Cosmology with Line Intensity Mapping

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Chris Anderson, Peter Timbie (U. Wisc)

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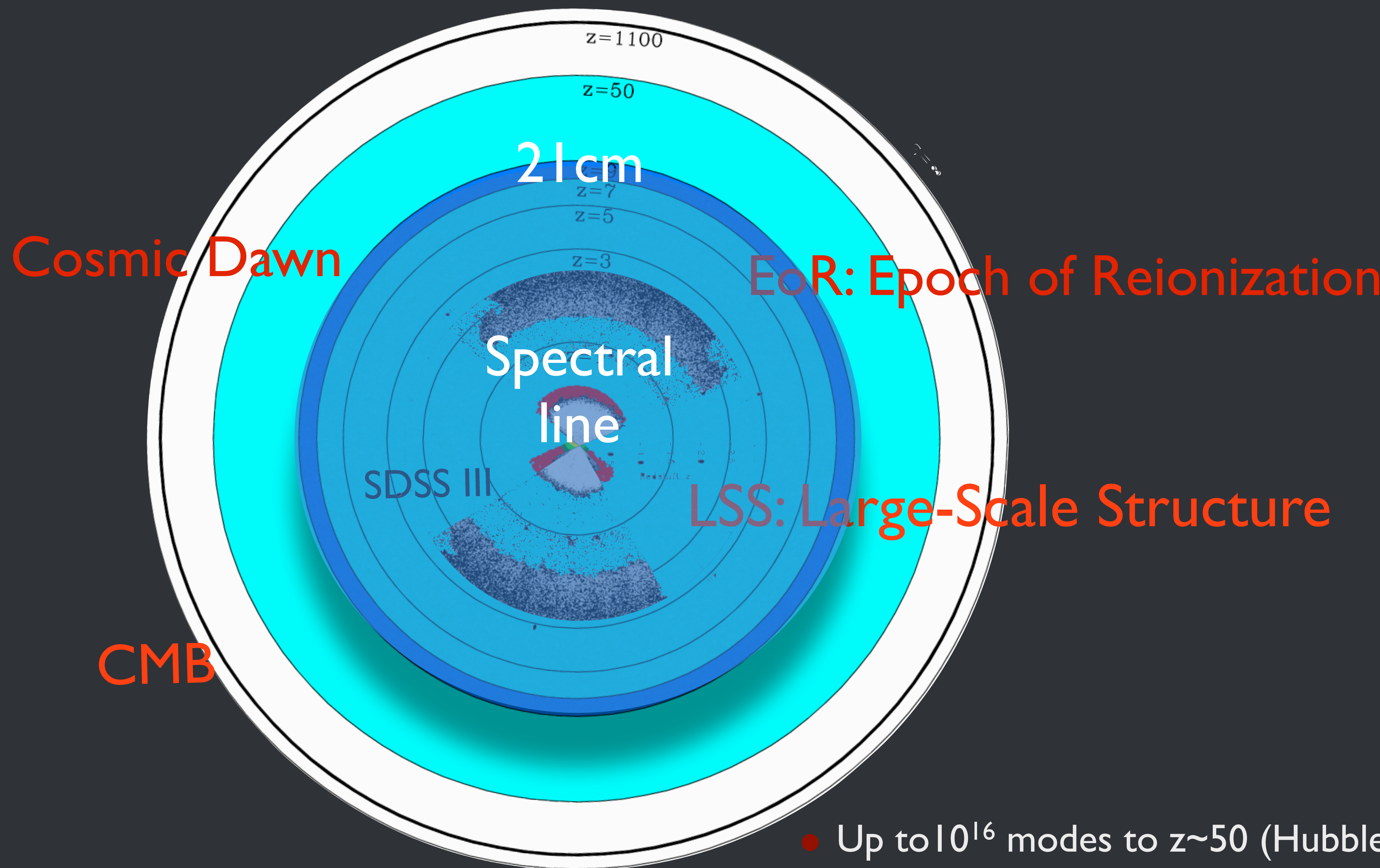
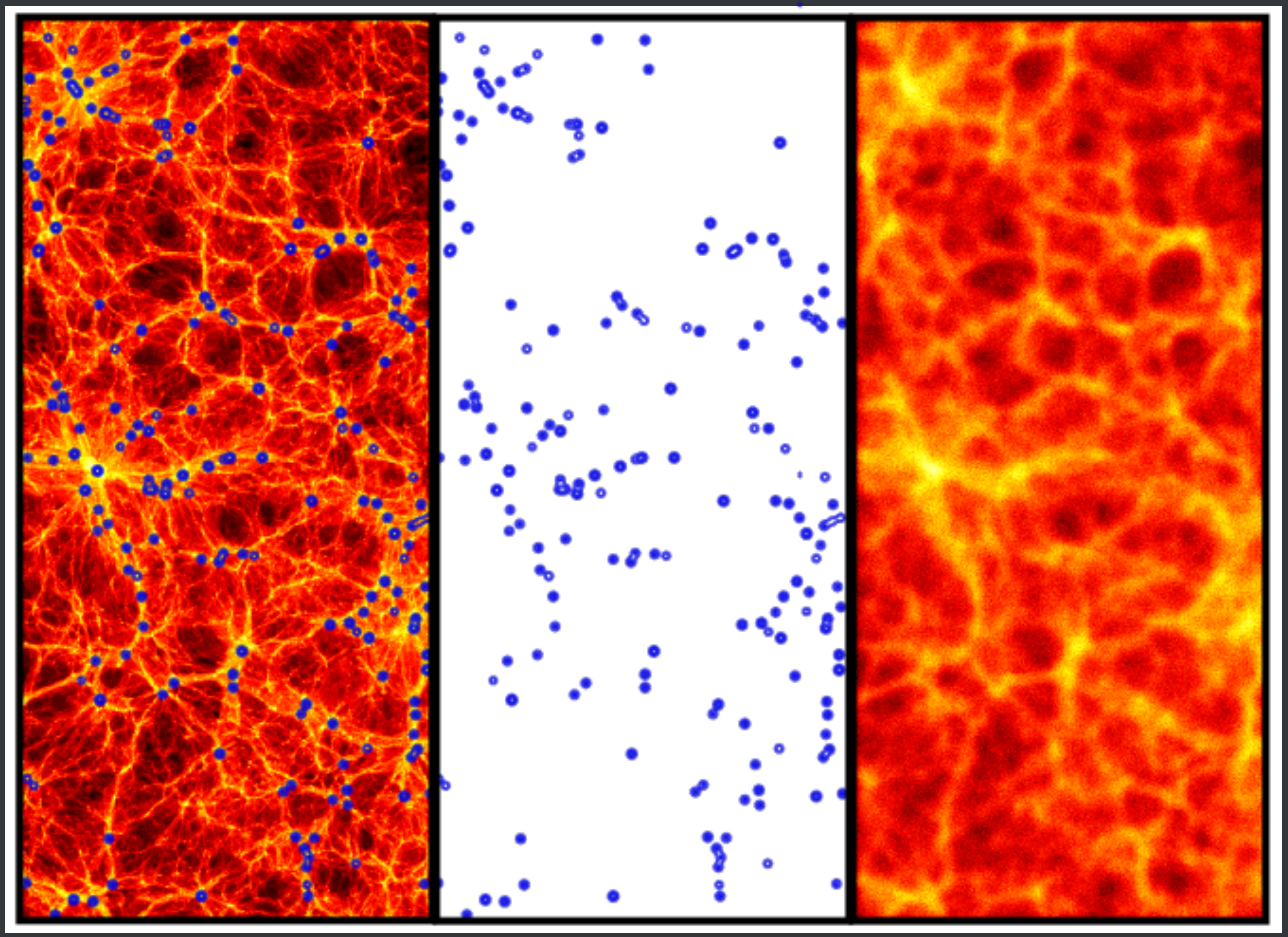
Line Intensity Mapping



- Up to 10^{16} modes to z~50 (Hubble/Jeans)^3

derived from Tegmark & Zaldarriaga 08

Line Intensity Mapping

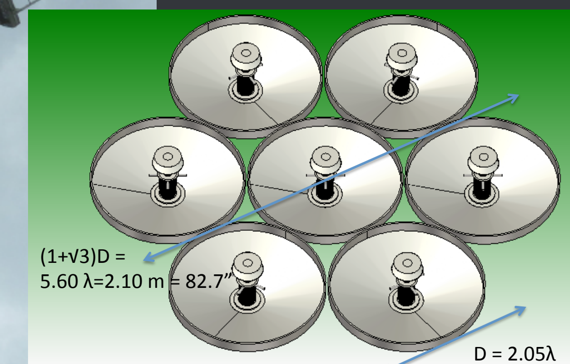


courtesy of Phil Korngut (Caltech)

- "Intensity Mapping" (Chang+ 2008, Wyithe & Loeb 2008):
    - Measure the collective emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.
- Use spectral lines as tracers of structure, retain high frequency resolution thus redshift information
- Measure brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D
- Low-angular resolution redshift surveys: economical, large survey volumes
- Confusion-limited. Foreground-limited.

