Cosmology with Neutral Hydrogen

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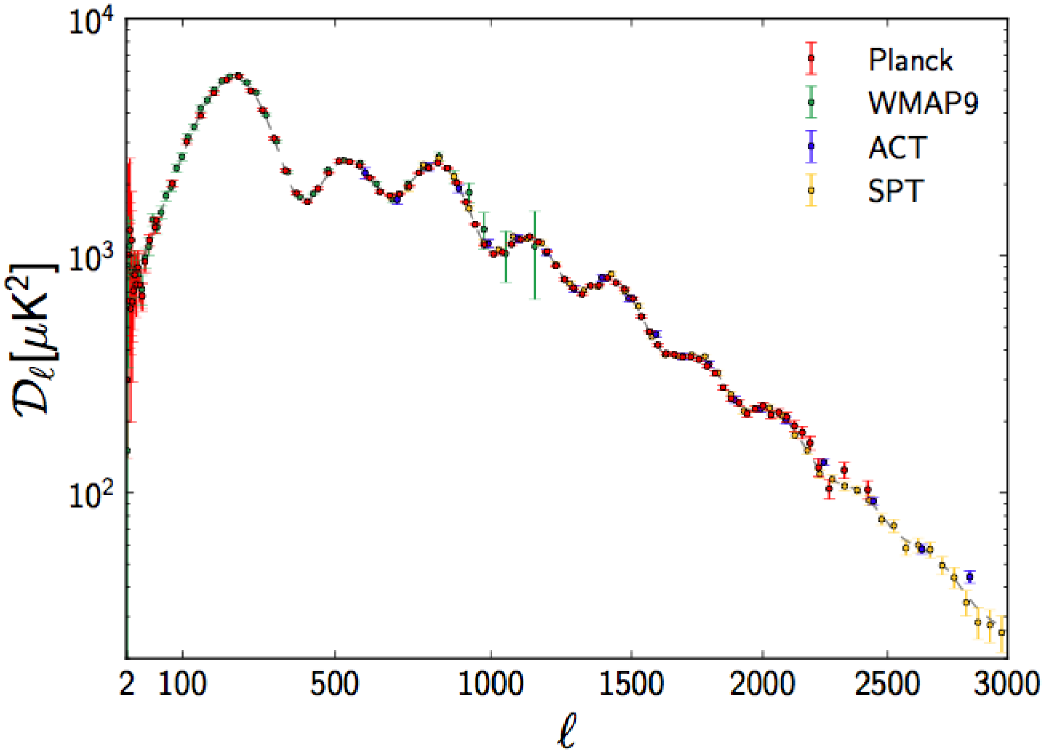
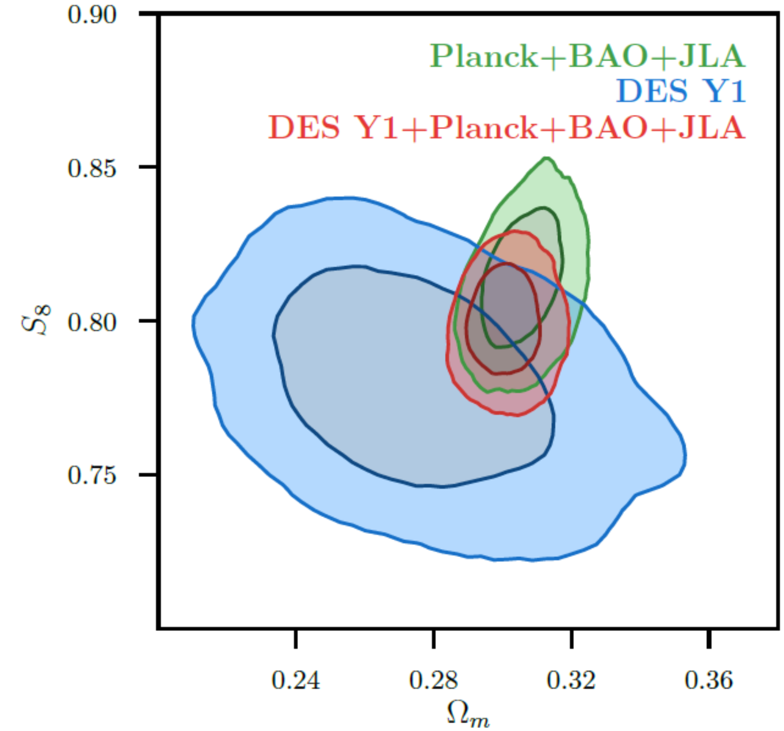
UC Berkeley

