Cosmology at ‘high’ redshift (large-scale structure at $2 < z < 6$)

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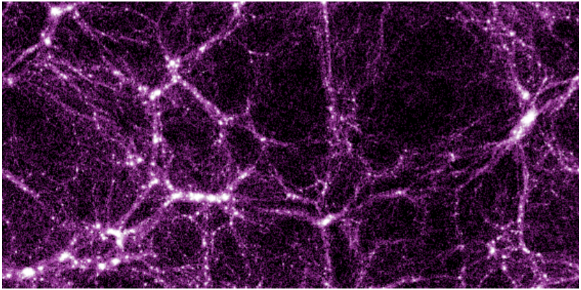
w/ Stephen Chen, Chirag Modi, Anze Slosar, Mike Wilson



http://mwhite.berkeley.edu/Talks

Outline

Large-scale structure is one of our premier laboratories for fundamental physics, cosmology and astrophysics.
Traditionally it has been done with galaxy redshift surveys at $z \approx 0$.
But that may be changing ...

- Cosmic brunch (science case).
- Imaging surveys and CMB lensing.
- HI intensity mapping (PUMA).
- Conclusions.

Cosmic brunch ($2 < z < 6$)

- Current $z \sim 0.5$ LSS constraints (from BOSS) on ΛCDM parameters are (nearly) competitive with those from *Planck* ...
- ... in the future LSS should overtake CMB for cosmological constraints.
  - Continuous quantitative improvements become qualitative change — "Quantity has a quality all its own" (Stalin)!
- Fundamentally progress (along the traditional route) requires more modes $\Rightarrow$ more volume.
- There is $3\times$ more volume at $2 < z < 6$ than $z < 2$.
- Less evolved, better understood, more correlated with $\delta_{\rm init}$.
- All standard mode-counting constraints improve significantly:
  - $P(k)$ shape, BAO, m_ν, $dn/d\ln k$, $N_{\rm eff}$, etc.
  - Features, higher-order correlators, ...

Next-generation science drivers

High-precision tests of the SM and GR

- Expansion history (BAO)
- Curvature
- Primordial non-Gaussianity ($f_{NL}^{\rm loc}$, $f_{NL}^{\rm eq}$, $f_{NL}^{\rm orth}$)
- Primordial features
- Dark energy during MD
- Neutrino mass
- Light relics ($N_{\rm eff}$)

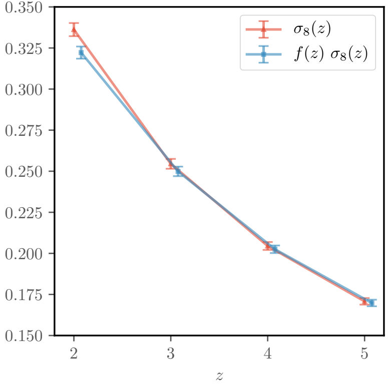
Probe metric, particle content and **both** epochs of accelerated expansion

Aside on theory

My interest was peaked because ...

- The Universe at high redshift is more linear, better correlated with the 'primordial' Universe.
- Start to get very high precision measurements of modes we can model well.
  - Large volume $\Rightarrow$ small errors at low k.
  - This is a regime where PT approaches work very well (small corrections to almost-linear quantities), c.f. CMB.
  - Still lots of room for improvement on the theory side.
- Techniques, tricks and trade-offs are a little different than at lower z, where many of the key ideas were developed in the 80's and 90's (textbook).
- Large-scale structure at high-z offers many of the same 'advantages' of primary CMB anisotropy while not being as mined out (theoretically).

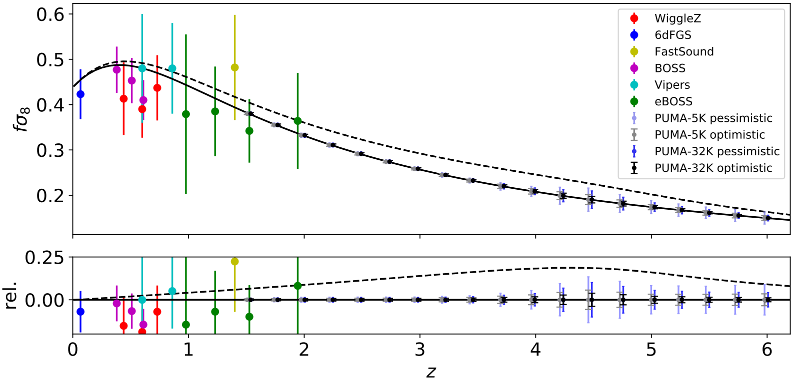
One example: growth rate



- Between $z \simeq 10^3$ and today, fluctuations grow by $\sim 10^3$.
- GR predicts growth very precisely.
- Marginalizing over unknown parameters, growth is predicted to 1.1% per bin (dominated by m_ν uncertainty; measure m_ν?).

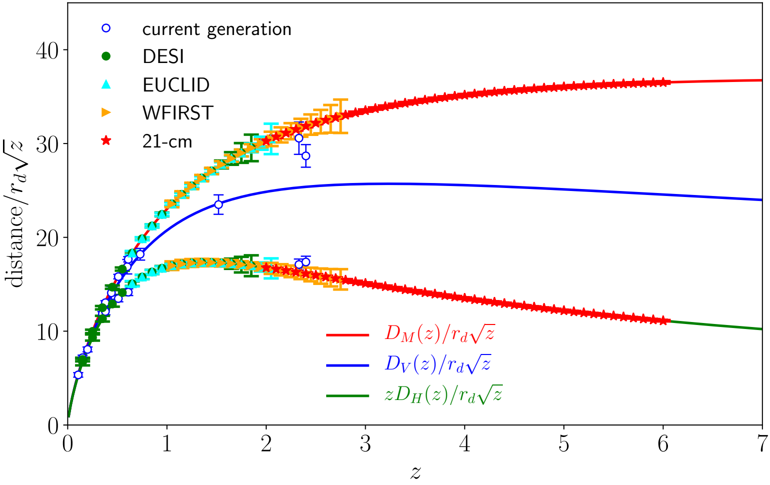
Is GR+ΛCDM right?

Growth rate



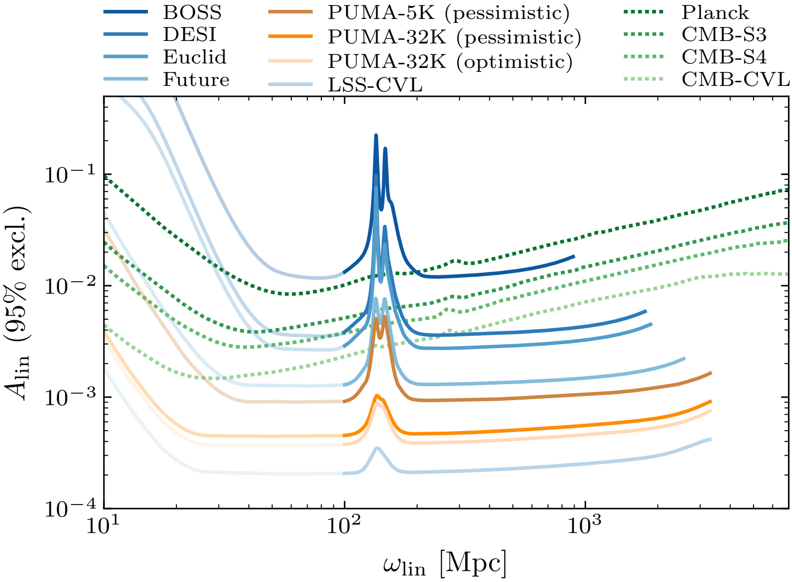
0.6
0.5
0.4
0.3
0.2
$f\sigma_8$
0.25
0.00
rel.
0
1
2
3
4
5
6
z
WiggleZ
6dFGS
FastSound
BOSS
Vipers
eBOSS
PUMA-5K pessimistic
PUMA-5K optimistic
PUMA-32K pessimistic
PUMA-32K optimistic

BAO



[Scale-factor + curvature defines the FRW metric!]