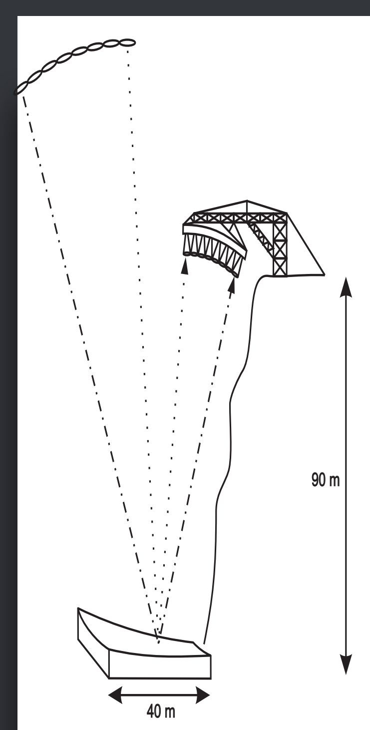
21cm Intensity Mapping Experiments

GBT-HIM multi-beam

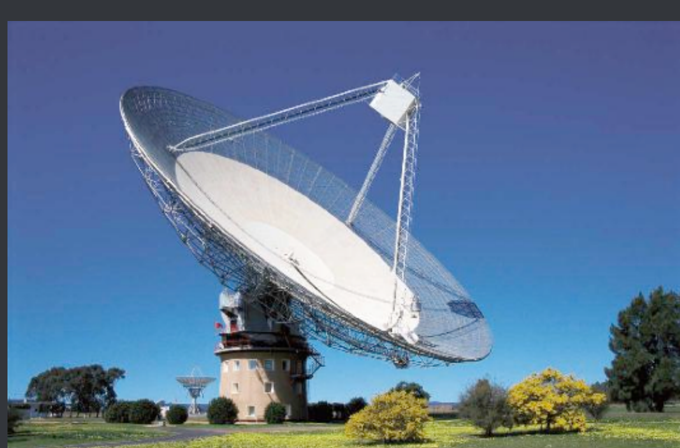


CHIME

HIRAX



Tian-Lai/ CRT/BAORadio



Parkes IM

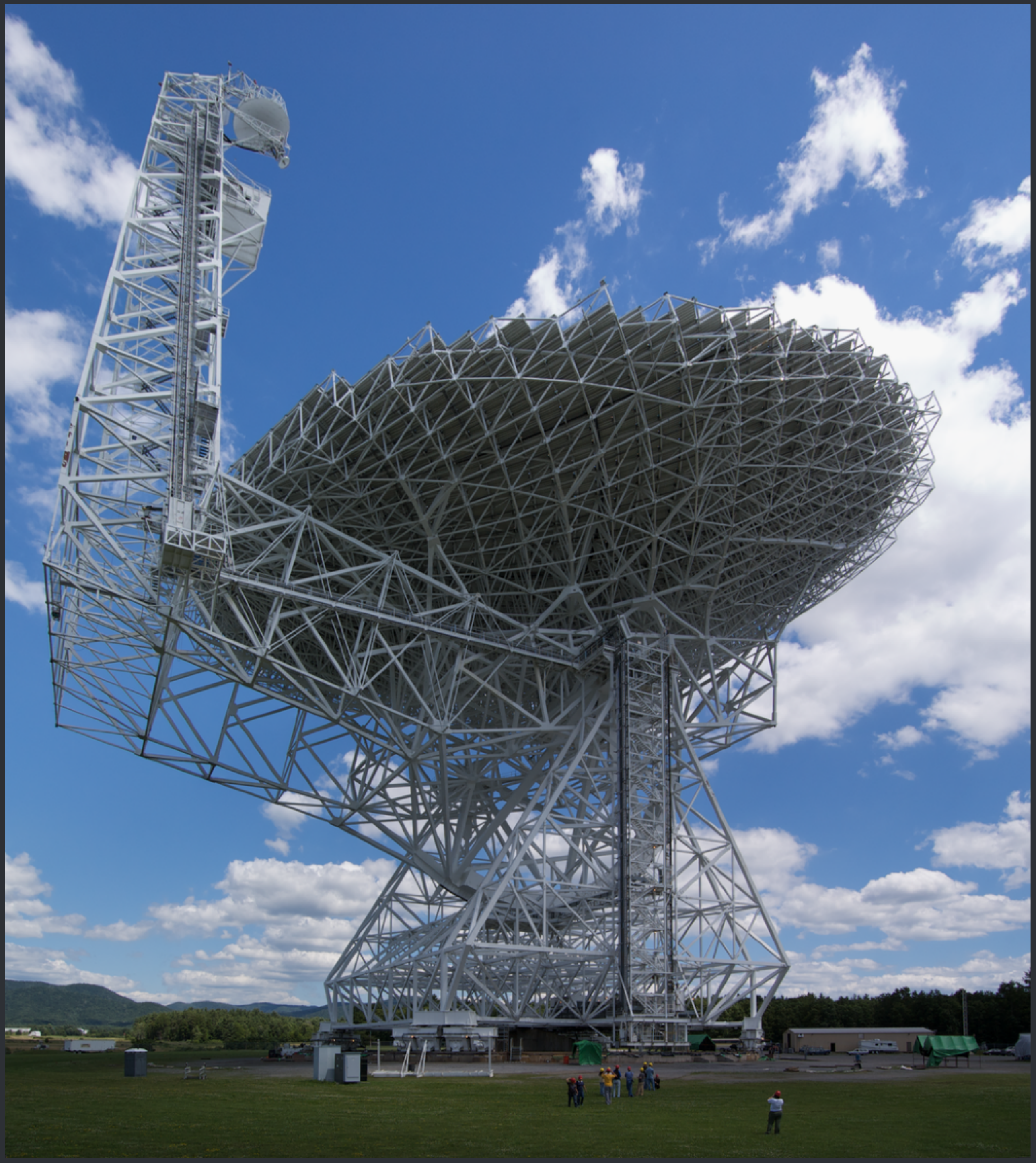
BINGO

SKA-mid Telescope

Status Update:
21cm Intensity Maps at z~0.8 with Green Bank Telescope

GBT-HIM

Pilot program at the Green Bank Telescope (GBT)

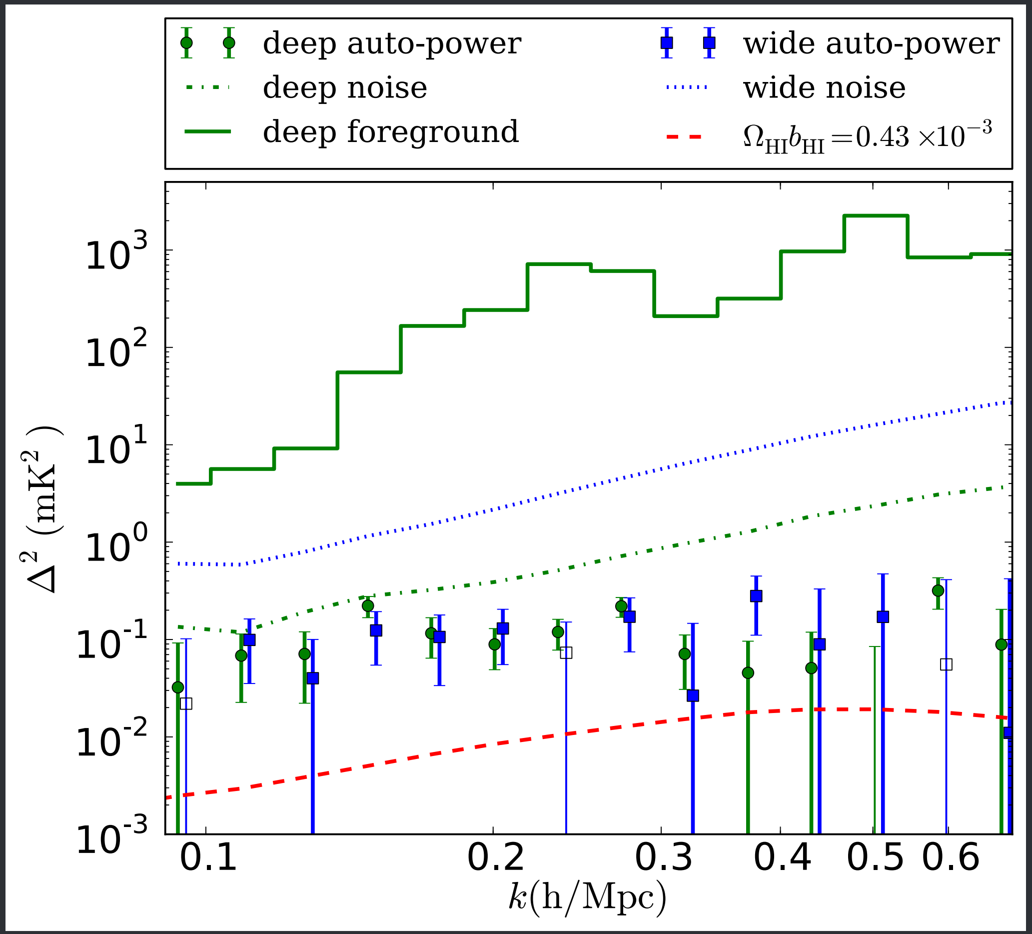


- Frequency: 700-900 MHz
  - $0.6 < z < 1$
- Spatial beam ~ 15'
  - 9 h^{-1} Mpc at z~0.8
- Spectral channel ~ 24 kHz
  - binned to 0.5 MHz
  - ~2 h^{-1} Mpc
- 100-m diameter. Large collecting areas
- Foregrounds are ~1000x stronger than the 21cm signals
- First detection in cross-correlation with DEEP2 galaxies at z=0.8 (Chang, Pen, Bandura, Peterson, 2010, Nature)