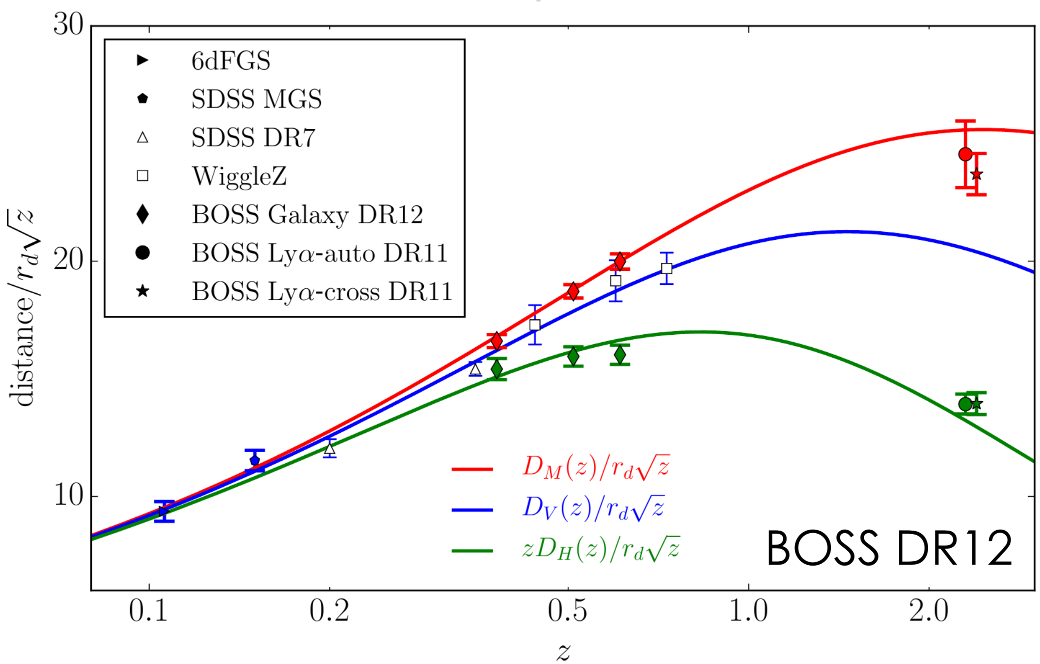
w/ Obuljen, Chen, Modi, Villaescusa-Navarro, White, Slosar, Feng
and the 21cm science working group

