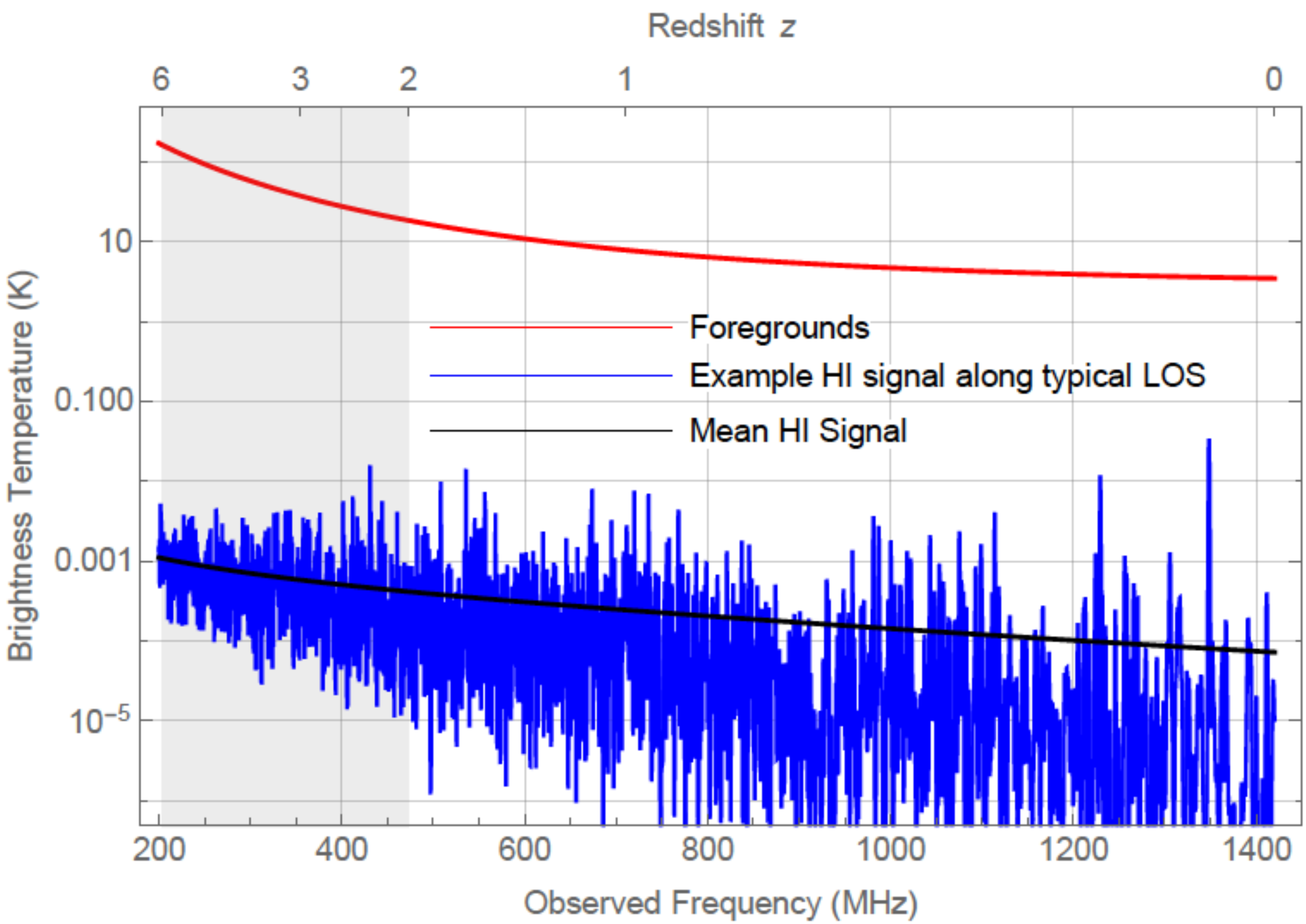
Galactic foregrounds are ~ 10^4 X brighter than HI at z ~ 1!



Cosmic Challenge!