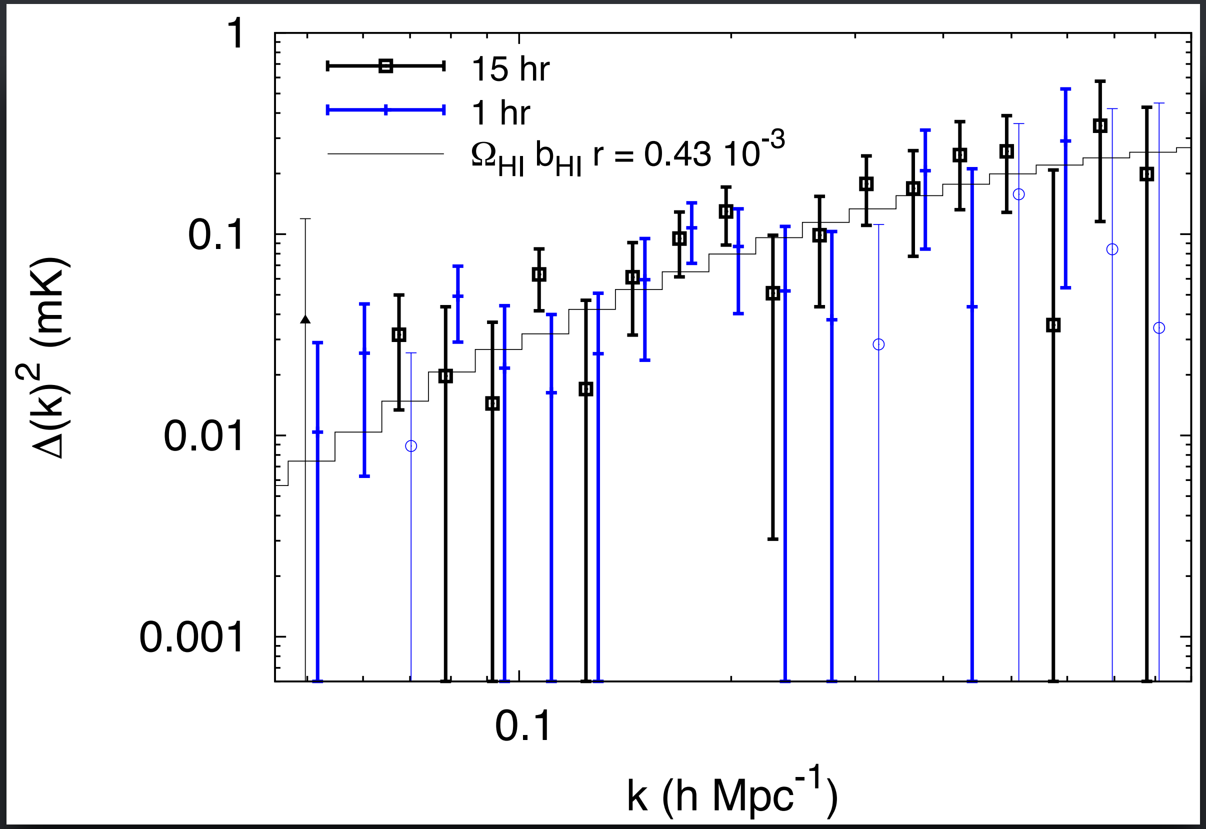
21cm Intensity Mapping at the GBT

- Frequency: 700-900 MHz
  - $0.6 < z < 1$
- Spatial beam ~ 15'
  - 9 h^{-1} Mpc at z~0.8
- Spectral channel ~ 24 kHz
  - binned to 0.5 MHz
  - ~2 h^{-1} Mpc

- 200-hr HI survey of the WiggleZ fields at $0.6 < z < 1$
- HI cross-power and auto-limits in 2013 at z=0.8 implies:
- $\Omega_{HI} b_{HI} = [0.62^{+0.23}_{-0.15}] \times 10^{-3}$

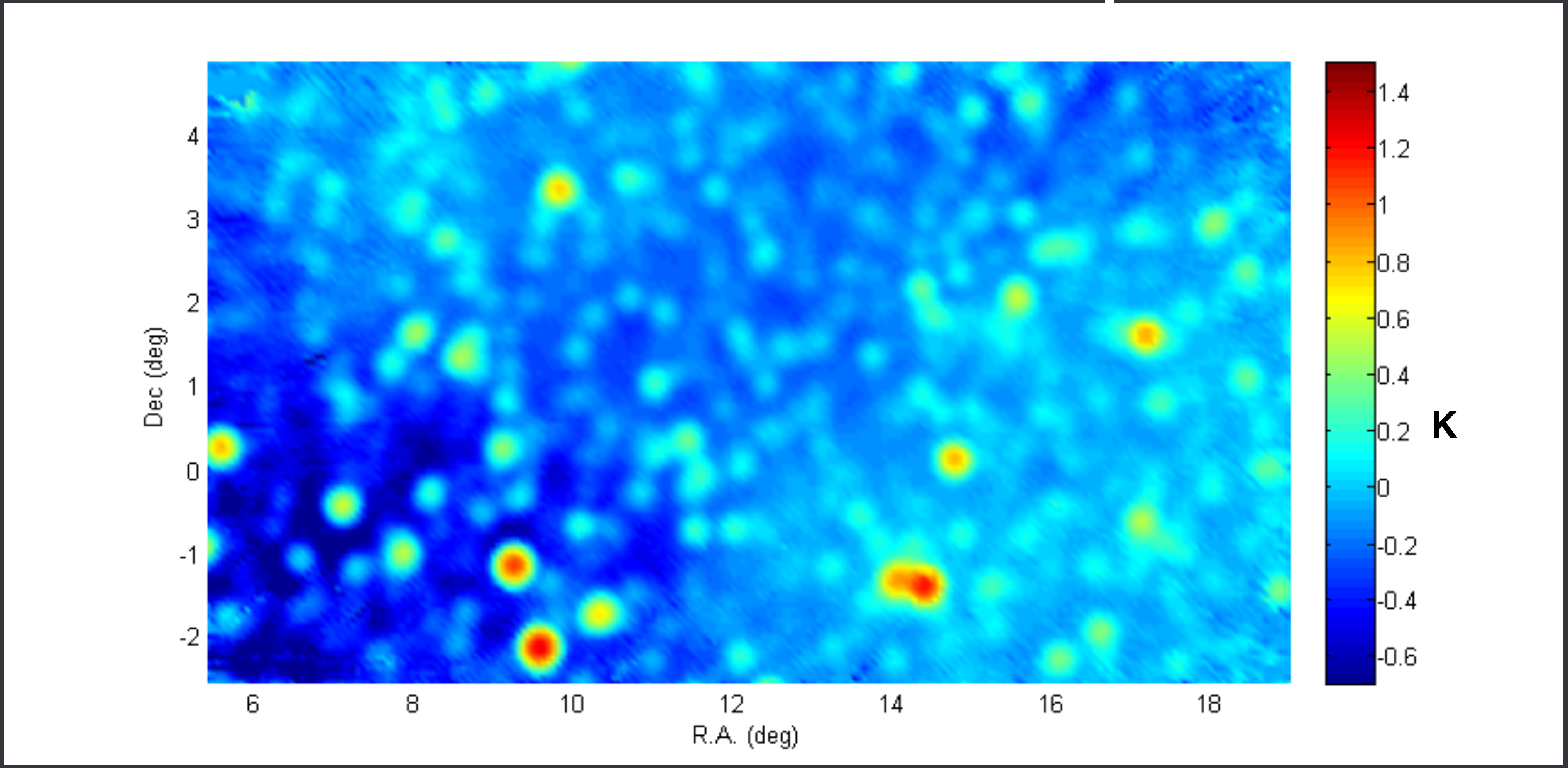


Auto-power limits, Switzer+13, GBT-HIM



Cross-power, Masui+ 13, GBT-HIM

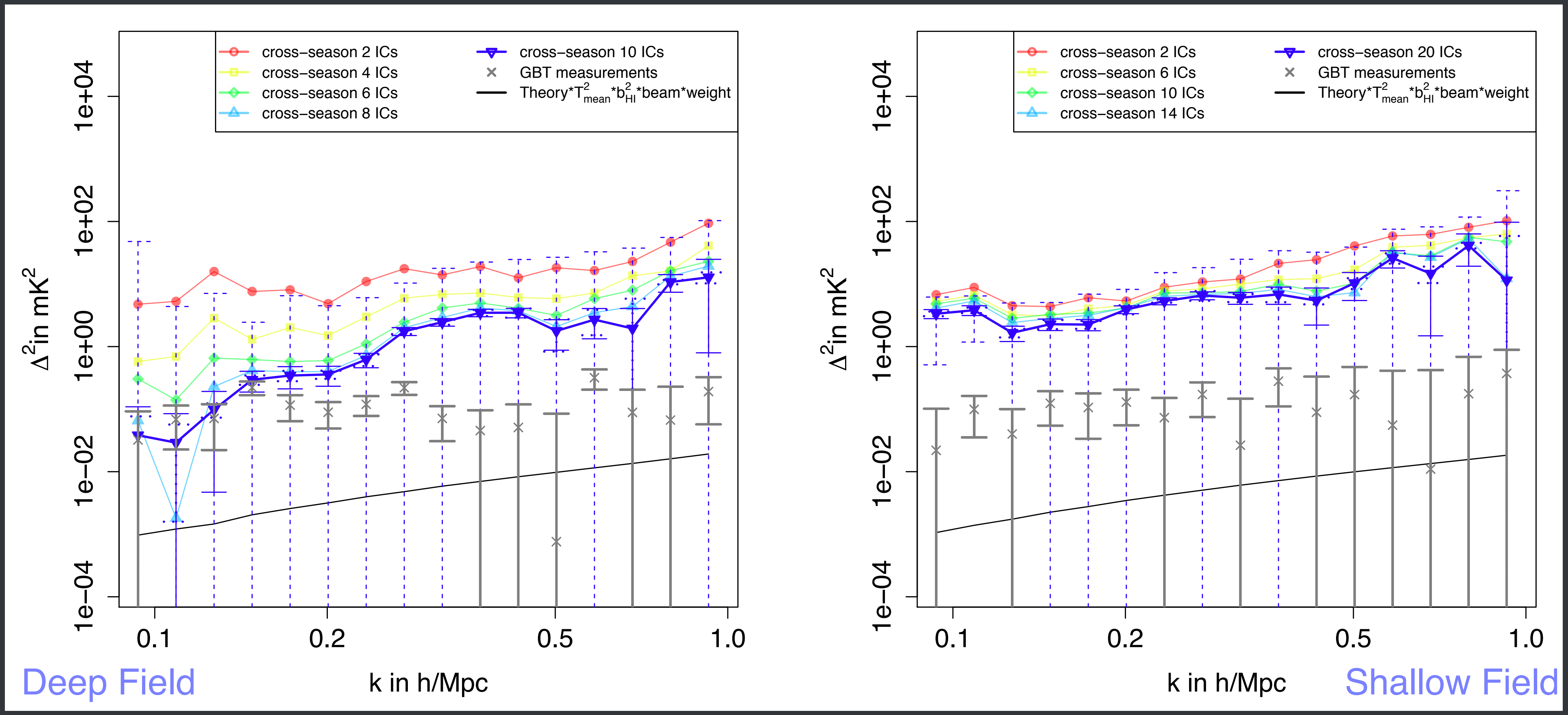
GBT-HIM Status Update



GBT WiggleZ 1hr field

- Analysis of ~800 hours of GBT observations 2010-2015.
  - WiggleZ 1hr, 11hr, 15hr, 22hr fields
- Improve HI power spectrum limits
- Measure HI-optical cross-power RSD effects
- Focus on the 1hr field, ~100 square deg, $0.6 < z < 1$:
  - Alternative Foreground cleaning techniques (Wolz + GBT-HIM team, 2016)
  - Polarization calibration improvement (Liao, Chang et al. 2016)
  - Polarization leakage power spectrum estimates (To, Chang et al., in prep)
  - Handling of residual ground-spill contamination (Liao, Chang, Masui et al., in prep)

