21-cm cosmology after 2021

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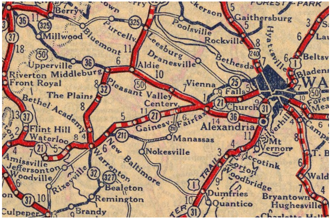


IPMU, December 2018

Plan for the talk

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

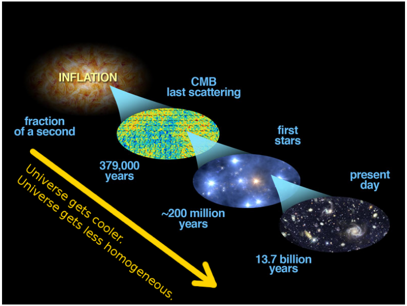
Apologies:

- This is a very US centric talk, because I'm a DOE politician

Cosmic pizza & the Universe

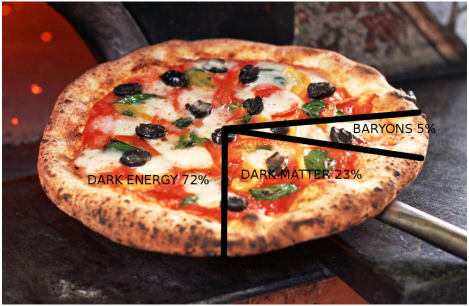
Universe is going:

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

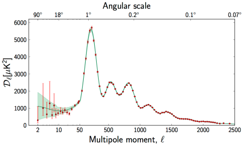
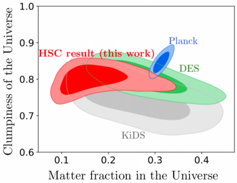
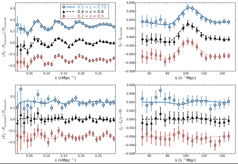


Components of the Universe:

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

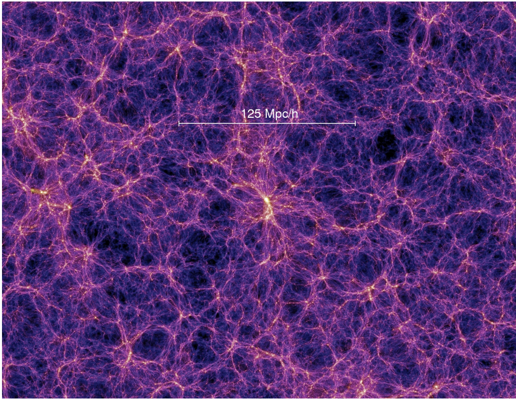


Study of the universe today: experiment

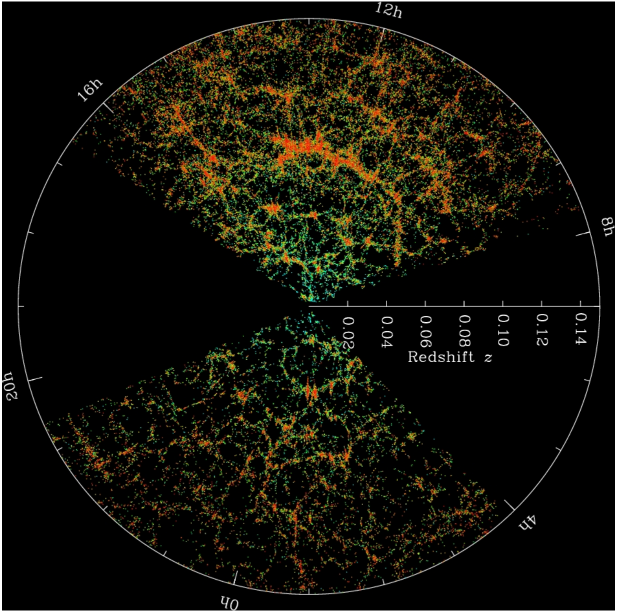
CMB: Early Universe, z > 1100 Easy to model (but getting harder) Primordial fluctuations: T, E, B Secondary: lensing, tSZ, kSZ, ISW		**Past:** Planck, WMAP **Future:** Simons Observatory, CMB-S4 ? LiteBird? Pixie??
Photometric experiments: Late Universe, z < 3 Harder to model (not getting easier) 2.5D: 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 - gastrophysics



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 $\rho_{\mathsf{m}} = \bar{\rho}_{\mathsf{m}}(1+\delta_{\mathsf{m}})$
- The galaxy formation process is local on some scale R:

$$\delta_{\mathsf{g}}(\mathbf{x}) = \mathsf{F}[\delta_{\mathsf{m}}],$$

  where F is an arbitrary functional that, however has no contributions for distances larger than R from **x**.

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

$$\delta_{\mathsf{g}}(\mathbf{k}) = (\mathsf{b}_{\delta} + \mathsf{b}_{\eta}\mathsf{f}\mu^2)\delta_{\mathsf{m}}(\mathbf{k}) + \epsilon,$$

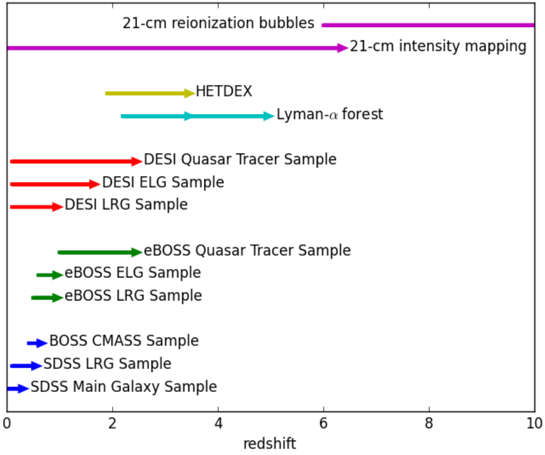
where bs are bias parameters and ϵ is a white noise stochastic variable.