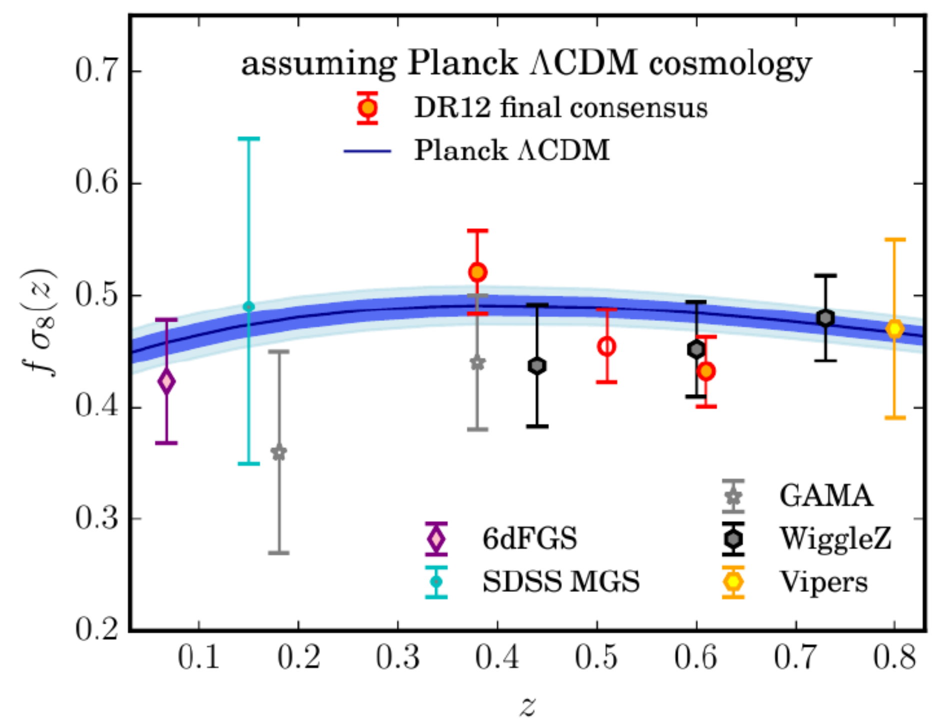
RPM, LBL, March 7th 2019

Observational status: a consistent picture

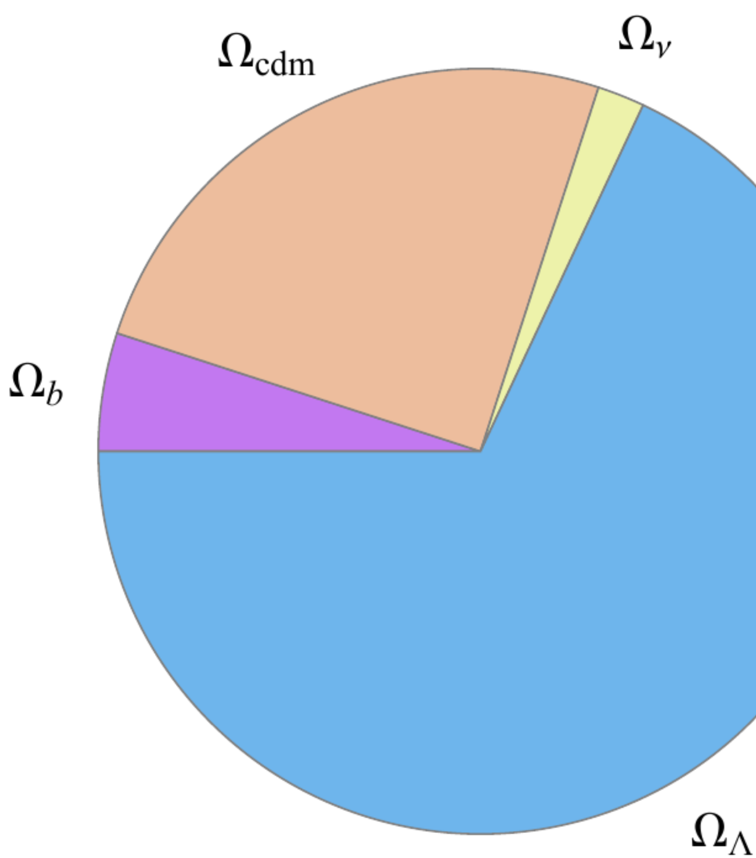








The pizza nobody asked for



+

~ Adiabatic
~ scale invariant
~ Gaussian initial conditions

Most, if not all, of the parameters lack fundamental interpretation

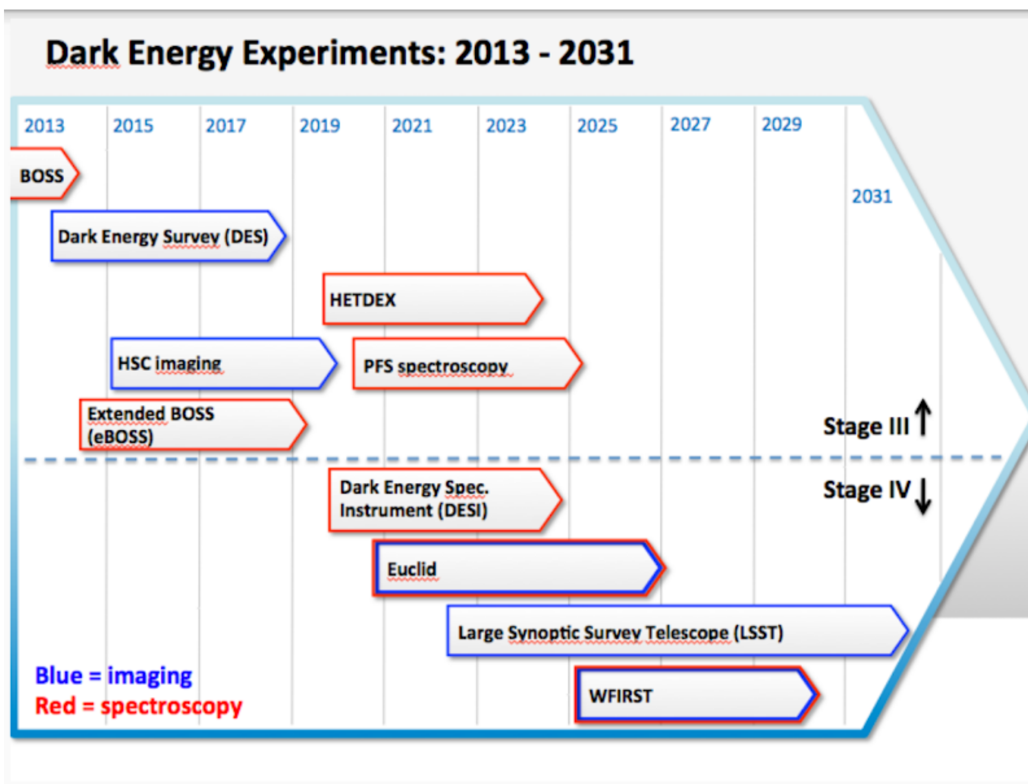
Outline

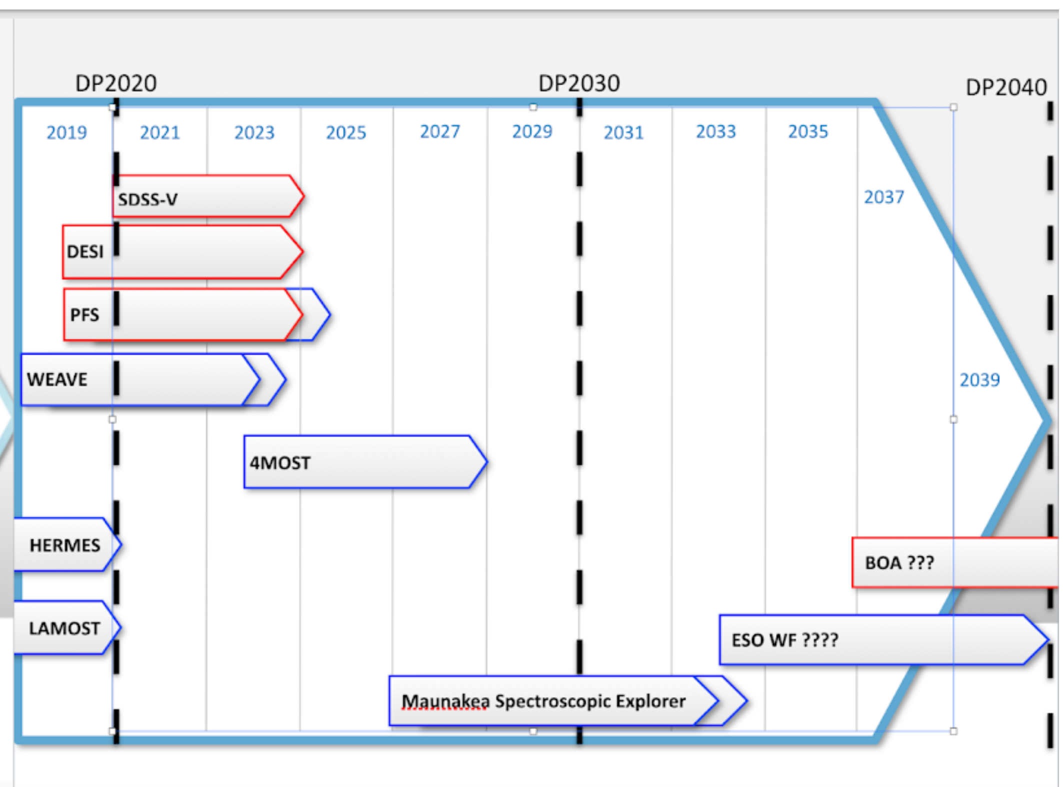
- Why I am giving this talk
- Crash course on 21 cm and interferometry
- The cosmological 21 cm signal : Theory and Simulations efforts
- Stage-II : opportunities and challenges
- Why DOE ?