Primordial features



The roadmap

So how do we "do LSS" in the high-z Universe?

- Near term: imaging and CMB surveys
- Longer term: 21 cm surveys

Imaging and CMB lensing

Imaging and CMB lensing

(measuring the amplitude of clustering)

CMB Surveys

An experimental revolution is happening at mm-wavelengths ...

Survey	Map RMS [μK-arcmin]	Resolution [$'$]	Area [deg^2]
Planck	30.0	7.0	21K
AdvACT	12.0	1.5	8K
Simons Observatory	6.0	1.0	27K
CMB-S4	1.0	1.4	17K
LiteBIRD	2.5	30.0	30K

A natural "by-product" of next generation CMB experiments to constrain primordial gravitational waves is high fidelity CMB lensing maps – probing the matter back to $z \simeq 1100$.

Optical surveys

Major new imaging and spectroscopic facilities ...

- Dark Energy Survey (DES)
- DECam Legacy Survey (DECaLS)
- Dark Energy Spectroscopic Instrument (DESI)
- Subaru Hyper Suprime-Cam (HSC)
- Prime Focus Spectrograph (PFS)
- Large Synoptic Survey Telescope (LSST)
- Euclid
- Wide-Field Infrared Survey Telescope (WFIRST)

These facilities can map large areas of sky to unprecedented depths!

The opportunity

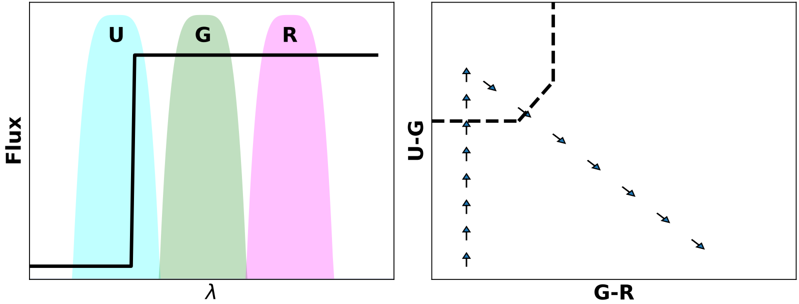
The combination can be "more than the sum of its parts".

- Since the CMB is behind 'everything', can work to very high z!
  - Sensitive to mass, not light.
  - Lensing gives access to both metric potentials.
- But lensing is projected, so no tomographic information.
- Galaxies come with distance information, but trace light.
- Lensing + LSS offers redshift specificity **and** higher S/N.

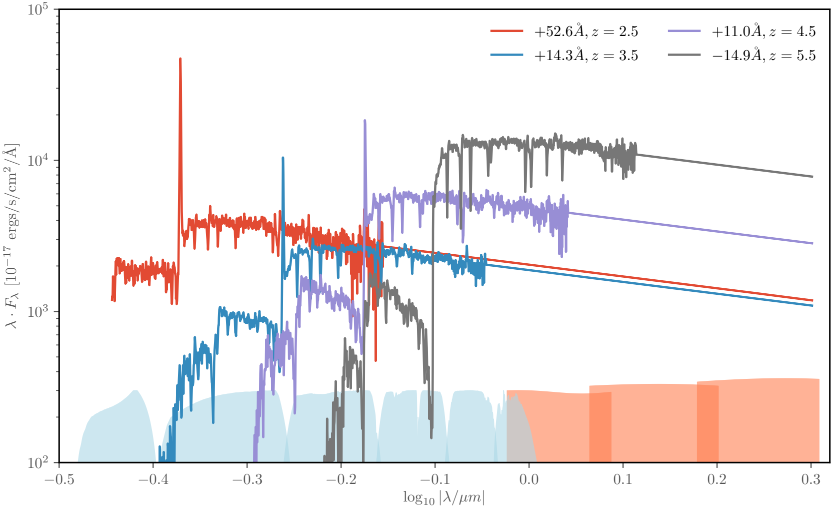
How can we push to high z and how we would model the data these surveys will (may?) return?

Dropout or Lyman-Break Galaxy (LBG) selection

Dropout color-color selection targets the steep break in an otherwise shallow F_ν spectrum bluewards of the 912Å Lyman limit due to absorption by the neutral hydrogen rich stellar atmospheres and interstellar photoelectric absorption. Lyman-series blanketing along the line-of-sight further suppresses flux short-ward of 1216Å for $z > 2$ sources



Composite spectra



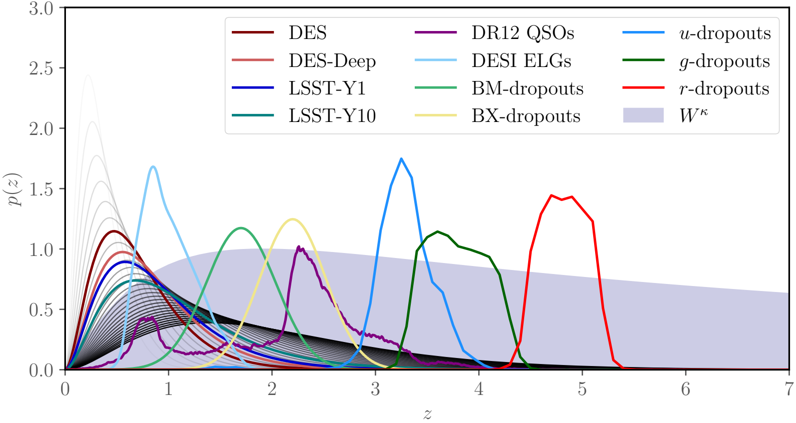
Wilson & White (2019)

Dropout or Lyman-Break Galaxy (LBG) selection

- Dropout selection requires only 3 filters, so is observationally efficient.
  - Easier to model selection than a photo-z based case.
- These objects have been extensively studied (for decades!) over the range $2 < z < 7$.
- Selects massive, actively star-forming galaxies – and a similar population over a wide redshift range.
- Rest-frame UV spectra dominated by O5 and B star emission with $M > 10\,M_\odot$ and $T > 2.5 \times 10^4$ K.
- LBGs lie on the main sequence of star formation and UV luminosity is approximately proportional to stellar mass.
- Galaxies of interest have $M_\star \sim 10^{10-11}\,M_\odot$, and high (angular) number densities ($10^2 - 10^3\,\mathrm{deg}^{-2}$)!

Tomographic lensing

The combination of galaxies with known redshifts and CMB lensing with its long lever arm can be particularly powerful ...



Wilson & White (2019)

Example: Measuring $P_{mm}(k, z)$

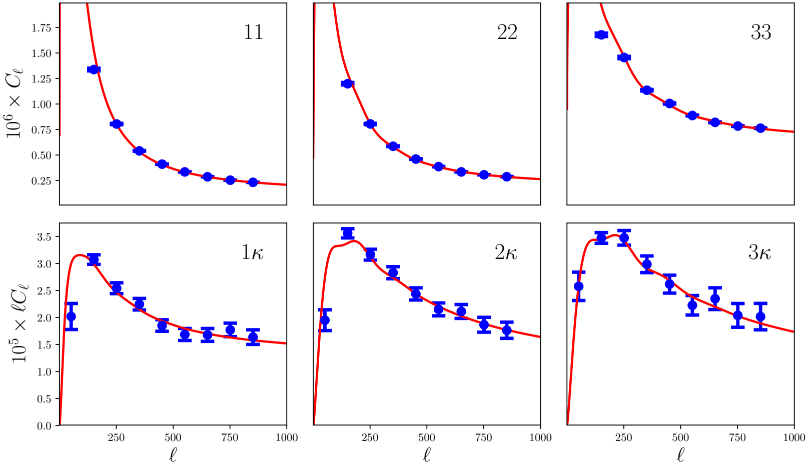
- A proper accounting of the growth of large scale structure through time is one of the main goals of observational cosmology – key quantity is $P_{mm}(k, z)$.
- Schematically we can measure $P_{mm}(k, z)$ by picking galaxies at z and

$$P_{mm}(k) \sim \frac{[bP_{mm}(k)]^2}{b^2 P_{mm}(k)} \sim \frac{[P_{mg}(k)]^2}{P_{gg}(k)} \sim \frac{\left[C^{\kappa g}_{\ell=k\chi}\right]^2}{C^{gg}_{\ell=k\chi}}$$

- Operationally we perform a joint fit to the combined data set.
  - With only the auto-spectrum there is a strong degeneracy between the amplitude (σ_8) and the bias parameters (b).
  - However the matter-halo cross-spectrum has a different dependence on these parameters and this allows us to break the degeneracy and measure σ_8 (and b).
- Need a model for the auto- and cross-spectra of biased tracers.