Trade-offs

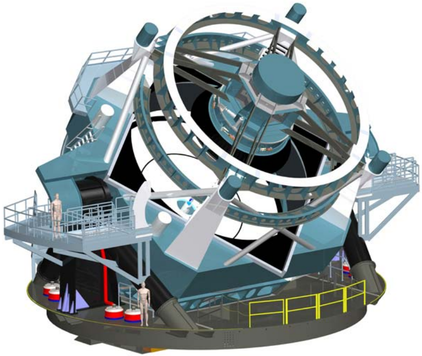
- CMB is early universe linear physics: we can model it to essentially arbitrary precision, but it is just one 2D surface
- Low-redshift is harder to model, but we can do it reliably on large scales
- The linear and weakly non-linear modes are what we can model with reasonable accuracy. This naturally 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

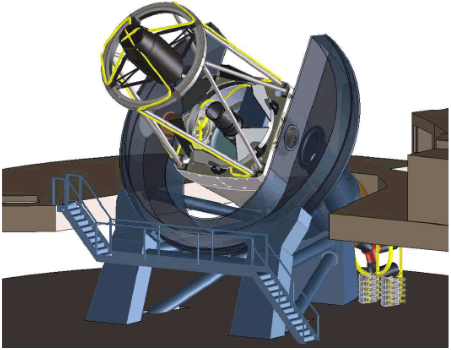


- Galaxy surveys have been slowly marching towards higher and higher redshift
- Progress is becoming increasing difficult. At higher redshifts:
  - Galaxies are fainter, fewer and redder
  - Dectors are less efficient
  - Sky is brighter and less transparent
- Nevertheless progress is amazing:
  - SDSS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

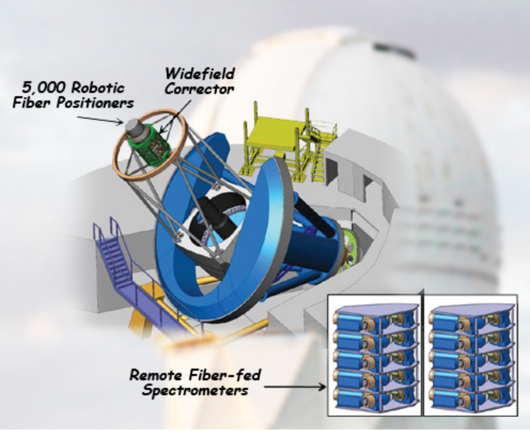
- Wide, fast, deep
- 3.2 Gpix camera on effectively 6.7m telescope
- 9.6 square degrees FOV – massive etendue
- Raft production in full swing at BNL
- First light $\sim$2019, operations $\sim$2022

Science:

- Will measure positions of $\sim$ 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

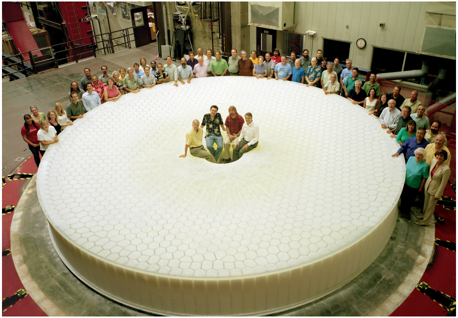


Science:

- 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

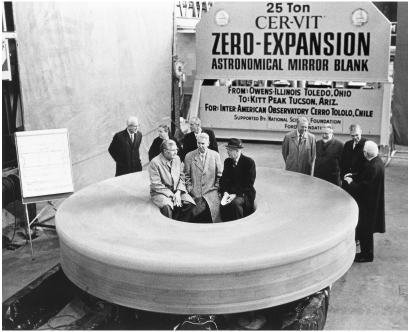
LSST:

- 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 $\sim$ 2011 as BigBOSS
- Used refurbished Mayall telescope
- We're running out of old telescopes



Using existing and old telescopes

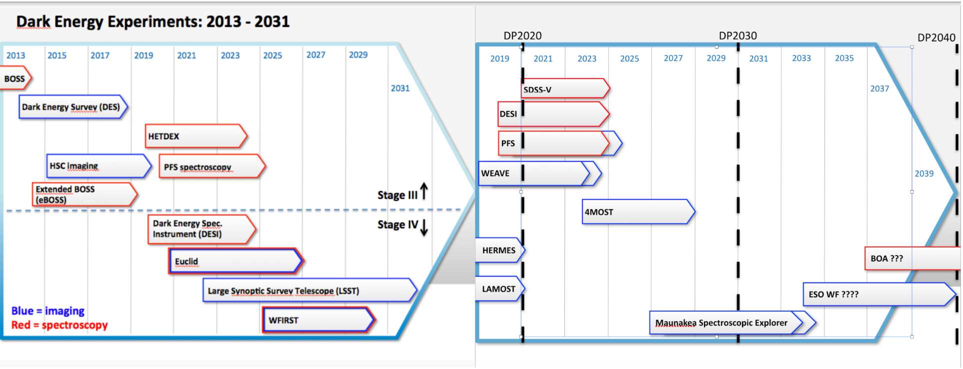
Name	Site	Notes and Exclusions	M1 f/#	M1 Diam. (m)	f/#	f (m)	Suitable for BigBOSS corrector?
Vista	Cerro Paranal, Chile	ESO Committed	f/1.0	4.1	1	4.1	no
Starfire	Kirtland AFB, New Mexico	Military	f/1.5	3.5	1.5	5.25	no
SOAR	Cerro Pachon, Chile		f/1.7	4.2	1.7	7.14	no
WIYN	Kitt Peak, Arizona		f/1.8	3.5	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?

