

21-cm cosmology in the coming decade

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Yale, December 2019

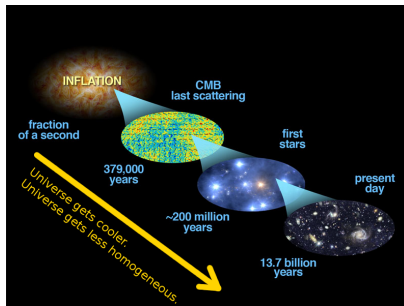
Plan for the talk

- ▶ Overview of current experimental landscape in cosmology
- ▶ 21 cm cosmology as a possible new technique on relatively short time-scales
- ▶ Stage II concept
- ▶ promises and drawbacks of this technique

Cosmic pizza & the Universe

Universe is going:

- ▶ hot & dense → cool & rarefied
- ▶ homogeneous → clustered
- ▶ easy to model → hard to model

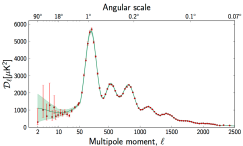
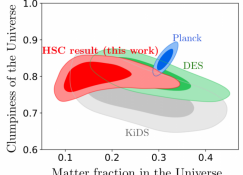
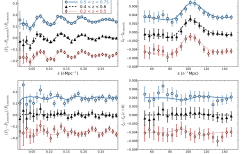


Components of the Universe:

- ▶ Baryons: the standard model of particle physics
- ▶ Dark Matter: mysterious within reason
- ▶ Dark Energy: very mysterious

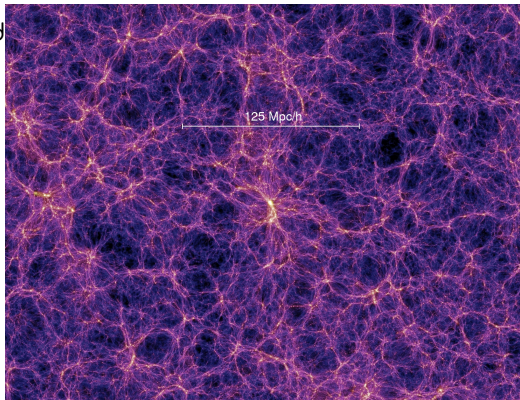


Study of the universe today: experiment

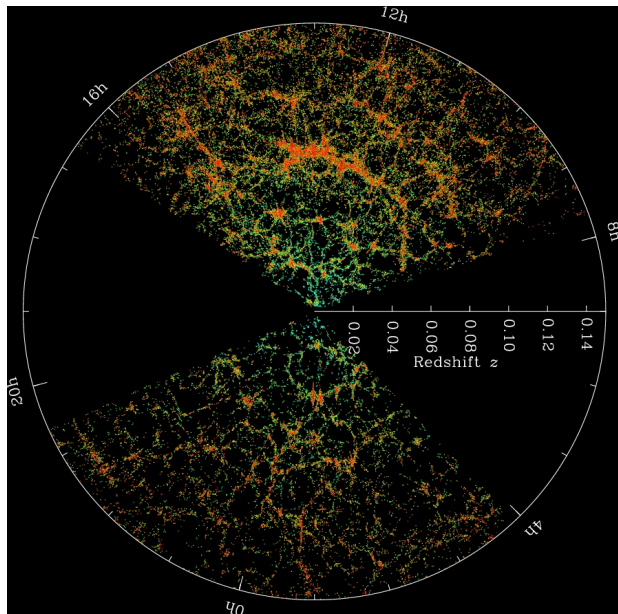
CMB: Early Universe, $z > 1100$ Easy to model (but getting harder) Primordial fluctuations: T, E, B Secondary: lensing, tSZ, kSZ, ISW		Past: Planck, WMAP Future: Simons Observatory, CMB-S4 ? LiteBird? Pixie??
Photometric experiments: Late Universe, $z < 3$ Harder to model (not getting easier) 2.5D: number density, weak lensing, cross-corr, clusters, SN		Current: DES, HSC, KiDS Future: LSST, (Euclid, WFIRST)
Spectroscopic experiments: Late Universe, $z < 3$ Harder to model (not getting easier) number density, RSD, Lyman-α forest		Current: eBOSS, VIPERS Future: DESI, PFS, (Euclid, WFIRST)
Other techniques using dedicated time & instruments : SN, high-res/density Lyman-α, etc.		

From CMB to non-linear Universe

- ▶ Evolution of dark matter fluctuations from initial small perturbations is well understood
- ▶ Large scales continue to follow linear theory
- ▶ Small scales evolve non-linearly; Dark matter collapses into structures called “halos”
- ▶ This can be simulated in computers very well – physics very simple (no chemistry, etc.)
- ▶ Baryons condense in these halos, cool and eventually form stars and galaxies
- ▶ The galaxy formation poorly understood - astrophysics



SDSS galaxies



Dark matter from galaxy clustering

Two very robust assumption about the galaxy formation process:

- ▶ The only field that matters on large scales are the fluctuations in the matter fluctuations $\rho_m = \bar{\rho}_m(1 + \delta_m)$
- ▶ The galaxy formation process is local on some scale R:

$$\delta_g(\mathbf{x}) = F[\delta_m],$$

where F is an arbitrary functional that, however has no contributions for distances larger than R from $\mathbf{x}$.

Under these assumptions, in the $k \rightarrow 0$ limit, galaxies in redshift-space must trace dark-matter following

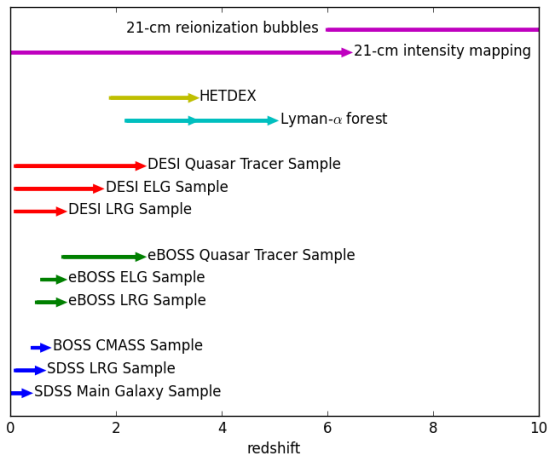
$$\delta_g(\mathbf{k}) = (b_\delta + b_\eta f \mu^2) \delta_m(\mathbf{k}) + \epsilon,$$

where bs are bias parameters and ϵ is a white noise stochastic variable.