Signal to noise: now (79 σ)

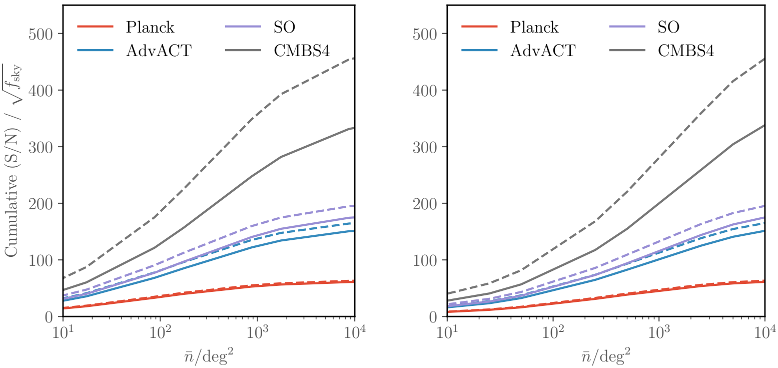
unWISE galaxies crossed with Planck lensing ...



Krolewski+19

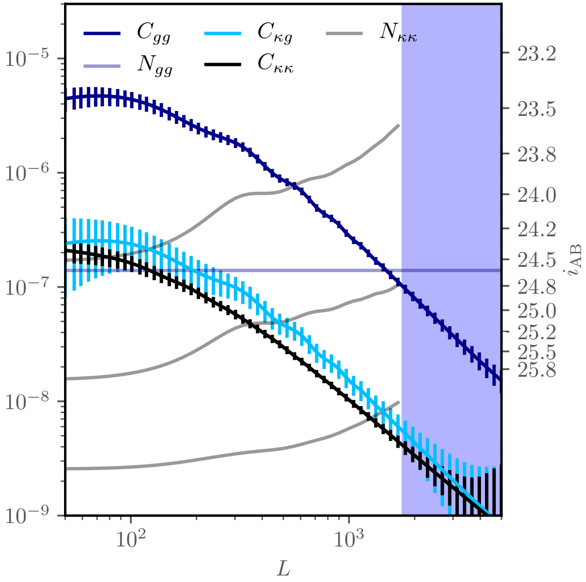
Signal to noise: the future

We could achieve $S/N \gtrsim 10^2$ at $z \simeq 3$ and at 4, larger than or comparable to S/N we can achieve in one bin at low z at present.



Wilson & White (2019)

Signal-to-noise: u-dropouts ($z \sim 3$)



- C_ℓ^{gg}, $C_\ell^{\kappa g}$ and $C_\ell^{\kappa\kappa}$.
- Grey lines: noise levels (per ℓ) for AdvACT, SO and S4.
- Horizontal line: shot noise
- Band at $L_{\rm nl}$.

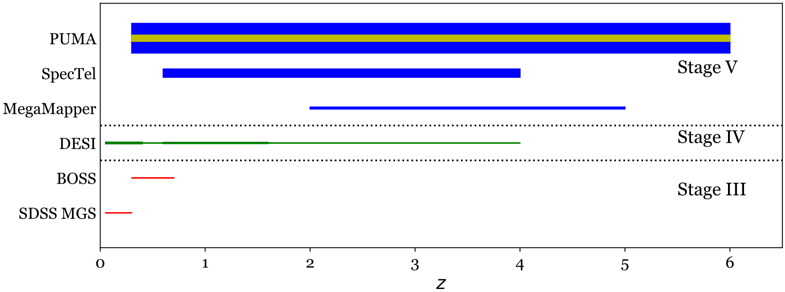
Wilson & White (2019)

What if we want it all?

But there are many more modes if we can get distances, i.e. map large-scale structure in 3D!

There's a "traditional" way to do it, and a "new" way to do it ...

Spectroscopic survey comparison



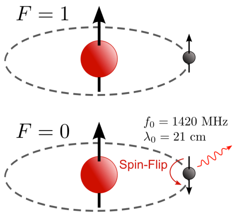
(Area of box ≈ effective number of galaxies)

PUMA: Future H I intensity mapping survey

High risk, high reward: intensity mapping of neutral hydrogen for large-scale structure science.

(Intensity mapping is simply a low-resolution map in which individual source [e.g. galaxies] are not resolved, but only the integrated emission. Much like we don't usually resolve individual stars in distant galaxies, just their integrated emission.)

Basics of 21 cm



(Wikipedia)

- Hyperfine (mag. dip.) transition of HI
- Spin-spin coupling between $p + e$

$$\begin{aligned} \Delta E &= 4 g_p \hbar^4 / (3 m_p m_e^2 c^2 a^4) \\ &\simeq 6\,\mu\mathrm{eV} \end{aligned}$$

- Very rare transition per atom ($\propto \mu^2/\lambda^3$):

$$\begin{aligned} A_{10} &= \frac{64\,\pi^4\,\mu_B^2}{3\,h\,\lambda^3} \\ &\simeq 2.85 \times 10^{-15}\,\mathrm{s}^{-1} \end{aligned}$$

- Little absorption or confusion (no line at 710 MHz!), but long wavelength.

Modeling 21 cm

- In the "intermediate" redshift Universe ($0.5 < z < 5$) most of the Hydrogen is ionized.
- HI signal comes from self-shielded regions
  - Most likely at densities between the outskirts of disks and where the gas becomes molecular.
  - (in the QSO context these are DLAs!)
- Hard problem computationally.
- Few constraints observationally:
  - Galaxy surveys at $z < 0.1$ (mass functions).
  - DLA abundance observations (for Ω_{HI}) at $z > 2$.
  - Clustering of DLAs at $z \sim 2$: $b_{DLA}(z=2) \simeq 2.0 \pm 0.1 \;\Rightarrow\; b_{HI} \approx 2$
  - HI intensity mapping at $z \sim 0.8$ provide an upper and a lower limit on $\widetilde{\Omega}_{HI} b_{HI}(z=0.8)$ consistent with $b_{HI}(z \simeq 1) \sim 1$.

Modeling 21 cm

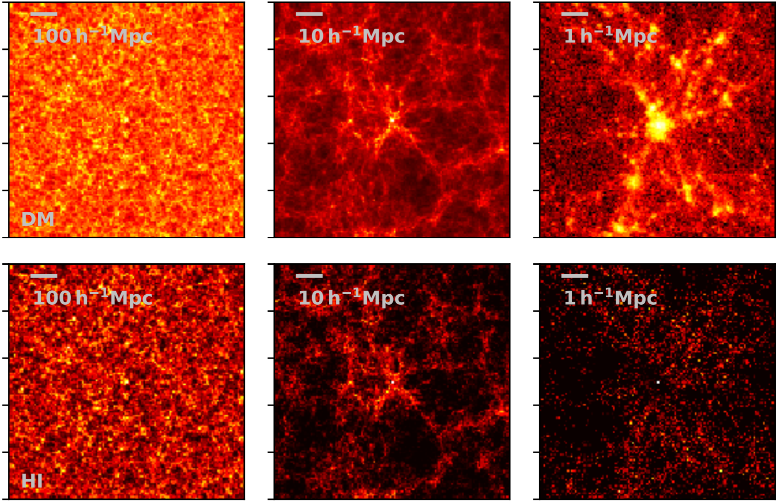
Hydrodynamic simulations and semi-analytic models suggest a halo occupancy that looks like

$$M_{HI} \propto M_h^{\alpha} \ \exp\left[-\frac{M_{\rm min}}{M_h}\right]$$

- Power-law index regulated by how fast HI accretes onto halos. Simulations suggest $\alpha \approx 1$ at $z > 2$, with expectations that $\alpha < 1$ because tidal interactions, ram-pressure stripping, mergers more efficient at removing HI than cooling hot gas.
- Low mass cutoff, $M_{\rm min} \sim 10^9\, h^{-1} M_\odot$, where self-shielding becomes inefficient, constrained by clustering (where available) $\Rightarrow$ low mass halos: numerous (low shot noise) and less biased (easier to model).