Foreground Mitigation: SVD v.s. ICA

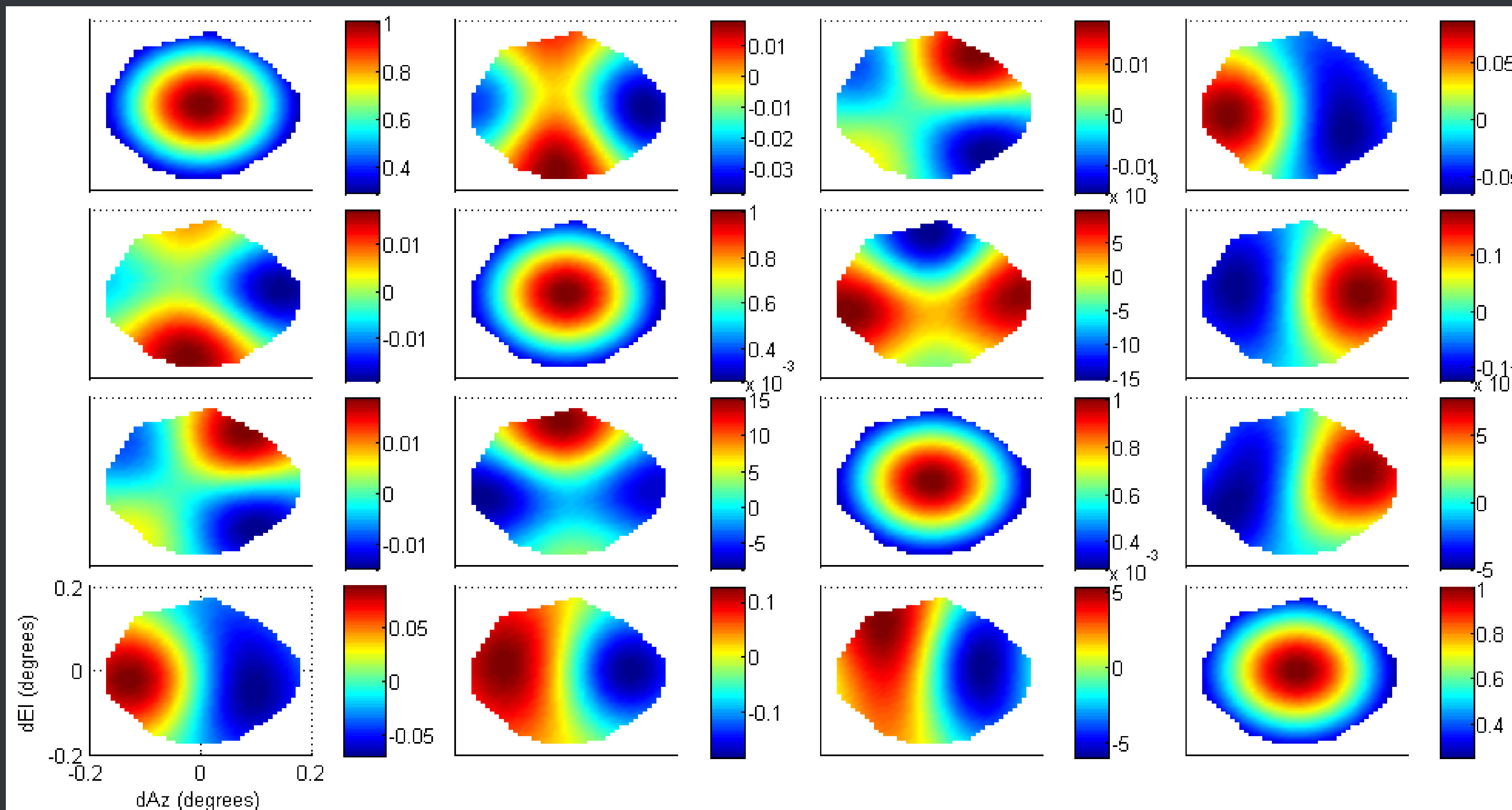


Laura Wolz et al., +GBT-HIM team, 2017

- Foreground Projection/Subtraction Methods:
  - SVD - singular value decomposition: spectral and spatial eigenmodes (Switzer, Chang, Masui, Pen, Voytek 2015).
  - ICA - independent component analysis. FastICA (Wolz et al. 2014).
  - SVD: signal loss, compensated by calculating transfer functions.
  - ICA: no signal loss. But more difficulty in handling systematics.
  - ICAxICA, SVDxICA maps: no obvious improvement on the power spectrum limits

Precision polarization calibration at GBT

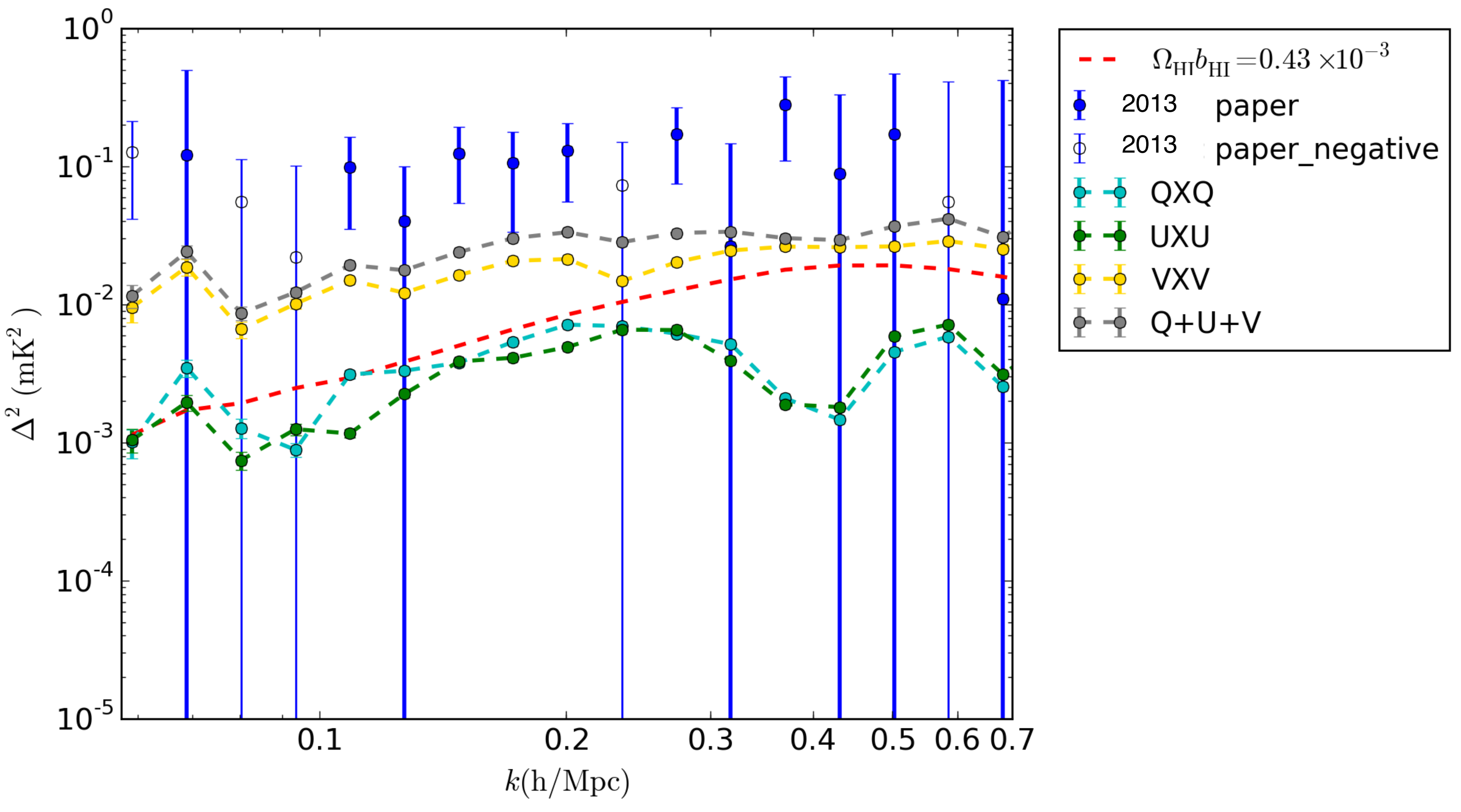
I
Q
U
V

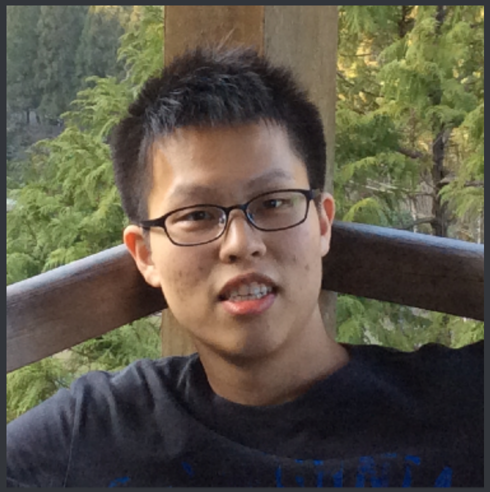


Liao, Chang et al., 2016

- GBT Mueller 4 x 4 beam
  - $S^{'} = J_B R_{\hat{v}}(\phi) S$
  - Make use of quasars, pulsars and noise-diode (switching at 16 Hz) to constrain six-parameter Jones/Mueller matrix.
  - Reached ~0.6% precision on-axis (boresight).
  - Correct for ionospheric RM ~ 2 deg m^{-2}. Polarization angle rotation ~10-20 deg.