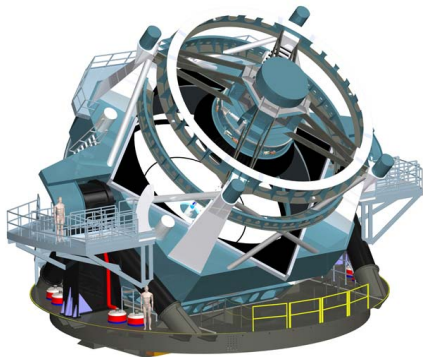
Trade-offs

- ▶ CMB is early universe linear physics: we can model it to essentially arbitrary precision, but it is just one 2D surface
- ▶ Low-redshift is harder to model, but we can do it reliably on large scales
- ▶ The linear and weakly non-linear modes are what we can model with reasonable accuracy. This naturally drives you towards:
 - ▶ large volumes
 - ▶ higher-redshift (less evolved universe)
 - ▶ less biased objects* (less non-linearity)
- * not always true, e.g. local non-Gaussianity
- ▶ There are two main classes of experiments: spectroscopic and photometric with different advantages
- ▶ Other tracers might provide different trade-offs

Spectroscopic surveys

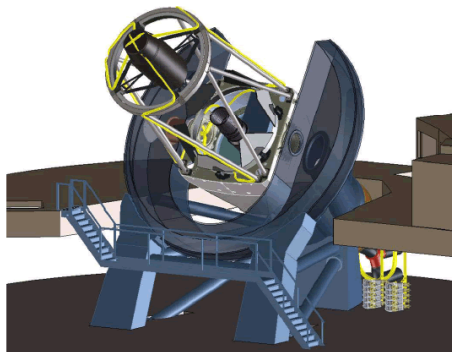


- ▶ Galaxy surveys have been slowly marching towards higher and higher redshift
- ▶ Progress is becoming increasingly difficult. At higher redshifts:
 - ▶ Galaxies are fainter, fewer and redder
 - ▶ Detectors are less efficient
 - ▶ Sky is brighter and less transparent
- ▶ Nevertheless progress is amazing:
 - ▶ SDSS DR1: $\sim 200k$ redshifts
 - ▶ BOSS : ~ 1 million redshifts
 - ▶ DESI : ~ 30 million redshifts



LSST:

- ▶ Photometric experiment: takes pictures of the sky
- ▶ 5 bands can give an estimate of a redshift
- ▶ Can do billions of galaxy and weak lensing
- ▶ Only roughly 3D and photo-z a limiting systematics



DESI:

- ▶ Spectroscopic experiment: takes spectra
- ▶ Spectra give redshifts - real 3D experiment
- ▶ But "only" millions of galaxies
- ▶ Need a targetting survey to select them first

Large Synoptic Survey Telescope

- ▶ Wide, fast, deep
- ▶ 3.2 Gpix camera on effectively 6.7m telescope
- ▶ 9.6 square degrees FOV – massive etendue
- ▶ Raft production in full swing at BNL
- ▶ First light ~2019, operations ~2022

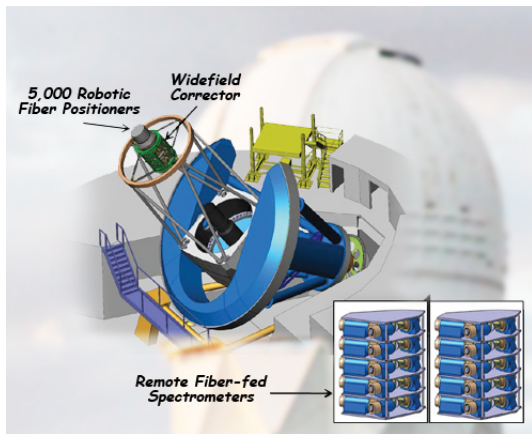


Science:

- ▶ Will measure positions of ~ 10 billion galaxies
- ▶ Missing third dimension, so essentially a few thick slices in radial direction
- ▶ Designed to measure weak lensing
- ▶ Photo-zs will be a problem

Dark Energy Spectroscopic Instrument

- ▶ BigBOSS+DESpec = DESI
- ▶ 4000 fiber robotically actuated spectrograph on 4m Mayal telescope
- ▶ Order of magnitude more powerful than BOSS with 20-30 millions measured spectra.
- ▶ First light ~2019

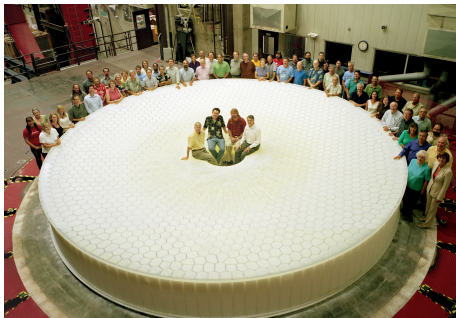


Science:

- ▶ Will measure 3D power spectrum of galaxies with unprecedented precision
- ▶ Main project is measuring expansion history through BAO
- ▶ Statistically, the anisotropic power spectrum is the most promising

LSST:

- ▶ First proposed in 1996 as Dark Matter Telescope
- ▶ From conception to science operations $\Delta t > 25$ years
- ▶ Building a new telescope is hugely expensive and timeconsuming



DESI:

- ▶ First proposed in ~ 2011 as BigBOSS
- ▶ Used refurbished Mayall telescope
- ▶ We're running out of old telescopes



Using existing and old telescopes

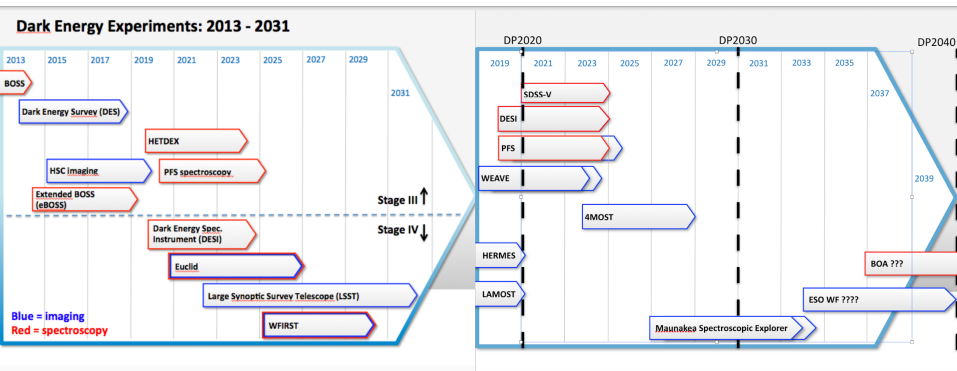
Name	Site	Notes and Exclusions	M1 f/#	M1 Diam. (m)	f/#	f (m)	Suitable for BigBOSS corrector?
Vista	Cerro Paranal, Chile	ESO Committed	f/1.0	4.1	1	4.1	no
Starfire	Kirtland AFB, New Mexico	Military	f/1.5	3.5	1.5	5.25	no
SOAR	Cerro Pachon, Chile		f/1.7	4.2	1.7	7.14	no
WIYN	Kitt Peak, Arizona		f/1.8	3.5	1.8	6.3	no
ARC	Apache Point, New Mexico		f/1.8	3.5	1.8	6.3	no
Discovery Channel	Lowell Obs, Arizona		f/1.9	4.2	1.9	7.98	marginal, with 1.5m C1
Galileo TNG	La Palma, Canary Islands, Spain		f/2.2	3.6	2.2	7.92	marginal
NTT ESO	Cerro La Silla, Chile	ESO Committed	f/2.2	3.5	2.2	7.7	yes
William Herschel	La Palma, Canary Islands, Spain		f/2.5	4.2	2.5	10.5	marginal
Victor Blanco	Cerro Tololo, Chile	Twin to Mayall	f/2.8	4	2.8	11.2	yes
Mayall	Kitt Peak, Arizona	Twin to Blanco	f/2.8	3.8	2.8	10.64	yes
AEOS	Maui, Hawaii	Military	f/3.0	3.7	3	11.1	yes
ESO 3.6m	Cerro La Silla, Chile	ESO Committed	f/3.0	3.6	3	10.8	yes
AAT	Coonabarabran, NSW, Australia	2 arcsec seeing	f/3.2	3.9	3.22	12.558	yes
Hale	Palomar Mountain, California		f/3.3	5.1	3.3	16.83	no, massive corrector
MPI-CAHA	Calar Alto, Spain	Poor seeing	f/3.5	3.5	3.5	12.25	yes
CFHT	Mauna Kea, Hawaii	Proposed 10m	f/3.8	3.6	3.8	13.68	yes