Where are we going ?

- There are no funded next-generation experiments post DESI/LSST
- There will be 30m+ optical telescopes, but their FoV is tiny

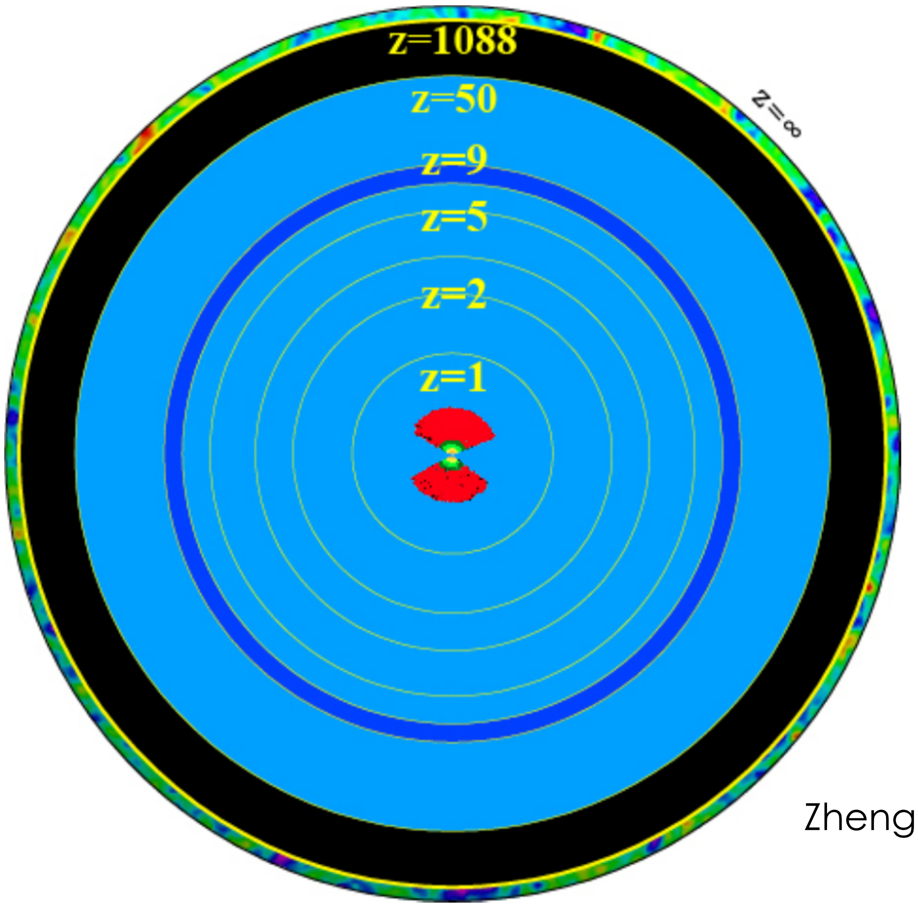
Independently of the outcome, it won't be over yet



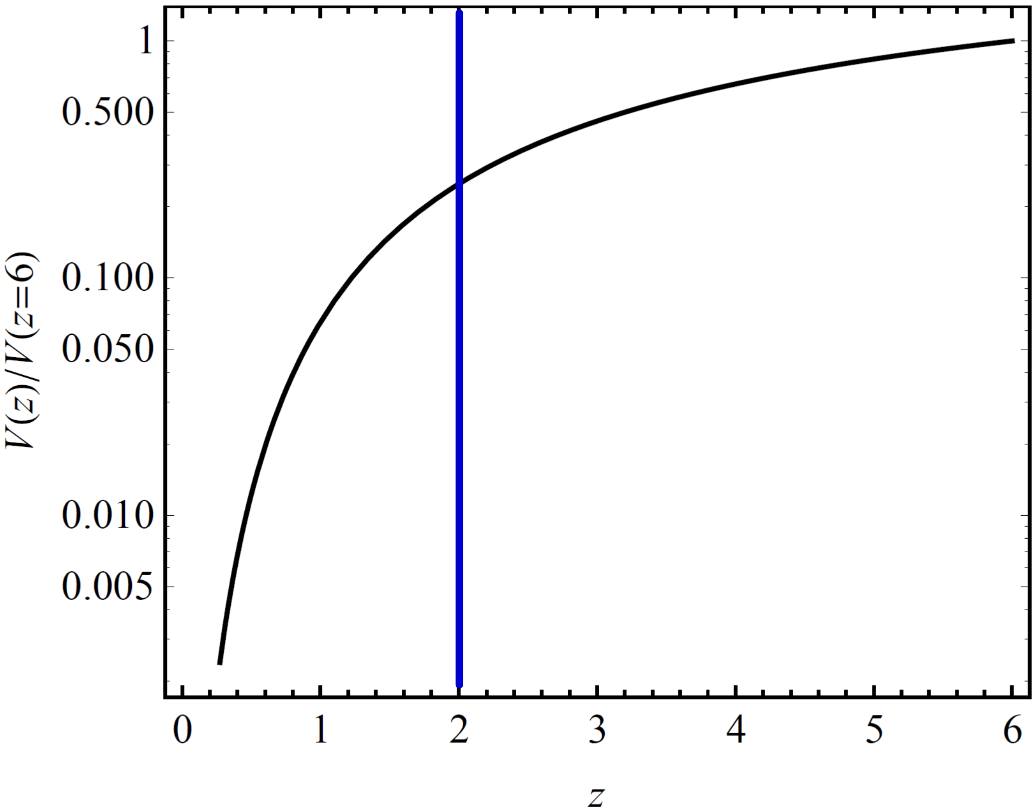


Where do we want to go next ?