Leakage power spectrum estimate



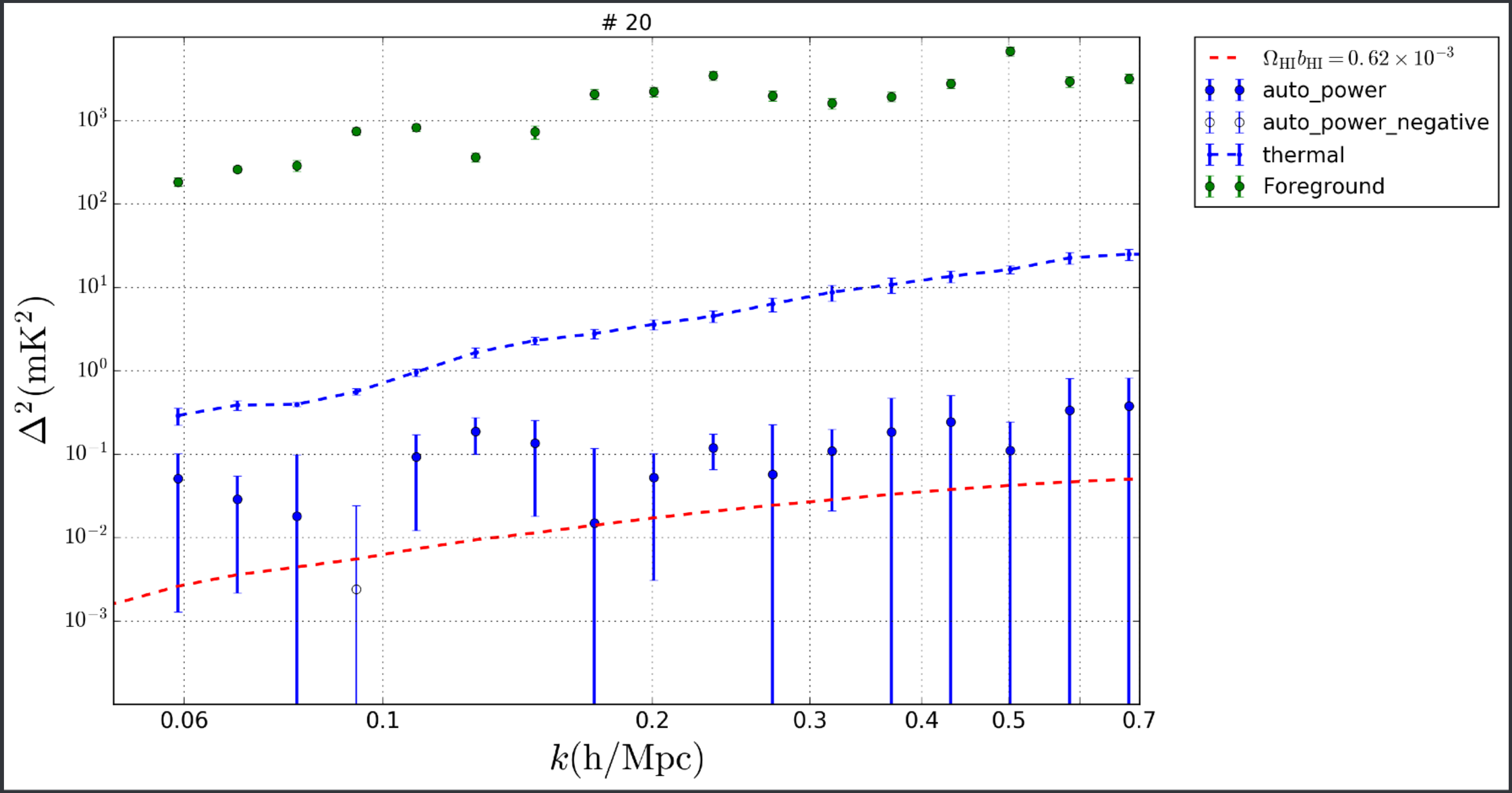


Chun-Hao To (Stanford)

To, Chang, Liao, GBT-HIM, in prep.

- Upper limits on leakage power spectrum contamination
  - Estimate (scan-averaged) pol-beam deconvolved maps, and calculate expected leakage.
  - Polarization leakage power spectra < 10% HI upper limits but can be10x expected HI signals; working on detailed simulations and error estimates
  - Incorporate full polarized beam model in map-making?

Work in progress: Updated HI auto-power spectrum at z~0.8



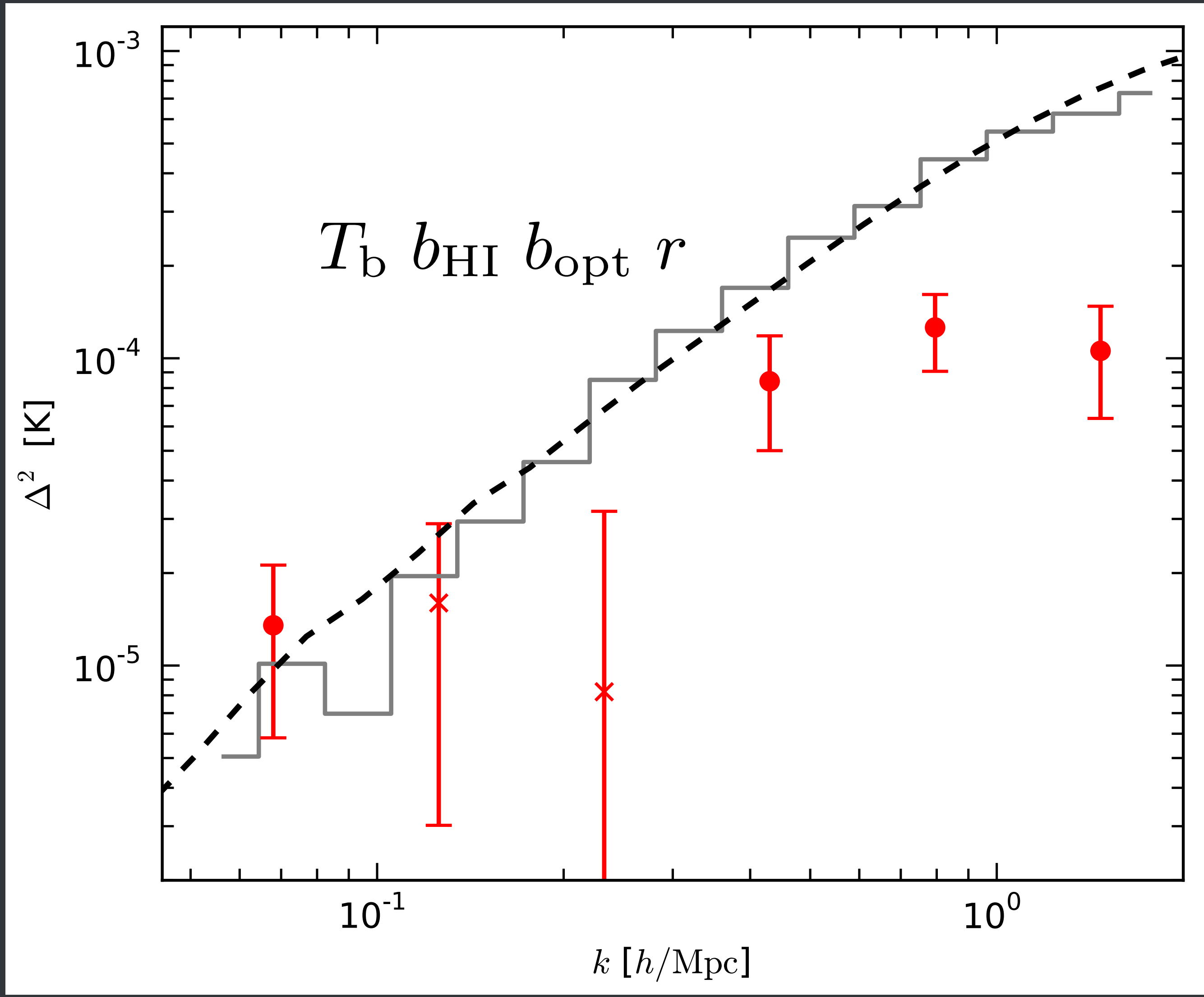
Chang, Liao, To + GBT-HIM, in prep.

- A ~4-sigma detection… of systematics?
- Currently running jackknife tests.
- More SNR would help!

Cross-correlation:

21cm Intensity Maps at z~0.08 with Parkes Telescope

Parkes HI-2dF Cross-power spectrum



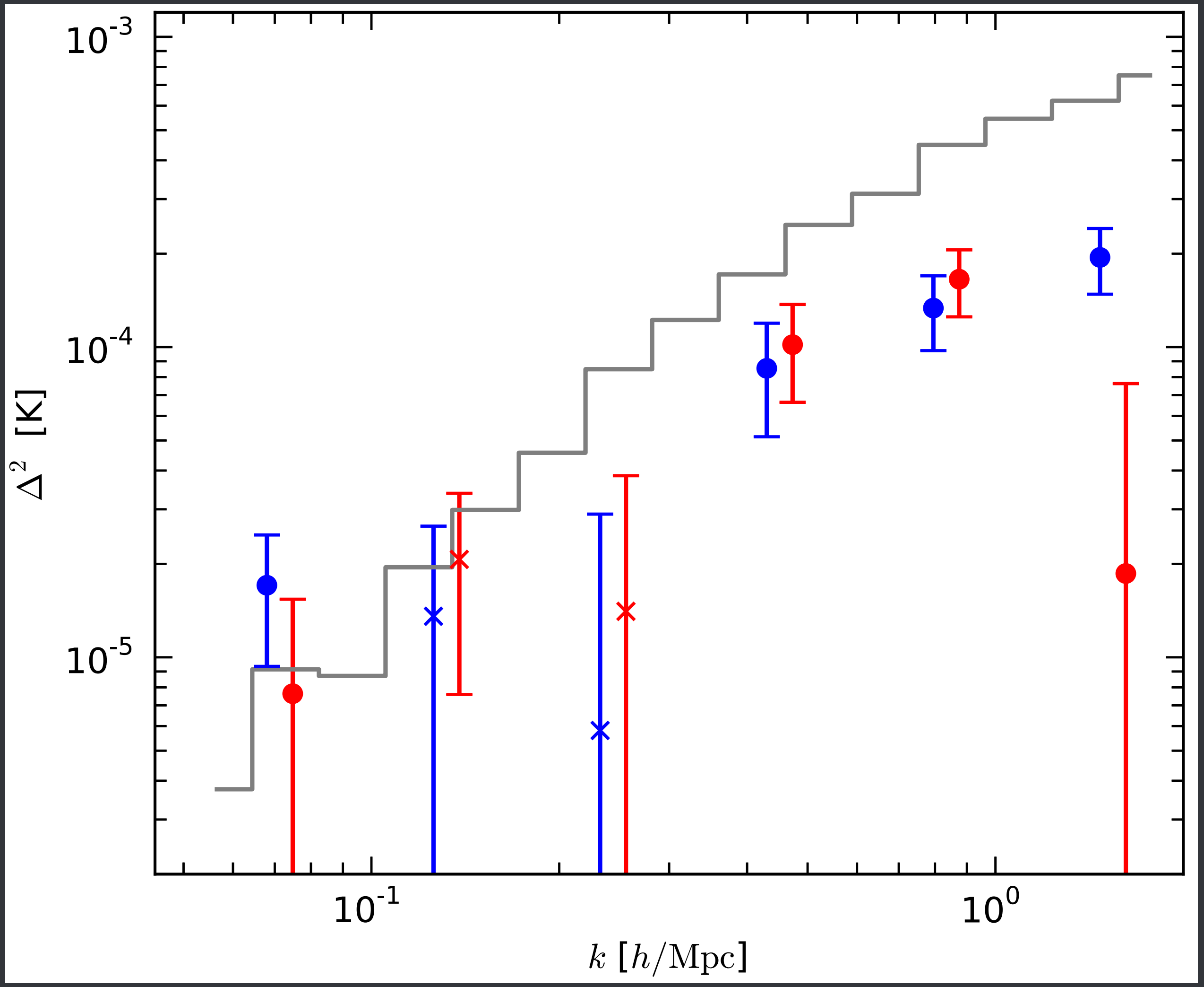
Chris Anderson
(UW Madison)

Nick Luciw
(CITA)

Anderson, Luciw + GBT-HIM, in prep.

