Cosmic Visions: 21-cm Roadmap

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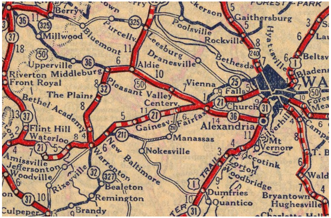


November 14, 2017

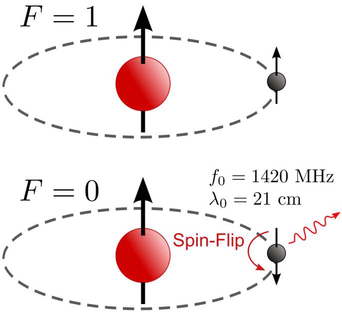
People

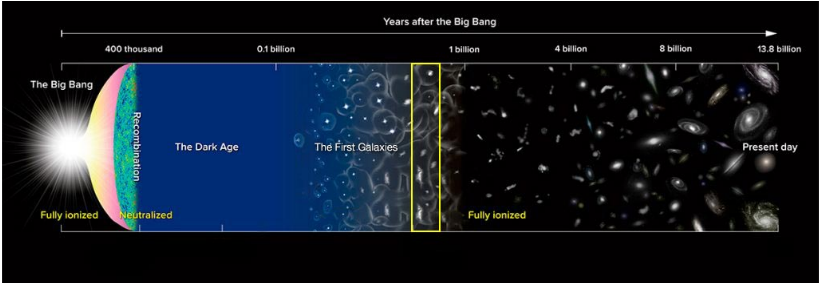
Numerous people working within Cosmic Visions working group helped with material presented here:

Collaborators (alphabetical): Marcelo Alvarez (Berkeley), Phil Bull (Berkeley), Emanuele Castorina (Berkeley), Tzu-Ching Chiang (JPL), Adrian Liu (Berkeley), Francisco Antonio Villaescusa Navarro (Flatiron Institute), Andrej Obuljen (ICTP), Paul O'Connor (BNL), Richard Shaw (CITA), Chris Sheehy (BNL), Paul Stankus (ORNL), Albert Stebbins (FNAL), Matteo Viel (SISSA)

21-cm emission

- Transition in neutral hydrogen at $\nu = 1420$MHz, $\lambda = 21.1$cm
- It is the only transition around – if you see a line at 710MHz, you can be sure it is a galaxy at $z = 1$.
- (not true in optical)





Dark Ages $20 \lesssim z \lesssim 150$:

- Pristine primordial density field, non-linearities non-existent
- CMB in 3D: amazing science
- Very low frequencies, very little bandwidth, atmosphere matters, 30 years from now

Epoch of reionization $6 \lesssim z \lesssim 20$:

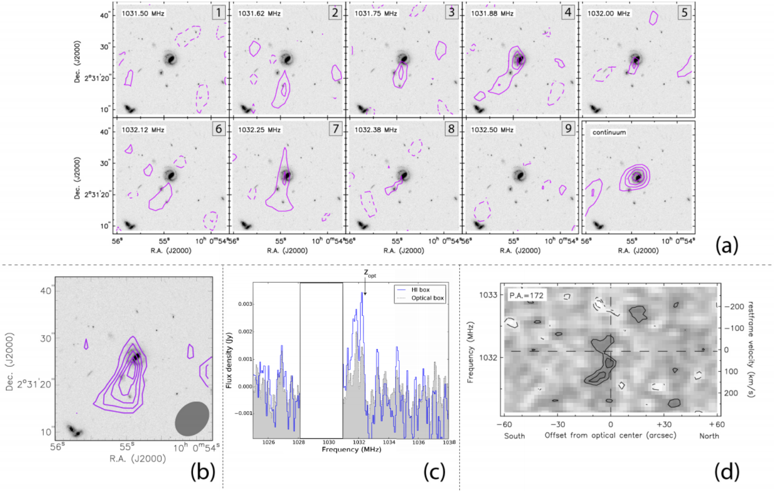
- First stars and galaxies are reionizing universe
- Large bubbles of ionized gas among neutral medium: large contrast
- Signal driven by astrophysics (although one could imagine some cosmological applications, e.g. weak lensing of bubbles)
- Non-DOE science
- Current generation: HERA, MWA

Low redshift $z \lesssim 6$:

- Universe is reionized, pockets of neutral hydrogen in galaxies
- One sees integrated emission from all galaxies, which could be in principle resolved
- Very similar science to standard galaxy surveys
- Current generation: CHIME, HIRAX, TIANLAI, GBT

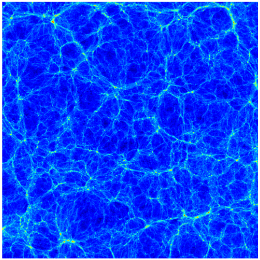
21-cm galaxies

It is a weak transition: 21-cm detection redshift record: $z = 0.376$ using 178 hours of VLA data (Fernández et al, 2016)