- Currently information comes from vary far away, CMB at last scattering (but 2ndary anisotropies), or 'low redshift", z<2.



Zheng+14



4x more volume available. Huge potential for cosmology

Tough game: cannot measure more modes than # galaxies in the survey

Cosmic Vision: ‘Dark Energy’

The DOE has tasked several Cosmic Visions groups to think about plans for >2020s

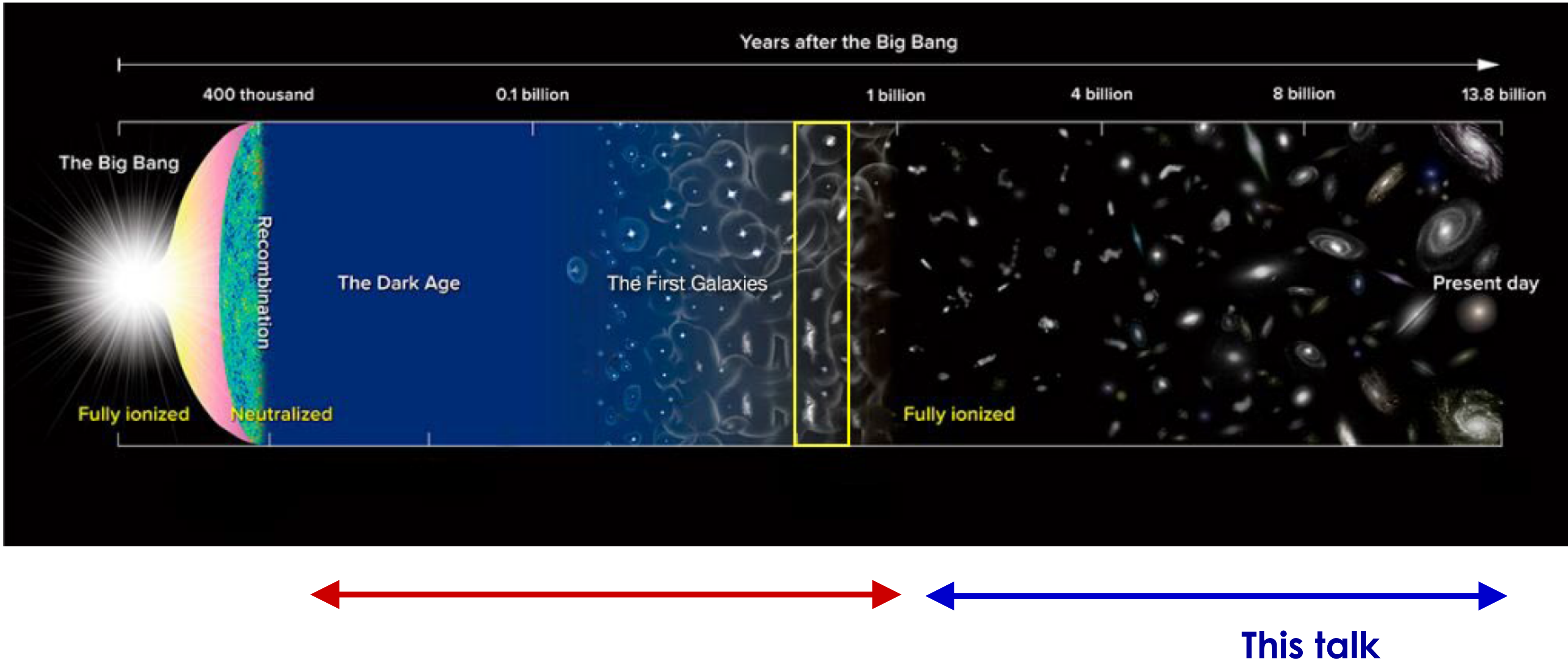
Five possible surveys proposed :

- Spectroscopy in the South ;
- DESI-II ;
- Low resolution spectroscopy of 1B galaxies ;
- High resolution spectroscopy of 1B galaxies (BOA) ;
- 21 cm experiment at $z<6$: Stage-II

Ongoing talks at US institutions to raise interest

21 cm basics

The long story short...



Signal from Dark Ages, Cosmic Dawn and EoR potentially very intersting, but hard to detect. Cosmology is degenarate with complicated astrophysics. Edges,LOFAR,HERA,SKA.

After EoR, the remaining fraction of neutral hydrogen lives in high density regions, Damped Lyman alpha systems (DLAs), where it is shielded from ionizing photons. 21cm in GBT,CHIME,HIRAX,Tianlai and Stage-II

Neutral hydrogen : observables

Neutral hydrogen offers a natural way of mapping the high-z Universe. There is a lot of it and it is "easy" to target.