Telescope	Primary mirror	Central obscuration	Mirror losses	FOV	Etendue (Area * FOV)
SDSS	2.5 m	1.25 m	$(0.9)^2$	7.0 deg ²	20.9 m ² deg ²
PanSTARRS-1	1.8 m	0.9 m	0.9	7.0 deg ²	12.0 m ² deg ²
Mayall/BigBOSS	3.8 m	1.8 m	0.9	7.0 deg ²	55.4 m ² deg ²
Blanco/DECam	4.0 m	1.6 m	0.9	3.0 deg ²	28.5 m ² deg ²
LSST	8.4 m	5.06 m	$(0.9)^3$	9.6 deg ²	247 m ² deg ²
Keck	10.0 m	1.4 m	$(0.9)^3$	0.087 deg ²	4.88 m ² deg ²
Subaru/HSC	8.2 m	0.95 m	0.9	1.8 deg ²	84.4 m ² deg ²

From Schlegel & Scholl

Where do we go?

- ▶ There will be upcoming 30m+ class telescopes: ELT, TMT, GMT
- ▶ But their field of view will be tiny: 40m mirrors at 10arc min FoV has etendue of 35 vs 250 for LSST
- ▶ Noting else on the retirement horizon...

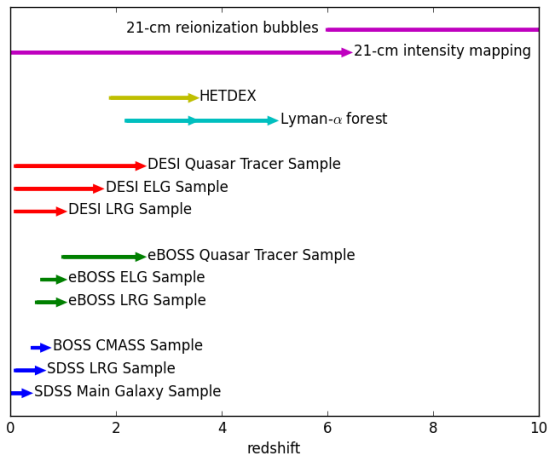


The bottom line

- ▶ Very little on finite- t horizon
- ▶ Concepts like Billion Object Apparatus are being thrown around, but today + 25yrs = 2045 (!!).
- ▶ To do transformational science, you need a new 10m+ class telescope with considerably larger field of view (consider e.g. eBOSS)
- ▶ Are we going to get billion USD+ on the right timescale?
- ▶ Let's open our minds!



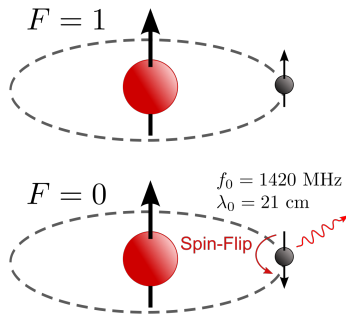
Other tracers

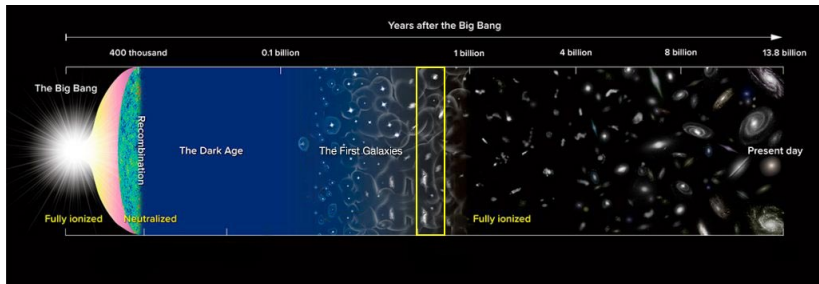


- ▶ Disclaimer: plot does not show number densities and does not include photometric experiments
- ▶ At $z < 2$ galaxies are best tracers: more galaxies $\rightarrow$ more dark matter
- ▶ At $z > 2$ different techniques offer advantages
- ▶ Systematics very different between tracers – multiple fundamentally different tracers always useful

21-cm emission

- ▶ Transition in neutral hydrogen at $\nu = 1420\text{MHz}$, $\lambda = 21.1\text{cm}$
- ▶ 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)
- ▶ Universe is mostly hydrogen (75%)
- ▶ It comes in three sorts: ionized, atomic, molecular
- ▶ Different phases at different times in the evolution of the universe





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

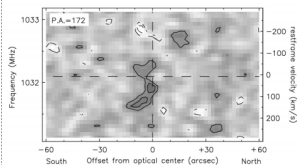
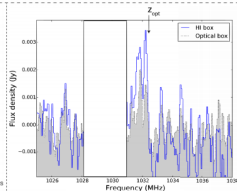
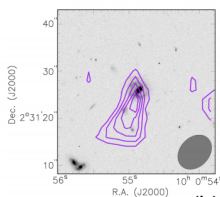
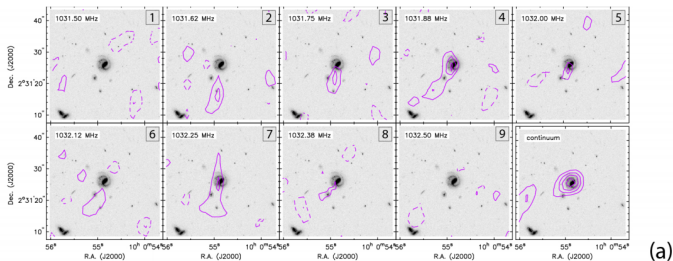
Low redshift

$z \lesssim 6$:

- ▶ 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

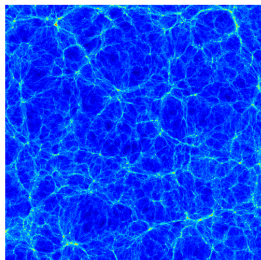
21-cm galaxies

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

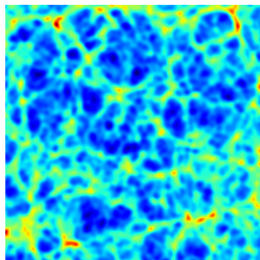


21-cm intensity mapping

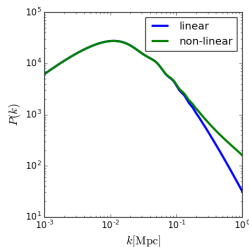
- ▶ The main idea is to give up on resolving individual galaxies:
- ▶ For scales much bigger than individual galaxies, the overall signal will still trace the underlying number density of galaxies
- ▶ Put SNR where you really need it – linear large scale modes
- ▶ Signal for galaxies is the only component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