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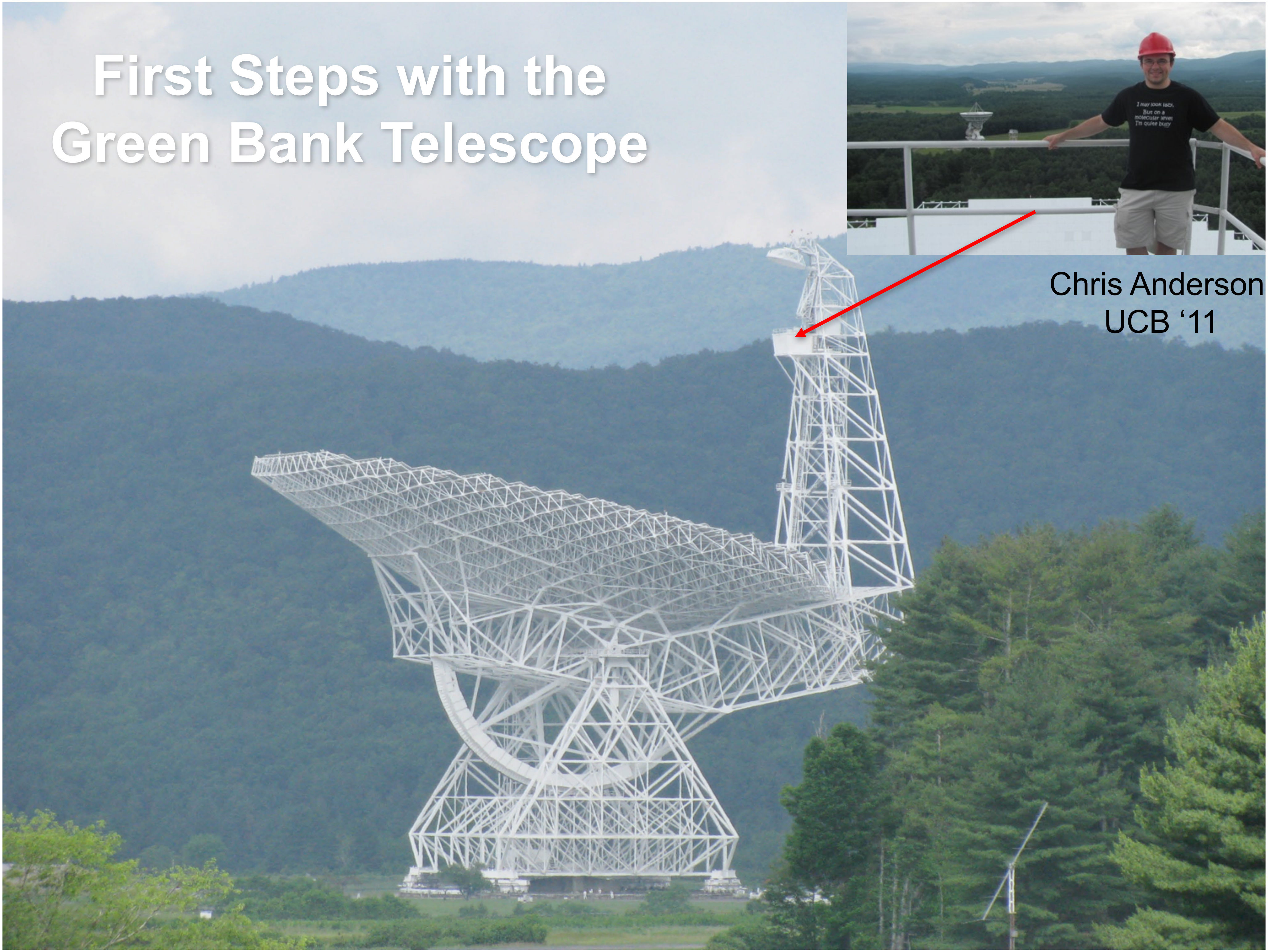
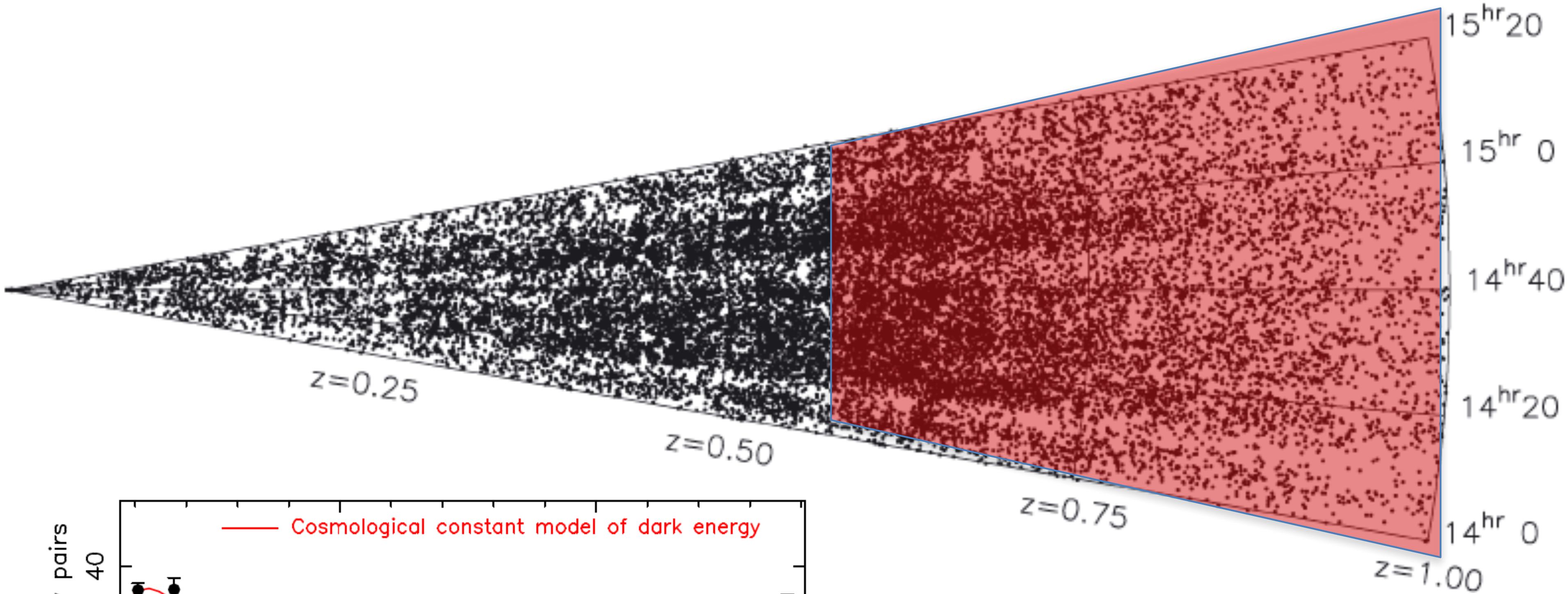
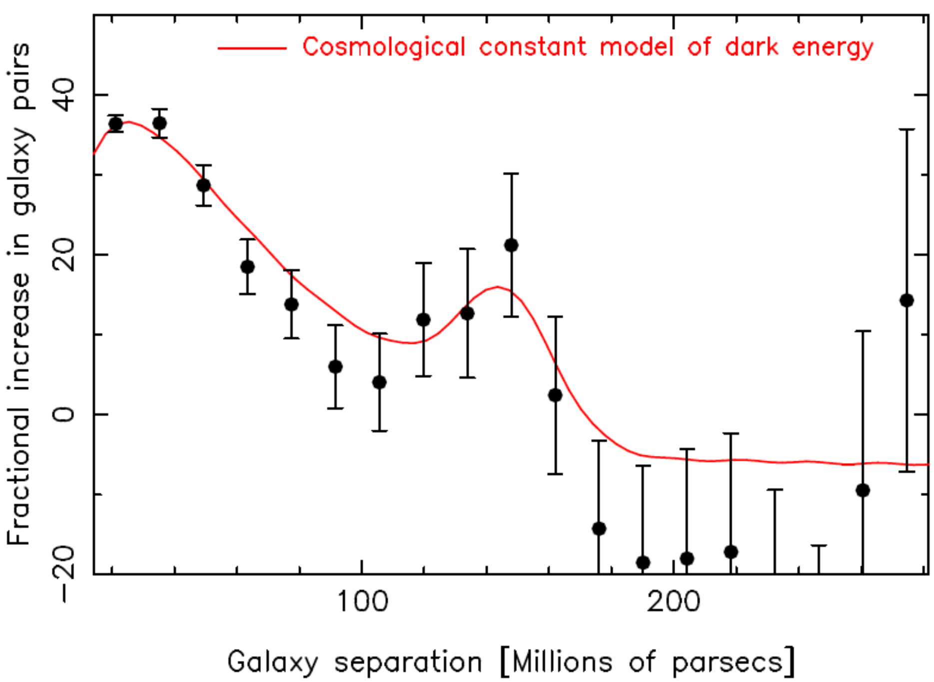

First Steps with the
Green Bank Telescope
Chris Anderson
UCB '11

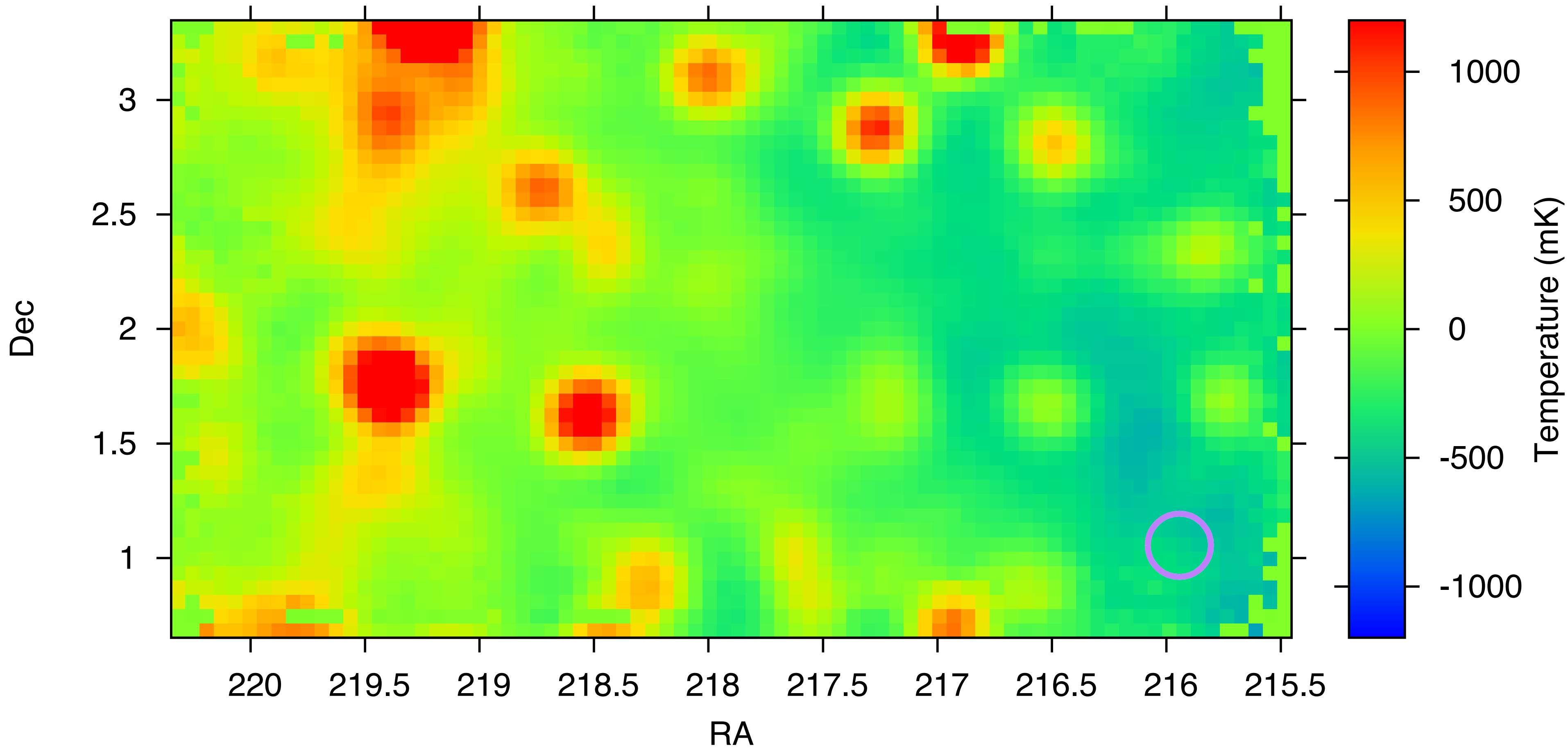
WiggleZ Dark Energy Survey: correlate with GBT survey