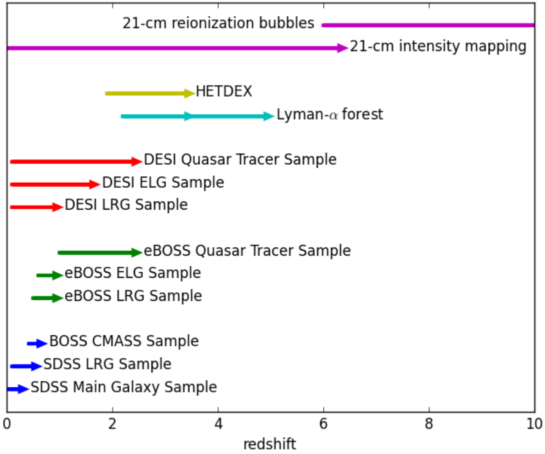
- There will be upcoming 30m+ class telescopes: ELT, TMT, GMT
- But their field of view will be tiny: 40m mirrors at 10arc min FoV has etendue of 35 vs 250 for LSST
- Noting else on the retirement horizon...



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!

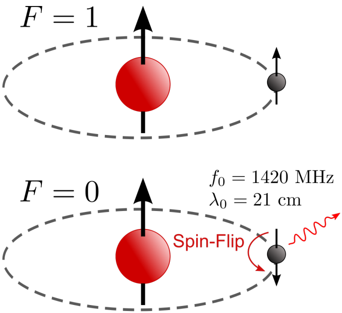
Other tracers

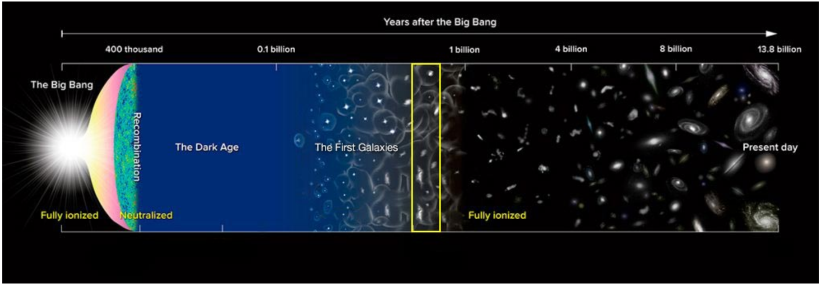


- Disclaimer: plot does not show number densities and does not include photometric experiments
- At z < 2 galaxies are best tracers: more galaxies $\rightarrow$ more dark matter
- At z > 2 different techniques offer advantages
- Systematics very different between tracers – multiple fundamentally different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

21-cm emission

- Transition in neutral hydrogen at $\nu = 1420$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)
- 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

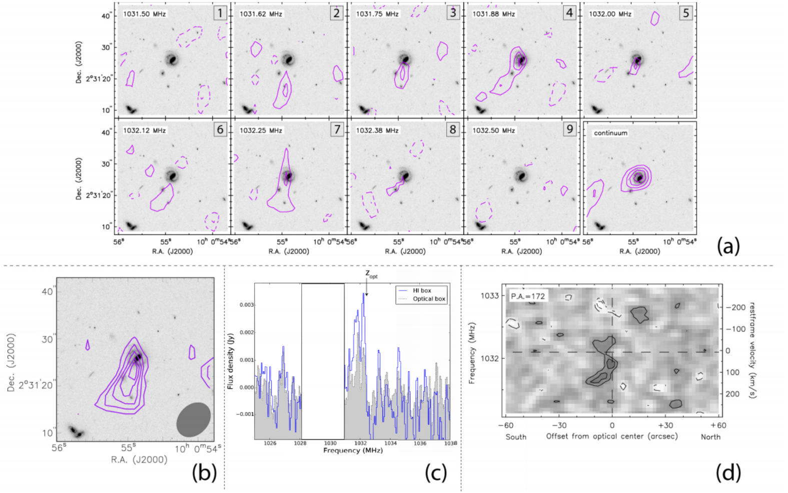
Low redshift

$z \lesssim 6$:

- 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

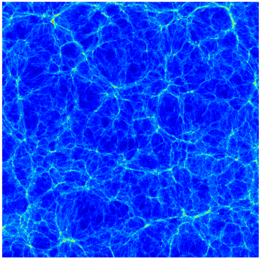
21-cm galaxies

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

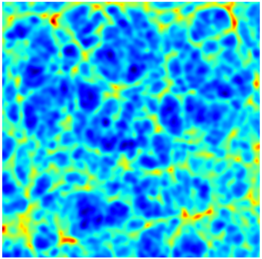


21-cm intensity mapping

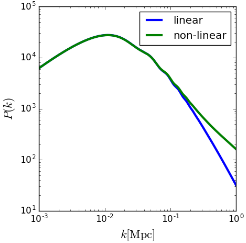
- The main idea is to give up on resolving individual galaxies:
- For scales much bigger than individual galaxies, the overall signal will still trace the underlying number density of galaxies
- Put SNR where you really need it – linear large scale modes
- Signal for galaxies is the only component that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