- Parkes L-band multi-beam observation, 0.06 < z < 0.1, over 1500 sq. deg. , 150 hrs
- Significant cross-power spectrum with 2dF galaxy measured at ~12 sigma.
- Comparison with individual detection HI surveys, HIPASS and ALFALFA.
  - Cross-power amplitude ~ $T_b\ b_{HI}\ b_{opt}\ r$
  - b_HI=0.85, Tb=0.064 mK (ALFALFA; Marin+ 2010), b_opt~1 (Cole+ 2005).
  - Cross-power shape: curves include linear + non-linear RSD effects.
  - r likely < 1. Power deficit at k~1.5 h/Mpc

Parkes HI-2dF Cross-power spectrum



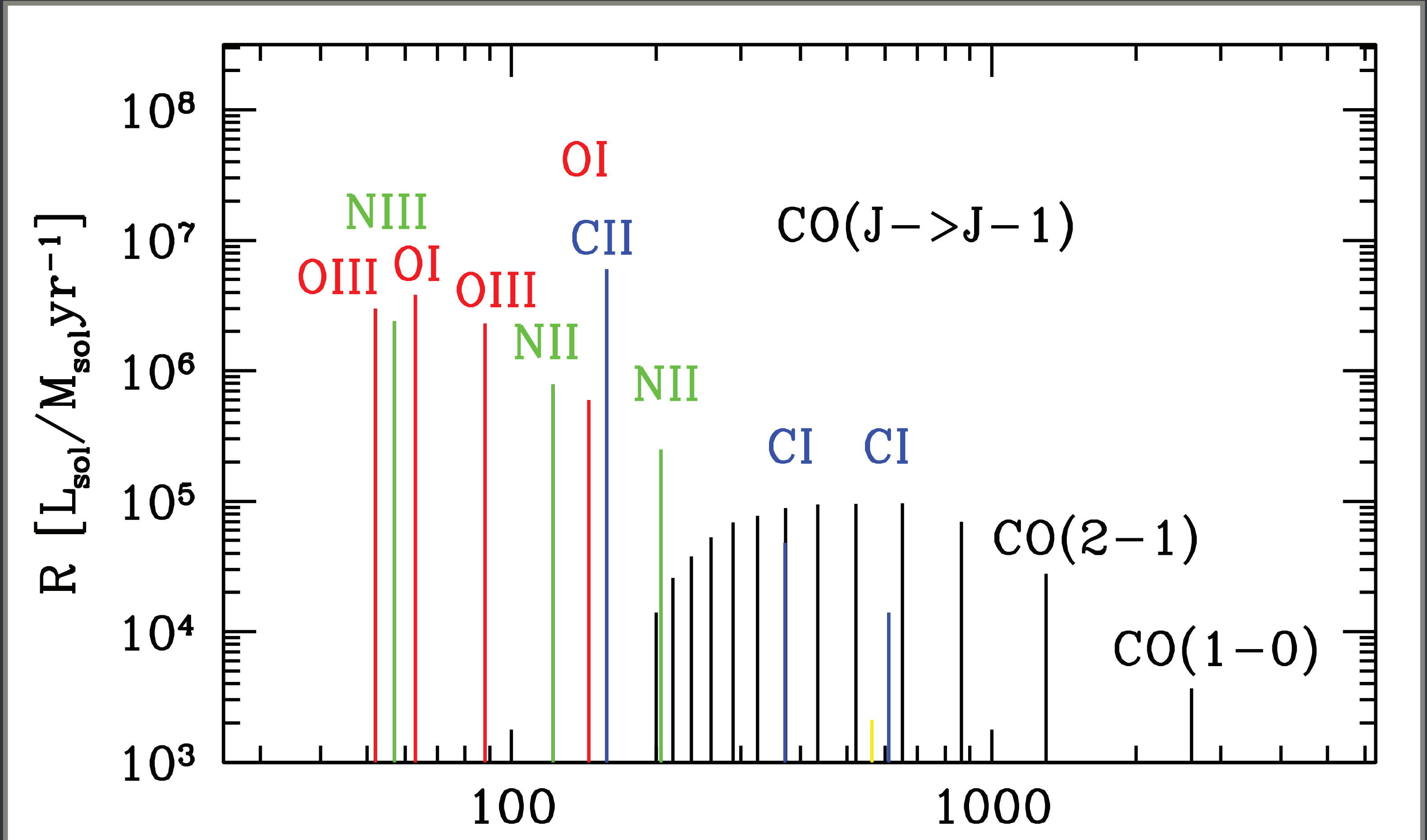
Anderson, Luciw + GBT-HIM, in prep.

- Cross-correlating with 2dF blue and red galaxies separately.
- HI follows distribution of blue galaxies but does not trace red galaxies at k~1.5 h/Mpc
- HI-galaxy cross-correlation coefficient appears scale- and color-dependent.
- Neither simple HI halo model (e.g. Padmanabhan+16) nor naive large-scale sims can capture this feature. We need better small-scale modeling!

EoR Sciences

[CII] Intensity Maps at z~5-9 with TIME

And all other spectral lines



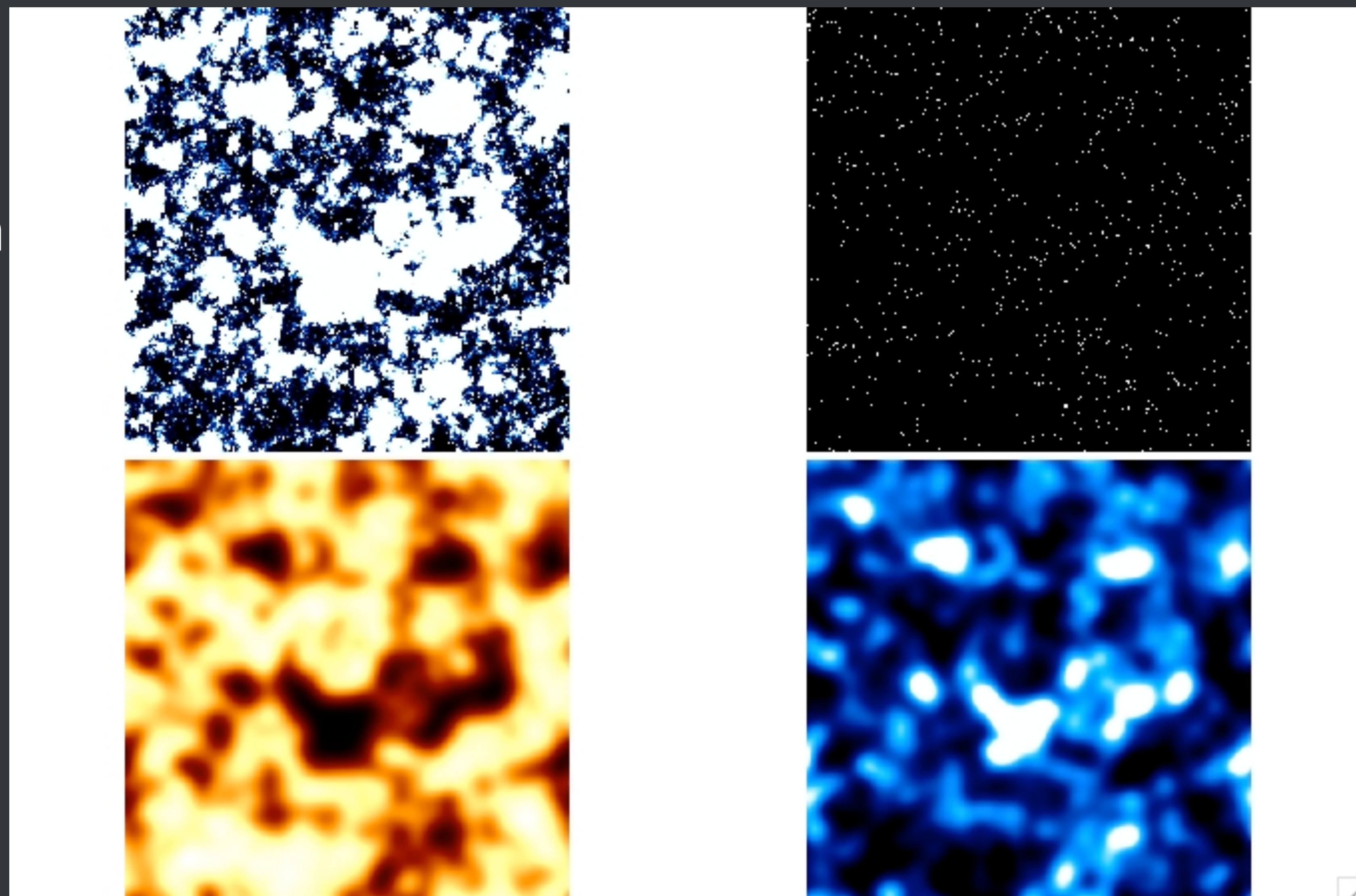
Visbal, Trac, Loeb 2011

- CO IM - CO rotational lines (CO(1-0) at 115 GHz rest frame): Righi+ 08, Visbal & Loeb 2010, Carilli 2011, Gong+11, Lidz+11, Pullen+13, Breysse+14, Breysse+15, Li+ 15, Mashian+ 15, Keating+15, Keating+16)
- [CII] IM - singly ionized carbon (158 μm rest frame): Gong+12, Silva+14, Yue+ 15, Serra+16, Cheng+16
- Lyman-alpha IM - Lya emission(1216 A rest frame): Silva+12, Pullen+13, Croft+16
- H-alpha IM - Ha emission (6562 A rest frame): Gong+ 16; Silva+ 17
- HeII IM - HeII (1640 A): Visbal, Haimann, Byran 2015