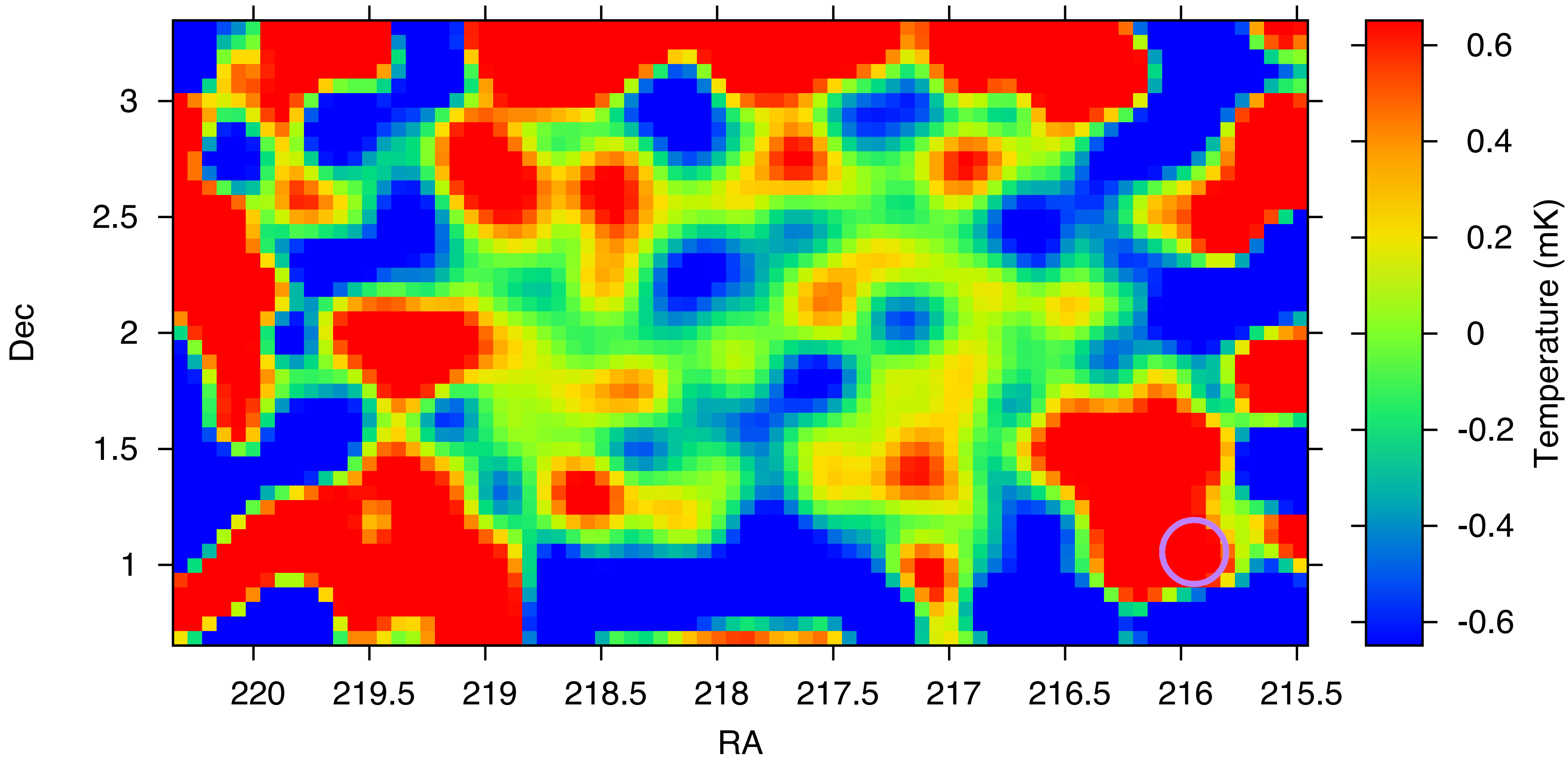
Drinkwater et al. MNRAS (2010)

GBT map at 804 MHz (z = 0.775) before foreground removal



Masui et al. ApJ 763:L20 (2013)

GBT map at 804 MHz (z = 0.775) after foreground removal



Masui et al. ApJ 763:L20 (2013)

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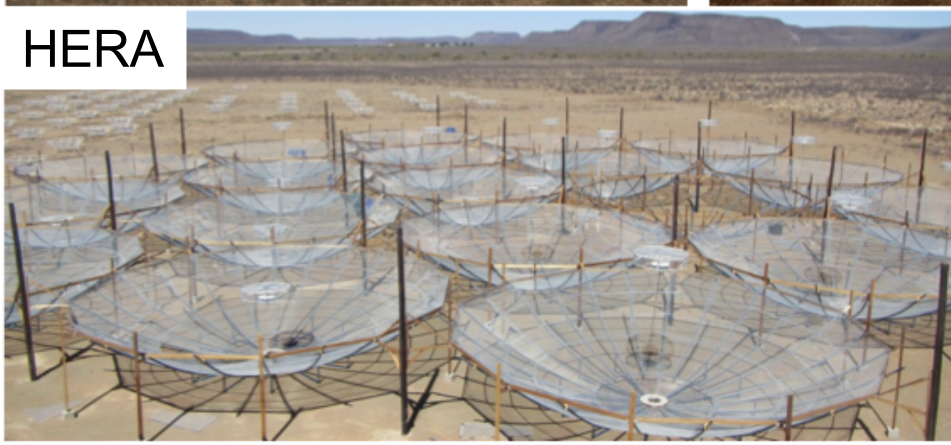
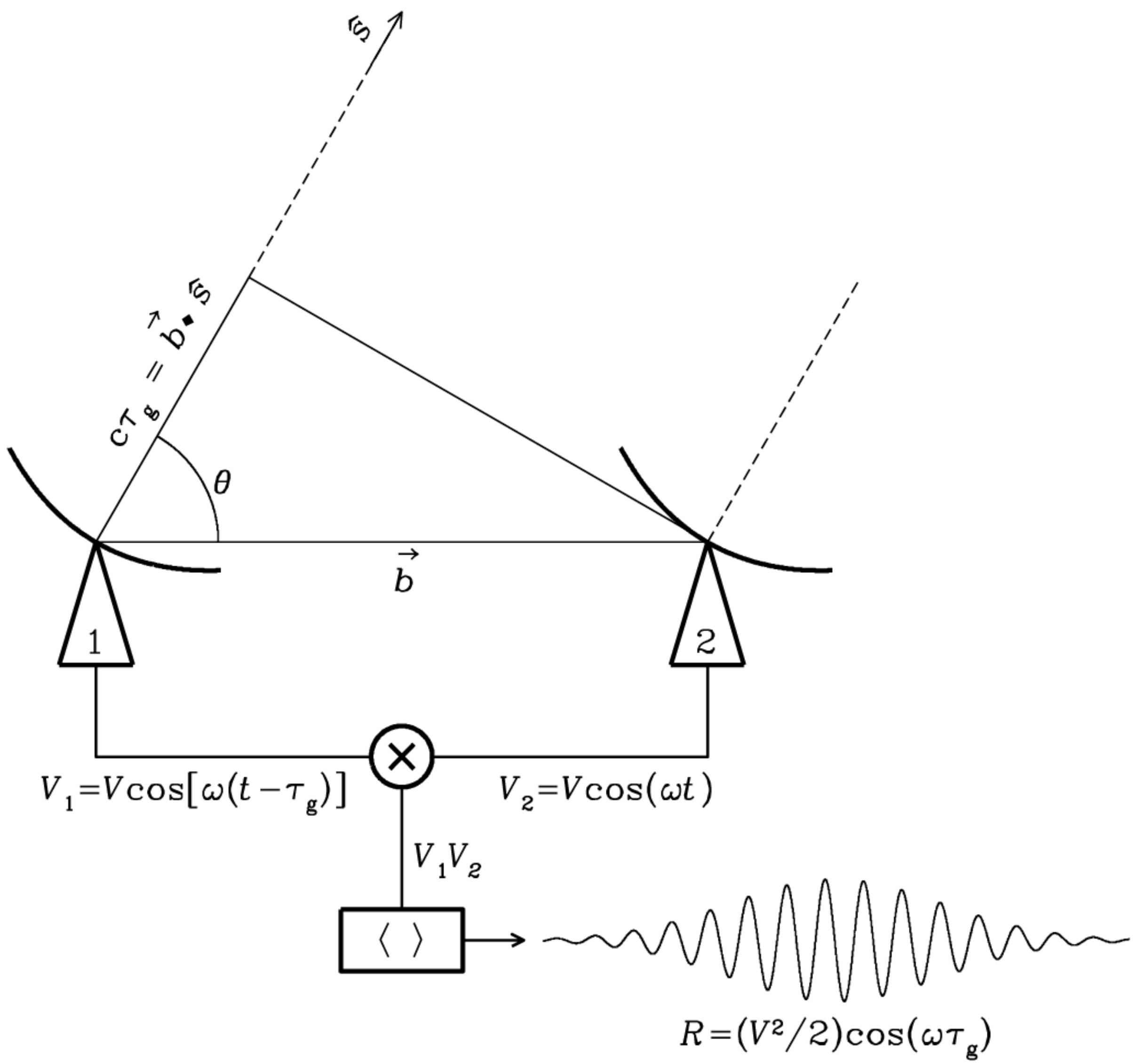
Early 'cylinder' transit radio telescope at CMU