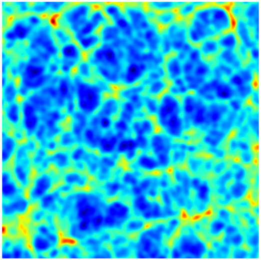


21-cm intensity mapping

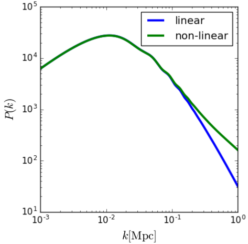
- The main idea is to give up on resolving individual galaxies:
- For scales much bigger than individual galaxies, the overall signal will still trace the underlying number density of galaxies
- Put SNR where you really need it – linear large scale modes
- Signal for galaxies is the only component that is not smooth in frequency



Full resolution

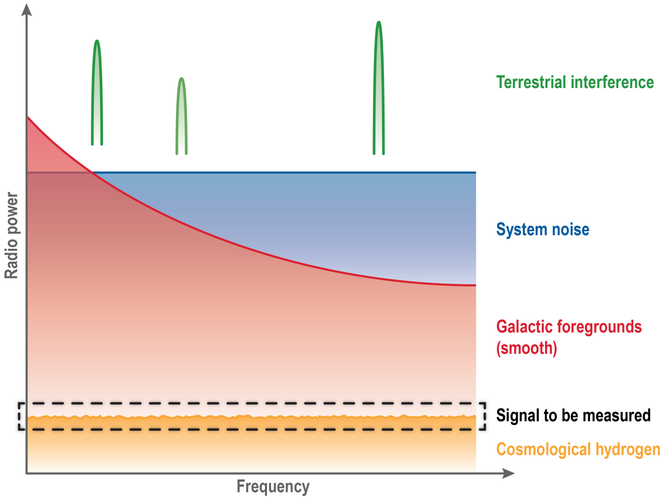


Low resolution



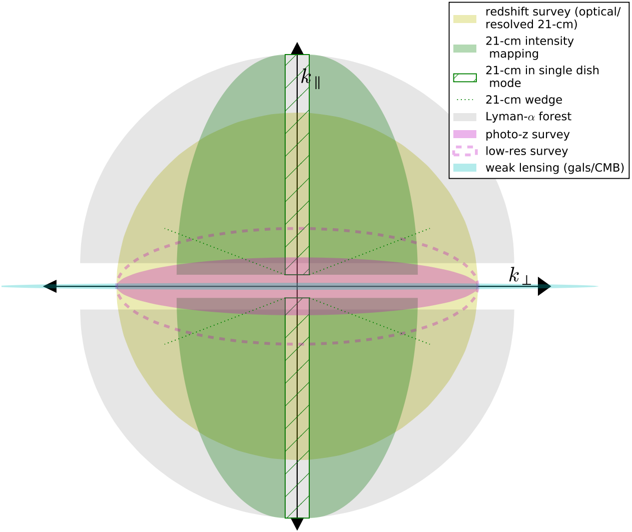
Matter power spectrum

Everything else...



- Signal is subdominant, but the only non-smooth component.
- Of course, instrument can have non-smooth, time-varying response too!

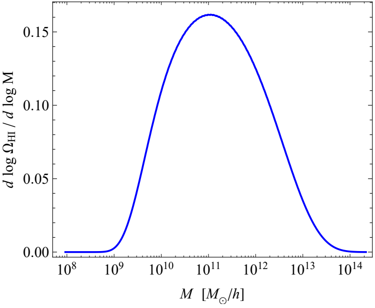
Main difference with galaxy surveys



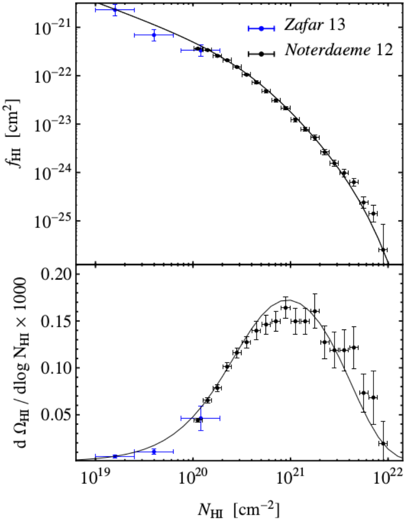
- We definitely loose low $k_\parallel$ modes ($k_\parallel \lesssim 10^{-2}\mathrm{Mpc}^{-1}$) directly
- Low $k_\parallel$ modes could be recovered using tidal reconstruction
- We potentially loose modes inside the wedge, but could get them back with good calibration
- Additionally, we do not have the mean signal, limiting usability of redshift-space distortions, but useful priors derived from other measurements are possible