Full resolution

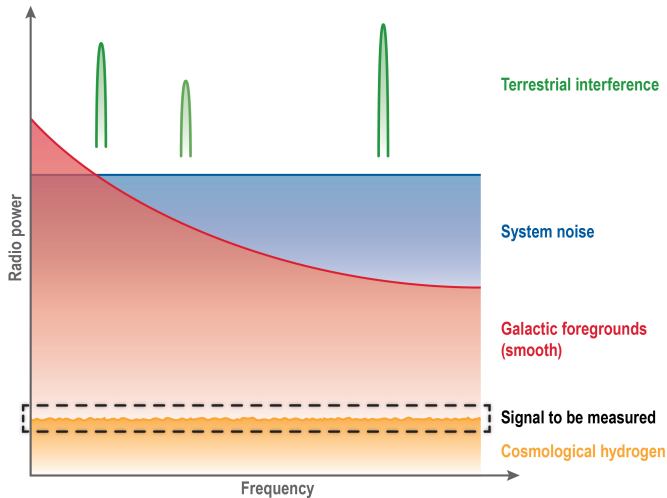


Low resolution



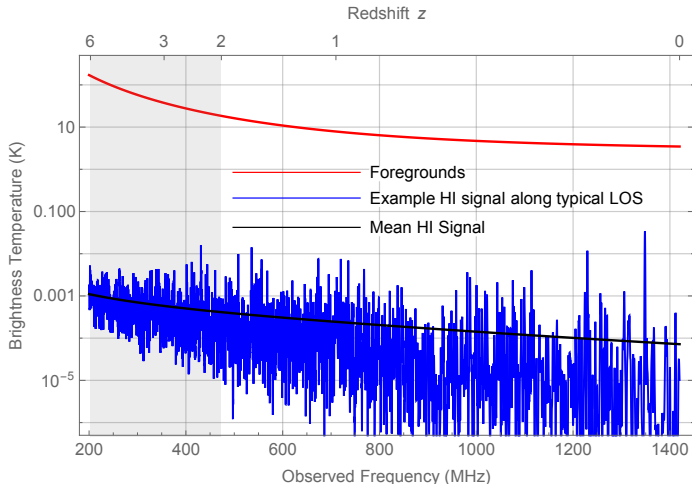
Matter power spectrum

Everything else...



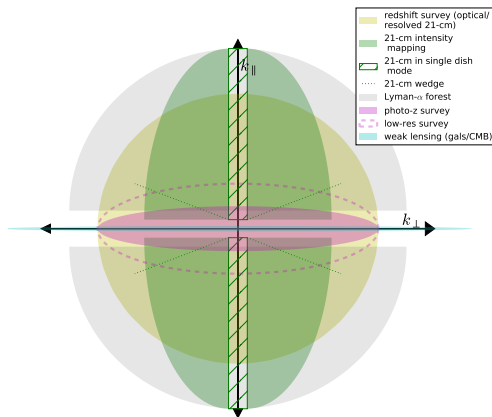
- ▶ Signal is subdominant, but the only non-smooth component.
- ▶ Of course, instrument can have non-smooth, time-varying response too!

Everything else...



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

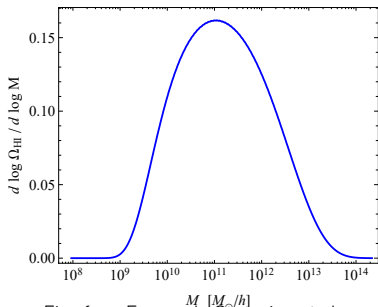
Main difference with galaxy surveys



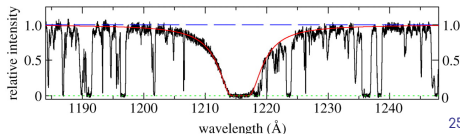
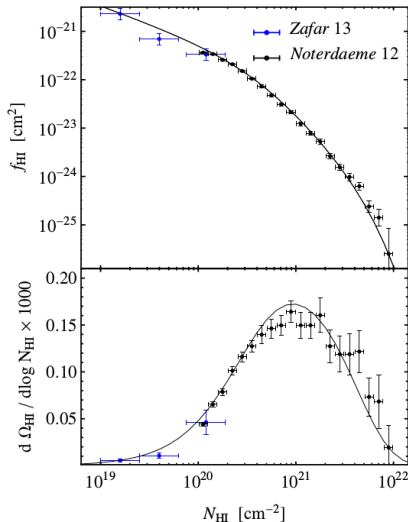
- ▶ We definitely lose low $k_{\parallel}$ modes ($k_{\parallel} \lesssim 10^{-2} \text{Mpc}^{-1}$) directly
- ▶ Low $k_{\parallel}$ modes could be recovered using several techniques
- ▶ We potentially lose modes inside the wedge, but could get them back with good calibration
- ▶ Additionally, we do not know the mean signal, limiting usability of redshift-space distortions

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

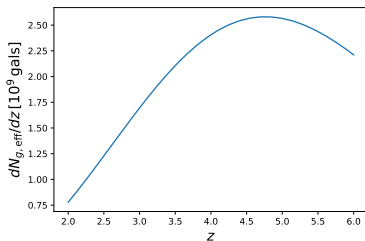
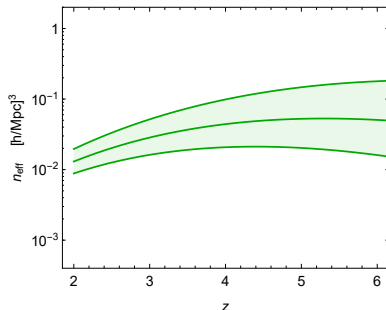


Figs from Emanuele Castorina et al



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_{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

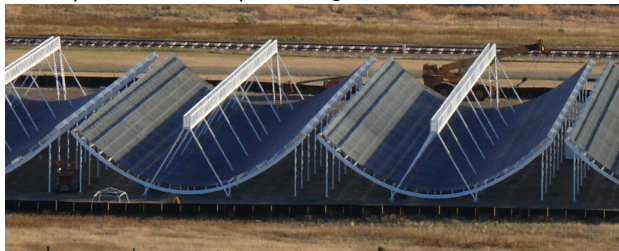
What kind of instrument you need

- ▶ 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?