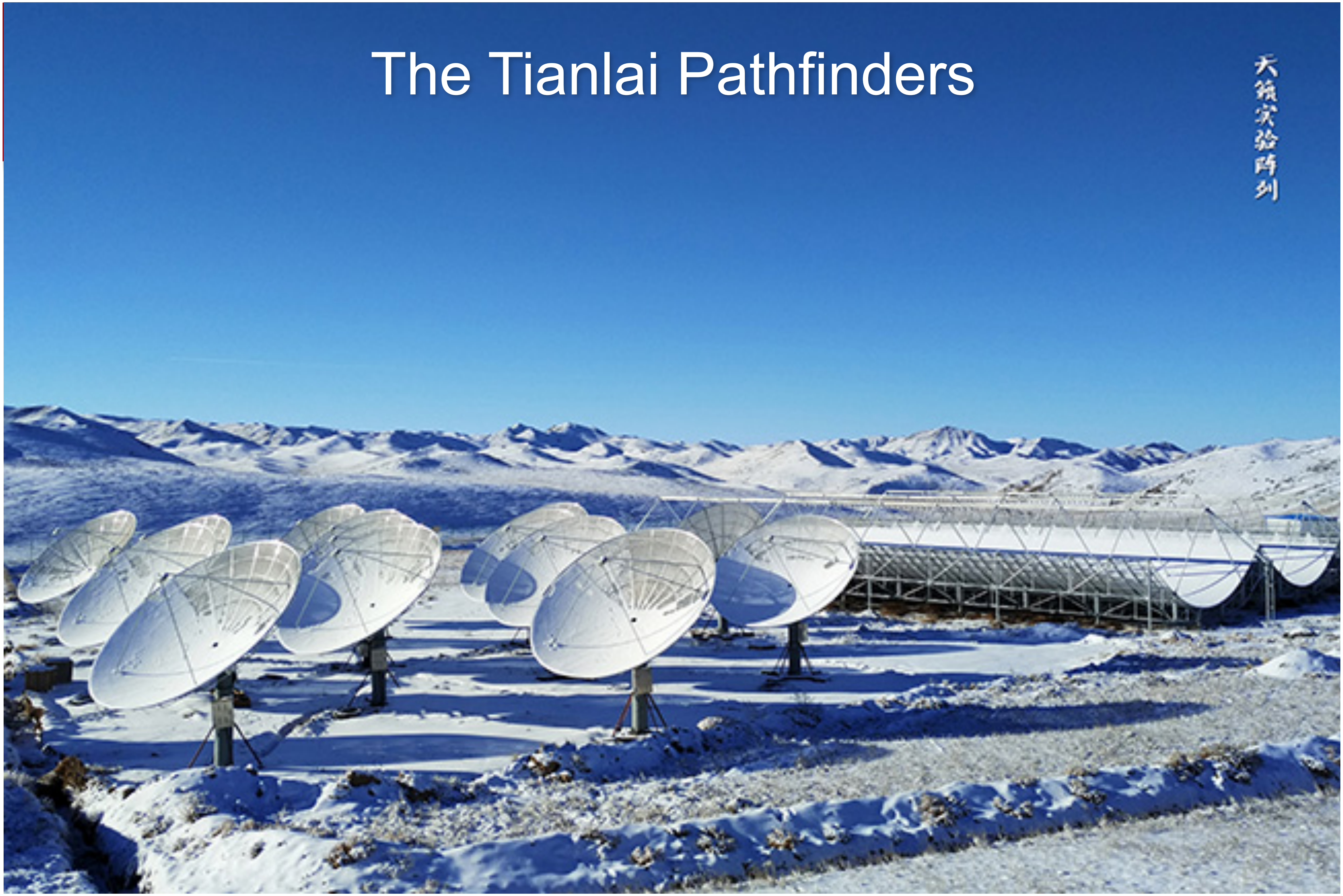
Hydrogen intensity mapping experiments: the next stage



Radio Interferometers measure Fourier modes of sky image



The Tianlai Pathfinders



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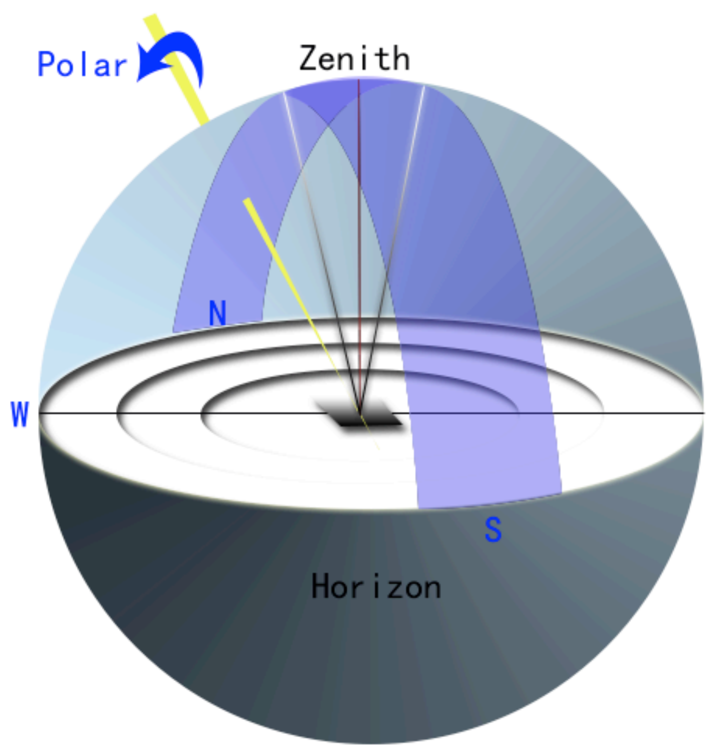
The Tianlai Pathfinders