Full resolution

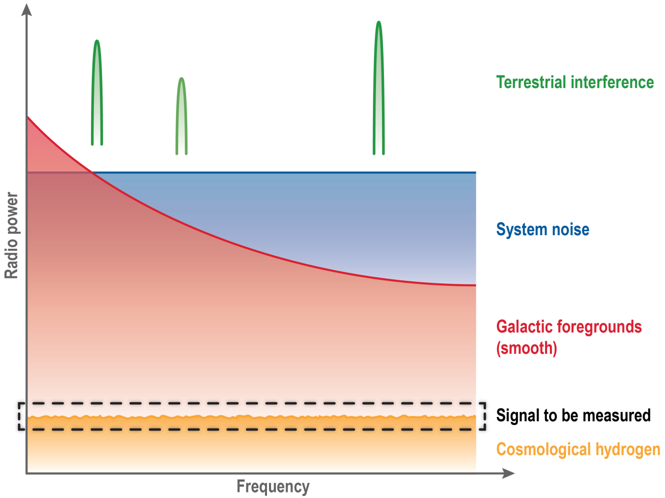


Low resolution



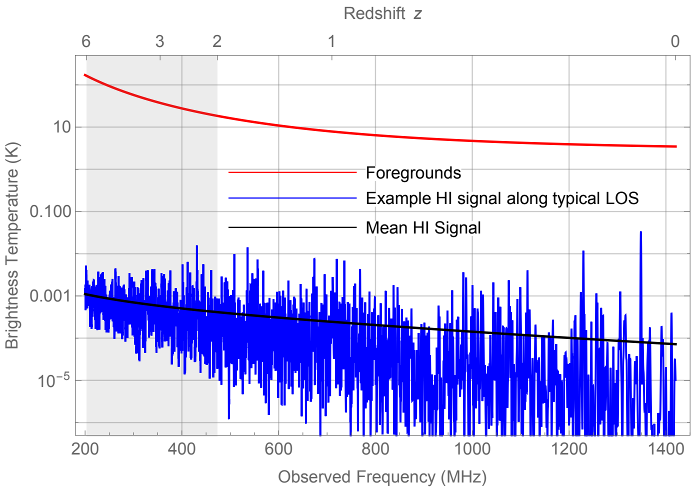
Matter power spectrum

Everything else...



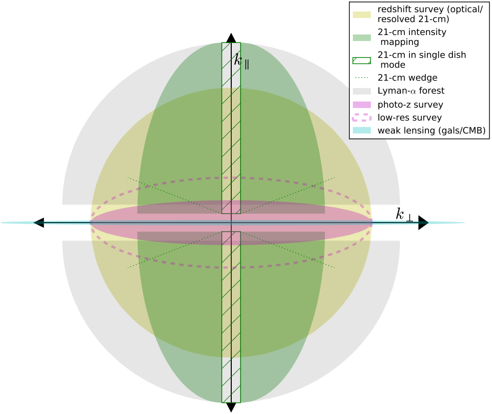
- Signal is subdominant, but the only non-smooth component.
- Of course, instrument can have non-smooth, time-varying response too!

Everything else...



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

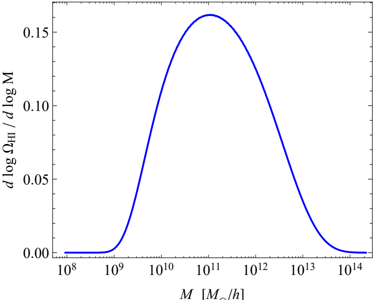
Main difference with galaxy surveys



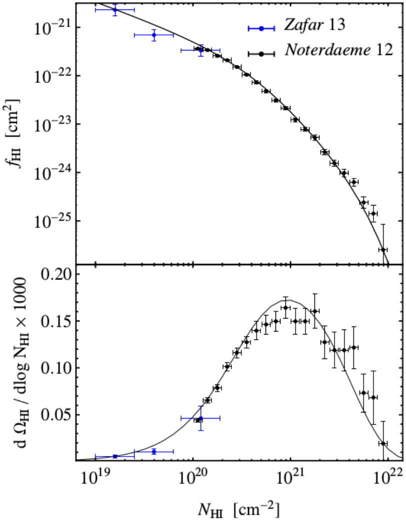
- We definitely loose low $k_\parallel$ modes ($k_\parallel \lesssim 10^{-2}\mathrm{Mpc}^{-1}$) directly
- Low $k_\parallel$ modes could be recovered using several techniques
- We potentially loose modes inside the wedge, but could get them back with good calibration
- Additionally, we do not know the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