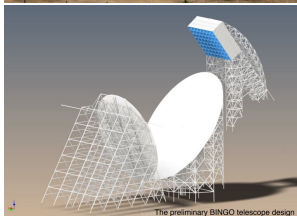
- ▶ You need exquisitely well calibrated telescope with sufficient resolution to resolve linear modes, but not more than that
- ▶ At low redshift this could mean single dish, at $z > 2$ almost certainly an interferometer
- ▶ SNR considerations favor **compact arrays**
- ▶ Survey/money consideration favor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



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

Current status worldwide

- ▶ CHIME – Canadian experiment – should detect BAO $z=0.75-2$
- ▶ HIRAX – South African experiment, seed funded and being prototyped
- ▶ FIRST: 500m single dish Chinese experiment
- ▶ BINGO, Brazilian experiment



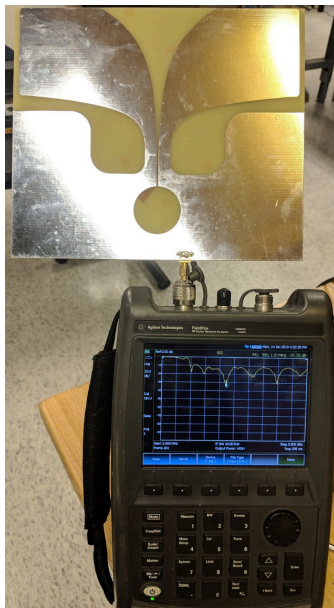
All these experiments will, in the next 5 years, demonstrate the promise of the technique. We call then Stage I.

Stage II concept

- ▶ In 2016 US DOE set up Cosmic Visions committees
- ▶ Within the DOE Cosmic Visions 21-cm WG, we discussed various possibilities and went through several iterations of the concept.
- ▶ The latest iteration is
 - ▶ 5000 6-m dishes upgraded to 32000 dishes, hexagonally closed-packed with 50% fill factor
 - ▶ $z = 0.3 - 6$
 - ▶ $f_{\text{sky}} = 0.5$
 - ▶ This is very reasonable: e.g. HIRAX is 32×32 array of 6m dishes and the estimated cost is \$10 million.
- ▶ Four scientific drivers:
 - ▶ Exceedingly good BAO to $z = 6$
 - ▶ Growth $z = 2 - 6$ through the non-linear power spectrum
 - ▶ Features in the primordial power spectrum
 - ▶ Primordial non-Gaussianity
 - ▶ Find 10^8 Fast Radio Bursts
 - ▶ Pulsar timing program

Enabling technologies

- ▶ Development of ultra-wide band feeds
 - ▶ price is $\sim 10\%$ coupling loss across the band
 - ▶ 6:1 frequency ratios achievable
- ▶ Commercial fast digitizers
 - ▶ 5 GS/s rate is becoming feasible
 - ▶ Cheaper to oversample than to make analog filters
 - ▶ integrated OMT/digitizer/channelizer dream
- ▶ Off-the-shelf digital network:
 - ▶ CHIME built an effectively proprietary FPGA based network
 - ▶ You can now use off-the-shelf 10Gb ethernet / switches
 - ▶ GPU correlation using FFT

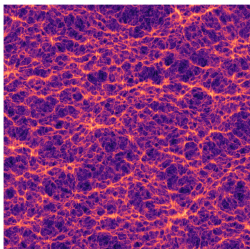


Stage II concept

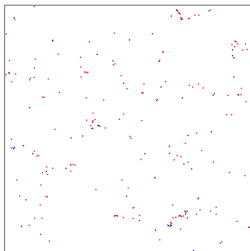
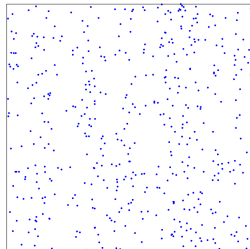
Science Objective	Scientific Measurement Requirement	Measurement objective	Instrument requirements
A. Characterize expansion history in the pre-acceleration era	Measure Baryonic Acoustic Oscillations to volume limited accuracy	Measure 21 cm intensity: - over $2 < z < 6$ - to $k \sim 0.4 \text{ hMpc}^{-1}$ - with SNR per mode ~ 1 at $k \sim 0.2 \text{ hMpc}^{-1}$	Bandwidth must include 200-475MHz Maximum baseline $L_{\text{max}} \gtrsim 600 \text{ m}$ $ND > 25 \text{ km}$ at $L_{\text{max}} = 600 \text{ m}^*$
B. Characterize structure growth in the pre-acceleration era	Measure growth through 21 cm power spectrum on weakly non-linear scales to volume limited accuracy	Measure 21 cm intensity: - over $2 < z < 6$ - to $k \sim 1.0 \text{ hMpc}^{-1}$ - with SNR per mode ~ 1 at $k \sim 0.6 \text{ hMpc}^{-1}$	Bandwidth must include 200-475MHz Maximum baseline $L_{\text{max}} \gtrsim 1500 \text{ m}$ $ND > 200 \text{ km}$ at $L_{\text{max}} = 1500 \text{ m}^*$
C. Constrain or detect primordial inflationary non-Gaussianity	Measure 21 cm bispectrum to achieve non-Gaussianity parameter sensitivity: - orthogonal: $\sigma [f_{\text{NL}}^{\text{ortho}}] < 10$ - equilateral: $\sigma [f_{\text{NL}}^{\text{equil}}] < 10$	Measure $\gtrsim 10^9$ linear modes with SNR per mode ~ 1	Same as above plus: bandwidth 200 – 1100 MHz ($z \sim 0.3 - 6$) assuming $f_{\text{sky}} \sim 0.5$
D. Constrain or detect features in primordial power spectrum	Constrain features in the matter power spectrum over available scales to - sensitivity $\sigma[A_{\text{lin}}] < 10^{-3}$	Same as above.	Same as above.
E. Characterize properties of Fast Radio Bursts	Detect: - 100 million FRBs - covering two frequency octaves		$N^{3/2} \Delta \nu^{3/4} \gtrsim 10^9 \text{ MHz}^\dagger$ Provide real-time FRB pipeline

Comparison at $z = 3$

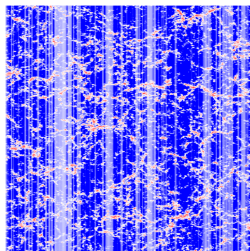
mass



LSST-like



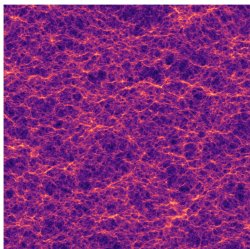
drop-out survey



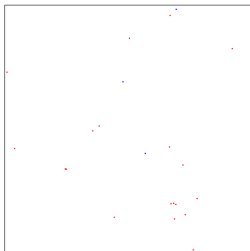
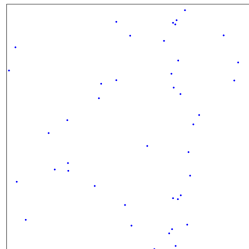
21cm