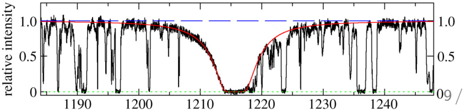
We're looking at small galaxies

- Most contributions from DLA-type galaxies, $M \sim 10^{11} M_\odot$
- These are less massive, but many more numerous than typical optical survey galaxies



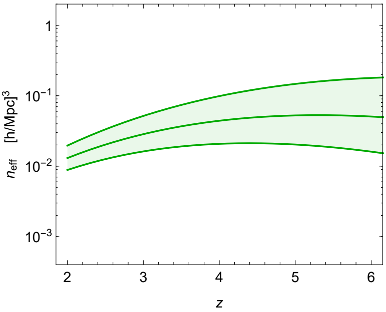
Figs from Emanuele Castorina et al

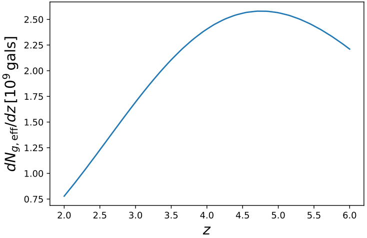




We're looking at many galaxies

- In any galaxy survey, $\bar{n}$ is the fundamental quantity that determines the shot noise contribution $P_s = \bar{n}^{-1}$.
- The shot noise is not beatable unless you get more galaxies
- 21-cm cosmology has $T_{\rm sys}$ noise contribution, but that is beatable with sufficiently big instrument
- A 15k square degree survey corresponds to ~ 8 billion galaxies
- This is twice the number of galaxies in LSST without loss of radial modes due to photo-zs (but no sample subdivision)





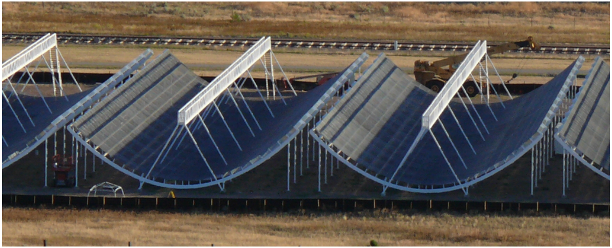
From Castorina & Villaescusa-Navarro

What kind of instrument you need

- Traditional radio telescopes are interferometers
- Dish size determines field of view
- Longest baseline gives resolution
- For intensity mapping one typically wants:
  - compact array
  - favor number of baselines over ability to track
- **Traditional radio telescopes do not cut it**

What do you need?

- You need exquisitely well calibrated telescope with sufficient resolution to resolve linear modes, but not more than that
- At low redshift this could mean single dish, at $z > 2$ almost certainly an interferometer
- SNR considerations favor **compact arrays**
- Survey/money consideration favor **transiting telescopes**
- Example: CHIME, operating in Canada:



- CHIME will map universe between $z = 0.8$ and $z = 2$ over half the sky

Frequently Asked Questions

Q: What can intensity mapping do for you that galaxy survey cannot?
A: It is a new window into the structure of the universe. It can be **cheaper** with **very different systematics**. It can probe deep into the **tail of the mass function**. Low-z 21-cm can act as a **stepping stone to dark ages** experiment.

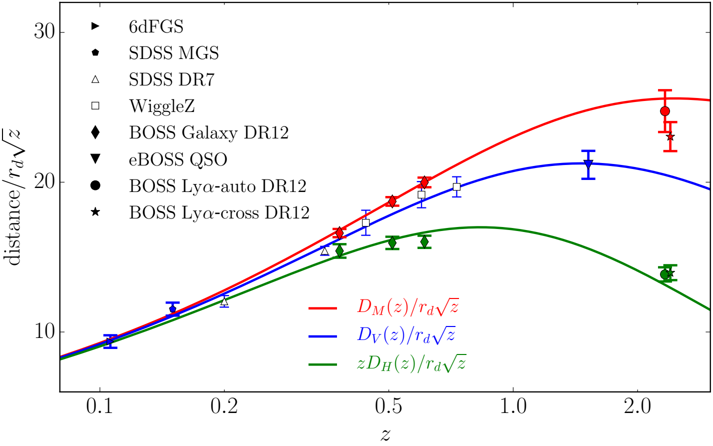
Q: But won't SKA do all of it?
A: No, SKA is a traditional radio telescope designed for resolving individual objects. It would do some, but not optimized for IM.

Q: But foregrounds will kill it anyway. . .
A: Foregrounds are a major issue, but techniques for dealing with them are being developed and tested as we speak.

What is the exciting science then?