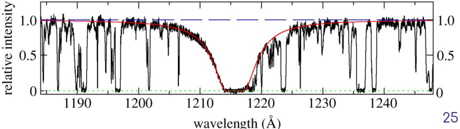
We're looking at small galaxies

- 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



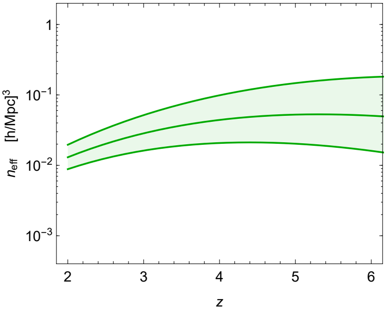
Figs from Emanuele Castorina et al

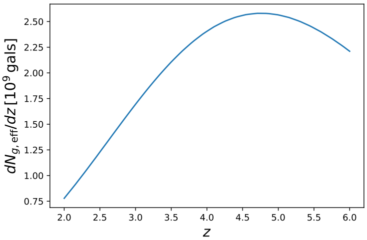




We're looking at many galaxies

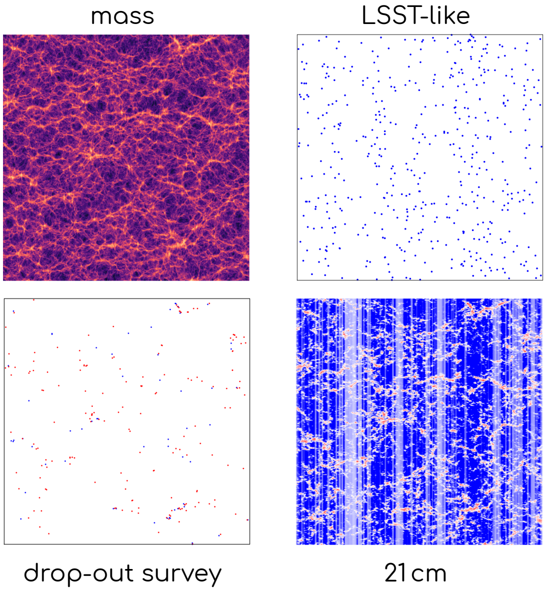
- In any galaxy survey, $\bar{n}$ is the fundamental quantity that determines the shot noise contribution $P_s = \bar{n}^{-1}$.
- The shot noise is not beatable unless you get more galaxies
- 21-cm cosmology has T_{sys} noise contribution, but that is beatable with sufficiently big instrument
- A 15k 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)





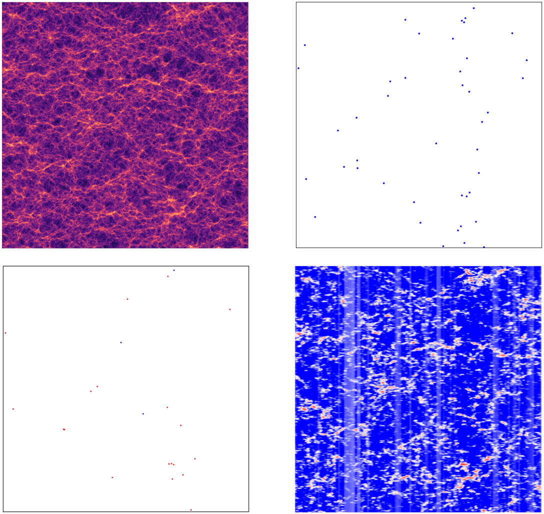
From Castorina & Villaescusa-Navarro

Comparison at $z = 3$



Comparison at z $= 5$

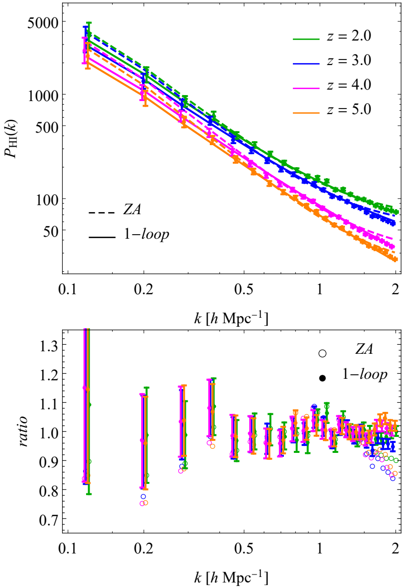
mass LSST-like



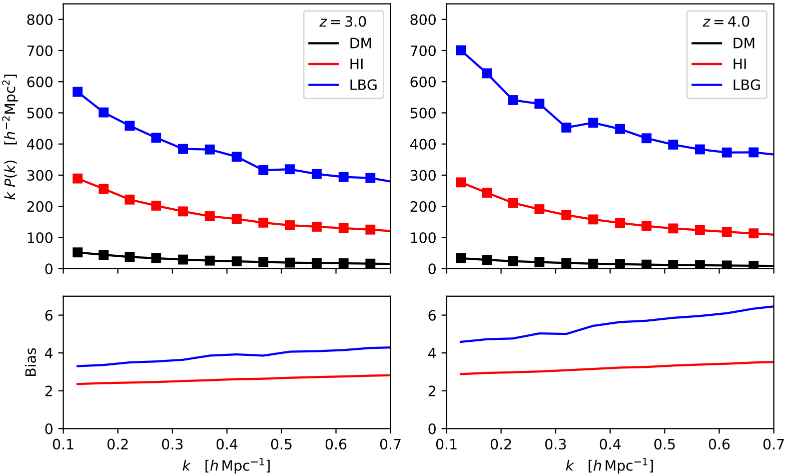
drop-out survey 21cm

Galaxies which we can model...