Comparison at $z = 5$

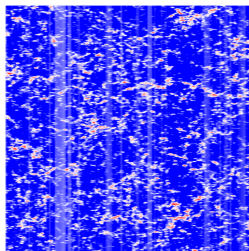
mass



LSST-like

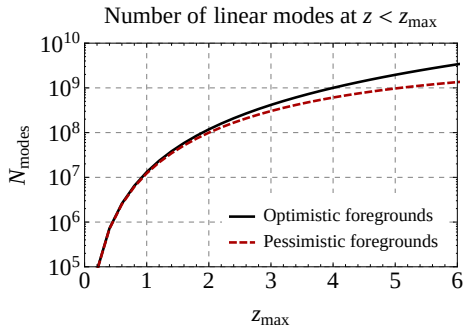
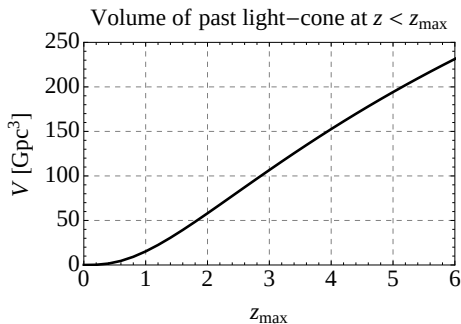


drop-out survey

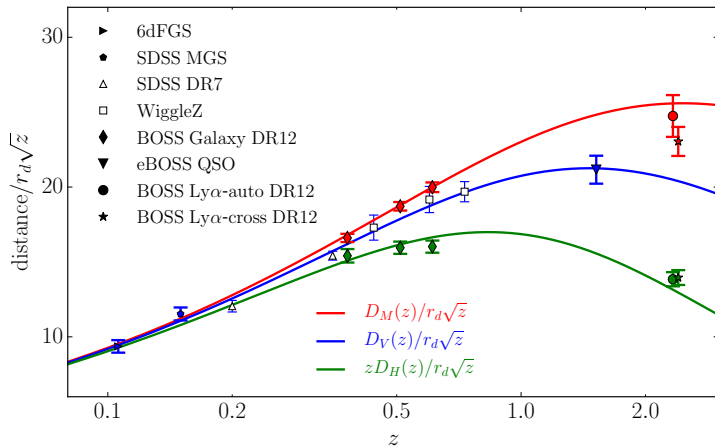


21cm

We're looking at linear modes and large amounts of volume



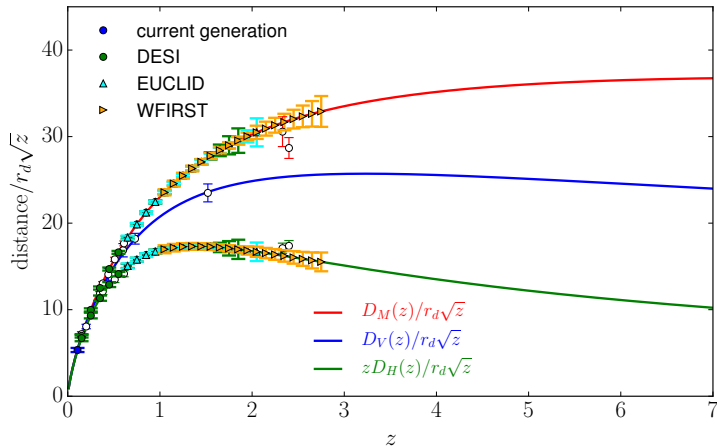
Measure Expansion History



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 $z \sim 2$

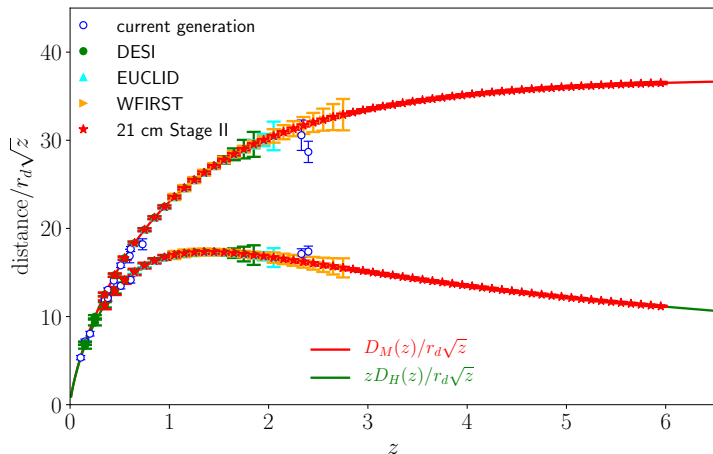
Measure Expansion History



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

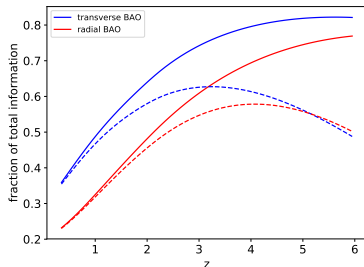
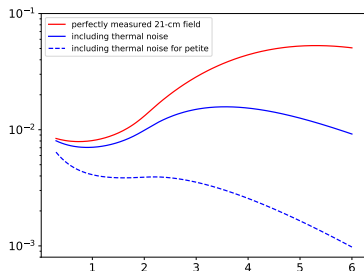


Current + DESI, Euclid, WFIRST + 21-cm strawman
Based on Obuljen et al 2017

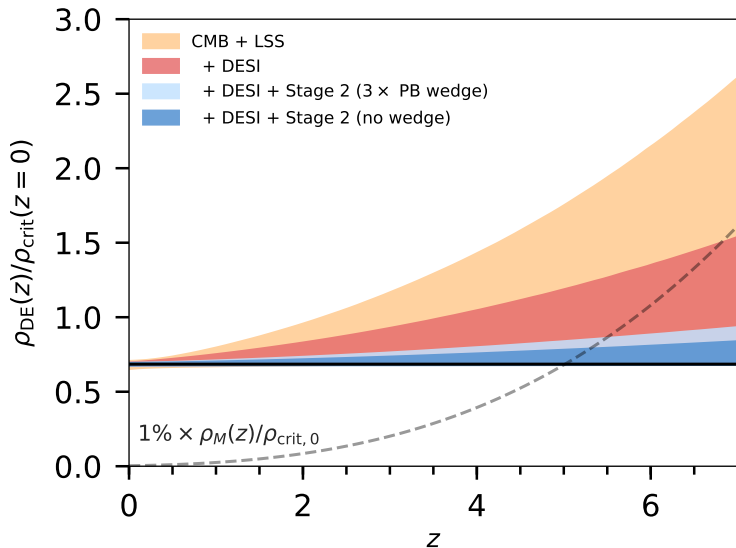
- Expansion history is a basic cosmological quantity
- There is a big picture argument that we should complete our program of measuring the expansion history throughout universe first
- 21-cm can realistically reach to $z \sim 6$
- no reconstruction used

Expansion history measurements

- ▶ At high- z no reconstruction needed
- ▶ Lots of volume available
- ▶ BAO surprisingly useless – because DE is less than 5% of total energy density, 1% measurements give you 20% constraints on DE