- Within the DOE Cosmic Visions 21-cm WG, we discussed various possibilities.
- We settled on the following straw-man experiment:
  - 64×64 array of 10m dishes, surveying $z = 2 - 6$ over $f_{\rm sky} = 0.5$
  - This is very reasonable: e.g. HIRAX is 32×32 array of 6m dishes and the estimated cost is $10 million.
- It so happens, that FRB people independently came with essentially the same concept (+few outriggers for localization)

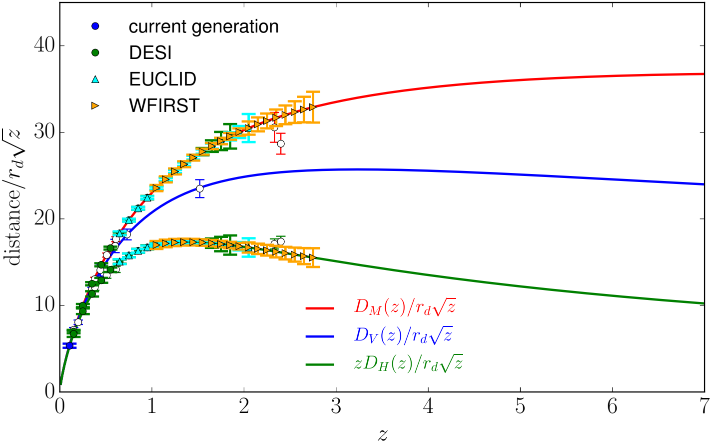
Measure Expansion History



Current expansion history measurements

- Expansion history is **basic cosmological quantity**
- There is a big picture argument that we should complete our program of measuring the expansion history throughout universe first
- Current measurement reach to $z \sim 2$

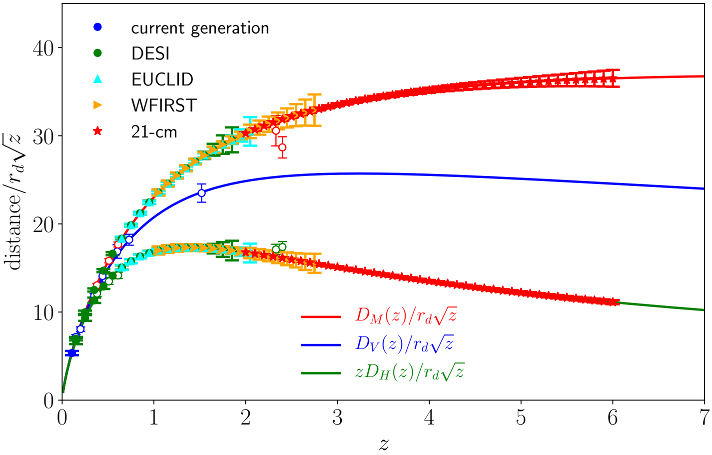
Measure Expansion History



Current + DESI, Euclid, WFIRST

- Expansion history is **basic cosmological quantity**
- There is a big picture argument that we should complete our program of measuring the expansion history throughout universe first
- Future measurements will reach to $z \sim 3$

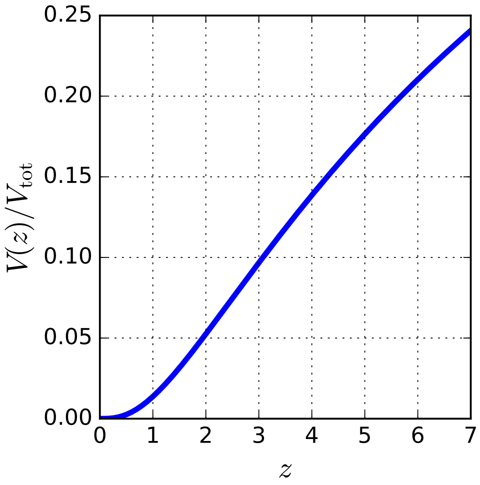
Measure Expansion History



Current + DESI, Euclid, WFIRST + 21-cm strawman
Based on Obuljen et al 2017

- Expansion history is a **basic cosmological quantity**
- There is a big picture argument that we should complete our program of measuring the expansion history throughout universe first
- 21-cm can realistically reach to $z \sim 6$
- Uses mid-Wedge, could do better