- Linear + one loop work predictions work very well
- Higher redshift - less evolved universe
- Small halos - less non-linear biasing

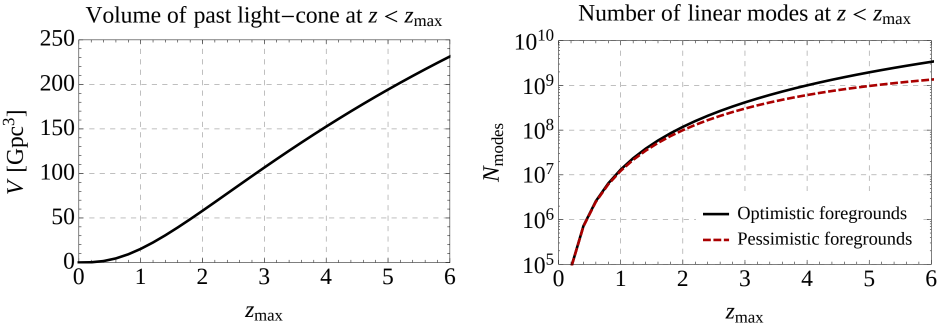


Galaxies which we can model ...



- If you are doing in optical, galaxies sit in rare halos – higher bias $\rightarrow$ harder to model

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

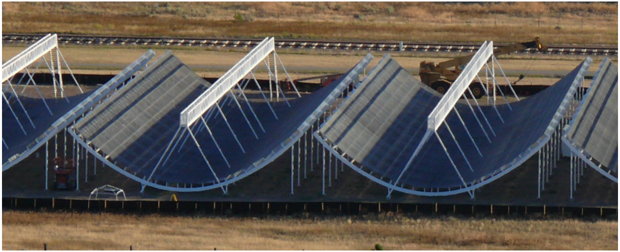


What kind of instrument you need

- 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:

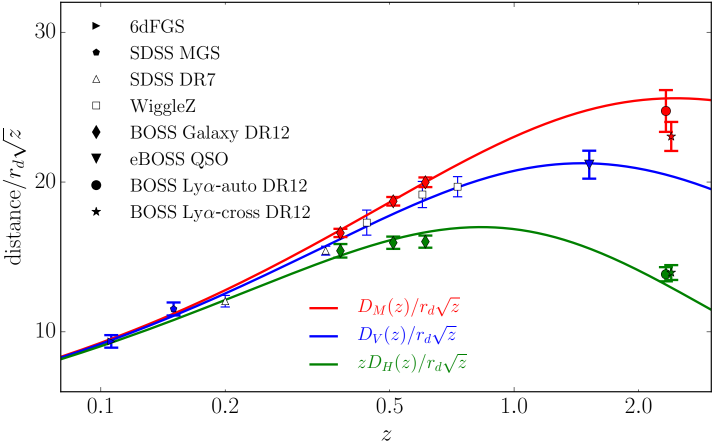


- CHIME will map universe between z $= 0.8$ and z $= 2$ over half the sky

What is the exciting science then?

- In 2016 US DOE set up Cosmic Visions committees
- Within the DOE Cosmic Visions 21-cm WG, we discussed various possibilities.
- We settled on the following straw-man experiment:
  - 256$\times$256 array of 6m dishes, surveying z $= 2 - 6$ over $f_{sky} = 0.5$
  - This is very reasonable: e.g. HIRAX is 32$\times$32 array of 6m dishes and the estimated cost is $10 million.
- Three main scientific goals:
  - Exceedingly good BAO to z $= 6$
  - Features in the primordial power spectrum
  - Primordial non-Gaussainity
- It so happens, that the same machine could do FRBs very well (+few outriggers for localization)

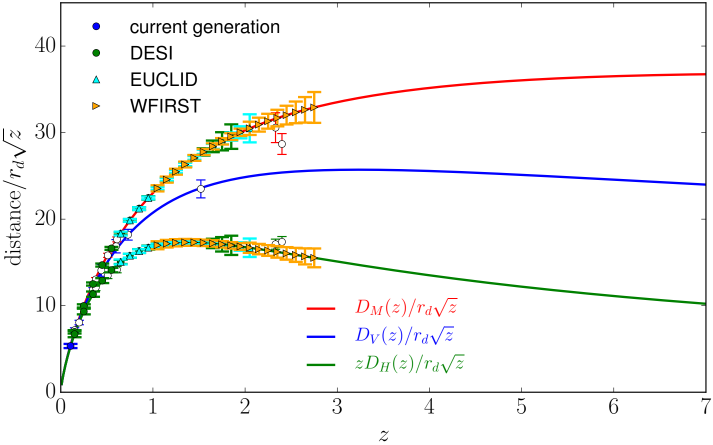
Measure Expansion History



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 ~ 2

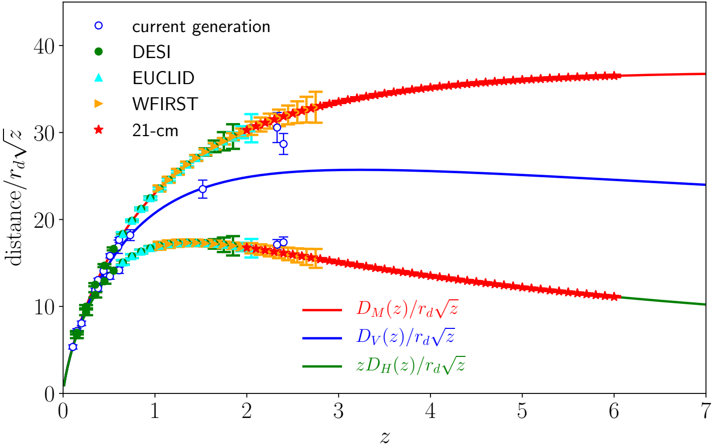
Measure Expansion History



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 ~ 3

Measure Expansion History

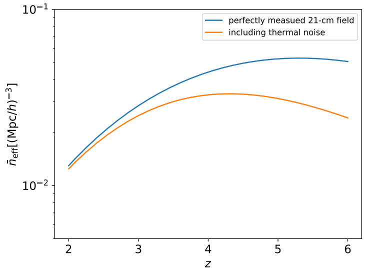


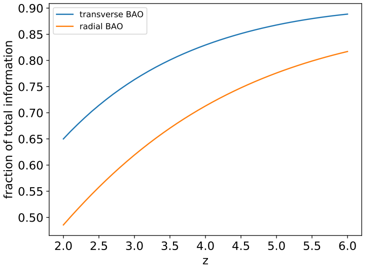
Current + DESI, Euclid, WFIRST + 21-cm strawman
Based on Obuljen et al 2017