- Emission: Lyman-alpha emitters (LAEs)

- Emission : 21 cm in signle dish or interferometric mode.

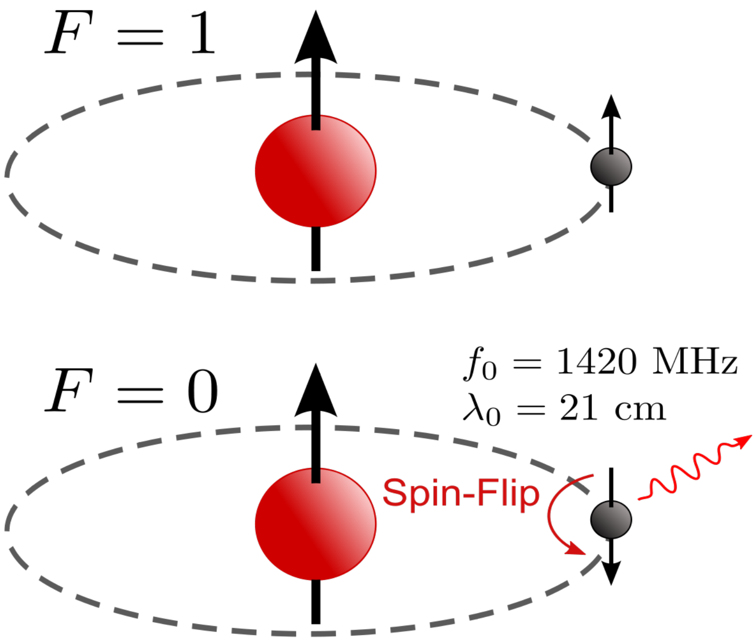
- Absorption: Lyman-alpha forest , $2<z<3.5$ in BOSS and DESI. <1 % of the HI

21cm in one slide

The infamous 21cm transition is associated with the hyperfine structure of the ground state of neutral hydrogen

$$n_1 = n_0 \frac{g_1}{g_0} e^{-T_*/T_S} \simeq 3n_0 = \frac{3}{4} n_{HI}$$

$$T_* = 0.068\,K \quad (5.84 \times 10^{-6} eV)$$

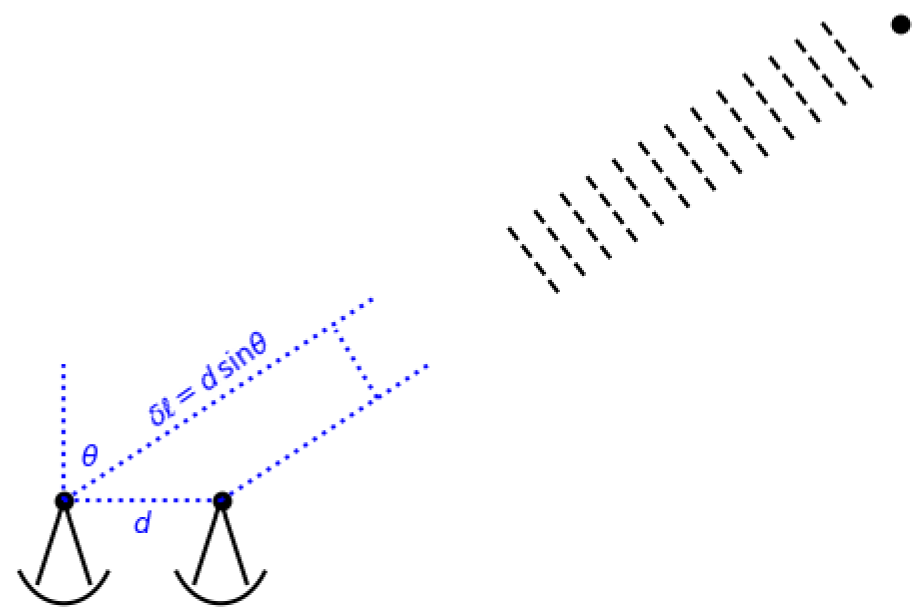


Rate of spontaneous emission is 10^7 years.

21cm emission at redshift z can be observed at radio frequency 1.42/(1+z) GHz.

Interferometer basics

- Each baseline (pair of antennas) measures a "visibility", Vij.
- Visibility is a Fourier component of the image
- Interferometer measures the sky image directly in the Fourier space
- This aspect leads to both advantages and disadvantages