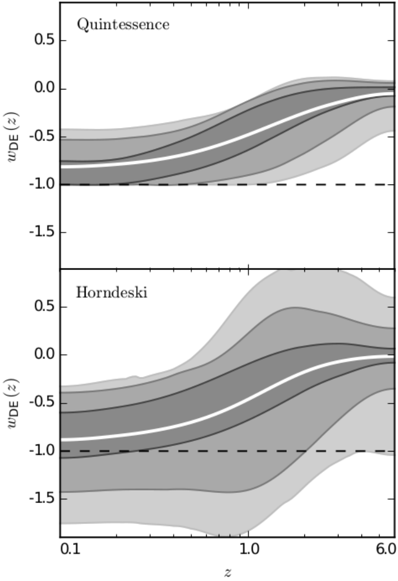
Triple the total surveyed volume



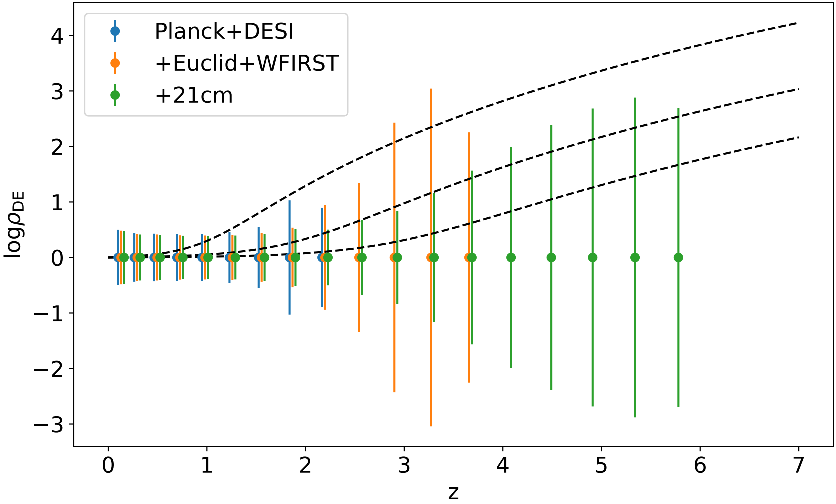
- There is approximately 3× comoving volume between $z = 2$ and $z = 6$ than there is between $z = 0$ and $z = 2$
- Any science that depends on the number of linear, *easy to model* modes will benefit
- E.g. non-Gaussianity, precision $N_{\rm eff}$

Constrain modified gravity / Early DE

- Horndeski theories are a very general class of modified gravity theory
- Under some parameterization, they do appear as early dark energy
- Expansion history to high-z is a natural place to look for these theories
- Plot adapted from Raveri et al. 2017

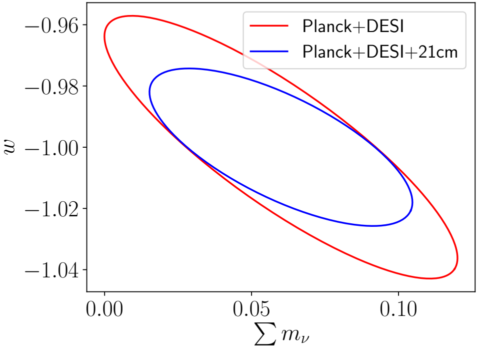


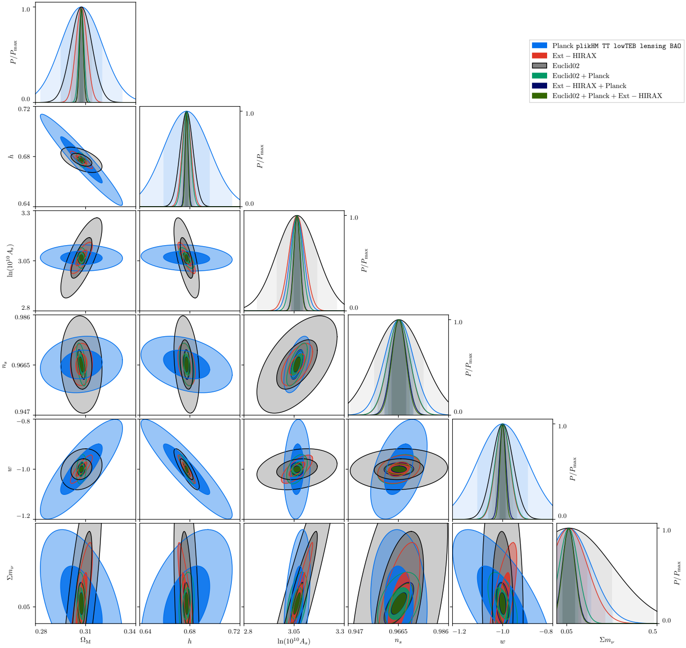
Follow Dark Energy through time



Help break $m_\nu - w$ *degeneracy*

- A long known degeneracy between w and $\sum m_\nu$.
- Often neglected in Fisher forecasts, most importantly DETF
- 21-cm helps by measuring expansion history in the pre-acceleration era
- Improves m_ν limit by 25% if simultaneously fitting for dynamical dark energy

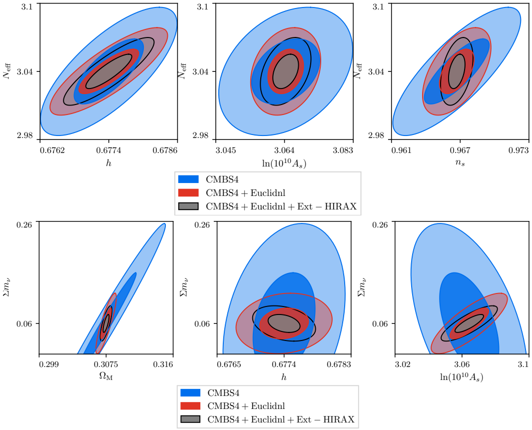




w from $\sigma[w] = 0.03$ to $\sigma[w] = 0.01$ (on Planck+Euclid /+ 21cm)