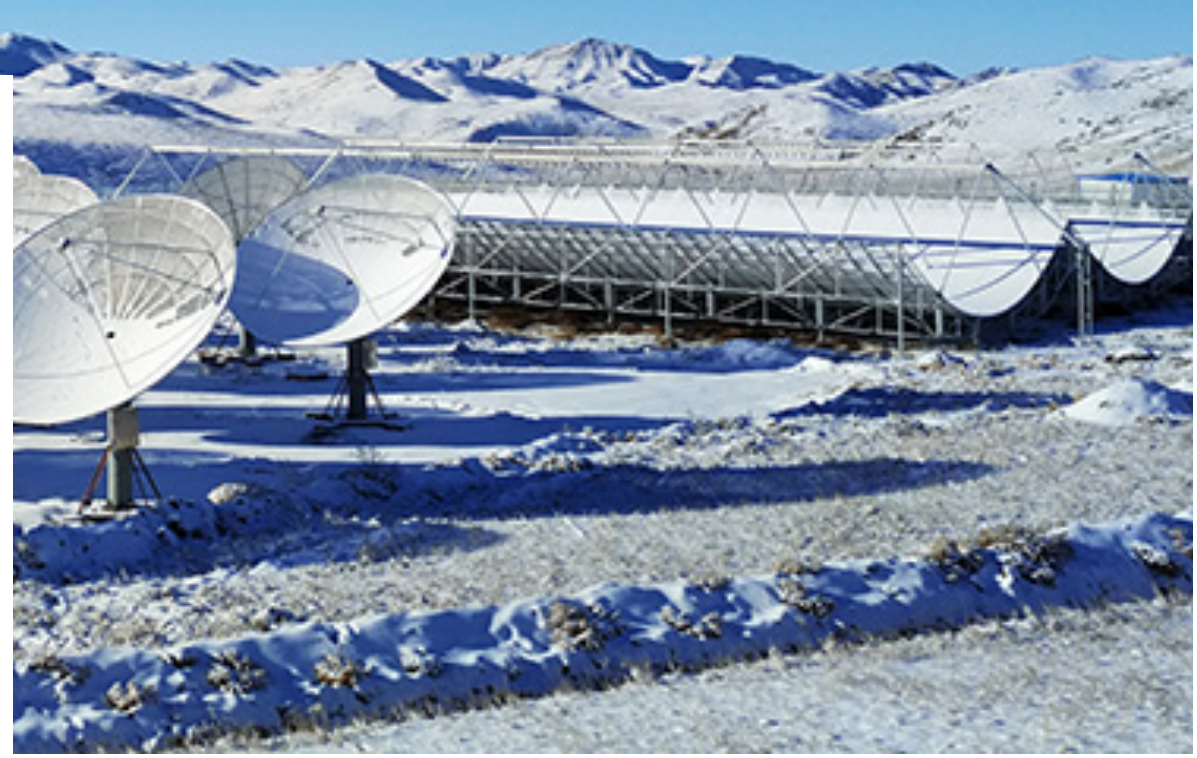
The Tianlai Pathfinders

天籁实验阵列

Currently observing: 700 – 800 MHz (1.03 > z > 0.78)

Will retune to: 1330 – 1430 MHz (0.07 > z > -0.01)





Tianlai Participants

China: X. Chen (PI at NAOC), CETC-54, Institute of Automation, Hangzhou Dianzi U., Xinjiang Astron. Obs.

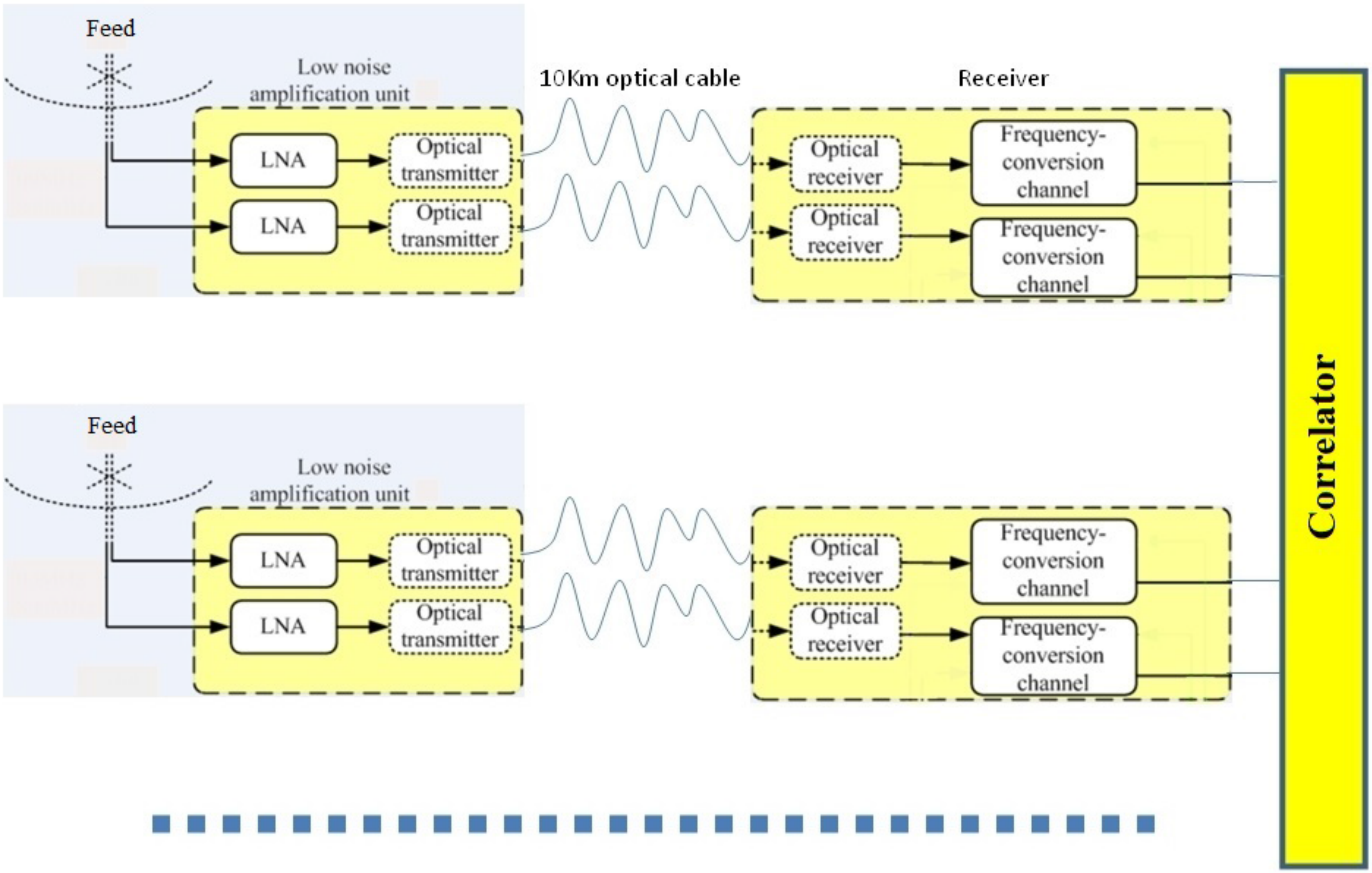
US: J. Peterson (CMU)
P. Timbie, S. Das, T. Oxholm, A. Phan (Wisconsin)
A. Stebbins, J. Marriner (Fermilab)
G. Tucker (Brown)

France: R. Ansari, J.E Campagne, M. Moniez, O. Perdereau (LAL/IN2P3)
J.-M. Martin, P. Colom (Obs. Paris)

Canada: U-L. Pen (CITA)