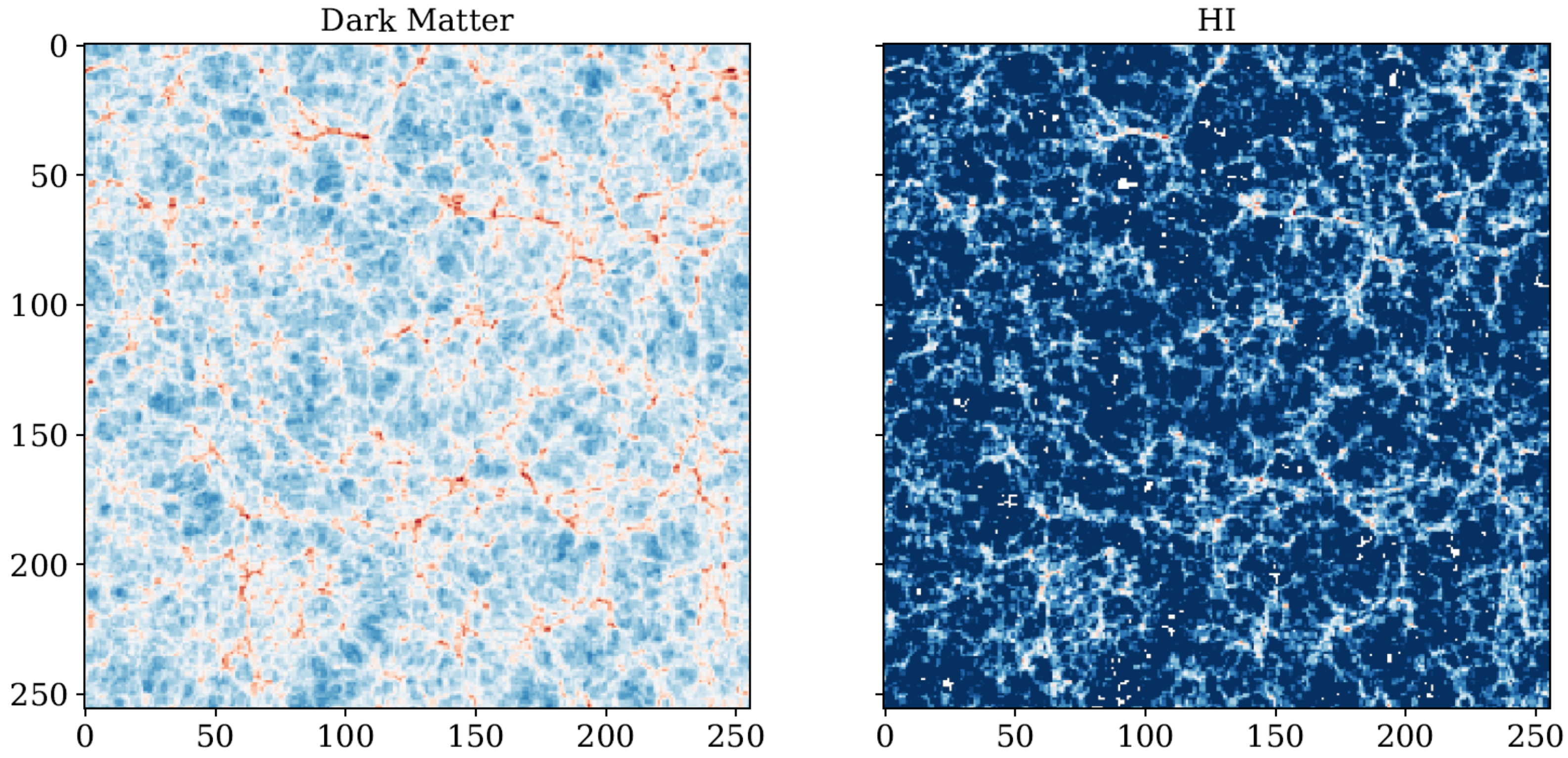
$$
\begin{aligned}
V_{ij} &= \left\langle E_i E_j^{\star} \right\rangle_{\mathrm{TIME}} \\
&= \sum_{\mathrm{SRC}} E^2 \exp\left[2\pi i \hat{n} \cdot d_{ij}/\lambda\right] \mathrm{BEAM} \\
&= \int d\hat{n} I(\hat{n}) B(\hat{n}) e^{2\pi i \hat{n} \cdot u_{ij}}
\end{aligned}
$$

No photons left behind

Give up on observing individual galaxies.

Accurate redshifts: frequency resolution of the receivers.

Much like the CMB, but in 3D. Many more modes !



$$P_{21}(k,\mu;z) = \bar{T}_b^2(z)\left(P_{HI}(k,\mu;z) + \frac{1}{n_{eff}}\right) = \bar{T}_b^2(z)\left[(b_{HI} + f\mu^2)^2 P_m(k,z) + \frac{1}{n_{eff}}\right]$$