Constrain N_{eff} and m_ν

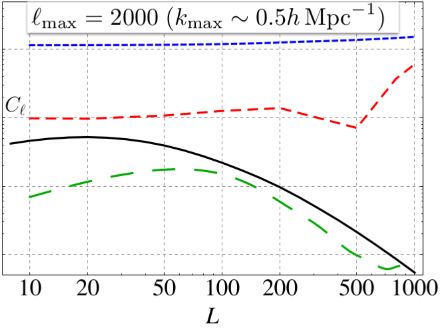
- Can significantly improve on N_{eff} and m_ν even after CMB S4 and DE S4 BAO
- Provides independent check – all probes are hitting systematic floors
- Without S4, it can reach $\sigma[N_{\text{eff}}] = 0.04$ with S4, optimistically $\sigma[N_{\text{eff}}] = 0.015$. Target value is 0.027 (a single additional particle that was at some point in thermal equilibrium with the Standard Model)
- Can improve $\sum m_\nu$ errors on S4 by factor 1.5 to 0.03eV



From Obuljen et al, 2017

Weak Lensing and Tidal reconstruction

- The small scale power spectrum will change locally due to: i) presence of lensing foreground at lower z, ii) presence of non-linear coupling to a large scale mode at the same z
- Can only do lensing in cross-correlation (but perhaps internally)
- Tidal mapping will allow us bring-back modes lost to foregrounds, perhaps with "delensing" first using other datasets



From Simon Foreman: contributions to CMB-like lensing estimator: $C_\ell^{\phi\phi}$(black), noise (blue), gravitational (red - unremovable, green removable)

Constraints on non-Gaussianity

	$f_{\rm NL}^{\rm loc} < O(1)$	$f_{\rm NL}^{\rm loc} > O(1)$
$f_{\rm NL}^{\rm eq.,orth.} < O(1)$	Single-field slow-roll	Multi-field
$f_{\rm NL}^{\rm eq.,orth.} > O(1)$	Single-field non slow-roll	Multi-field

- Measuring these parameters to this precision informative either way
- The least well forecasted aspect in 21cm
- In principle, it should be easier than with galaxies, because we're working with continuous fields rather than tresholded objects
- A four-point estimators can presumably be constructed relying on tidal mapping for large modes
- Can stay in observed quantities and link to primordial NG:

$$\langle V_{\tau,\mathbf{a}} V_{\tau',\mathbf{a}'} V_{\tau'',\mathbf{a}''} \rangle = \frac{\bar{I}^3}{(2\pi)^9} \int B\left(k, k', |-\mathbf{k}-\mathbf{k}'|; k_{\parallel} = \frac{2\pi(\tau + \mathbf{a}\cdot\theta)}{c_{\parallel}} k'_{\parallel} = -\frac{2\pi(\tau+\tau''}{\ldots}\right.$$

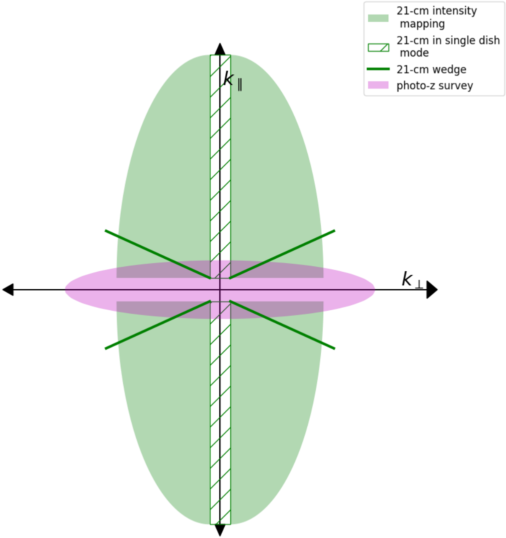
$$e^{i\mathbf{k}_{\perp} c_{\perp}(\theta''-\theta) + i2\pi(\mathbf{a}\theta + \mathbf{a}'\theta'' + \mathbf{a}''\theta'')\nu + i2\pi(\tau+\tau'+\tau'')\nu} d^2\theta d^2\theta'' d\nu d^2 k_{\perp} \quad (1)$$

Dark Ages

- Whether dark ages can be done is highly-speculative, but it is the natural follow-up
- This would be **transformative**.
- System essentially linear, we observe pure density fluctuations
- CMB in 3D
- The only known alternative to measures primordial tensors
- It gives a natural ultimate experimental target