- 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 ~ 6
- no reconstruction used

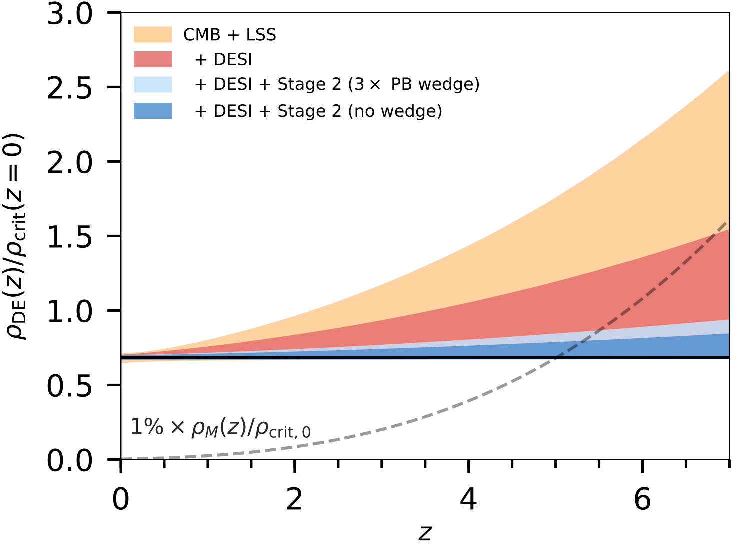
Expansion history measurements

- 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



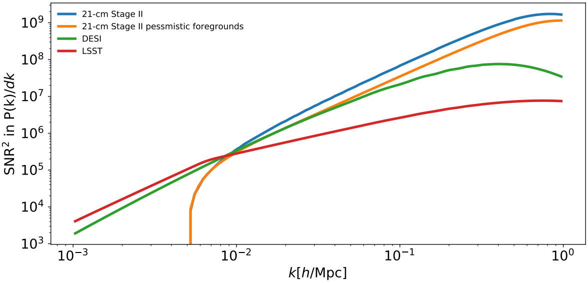
mocker early dark energy models

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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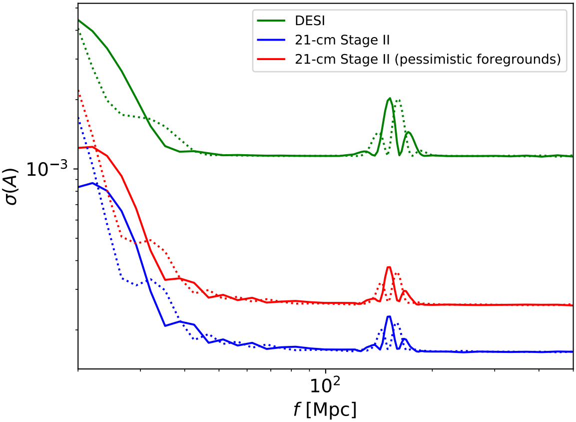
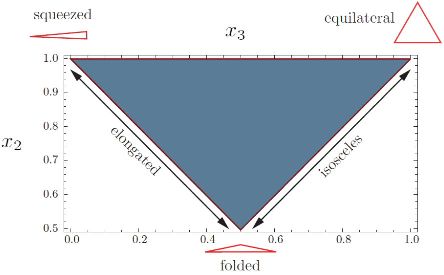


Minimal inflation $\rightarrow$ Gaussianity

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

$$B_\zeta \propto f_{NL}\delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)\frac{S(k_1, k_2, k_3)}{(k_1 k_2 k_3)^2}\Delta_\zeta^2$$



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 $f_{NL} \rightarrow$ multi-field inflation
- Generically (e.g. curvaton scenario) see $|f_{NL}| > O(1)$

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 $f_{NL}^{eq,orth.} > O(1)$, the coupling is so strong that it breaks the slow-roll.
- Conversely, confirming that $f_{NL}^{eq,orth.} < O(1)$ means that we live in world with slow-roll inflation + weak interactions that be described as small perturbations.