CO/[CII]/Ha intensity mapping

Ionization field

galaxy/halo field



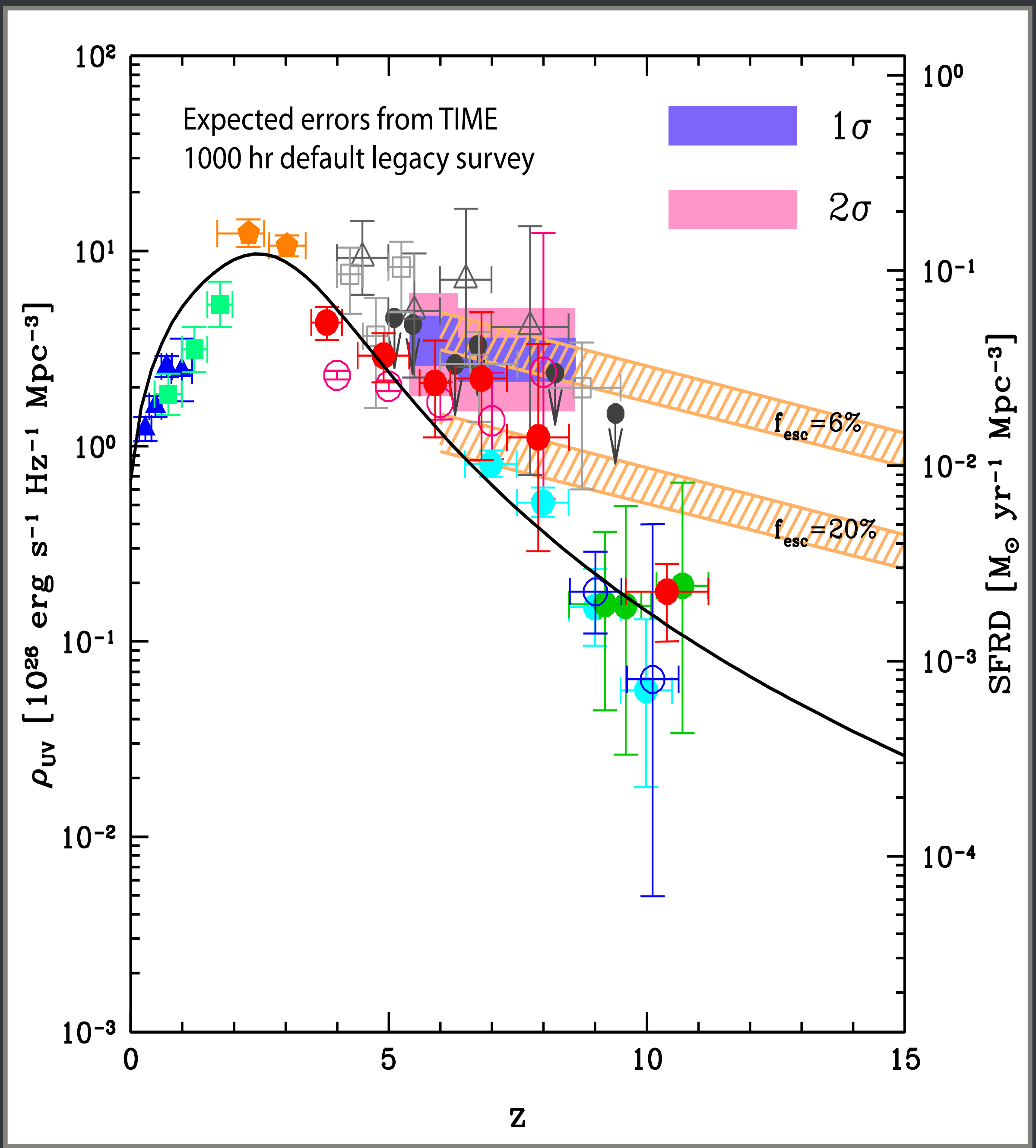
HI field

CO/[CII]/Ha field

Lidz et al. 2011

- CO/[CII]/Ha trace star formation activities on large-scales at EoR, anti-correlate with 21cm emissions on ionized bubble scales and can be used to derive bubble evolution and reionization history (Lidz et al. 2009; Chang et al. 2015).
- Continuum foregrounds are much less of an issue. Need to worry about line interlopers.

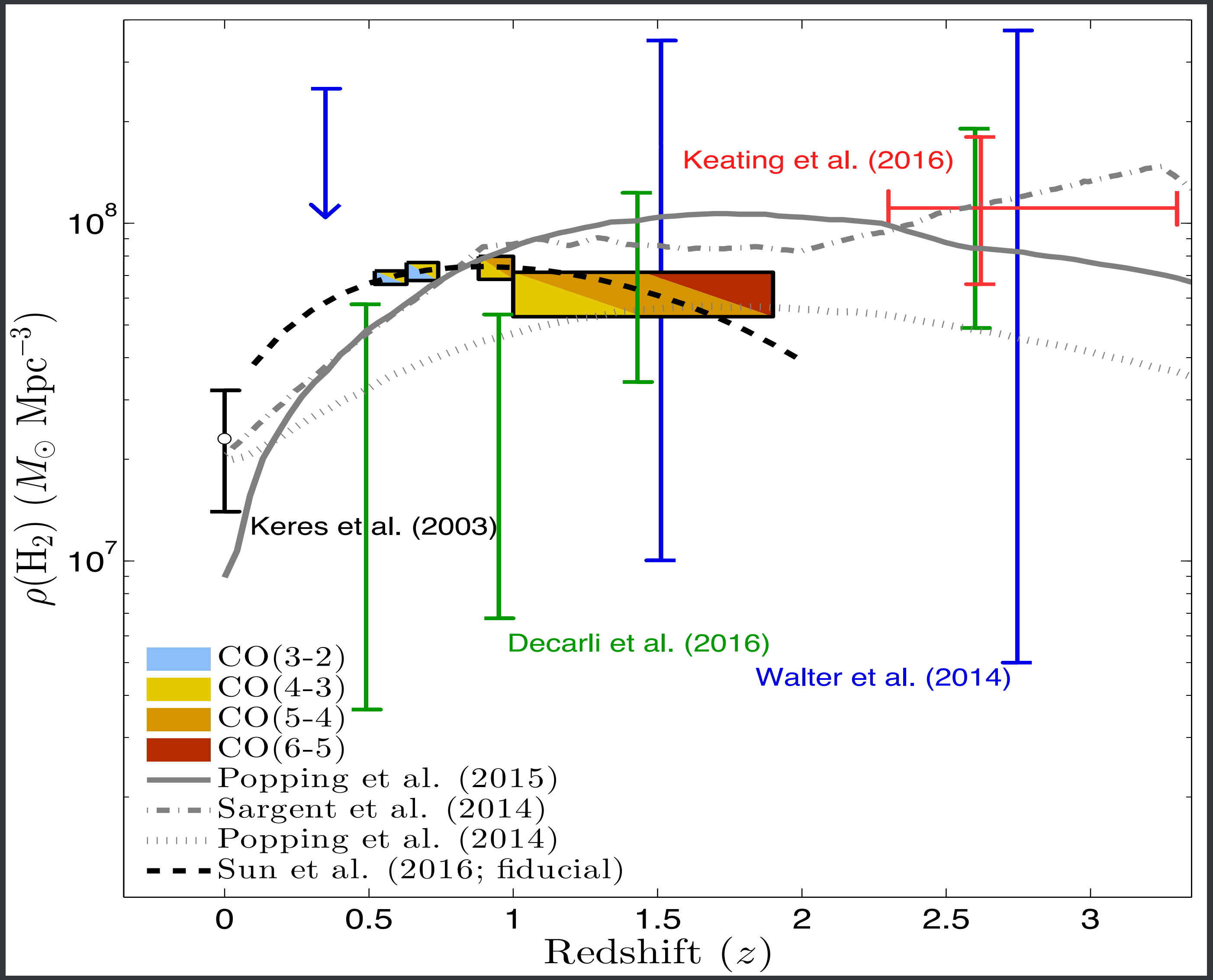
TIME: [CII] Intensity Mapper
Tomographic Ionized-C Mapping Experiment



TIME collaboration

- A [CII] Intensity Mapper for EoR at 6<z<9
  - 1840 TES bolometer array
  - 195-295 GHz, 32-channel spectrometer
  - to be installed on APA 12-m.
  - Caltech (J. Bock), JPL (M. Bradford, T.-C. Chang), ASIAA (C.-T. Li), UCI (A. Cooray), U Arizona (D. Marrone)
  - Engineering run expected fall 2018.
- [CII] IM traces star formation activities
- 1000 hours of observation, starting ~2019
- Measure [CII] P(k) at several 10s of sigma (model dependent)