Help calibrate photometric redshifts

- LSST scientific reach will most likely be limited by photo-z systematics
- Individual redshift samples will have systematic offsets in mean and variance of $N(z)$ that can matter at the statistical precision
- Cross-correlation technique can alleviate this and 21-cm offers a very good opportunity to do so at $z>0.75$
- Combination of DESI/Euclid/WFIRST can achieve the same, but this could be an interesting alternative from a single instrument

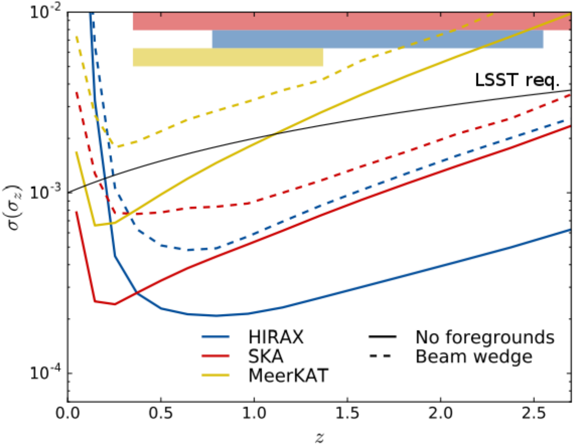


- Photo-Zs act as a low pass filter in $k_{||}$
- 21-cm systematics forces a high-pass filter in $k_{||}$
- Wedge, due to interferometric beam chromaticity additionally cuts the number of common modes
- The expected sensitivity very dependent on the number of common modes measured
- The better LSST does, the more 21-cm can help it!!

Nominal predictions

Not too hopeless, assuming:

- Foregrounds are smooth to $\Delta f/f \sim 0.1$
- We can live inside primary beam wedge



Current status worldwide

Outside DOE:

- CHIME – Canadian experiment, starting first light with full array – should detect BAO z=0.75-2
- HIRAX – South African experiment, seed funded and being prototyped
- FIRST: 500m single dish Chinese experiment
- BINGO, proposed UK experiment

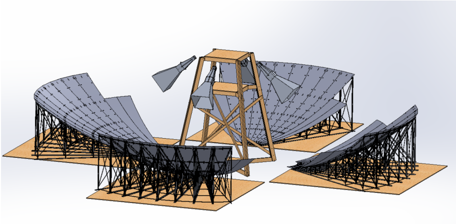
Inside DOE:

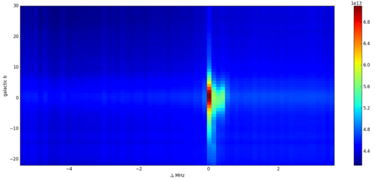
- Tianlai involvement at Fermilab
- BMX prototype at BNL

All these experiments will, in the next 5 years, demonstrate the promise of the technique.

BMX

- A 4-dish interferometer on-site funded by LDRD
- Low-redshift $z < 0.3$
- Technology demonstrator
- Orthogonal to others: expensive and small rather than cheap and big
- Beam calibration methods, lowest $k_{||}$, etc.





Roadmap

	White Paper Expt	Post LSST/DESI	Dark Ages	Context
2018-2020	Downselect and Design of LSST redshifting expt.			CHIME first resuts
2020-2025	data taking	Collaboration forming and CD0/1		HIRAX first results, SKA online
2025-2030	data analysis	Construction, start of data taking	feasibility study, preliminary design	SKA results coming
2030-2035		data taking & analysis	Moving forward if feasible	?
2035 -			Design, construction, victory	?

LSST redshifting in 21-cm

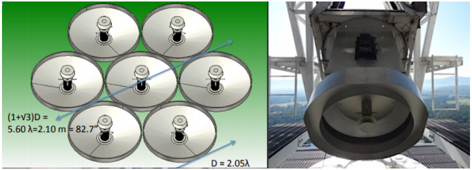
- Cosmic Visions 21-cm WG identified LSST redshifting as a short-term opportunity
- Several options for this particular goal:
  - Build an instrument for GBT
  - Join an existing interferometric experiment
  - Build our own interferometric experiment

GBT instrument

- GBT is a 100m dish in search of love
- Some 6k square degrees overlap with LSST
- If one sticks to low-frequencies, very cheap to operate (O(1-2)$k per hour)
- Does not suffer from the wedge issue
- A few million could build and operate a dedicated instrument
- Main problem is that limited amount of space at the primary focus

GBT instrument

- Pixels with short back-fire antenna: compact, but limited in bandwidth
- phased array feed: potentially possible, but lots of R&D to make it work
- Forecasts show least margin: but no wedge could compensate