Hidden Valley

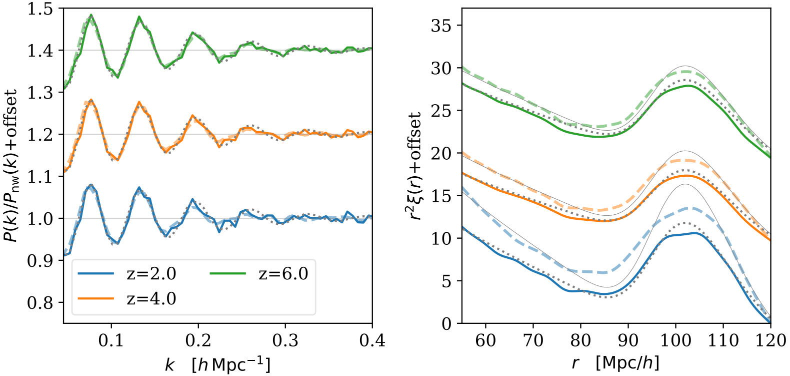
A set of $> 10^{12}$ particle N-body simulations directed at IM science ...



cyril.astro.berkeley.edu

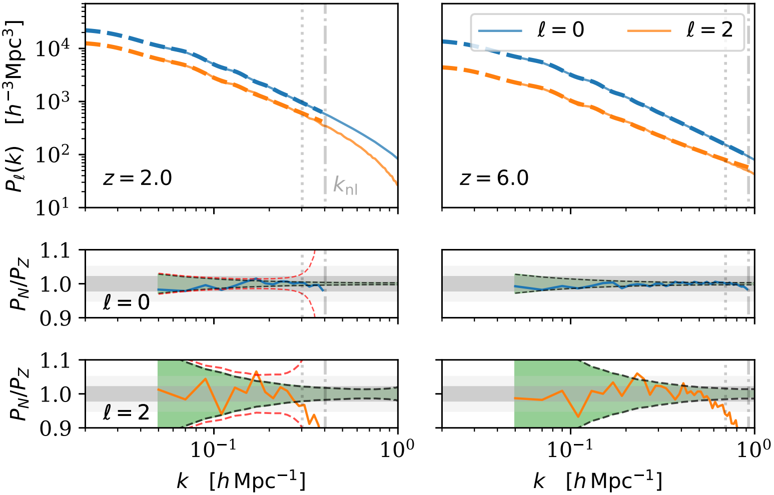
Hidden Valley: BAO

The simulation volume is large enough to see BAO in the power spectrum (and correlation function).



Modi+19a

Hidden Valley: HI is simple to model – $P(k)$

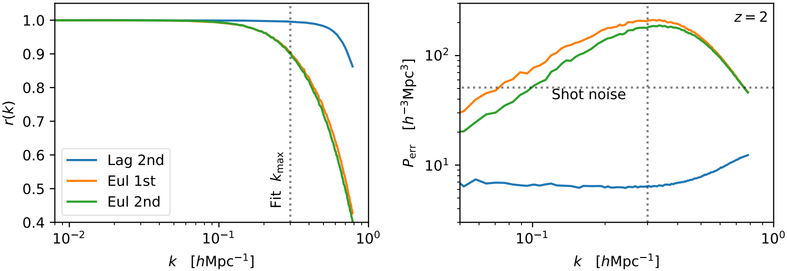


Lowest order (tree level) LPT already does well ...

Modi+19a

Hidden Valley: HI is simple to model – at the field level

A quadratic Lagrangian bias model reproduces the HI density field to better than shot-noise over a broad range of scales even at relatively low z!



Modi+19b

Sounds good!

So the science is compelling, and the theory is well-motivated and well-controlled ...

... how do we get these data?

Big radio telescopes

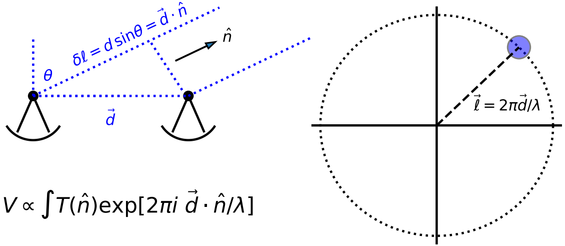
- Long wavelength ⇒ low resolution for single dish.
- Very weak (record holder: $z = 0.376$ from 178hr on VLA)
- Need big arrays for sensitivity ($+$ resolution)
- Many elements and channels ⇒ big data problem!
- Radio arrays have not been big enough for high z surveys ...
- ... because we haven't been able to handle the data!

The steady advance of computing and signal processing capability (paid for by the telecommunications industry and chip manufacturers) is making this tractable!

Broadband receivers make large z range possible in a single instrument.

Interferometer basics: Visibilities

The sky signal at a dish pair has a rel. phase, $\propto d/\lambda$.
Each pair of dishes measures a "visibility" (the FT of the sky) "averaged" over a small region of $\vec{\ell}$-space.
The $\vec{\ell}$ mode is determined by the dish spacing while the averaging region is determined by the dish diameter (primary beam).

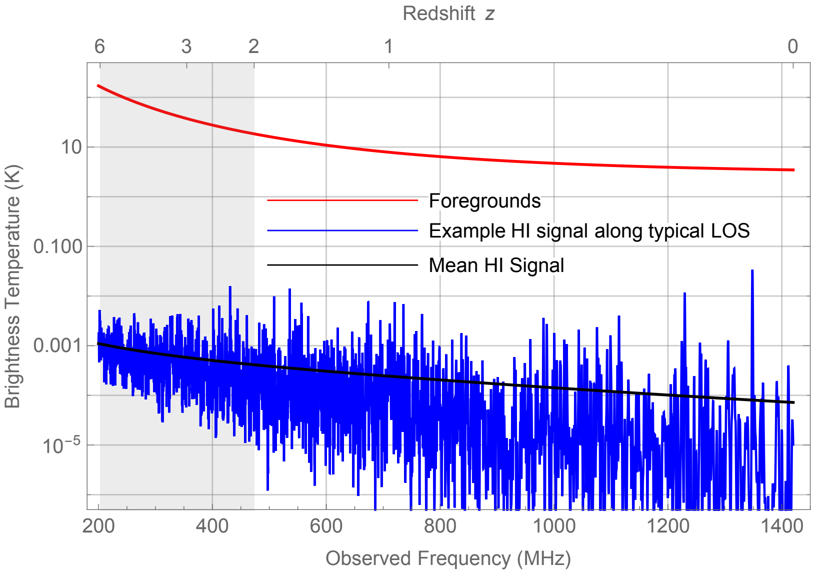


As the sky rotates over the fixed dishes, the visibility sweeps a circle in the $\vec{\ell}$-plane of fixed $|\vec{\ell}|$.

So what's the catch?