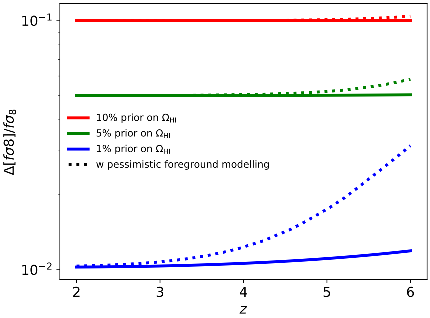
Constraints on non-Gaussianity

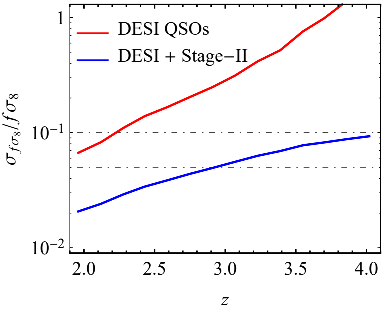
	$f_{NL}^{loc} < O(1)$	$f_{NL}^{loc} > O(1)$
$f_{NL}^{eq.,orth.} < O(1)$	Single-field slow-roll	Multi-field
$f_{NL}^{eq.,orth.} > O(1)$	Single-field non slow-roll	Multi-field

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

	f_{NL}^{loc}	f_{NL}^{eq}	f_{NL}^{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

Redshift-space distortions

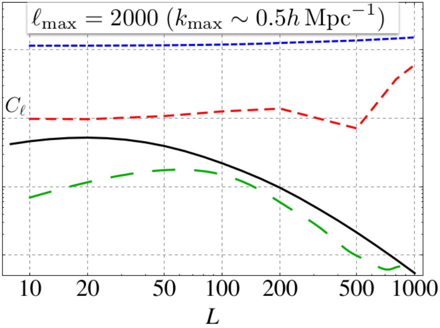




- In galaxy surveys, $\bar{n}$ is known, signal proportional to $(b + f\mu^2)\delta_k$ -
- In 21 cm, $\bar{T}$ is not known, so signal proportional to $\Omega_{HI}(b + f\mu^2)\delta_k$:
- Either prior on Ω_{HI} from e.g. Lyman-α forest
- Or calibrate using cross-correlations

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

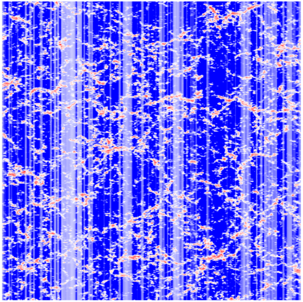
Table: Total signal to noise on measurements of auto or cross power spectra related to gravitational lensing of 21-cm maps. We expect cross-correlations of 21-cm lensing with LSST galaxy clustering or cosmic shear (galaxy lensing) to be measured at a precision competitive with that of cross-correlations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

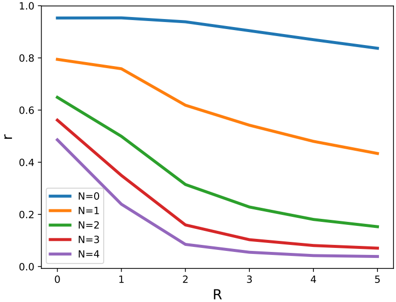
Something much more idiotic...

- 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:

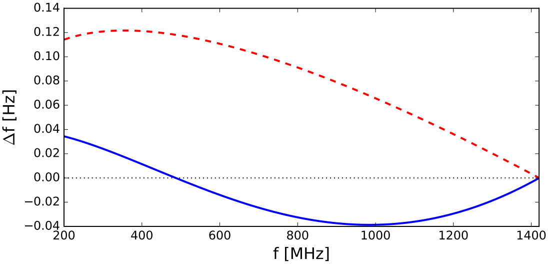
$$m = \sum_{i=2}^{N} w_i \delta^i$$

  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





Direct measurement of expansion history



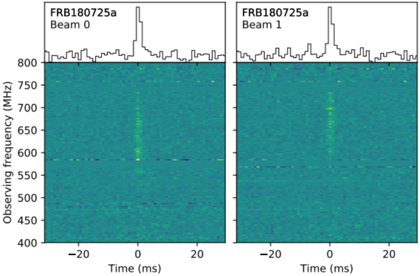
- Universe keeps on expanding
- The rate goes with inverse Hubble parameter, $\sim 10^{-10}$ per year:

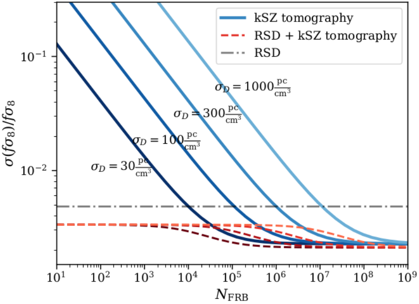
$$\frac{dz}{dt} = (1+z)H(0) - H(z), \tag{1}$$

- 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 is pretty difficult, except at lowest redshifts
- Using cold lines seen in absorption is more promising: CHIME forecasts around 5σ, but uncertainties very large

Fast Radio Bursts

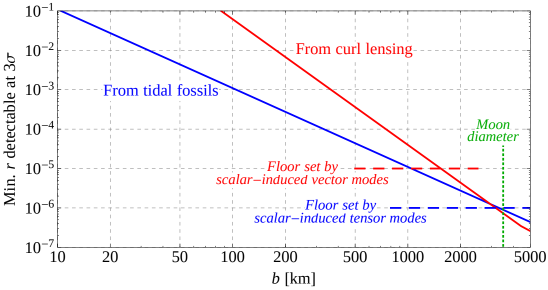
- First discovered serendipitously in 2007, currently in 10s
- ms bursts that are dispersed into seconds
- Characterized by 3 numbers: amplitude, frequency, dispersion measure
- CHIME will see thusands, Stage 2 millions
- Paper by Madhavacheril and co soon out: there is already first application in calibrating kSZ, perhaps more will come





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)

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.

Conclusions

- We should do it!
- An interesting optical experiment would cost > 1billion after LSST and DESI complete. An interesting 21-cm experiment an order of mangitude 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

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 raise 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.**