Tzu-Ching Chang's 7-pixel array

ASKAP phase array

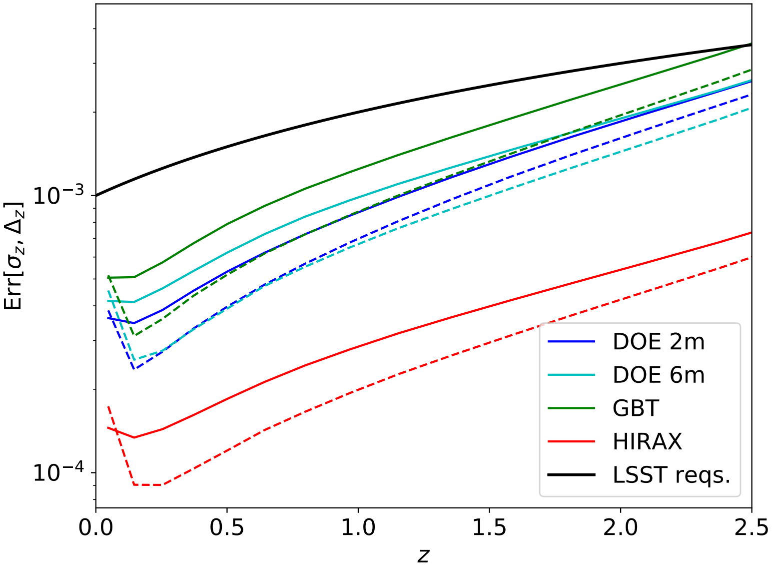
Joining existing experiment

- HIRAX is exciting, because it is on the southern hemisphere
- If operating at spec, the SNR is plenty for LSST redshifting
- The cost is exciting: 5-10 million USD for significant participation
- Will also do BAO and $z = 0.8 - 2.5$
- Currently have $\sim$ 1.5mil USD for prototyping
- Excellent site on SKA grounds agreed
- The real issue is whether a mutually agreed modus operandi can be agreed
- Other possibility: Tianlai: smaller overlap with LSST but dynamics might be different

Build our own

- We have been looking at small configurations 16×16 elements that are either 2m or 6m.
- Based on US soil to save money, 6k square degrees overlap
- It is doable for about \$10M (correlator around 0.5, elements around 0.5, infrastructure around 2, data management around 0.5, operations around 1.5 + overhead + contingencies)
- Better in terms of know-how development
- Novel design using BINGO inspired foam horns – beautiful beam

2 m horn with 78 sheets of 25 mm thick foam



- Projections by David Alonso
- Have nominal foregrounds but no wedge
- We have our own code that has not quite converged

Synergies with DOE

- **Precision RF technology**: people who do accelerator RF cavities can do antenna design
- massive bandwidth, real time **digital signal processing**: lots of experience from accelerator triggering and processing
- **Project management**: radio interferometers are made of many identical pieces to be accurately replicated, tested, databased
- **Data Analysis**: Datasets are huge requiring use of HPC facilities
- A good **philosophical match**: few numbers, army of drones

Synergies with CMB S4

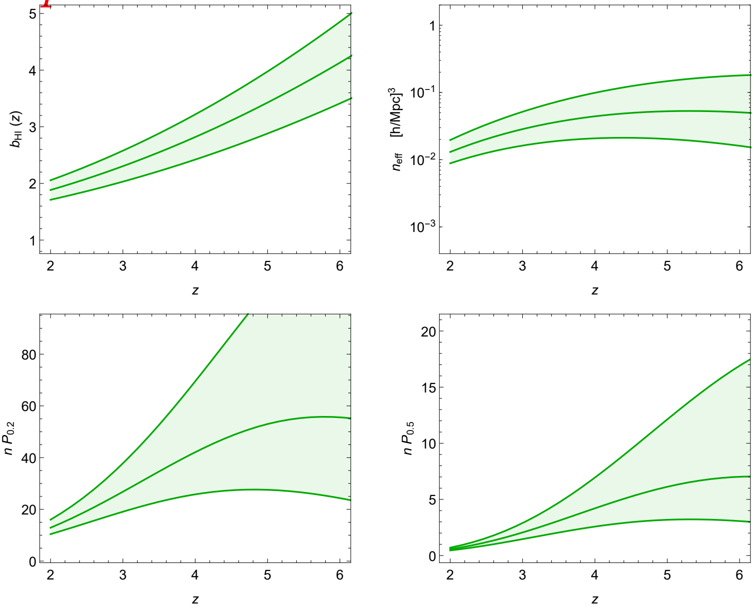
- **Importance of beam characterization** common to CMB S4 and 21-cm: could use common technology and solutions (using e.g. drones)
- **Map-making and foreground removal** schemes potentially similar
- Data analysis and **systematic mitigation** similar
- Lots of CMB S4 people have deep knowledge and understanding of interferometers from early CMB days

Conclusions

- We should do it!

BACKUP SLIDES

Bias plots



Motörhead

If you like to gamble, I tell you I'm your man,
You win some, lose some, it's all the same to me,
The pleasure is to play, makes no difference what you say,
I don't share your greed, the only card I need is
The Ace Of Spades