So that seems pretty easy …

Foregrounds

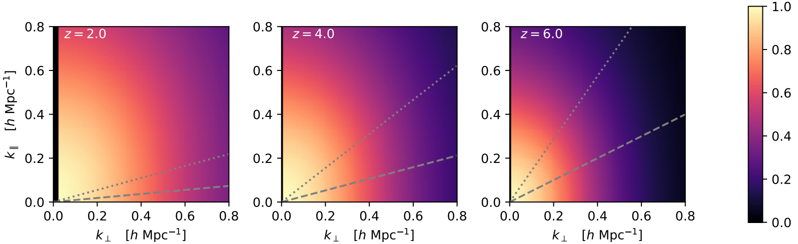


Foregrounds

- Foreground amplitude is orders of magnitude larger than the signal.
- Primarily galactic (synchrotron and free-free) and unresolved point sources.
- Spectrally smooth $\Rightarrow$ filter out low $k_{\parallel}$ modes (high-pass filter).
- A variety of methods could be used for the filter ...
- Complication: a fixed baseline probes ν-dependent $k_{\perp}$. Any baseline miscalibration adds structure along $k_{\parallel}$.
- Generically lose access to modes within a foreground wedge.
  - Problem more pronounced at higher z.
  - Purely technical challenge!

Foreground wedge

$S/(S+N)$, including shot-noise and instrument noise, for a next-generation 21-cm interferometer designed for LSS studies.

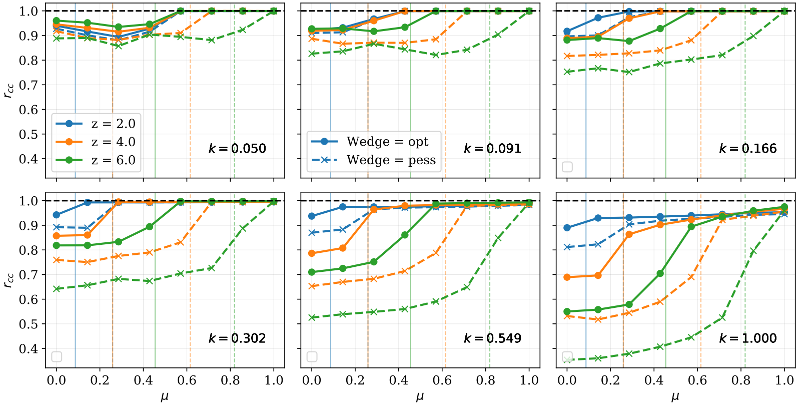


The foreground wedge for $1\times$FOV and $3\times$FOV are shown as the dashed and dotted lines (respectively).

arXiv:1907.02330

Foreground wedge recovery?

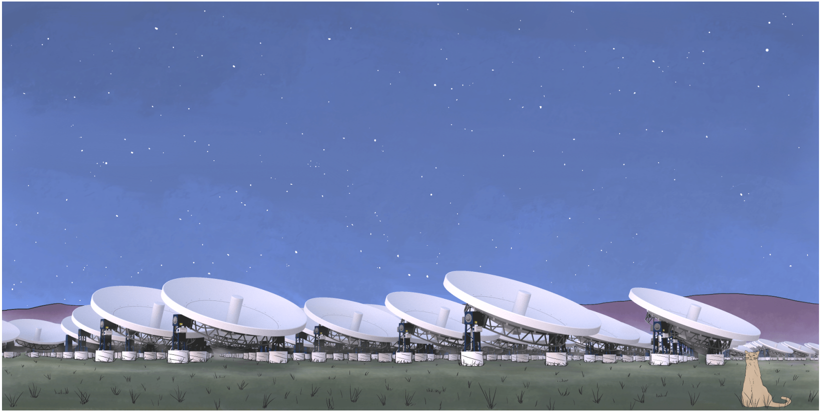
New forward modeling approaches offer the hope of reconstructing many of these missing modes.



arXiv:1907.02330

PUMA

The **P**acked **U**ltra-wideband **M**apping **A**rray



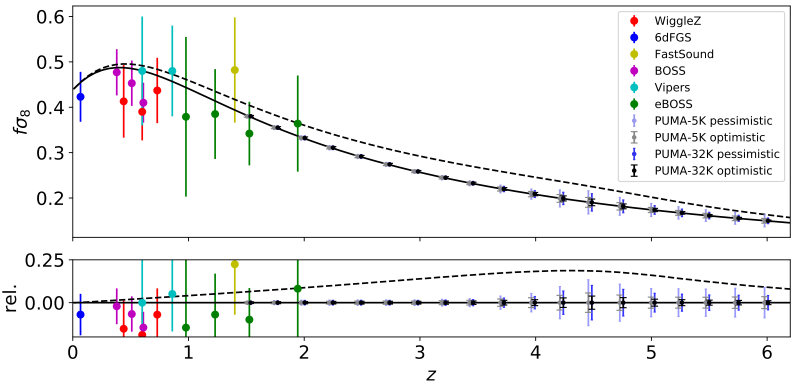
$10^3 - 10^4$, transiting 6 m dishes with $200 - 1100$ MHz receivers.

Science $\rightarrow$ Instrument

The science goals naturally determine the basic parameters of the experiment:

- To resolve quasi-linear modes $\Rightarrow$ longest baseline required and thus linear extent of the array ($\simeq 1.5\,\mathrm{km}$).
- Required sensitivity $\Rightarrow$ determines $N\,D > 200\,\mathrm{km}$.
- Low $k_\perp$ sensitivity $\Rightarrow$ close-packed.
- Good beam-forming sets minimum $D \simeq 6\,\mathrm{m}$.

Growth rate



$f\sigma_8$
0.6
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WiggleZ
6dFGS
FastSound
BOSS
Vipers
eBOSS
PUMA-5K pessimistic
PUMA-5K optimistic
PUMA-32K pessimistic
PUMA-32K optimistic
rel.
0.25
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1
2
3
4
5
6
z

Challenges and opportunities

Numerous hardware challenges, but also

- New science cases, new approaches (missing low-$k_{\parallel}$, the wedge, uncertain $\bar{T}$).
- Theory needs to be developed for these approaches.
- Calibration and analysis (foregrounds, RFI, beamforming, processing algorithms all 'at scale').
- Simulations (theory, mocks, end-to-end).
- High-performance computing ('big data': $> 10^2$ TB/day).

This field is like galaxy surveys of the 1990's or 2000's, and much of the CMB/LSS technology still needs to be rethought and adapted to this science.

Conclusions

- There are many (quasi-)linear modes in the Universe left to map.
- These will allow precisions tests of SM and GR, and improve constraints on parameters by substantial factors (or find something new!).
  - Already percent-ish level constraints at lower z are turning up much-discussed "tensions".
- This presents an interesting, and very 'principled', theoretical challenge.
- There will be a large role for simulations (theory, mocks, end-to-end).
- The community is already planning or building next-generation instruments.
- The best observational approaches are still TBD.

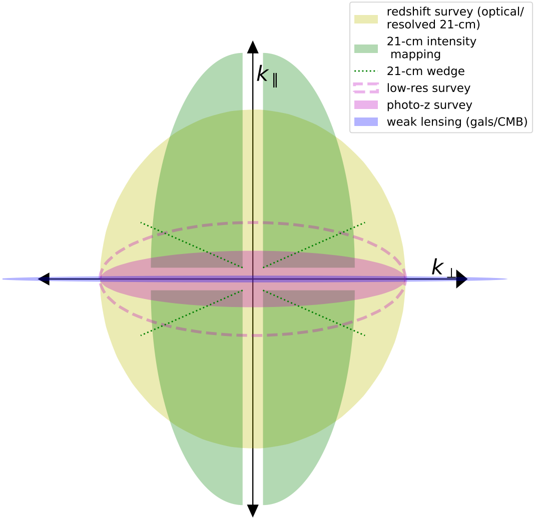
Resources

This talk is online at http://mwhite.berkeley.edu/Talks

- Cosmic Visions (Dark Energy) white paper
- Testing inflation with large scale structure
- Inflation and dark energy from spectroscopy at $z > 2$
- Dark energy and modified gravity
- Inflationary archaeology through features in the power spectrum of primordial fluctuations
- Cosmology with dropout galaxies
- Megamapper
- PUMA whitepaper (https://www.puma.bnl.gov)
- Intro lecture on 21-cm intensity mapping
- IM review (Kovetz+18)

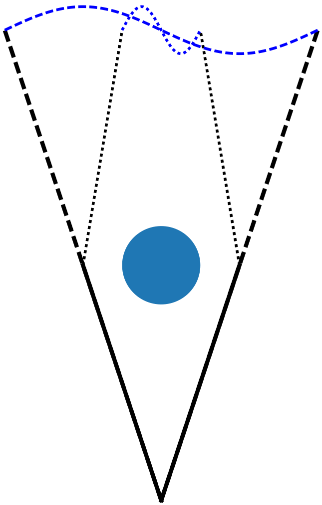
The End!