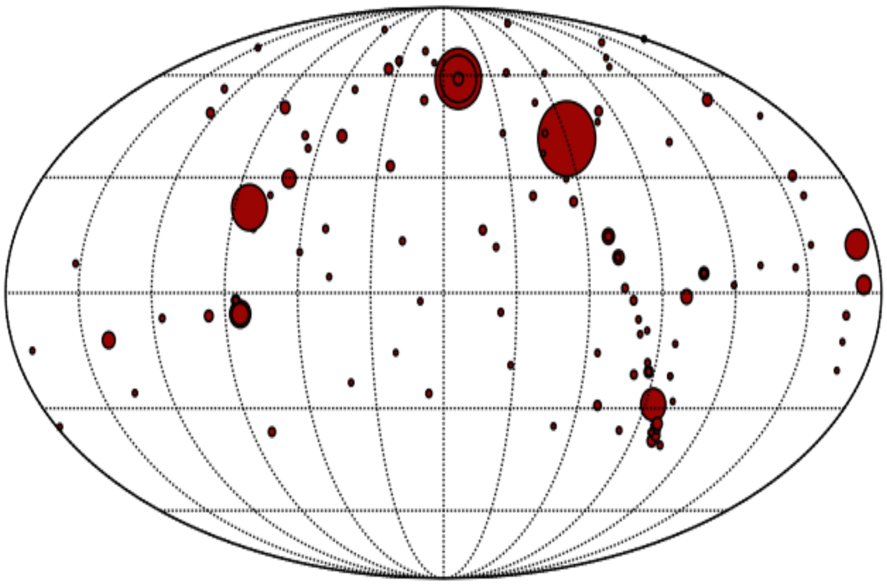
The concept of "tianlai"-- the heavenly sound was coined by ancient Chinese philosopher Zhuang-Zi
(Chuang-Tzu, 369 BC-286 BC)

Tianlai signal processing

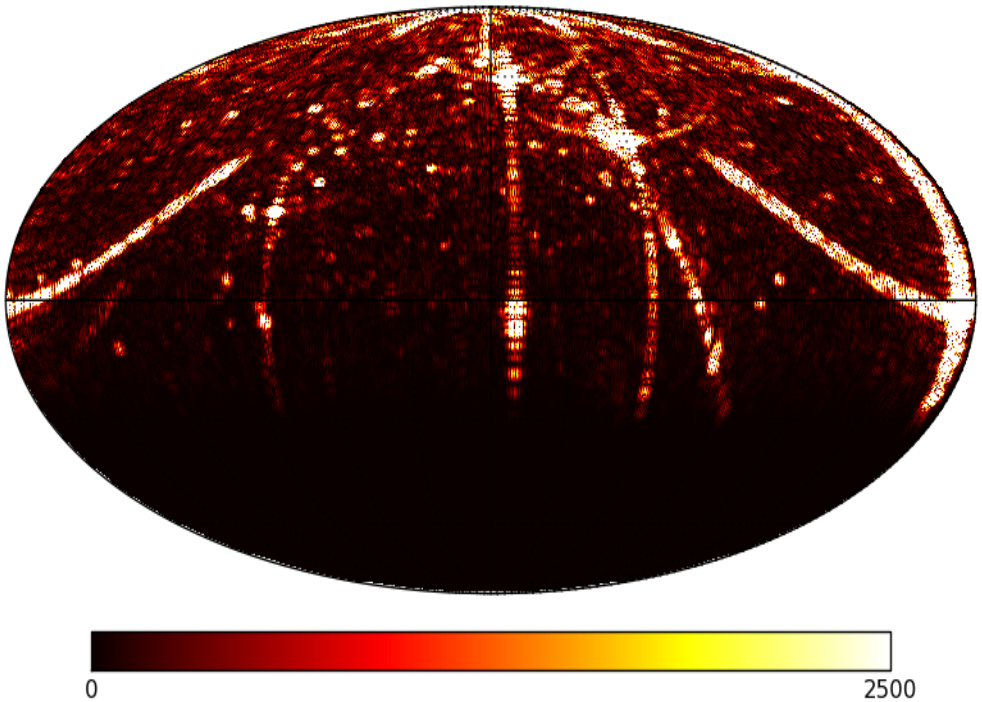


- ROACH2 FPGA-based correlator for dish array → 0.4 TB/day
- Custom DSP-based correlator for cylinders →3.3 TB/day