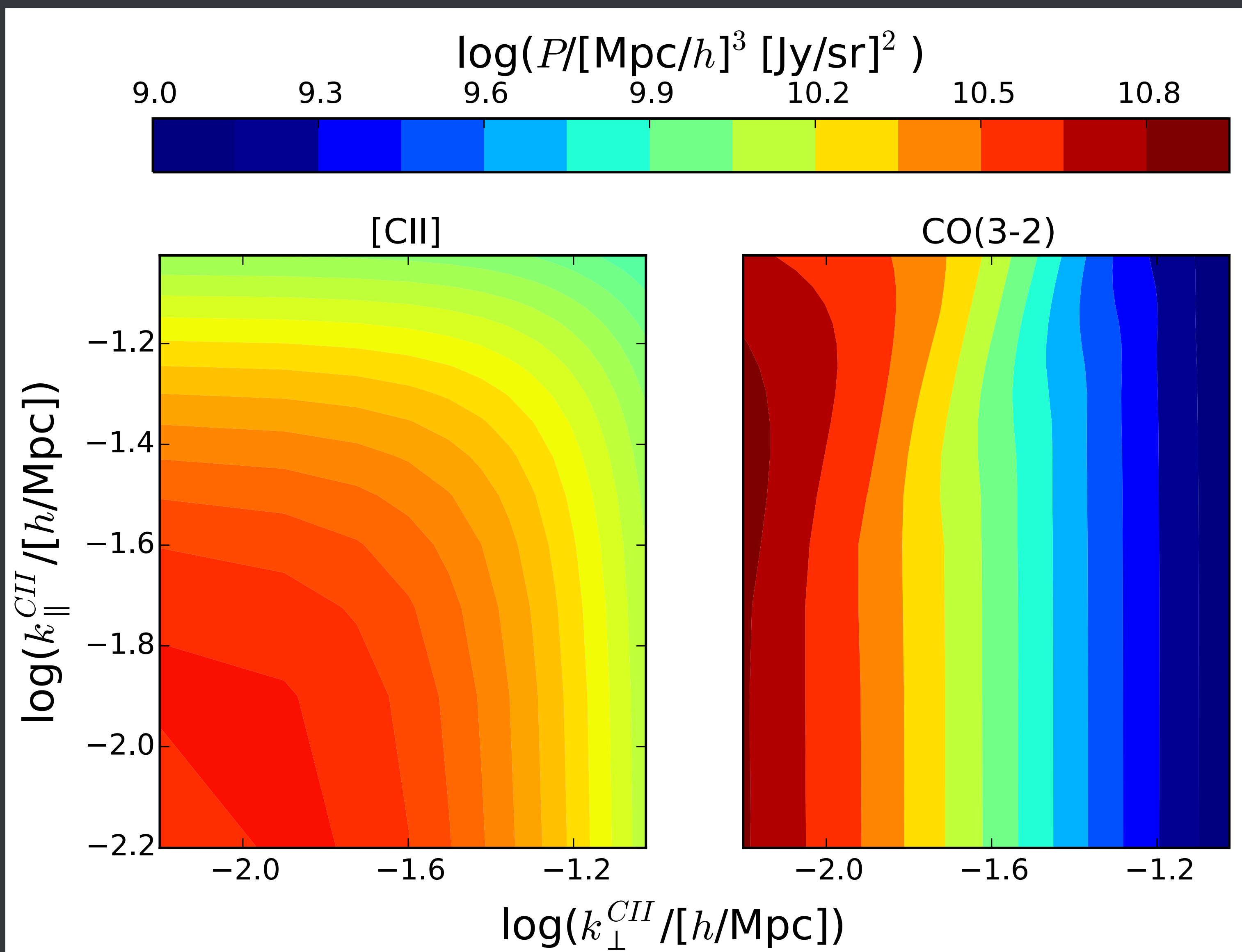
TIME measures CO/H_2 abundance at z=0.5-2



TIME collaboration

- TIME will measure multiple CO J rotational transitions at 0.5 < z < 2
- Can be achieved via in-band cross-correlations of different J lines
- TIME will constrain the cosmic molecular hydrogen abundance across redshifts

CO, [CII] signal de-confusion



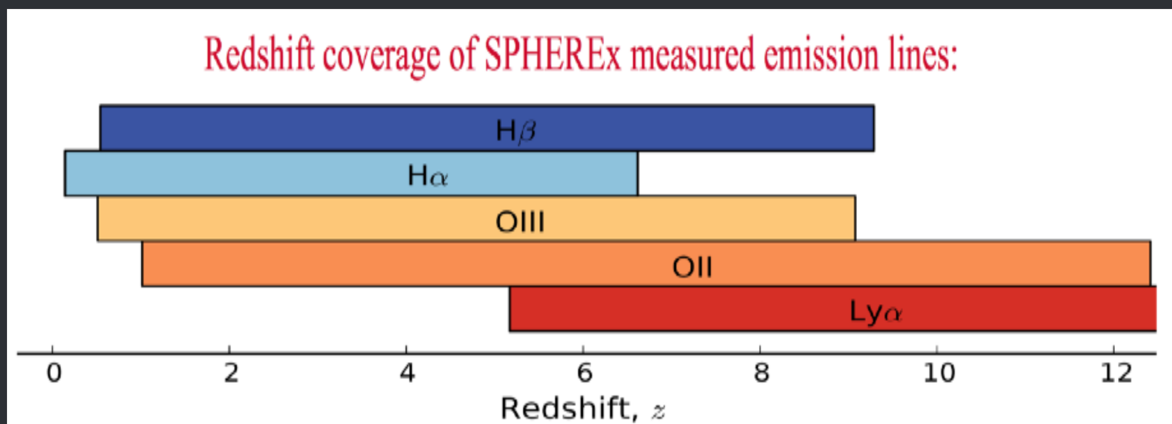
TIME collaboration (Cheng, Chang et al. 2016)

- High-z [CII] and low-z CO rotational lines can be confused in TIME
- Can use the redshift-dependence of CO and [CII] from observing to comoving coordinates to distinguish the lines (Lidz & Taylor 2016; Cheng, Chang et al. 2016).

EoR Sciences

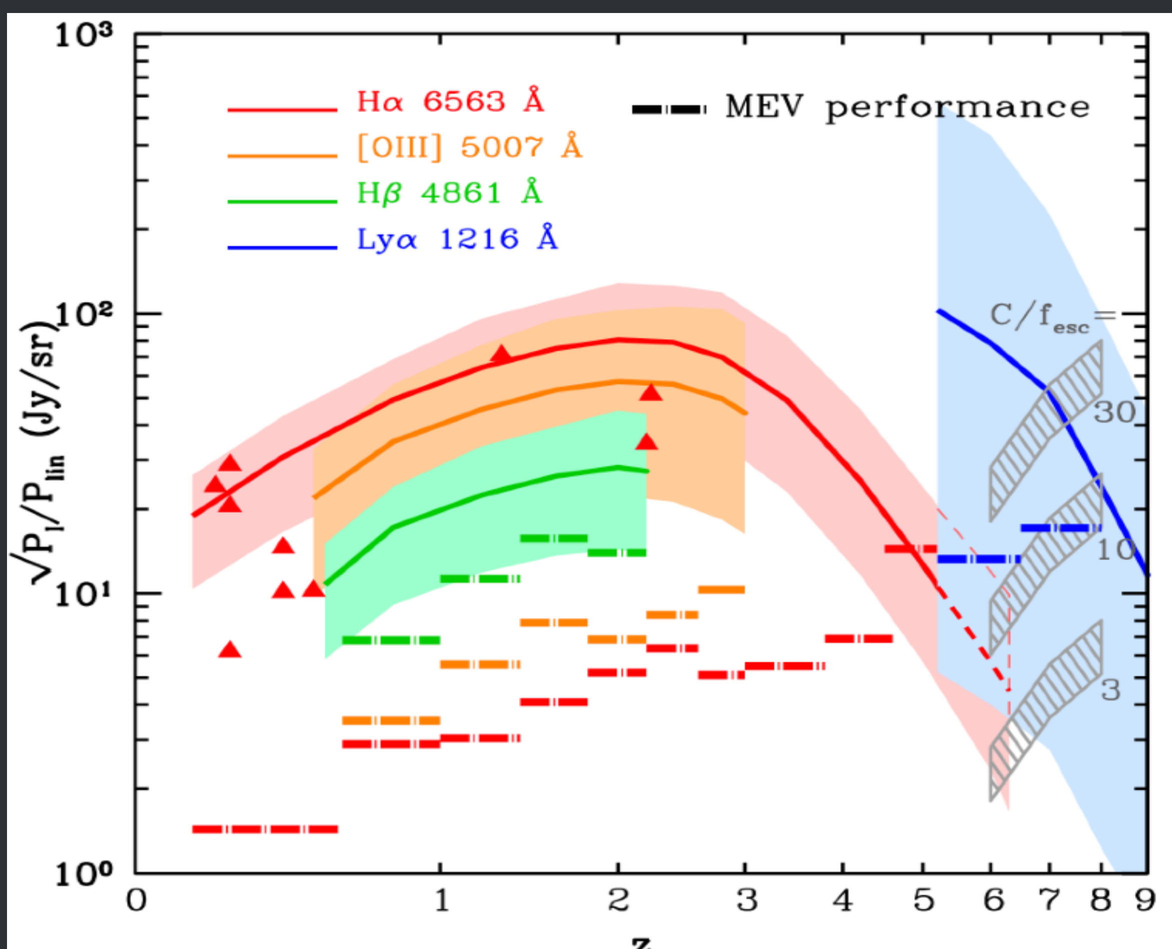
Lya, Ha Intensity Maps at z~6-9 with SPHEREx

Line Intensity Mapping with SPHEREx



Fluctuations in Line Emission

Clustering amplitude (bias)



Doré, Bock et al., arXiv:1412.4872

SPHEREx: low-resolution spectroscopic all-sky survey

For every ~3” pixel over the entire sky:

- ➡ **R=40 spectra spanning (0.75 μm < λ < 4.81 μm).**
- ➡ **R=150 spectra (4.1 μm < λ < 4.81 μm).**

- SPHEREx will measure 3D clustering of multiple line tracers at high SNR their luminosity-weighted biases.
- SPHEREx will map SFR throughout cosmic time
- SPHEREx might have sensitivity to detect Lya from EoR
- SPHEREx currently in MIDEX competition.

Summary

- Line Intensity Mapping offers an exciting and unique probe of a significant fraction of the Universe
- 21cm Intensity Mapping proof of concept demonstrated at z~0.8 (Chang et al. 2010).
  - Opens up 21-cm 3D large-scale structure studies (GBT-HIM multi-beam array; HIRAX, CHIME, Tian-Lai in progress; and possibly SKA1-mid.)
- [CII] Intensity Mapping offers a complementary probe of the Epoch of Reionization
  - TIME will probe the [CII] source clustering at $6 < z < 9$. First light expected 2018.
- CO Intensity Mapping: a ~2-sigma detection at z=2-3 (Keating et al. 2016).
  - COMAP (PI: K. Cleary; Caltech) and AIM-CO (PI: Y.-H. Chu, ASIAA) underway
- Lyman-alpha IM: a 3-sigma cross-correlation detection at z~2-3.5 (Croft et al. 2016).
  - SPHEREx may potentially probe Lya IM at z~6-8. HETDEX at z=2-3.
- EoR 21-cm detection may come from several groups with different approaches soon (LOFAR, PAPER, MWA). HERA/SKA1-LOW will bring next generation transformational sciences.