Comparison: k-space



https://github.com/slosar

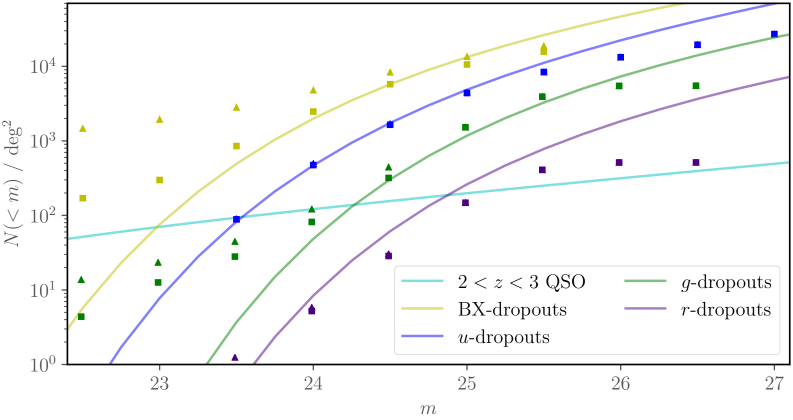
Measuring lensing from the CMB



- CMB fluctuations have a characteristic scale.
- Lensing "reconstruction" finds κ by measuring a local stretching of the power spectrum.
- Magnified regions shift power to larger scales (smaller ℓ).
- Demagnified regions shift power to smaller scales (higher ℓ).

Measure (projected) mass density across the sky.

Large numbers of galaxies



Wilson & White (2019)

MegaMapper

MegaMapper is a highly-multiplexed spectroscopic survey designed to characterize the two (known) epochs of accelerated expansion.

- MegaMapper couples a (new) 6.5-m Magellan telescope with (new) DESI spectrographs to achieve 20,000 multiplex.
- Covers $360 - 980\,\text{nm}$ with $\lambda/\Delta\lambda \simeq 2000 - 5500$ with $70 - 90\%$ optical efficiency.
- MegaMapper will target $\approx$ 100Million galaxies that span $2 < z < 5$.
- Targets are a combination of Lyman-Break galaxies (LBGs), selected using dropout techniques, and Lyman$-\alpha$ emitters (LAEs) for which broad-band color selection is possible
- The MegaMapper would be located at Las Campanas Observatory in the southern hemisphere, and would have full access to LSST imaging for target selection.

Improvement in parameters

The survey design, operations and analysis follows well established methods in large-scale structure.

$$\sigma(f_{NL}^{\rm loc}) \approx 0.1,\ \sigma(f_{NL}^{\rm eq}) \approx 20,\ \sigma(f_{NL}^{\rm orth}) \approx 8.$$

Parameter	DESI	MegaMapper
$10^4\Omega_K$	12	6.6
$\sum m_\nu$ [meV]	32	28
n_s	0.0029	0.0026
$dn_s/d\ln k$	0.004	0.003
$N_{\rm eff}$	0.078	0.069
Slip	0.01	0.008

arXiv:1903.09208

Brightness temperature

Rather than intensity we talk about measuring fluctuations in brightness temperature $[I_\nu = 2k_B T_B(\nu/c)^2]$ around the mean: $\bar{T}$. The mean cosmological brightness temperature for 21-cm is

$$\begin{aligned}\bar{T} &= \frac{3h_P c^3 A_{10}}{32\pi\, m_H k_B \nu_{21}^2} \frac{(1+z)^2}{H(z)}\, \rho_{HI} \\ &\simeq 188h\, \frac{(1+z)^2}{E(z)} \widetilde{\Omega}_{HI}(z)\, \mathrm{mK}\end{aligned}$$

Note that unlike galaxy surveys we don't know $\bar{T}$ because we don't really know $\widetilde{\Omega}_{HI}$ all that well [1709.07596]:

$$\widetilde{\Omega}_{HI}(z) = (4\pm?) \times 10^{-4}(1+z)^{0.6} \quad [1 < z < 6]$$

This means the amplitude of the fluctuations (bias) is degenerate with $\bar{T}$.

Dirac equation and magnetic dipole

- At low E we can ignore 2^{nd} quantization for $e^{\pm}$.
- Then $H_D = \alpha \cdot \mathbf{p} + \beta m$ with $\alpha_i^2 = \beta^2 = 1$ and $\{\alpha_i, \alpha_j\} = \{\alpha_i, \beta\} = 0$.
- In the NR limit ($E \approx mc^2$) in the standard representation with 2-spinors $\psi_\pm$ this becomes:

$$\begin{pmatrix} m - E & \sigma \cdot \mathbf{p} \\ -\sigma \cdot \mathbf{p} & m + E \end{pmatrix} \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

- For NR particles

$$\psi_- \approx \frac{\sigma \cdot \mathbf{p}}{2m} \psi_+ \quad \Rightarrow \quad (E - m)\psi_+ = \frac{(\sigma \cdot \mathbf{p})^2}{2m} \psi_+$$

- Including $\mathbf{B}$ field takes $\mathbf{p} \to \mathbf{p} - q\mathbf{A}$ so using σ identities

$$H_{\text{hf}} = \frac{e}{2m} [\mathbf{p} \cdot \mathbf{A} + \mathbf{A} \cdot \mathbf{p}] - \mu_B \sigma \cdot \mathbf{B}$$

with the last term $2(\mu_B/\hbar)\, \mathbf{S} \cdot \mathbf{B}$ that we need.

The semi-relativistic Hamiltonian

$$H_D \approx \underbrace{\frac{\mathbf{p}^2}{2m} + V}_{\text{Schrodinger}} \underbrace{- \overbrace{\frac{\mathbf{p}^4}{8m^3}}^{\text{SR}} - \overbrace{\frac{\hbar^2}{4m^2}\frac{\partial V}{\partial r}\frac{\partial}{\partial r}}^{\text{Darwin}} + \overbrace{\frac{1}{2m^2 r}\frac{\partial V}{\partial r}\mathbf{S}\cdot\mathbf{L}}^{\text{spin}-\text{orbit}}}_{\text{fs}\sim\mathcal{O}(v^2)}$$

$$\underbrace{+\frac{q}{2m}\left[\mathbf{p}\cdot\mathbf{A} + \mathbf{A}\cdot\mathbf{p}\right] - 2\frac{\mu_B}{\hbar}\overbrace{\mathbf{S}\cdot\mathbf{B}}^{\text{mag.dip.}}}_{\text{hf}\sim\mathcal{O}([m_e/m_p]v^2)} + \underbrace{\frac{q^2}{2m}\mathbf{A}\cdot\mathbf{A}}_{2-\text{photon}}$$

Hyperfine energy splitting

Recall the hyperfine levels arise from the coupling of the proton and electron spin, described by

$$H_{\mathrm{hf}}^{\ell=0} \propto \frac{e^2\, g_p\, g_e}{m_p\, m_e}\; \delta^{(3)}(\mathbf{r})\; \mathbf{S}_p \cdot \mathbf{S}_e$$

The states are defined by S^2, S_p^2 and S_e^2 and we want

$$\langle n\ell s s_p s_e \,| H_{\mathrm{hf}} |\, n\ell s s_p s_e \rangle$$

But

$$\langle \mathbf{S}_p \cdot \mathbf{S}_e \rangle = \frac{\hbar^2}{2}\left(\langle S^2 \rangle - \frac{3}{2} \right) = \frac{\hbar^2}{4} \begin{cases} +1 & s = 1 \\ -3 & s = 0 \end{cases}$$

and for the g.s. of H we have $\langle \delta^{(3)}(\mathbf{r}) \rangle = |\psi_{100}(\mathbf{0})|^2 = 1/\pi a^3$. This gives $\Delta E \simeq 6\,\mu\,\mathrm{eV}$.