First sky maps with Tianlai cylinders



NVSS（1.4GHz）bright sources



1 redshift slice 750 MHz

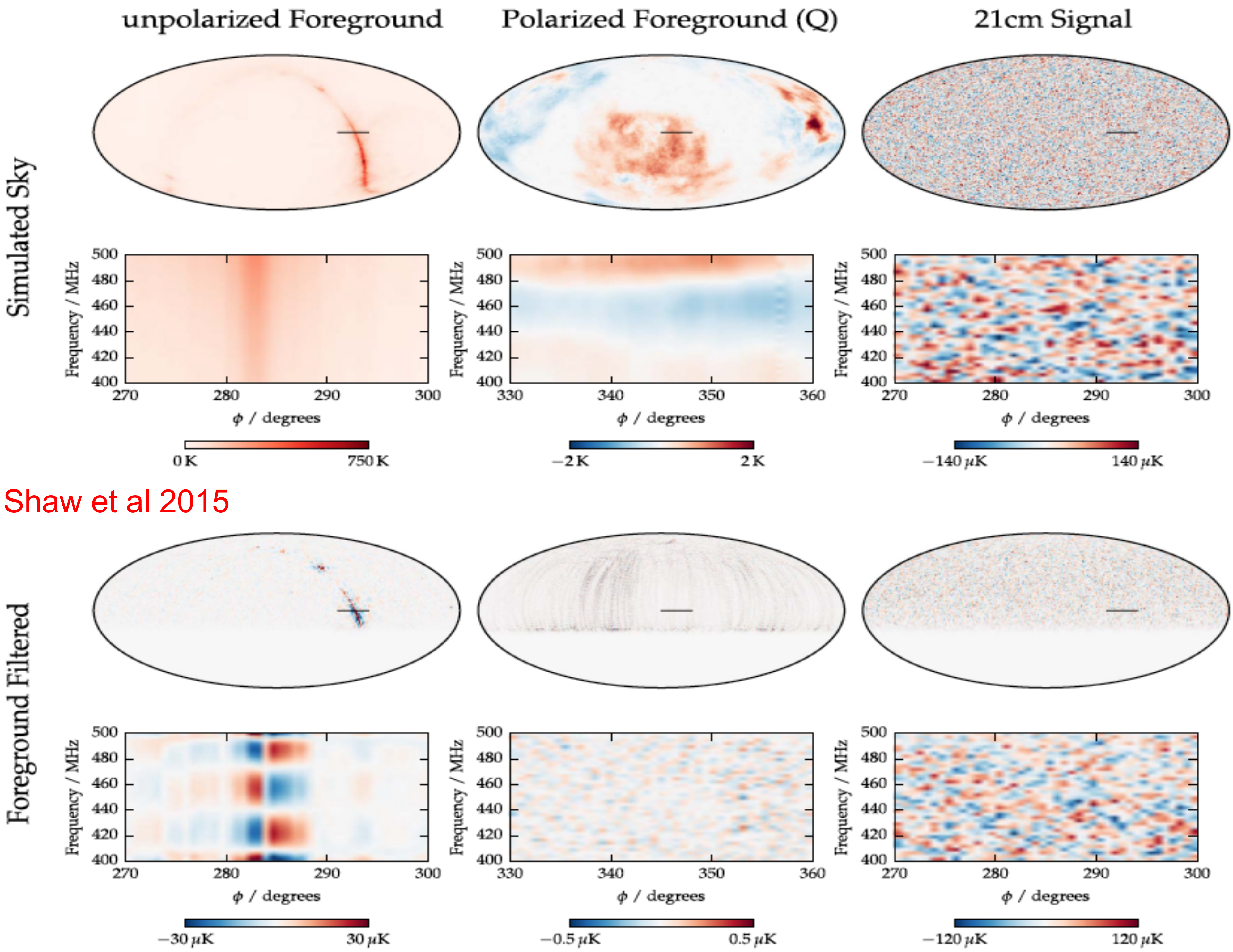
Richard Shaw: foreground removal

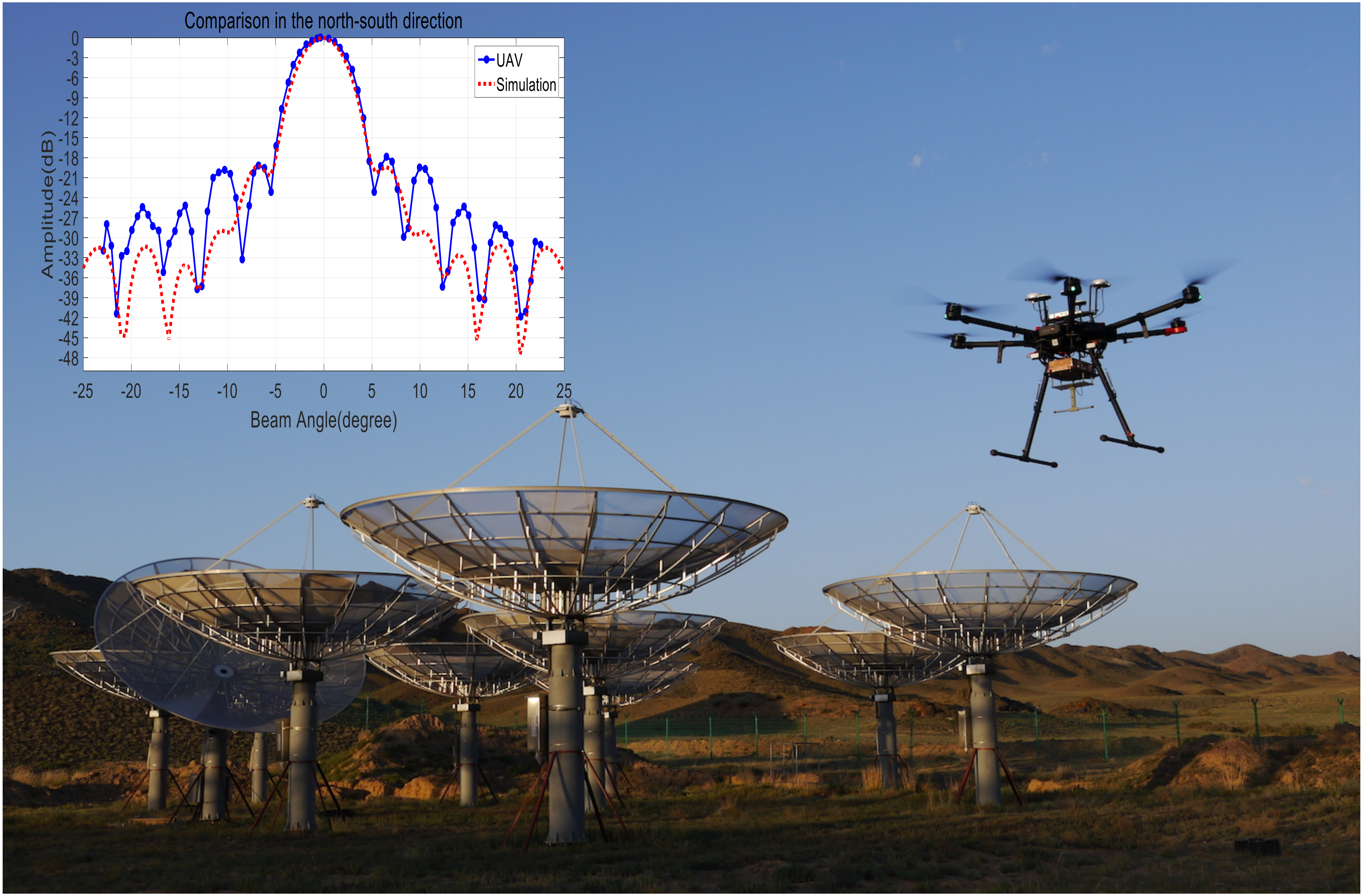
ALL-SKY INTERFEROMETRY WITH SPHERICAL HARMONIC TRANSIT TELESCOPES
Shaw, Sigurdson, Pen, Stebbins, Sitwell ApJ 781 2014

Foreground removal with signal/contamination eigenmodes
- requires model for signal and for foregrounds & noise

Include simulations of polarized foregrounds and 'mode-mixing'

Simulations for CHIME recover unbiased power spectra when:
- per-feed beamwidth is measured to 0.1%
- amplifier gains known to 1% within each minute


unpolarized Foreground
Polarized Foreground (Q)
21cm Signal
Simulated Sky
Frequency / MHz
500
480
460
440
420
400
270
280
290
300
330
340
350
360
ϕ / degrees
0 K
750 K
−2 K
2 K
−140 μK
140 μK
Shaw et al 2015
Foreground Filtered
−30 μK
30 μK
−0.5 μK
0.5 μK
−120 μK
120 μK



Comparison in the north-south direction
UAV
Simulation
Amplitude(dB)
Beam Angle(degree)

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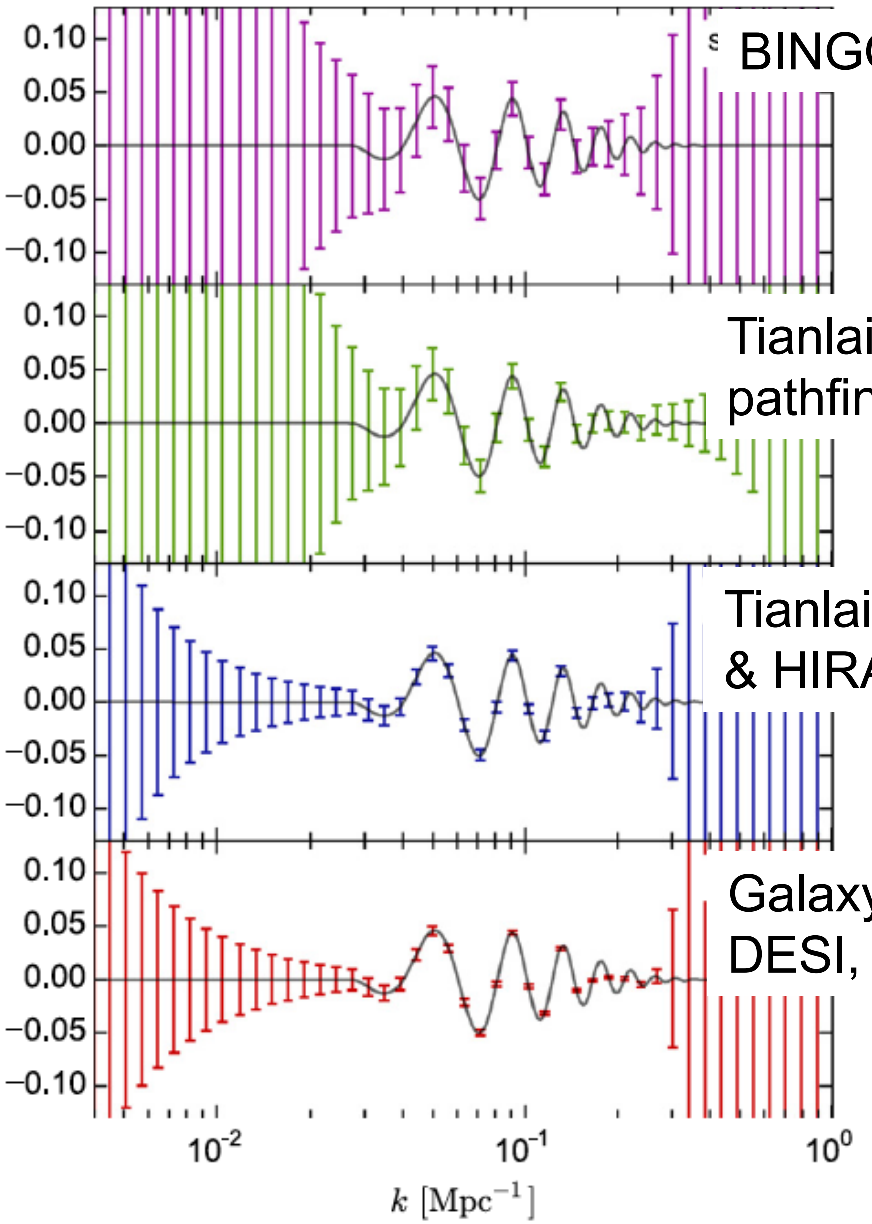
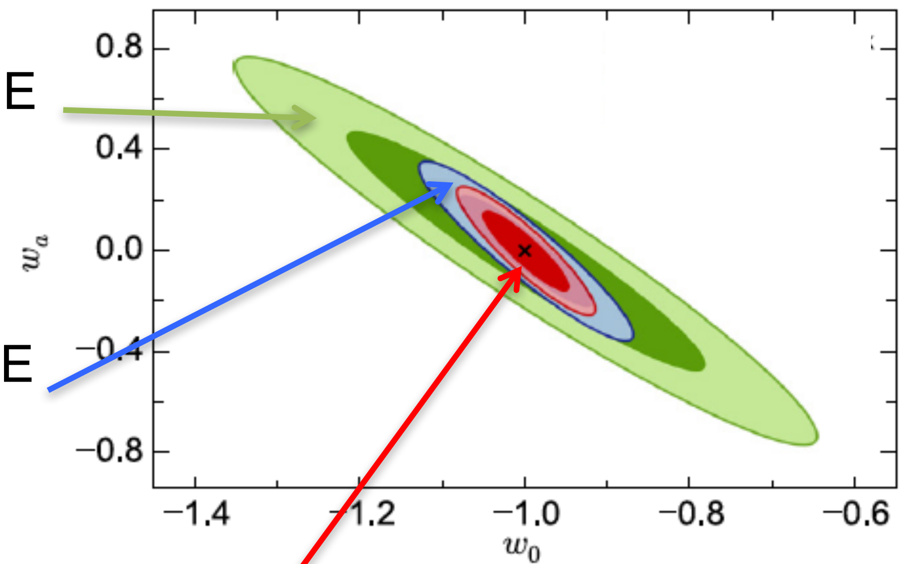
Baryon Acoustic Oscillation forecasts