Follow Dark Energy through time



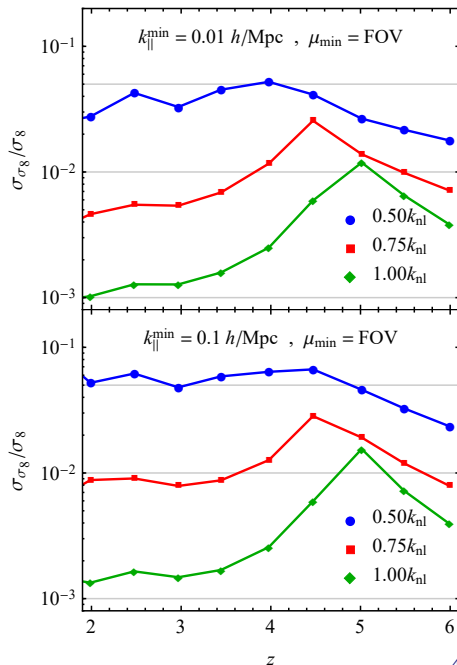
mock early dark energy models

Measuring growth

- ▶ Redshift-space distortions cannot be used as in galaxy surveys, unless you know T_b :

$$P = T_b^2 (b + f\mu^2)^2 P_l(k) \quad (1)$$

- ▶ Weakly non-linear scales break the degeneracy
- ▶ Need to be able to model the signal, at the moment this is possible for $z > 2$
- ▶ Amazing modified gravity probe

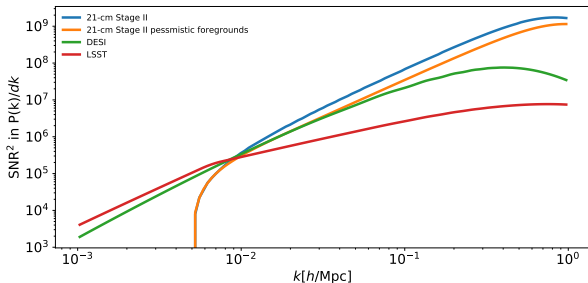


Constraining inflation

- ▶ Shape of the primordial power spectrum ✓
- ▶ tensor fluctuations
- ▶ non-Gaussianity ✓
- ▶ non-adiabatic primordial perturbations

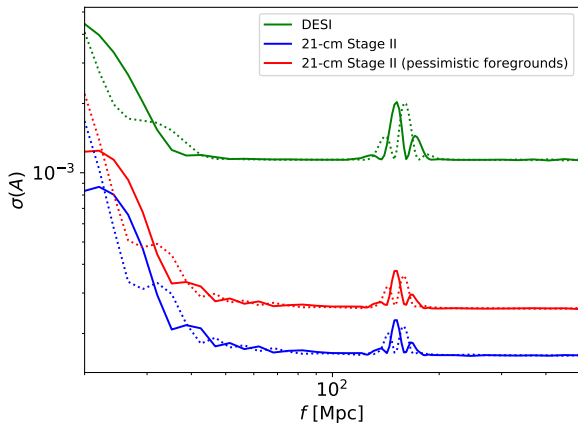
Features in the primordial power spectrum

- ▶ primordial power-law index one of the best measured numbers in cosmology
 $n_s = 0.968 \pm 0.006$
- ▶ Can add running – tells you about the second derivative of scalar potential
- ▶ Can add features – generic in many string-inspired models

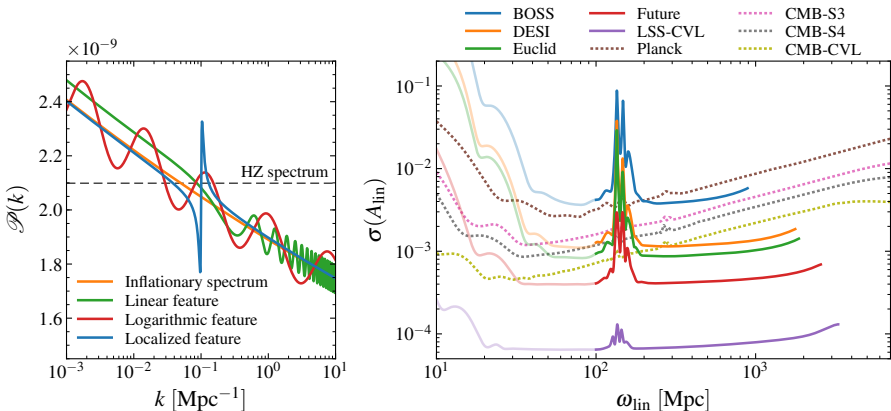


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Features in the primordial power spectrum



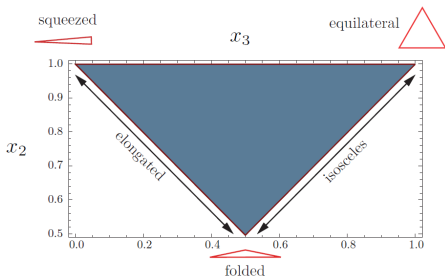
From the submission to the Decadal Survey of Astronomy & Astrophysics

Minimal inflation → Gaussianity

In minimal inflation:

- ▶ Each mode starts in Bunch-Davies vacuum and then freeze as it leaves horizon
- ▶ This leads to perfectly Gaussian initial conditions
- ▶ Departures from this will appear, to leading order, in the bispectrum of the initial perturbations

$$B_{\zeta} \propto f_{\text{NL}} \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \frac{S(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)}{(\mathbf{k}_1 \mathbf{k}_2 \mathbf{k}_3)^2} \Delta_{\zeta}^2$$



Squeezed:

- ▶ Small scale power spectrum (two high- k modes) modulated by large scale (low- k) mode
- ▶ For single field minimal inflation no NG:
 - ▶ Since inflation is an attractor solution, the effect of the mode is forgotten very soon after it leaves horizon
 - ▶ Alternatively: the long mode is rescaling of the coordinates $\rightarrow$ consistency relations
- ▶ Observed $f_{\text{NL}} \rightarrow$ multi-field inflation
- ▶ Generically (e.g. curvaton scenario) see $|f_{\text{NL}}| > O(1)$

Folded, equilateral:

- ▶ At minimum it implies modes to be coupled, for example $(\partial_\mu \phi)^4$ term in Lagrangian
- ▶ More careful analysis shows that if $f_{\text{NL}}^{\text{eq, orth.}} > O(1)$, the coupling is so strong that it breaks the slow-roll.
- ▶ Conversely, confirming that $f_{\text{NL}}^{\text{eq, orth.}} < O(1)$ means that we live in world with slow-roll inflation + weak interactions that be described as small perturbations.