Notes

- Classically $dE/dt \sim \ddot{\mu}^2 \sim \omega^4 \mu^2 \Rightarrow$ Rate$\sim \frac{\omega^4 \mu^2}{\hbar\omega} \sim \omega^3 \mu^2$.
- In QM Fermi Golden rule says

$$R \sim \frac{2\pi}{\hbar} \delta(\Delta E - \hbar\omega) \, |\langle f|V|i\rangle|^2$$

- Have $V \sim \vec{A}$, with $A \ni \omega^{-1/2} \epsilon_{k\lambda} a^\dagger_{k\lambda} \exp[ikx]$ (normalized so that $H \sim E^2 + B^2 \sim (\partial A)^2 \sim \hbar\omega a^\dagger a$).
- Final state $d^3k \sim k^2 \, dk \, d\Omega$. Use the δ-fn to kill dk, the $\omega^{-1/2}$ squared kills one k.
- Summing over λ gives $P_{ij} = \delta_{ij} - \hat{k}_i \hat{k}_j$
- Magnetic dipole comes from ikx from exponential.

Hyperfine transition rate

- The transition rate can be computed from Fermi's Golden Rule with an interaction $\propto \mathbf{S}_e$ (and 2^{nd} quantized radiation).
- The $\vec{E}$-dipole transition is zero by parity.
- The transition proceeds via the magnetic dipole for the e^-, e.g.

$$R_{\downarrow\uparrow} \propto \omega^3 \, \mathcal{P}_{ij} \, \langle \downarrow | \mathbf{S}_i^e | \uparrow \rangle^\dagger \, \langle \downarrow \left| \mathbf{S}_j^e \right| \uparrow \rangle$$

(i.e. it is a *forbidden* transition).

- Find

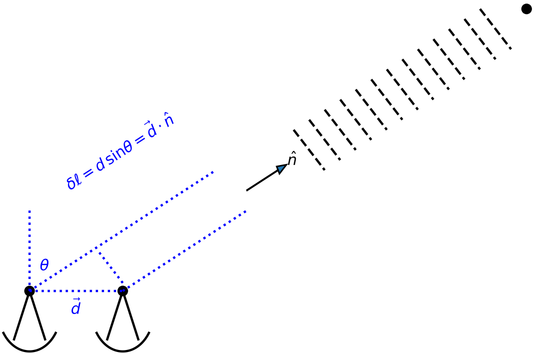
$$\begin{aligned} A_{10} &= \frac{64\,\pi^4\,\mu_B^2}{3\,h\,\lambda^3} \qquad (\propto \omega^3 \mu_B^2) \\ &\simeq 2.85 \times 10^{-15}\,\mathrm{s}^{-1} \end{aligned}$$

Experimental landscape

- HI is relatively well studied in the $z \simeq 0.1$ Universe.
- Clustering has been bounded with single-dish, GBT data at $z \simeq 1$ (see earlier).
- Currently the CHIME experiment is the "leader", but they have no cosmology results to date.
- Various other surveys in commissioning, construction or planning ...

Interferometer basics: Visibilities

In an interferometer the fundamental data is the correlation between two feeds (or antennae), known as a visibility.



$$V_{ij} = \langle E_i E_j^{\star} \rangle_{\mathrm{time}}$$

Interferometer basics: Visibilities

In an interferometer the fundamental data is the correlation between two feeds (or antennae), known as a visibility. For an intensity measurement the visibility is

$$V_{ij} \propto \int d^2\hat{n}\ A^2(\hat{n})T(\hat{n})\ e^{2\pi i \hat{n}\cdot\vec{u}_{ij}}$$

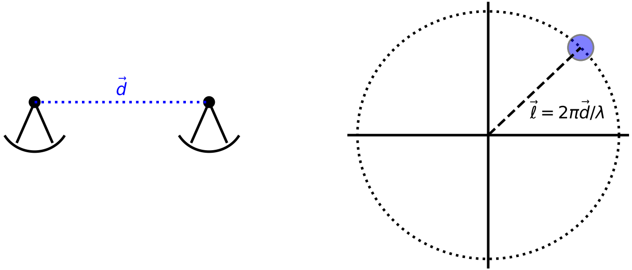
where

- $T(\hat{n})$ is the brightness temperature in the sky direction $\hat{n}$,
- A is the primary beam (assumed the same for all feeds) and
- $\vec{u}_{ij}$ is the difference in position vectors of the $i^{\rm th}$ and $j^{\rm th}$ feeds in units of the observing wavelength.

An interferometer works natively in (angular) Fourier space. The $\vec{\ell}$-modes measured are set by the spacing of the feeds.

Interferometer basics: Visibilities

Each visibility measures the FT of the sky, "averaged" over a small region of $\vec{\ell}$-space. The $\vec{\ell}$ mode is determined by the dish spacing while the averaging region is determined by the dish diameter.



As the sky rotates over the fixed dishes, the visibility sweeps a circle in the $\vec{\ell}$-plane of fixed $|\vec{\ell}|$.

Instrument noise (FWIW)

In addition to shot-noise we have some "thermal" noise:

$$P_{21}(k,\mu) \simeq \bar{T}^2 \left(b_{HI} + f\mu^2\right)^2 P_m(k) + \bar{T}^2 P_{SN} + P_{\rm th}.$$

where

$$P_{th} = T_{\rm sys}^2 \left(\frac{\lambda^2}{A_{\rm e}}\right)^2 \left(\frac{4\pi f_{\rm sky}}{\Omega_p(z)}\right) \frac{1}{n_{\rm pol}\nu_0 t_{\rm obs} n(\vec{u})} \, \frac{d^2V}{d\Omega\, d(\nu/\nu_0)}$$

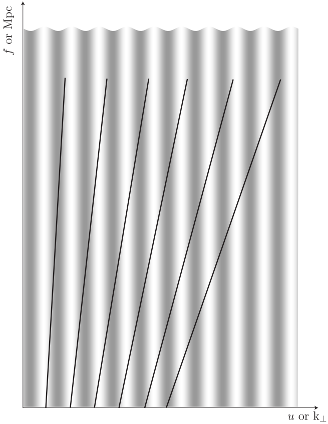
and

$$\frac{d^2V}{d\Omega\, d(\nu/\nu_0)} = \chi^2 \frac{d\chi}{dz} \nu_0 \frac{dz}{d\nu} = \chi^2 \frac{c\,(1+z)^2}{H(z)} \quad .$$

and

$$T_{\rm sys} = \underbrace{55\,{\rm K}}_{\rm ampl} + \underbrace{2.7\,{\rm K}}_{\rm CMB} + \underbrace{30\,{\rm K}}_{\rm grnd} + \underbrace{25\,{\rm K}\left(\frac{\nu_{\rm obs}}{400\,{\rm MHz}}\right)^{-2.75}}_{\rm sky}$$

Foreground wedge



Morales+19

- Wedge arises because a baseline probes ν-dependent $k_\perp$.
- Consider a foreground with $k_\parallel \approx 0$ (grey bands).
- Baseline miscalibration adds structure along $k_\parallel$.
- Worst at high $k_\perp$, where run of $k_\perp(\nu)$ strongest.
- Leads to "foreground wedge".
- Problem more pronounced at higher z.
- Purely technical challenge!