BINGO, Parkes, GBT-7

$$P/\rho = w(a) = w_0 + (1-a)w_a$$



Tianlai & CHIME pathfinders

Tianlai & CHIME & HIRAX full

Galaxy redshift surveys DESI, Euclid, WFIRST

Bull et al. (2015)

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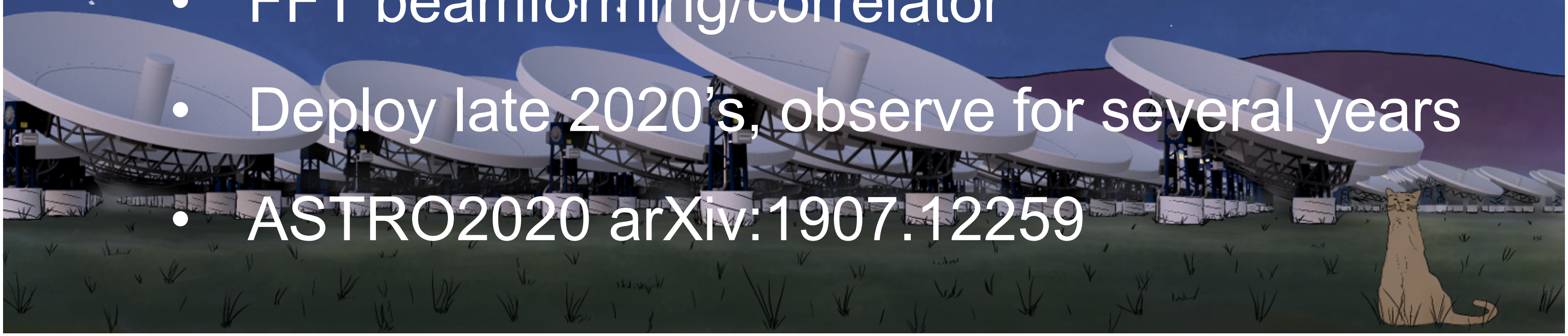
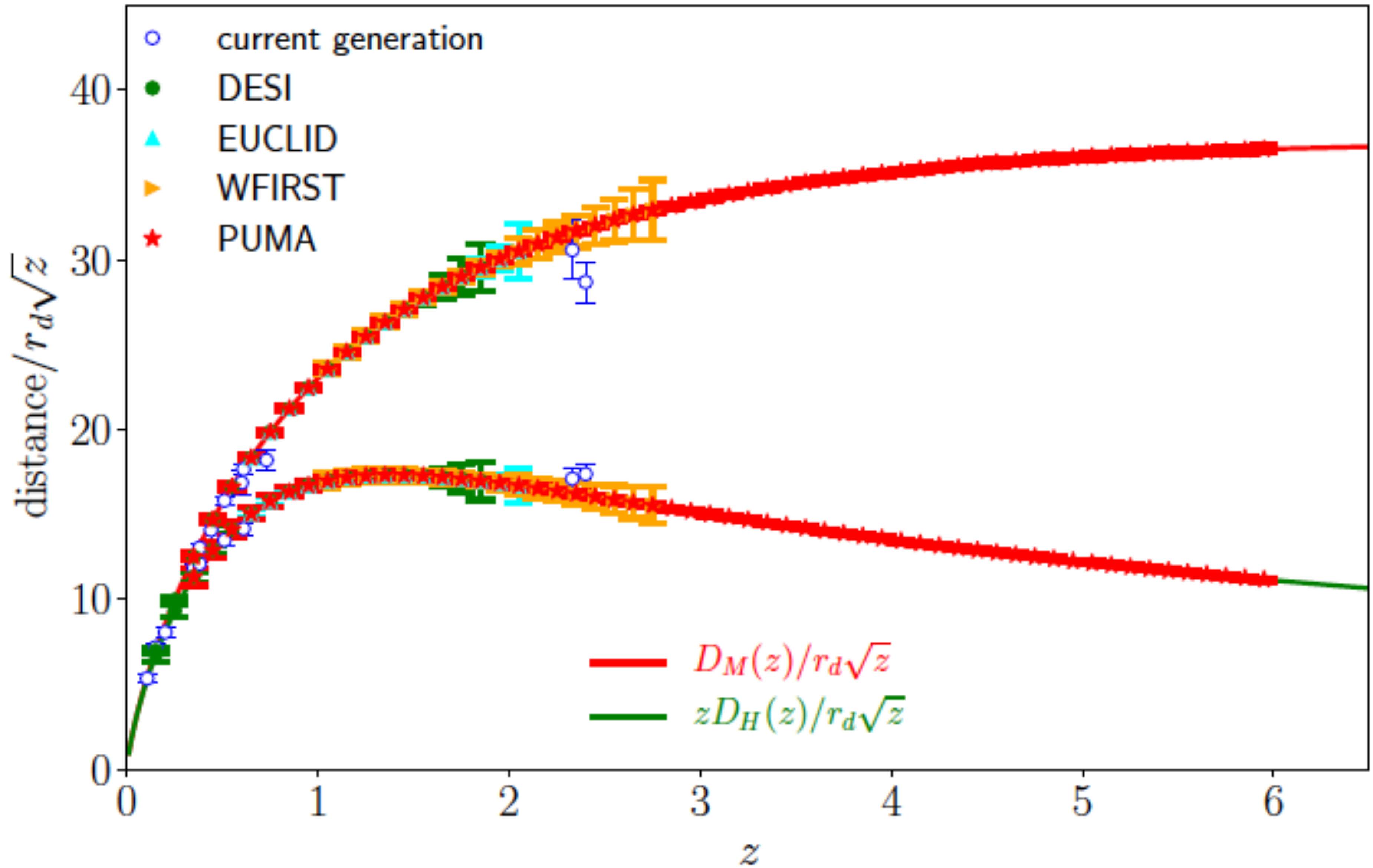
Packed Ultra-wideband Mapping Array (PUMA): ‘Stage II’ intensity mapping

- 0.3 < z < 6   (1100 MHz – 200 MHz)
- Close-packed 6 m dishes:

  5000 *petite*, 32,000 *full*, 64,000 *super*
- Drift scanning (non-tracking)
- Single wide-bandwidth feed/receiver
- FFT beamforming/correlator
- Deploy late 2020’s, observe for several years
- ASTRO2020 arXiv:1907.12259



PUMA: expansion history



Challenges & Opportunities

天籁实验阵列

- Foreground removal algorithms
- Array uniformity & stability & calibration
- Data rate
- Cross-correlation with galaxy surveys - NCCS