Constraints on non-Gaussianity

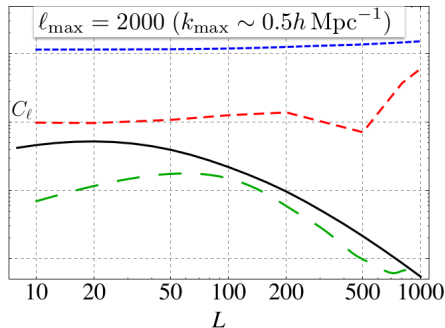
	$f_{\text{NL}}^{\text{loc}} < O(1)$	$f_{\text{NL}}^{\text{loc}} > O(1)$
$f_{\text{NL}}^{\text{eq.,orth.}} < O(1)$	Single-field slow-roll	Multi-field
$f_{\text{NL}}^{\text{eq.,orth.}} > O(1)$	Single-field non slow-roll	Multi-field

- ▶ Measuring these parameters to this precision informative either way
- ▶ Stage 2 constraints very interesting:

	$f_{\text{NL}}^{\text{loc}}$	$f_{\text{NL}}^{\text{eq}}$	$f_{\text{NL}}^{\text{ortho}}$
Planck T+Pol	0.8 ± 5	-4 ± 43	-26 ± 21
CMB-S4	± 2	± 21	± 9
21-cm Stage 2 pessimistic	± 0.5	± 15	± 6.5
21-cm Stage 2 optimistic	± 0.2	± 5	± 2.7

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
- ▶ This allows us to use small modes to:
 - ▶ Reconstruct large modes
 - ▶ Reconstruct gravitational lensing along the line of sight



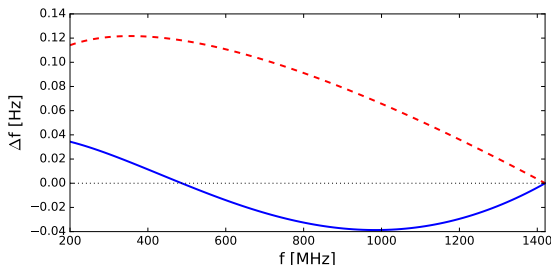
From Simon Foreman: contributions to CMB-like lensing estimator: $C_{\ell}^{\phi\phi}$ (black), noise (blue), gravitational (red - unremovable, green removable)

Weak Lensing

quantity / experiment	CMB S4	21-cm-S2, no wedge	21-cm-S2, with wedge
Lensing $\times$ LSST galaxies	367	466	300
Lensing $\times$ LSST shear	178	263	191
Lensing auto	353	84	6
Tidal reconstruction auto	X	1408	291

Table: Total signal to noise on measurements of auto or cross power spectra related to gravitational lensing of 21-cm maps. We expect cross-correlations of 21-cm lensing with LSST galaxy clustering or cosmic shear (galaxy lensing) to be measured at a precision competitive with that of cross-correlations with CMB-S4 lensing, with the advantage that the former will contain much more (tomographic) information about the growth of low-redshift structure.

Direct measurement of expansion history



- ▶ Universe keeps on expanding
- ▶ The rate goes with inverse Hubble parameter, $\sim 10^{-10}$ per year:

$$\frac{dz}{dt} = (1+z)H(0) - H(z), \quad (2)$$

- ▶ Clocks with this accuracy can be bought off-shelf
- ▶ Structure smoothed on 100km/s, signal moves it by 3×10^{-5} km/s over 5 years. But it is a question of SNR.
- ▶ Using global structure, it might be possible at low redshift
- ▶ Using cold lines seen in absorption is more promising: CHIME forecasts around 5σ , but uncertainties very large

Fast Radio Bursts

- ▶ First discovered serendipitously in 2007, currently in 10s
- ▶ ms bursts that are dispersed into seconds
- ▶ Characterized by 3 numbers: amplitude, frequency, dispersion measure
- ▶ CHIME will see thousands, Stage 2 , 100 million
- ▶ Can be used for cosmology, through electron dispersion measure, see Madhavacheril et al.

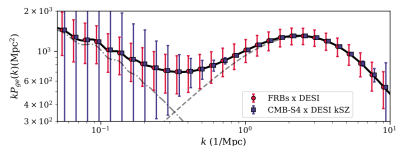
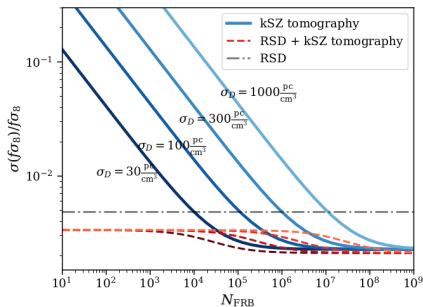
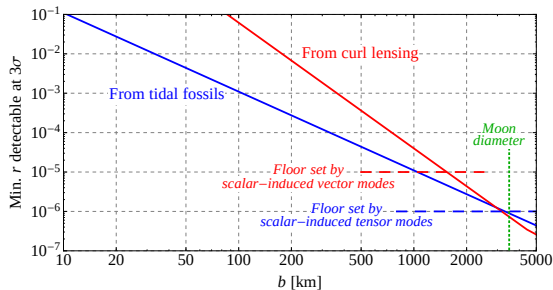


FIG. 2: The cross-power-spectrum of galaxies and electrons as measured either through kSZ tomography with CMB-S4 and DESI (blue) with fixed cosmology, or through cross-correlation of dispersion measures of 10^4 FRBs with DESI galaxies (red), where the RMS scatter of DMs is assumed to be $300 \frac{\text{pc}}{\text{cm}^2}$. FRB DMs measure the power over a broad range of scales including the 2-halo regime (dot-dashed), while kSZ tomography provides an extremely tight measurement in the 1-halo dominated regime (dashed).



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



(Simon Foreman et al)

Conclusions

- ▶ We should do it!
- ▶ An interesting optical experiment would cost > 1 billion after LSST and DESI complete. An interesting 21-cm experiment an order of magnitude lower
- ▶ There will be Moore's law efficiencies to be gained for at least a few generations of experiments
- ▶ Completes the programmatic goal of mapping the entire visible universe
- ▶ It's fun!

BACKUP SLIDES

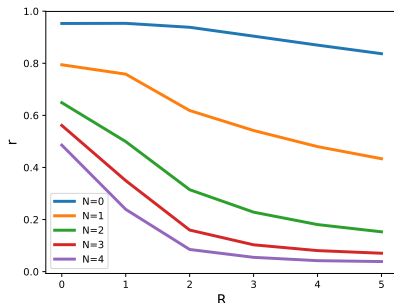
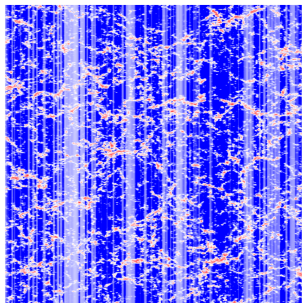
Something much more idiotic...

- ▶ As long as noise is not too high and resolution not too bad, one can just detect objects
- ▶ But with finite noise, resolution, things get blurry...
- ▶ Instead, blindly write a transformed map:

$$m = \sum_{i=2}^N w_i \delta^i$$

where δ is missing large scale modes

- ▶ Find coefficients w_i that maximize cross-correlation with filtered large scale modes
- ▶ You could do the same in survey, using helper-survey, or largish but still unfiltered modes



The wedge

- ▶ A single interferometric baseline cannot tell apart a non-monochromatic source at zenith from monochromatic source far from zenith
- ▶ In per-baseline analysis, this gives rise to “dirty” area inside the wedge and clean area outside
- ▶ In baseline-combining analysis this cleans the area inside the wedge but miscalibrations splatter the dirt into clean area
- ▶ It is fundamentally a technical problem of sufficiently good calibration.