Foreground wedge

Due to foregrounds modes with

$$\frac{k_\parallel}{k_\perp} < \sin\theta\,\mathcal{R} \quad , \quad \mathcal{R} \equiv \frac{\chi(z)\,H(z)}{c(1+z)} = \frac{E(z)}{1+z}\int_0^z \frac{dz'}{E(z')}$$

are lost.

The value of θ is under debate in the community!

$\theta = \pi/2$ is known as the "horizon wedge".
$\theta =$FOV or $\theta = 3\times$FOV are more optimistic.

PUMA science drivers

1. Characterize the expansion history in the pre-acceleration era.
2. Characterize structure growth in the pre-acceleration era.
3. Constrain (or detect) primordial non-Gaussianity.
4. Constrain (or detect) features in the primordial $P(k)$.
5. Fast radio burst (FRB) tomography.
6. Monitor all pulsars discovered by SKA.

arXiv:1810.09572

PUMA forecasts

Parameter	LSST + DESI + Planck	CMB S4	PUMA + Planck	LSST + DESI + PUMA + Planck	CMB-S4 + PUMA	All experiments combined
$\sum m_\nu$ [meV]	38	59	31 / 27	25 / 22	24 / 21	15 / 14
$\sum m_\nu + \tau$ prior	—	15	—	—	14 / 13	10.4 / 10.2
$\sum m_\nu$ (free w)	50	—	33 / 29	26 / 23	—	—
$N_{\rm eff}$	0.050	0.026	0.043/0.037	0.033/0.030	0.014/0.013	0.012/0.011
w (free $\sum m_\nu$)	0.017	—	0.006/0.005	0.005/0.004	—	—

arXiv:1810.09572

PUMA forecasts

$f_{\rm NL}$	CMB error		PUMA error	
	Planck (current)	CMB-S4 (forecast)	PUMA-5K	PUMA-32K
Squeezed (local)	5.0	2.0	0.7 (1.4)	0.3 (0.8)
Equilateral	43	21	10 (30)	5.0 (23)
Orthogonal	21	9.0	6.5 (13)	3.0 (8.5)

arXiv:1810.09572

HI IM Resources

- Kovetz+18
- CVDE white paper: arXiv:1810.09572
- Interferometric 21-cm, LSS experiments:
  - https://chime-experiment.ca,
  - (https://www.ska.ac.za/gallery/meerkat/)
  - OWFA
  - http://tianlai.bao.ac.cn/
  - https://hirax.ukzn.ac.za,
  - https://www.puma.bnl.gov
- Software
  - CRIME and CoLoRe
  - CORA, driftscan and draco.
  - https://github.com/andreimesinger/21cmFAST
  - https://gitlab.com/radio-fisher/bao21cm
- Mock data
  - http://cyril.astro.berkeley.edu

Perturbation theory

- CMB anisotropies are "everyone's favorite", linear, cosmological perturbation theory calculation ...
- Arguably, CMB anisotropies form the gold standard for cosmological inference and cosmological knowledge.
- A well controlled, analytic calculation which can be compared straightforwardly to observations.
- As we move to lower redshifts we need to start worrying about structure going non-linear and about the relation between the matter field and what we see (bias).

Lowest order I

$$
\begin{aligned}
P_{\rm tree} &= 4\pi \int q^2\, dq\ e^{-(1/2)k^2(X_L+Y_L)} \Bigg\{ \\
& \left[1 + b_1^2\left(\xi_L - k^2 U_L^2\right) - b_2\left(k^2 U_L^2\right) + \frac{b_2^2}{2}\xi_L^2\right] j_0(kq) \\
&+ \sum_{n=1}^{\infty} \Bigg[1 - 2b_1 \frac{q\, U_L}{Y_L} + b_1^2\left(\xi_L + \left[\frac{2n}{Y_L} - k^2\right] U_L^2\right) \\
& +b_2\left(\frac{2n}{Y_L} - k^2\right) U_L^2 \\
& -2b_1 b_2 \frac{q\, U_L\, \xi_L}{Y_L} + \frac{b_2^2}{2}\xi_L^2\Bigg] \left(\frac{k\, Y_L}{q}\right)^n j_n(kq)\Bigg\}
\end{aligned}
$$

For cross-correlations: $b_1 \to \frac{1}{2}\left(b_1^A + b_1^B\right)$, $b_1^2 \to b_1^A b_1^B$, etc.

Lowest order II

Where

$$\xi_L(q) = \frac{1}{2\pi^2}\int_0^\infty dk\ P_L(k)\left[k^2 j_0(kq)\right]$$

$$X_L(q) = \frac{1}{2\pi^2}\int_0^\infty dk\ P_L(k)\left[\frac{2}{3} - 2\frac{j_1(kq)}{kq}\right]$$

$$Y_L(q) = \frac{1}{2\pi^2}\int_0^\infty dk\ P_L(k)\left[-2j_0(kq) + 6\frac{j_1(kq)}{kq}\right]$$

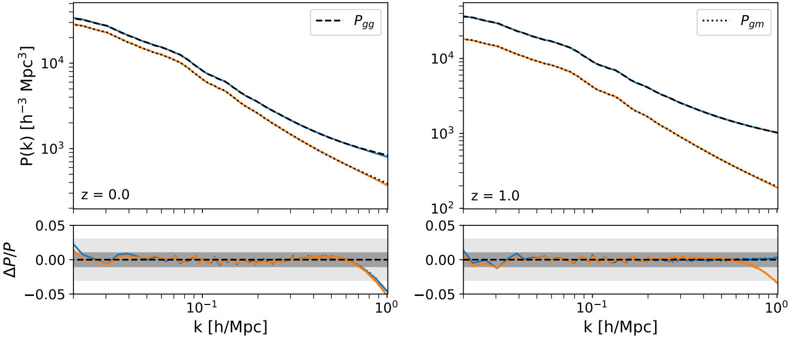
$$U_L(q) = \frac{1}{2\pi^2}\int_0^\infty dk\ P_L(k)\left[-k\, j_1(kq)\right]$$

The integrals over q can be done efficiently using fast Fourier transforms or other methods.

The full expressions contain "1-loop" terms which are integrals of P_L^2.

Hybrid emulator

Combine N-body simulations with symmetries-based bias expansion to build an efficient emulator for $P(k)$ ...



arXiv:1910.07097

Intensity mapping

Review: Kovetz+ arXiv:1709.09066

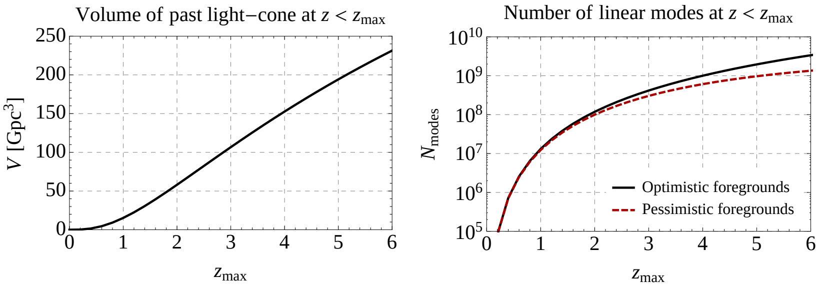
Give up on resolving individual galaxies, put S/N where you want it (quasi-linear modes). Overall HI still traces δ:

	Traditional	IM
Focus	individual objects	cosmic web (quasi-linear modes)
Design	small number of capable elements	large number of passive elements
Resolution	high	low ($k_{\mathrm{max}} \sim 1\,h\,\mathrm{Mpc}^{-1}$)
Allocation	PI led	survey

(Galaxy people who don't resolve stars do this all the time!)

Volume and modes

Note: $z = 6$ is over half way to the edge of the Universe!



arXiv:1810.09572