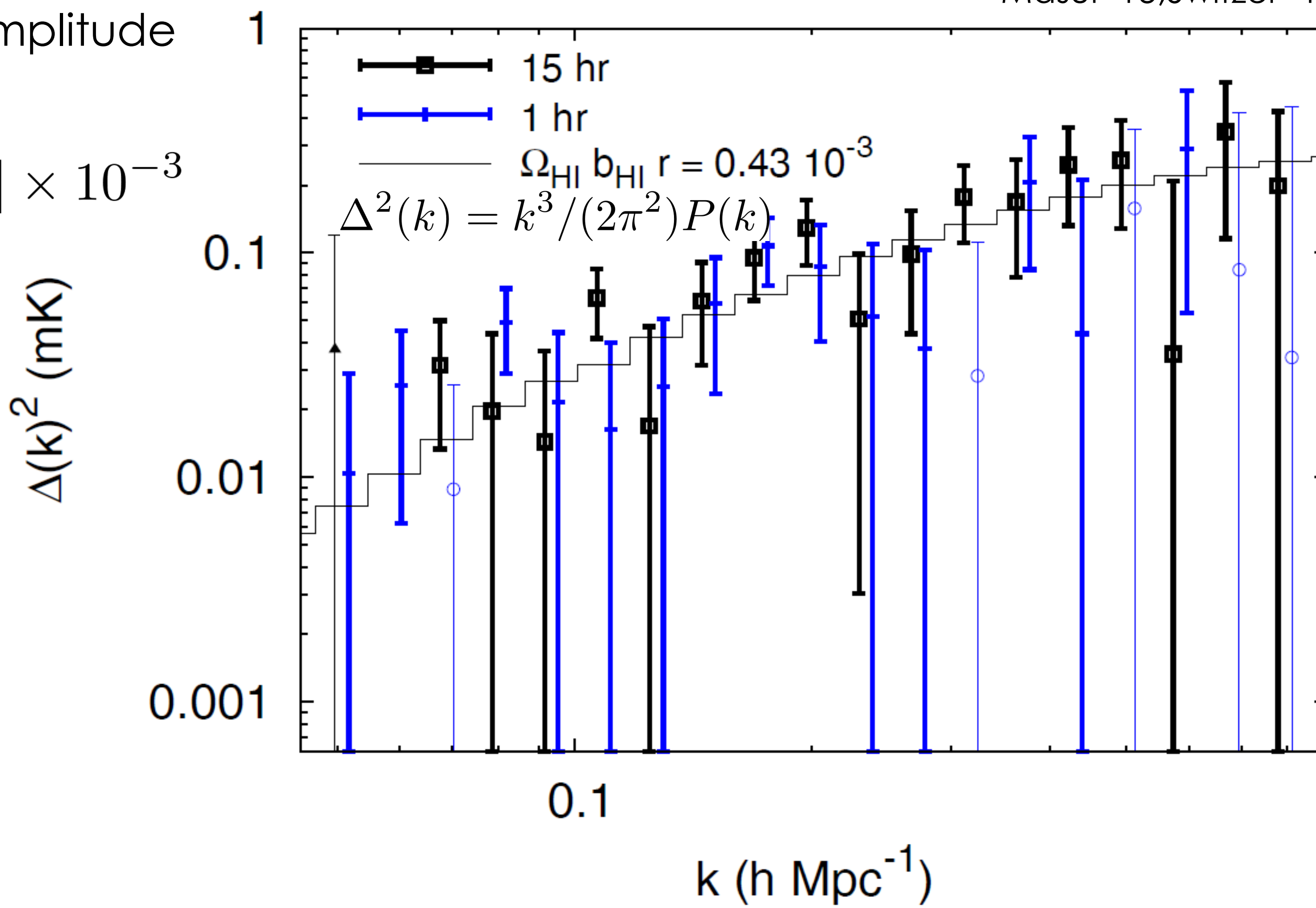
Observational status

We have several detections of 21cm P(k) at low-z in cross-correlation with galaxy surveys, only upper limits in auto.

Masui+13,Switzer+13

Measurement of the amplitude

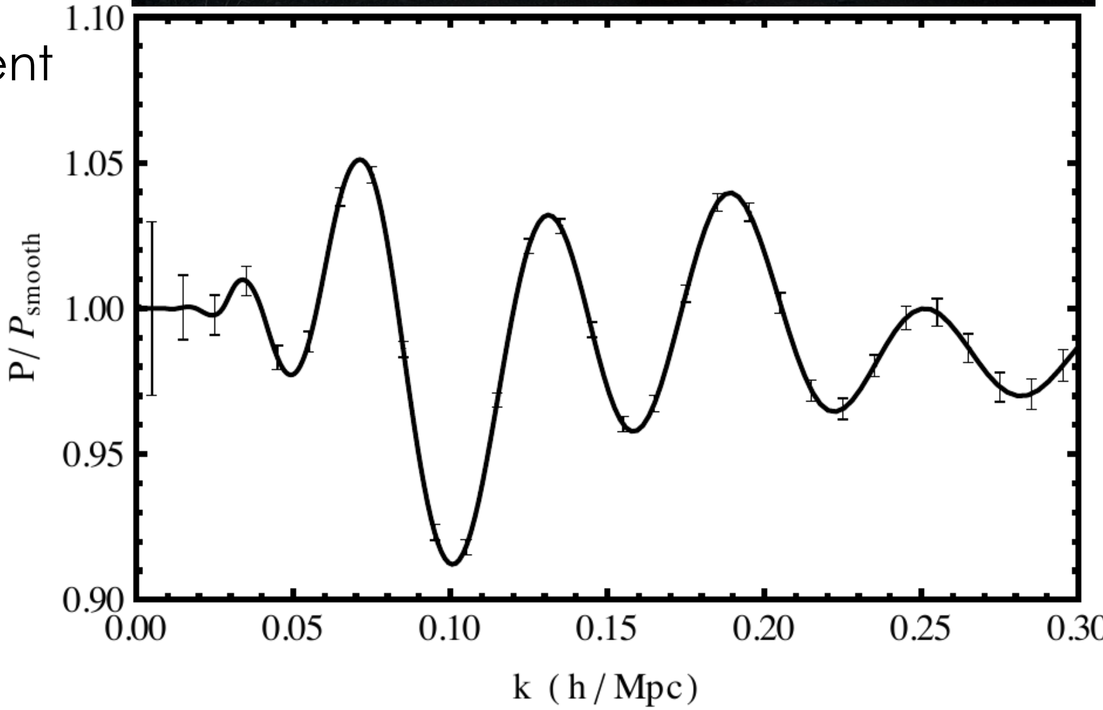
$$\Omega_{HI} b_{HI} = [0.62^{+0.23}_{-0.15}] \times 10^{-3}$$



Observational status

Outside DOE:

- CHIME – Canadian experiment, taking data
  – will detect BAO z=0.75-2
- HIRAX – South African experiment,
  1/2 funded and being prototyped
- FIRST: 500m single dish Chinese experiment
- BINGO, proposed UK experiment



Inside DOE:

- Tianlai involvement at Fermilab
- BMX testbed at BNL.
  Cross correlation w/ SDSS in 2019

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

Observational status

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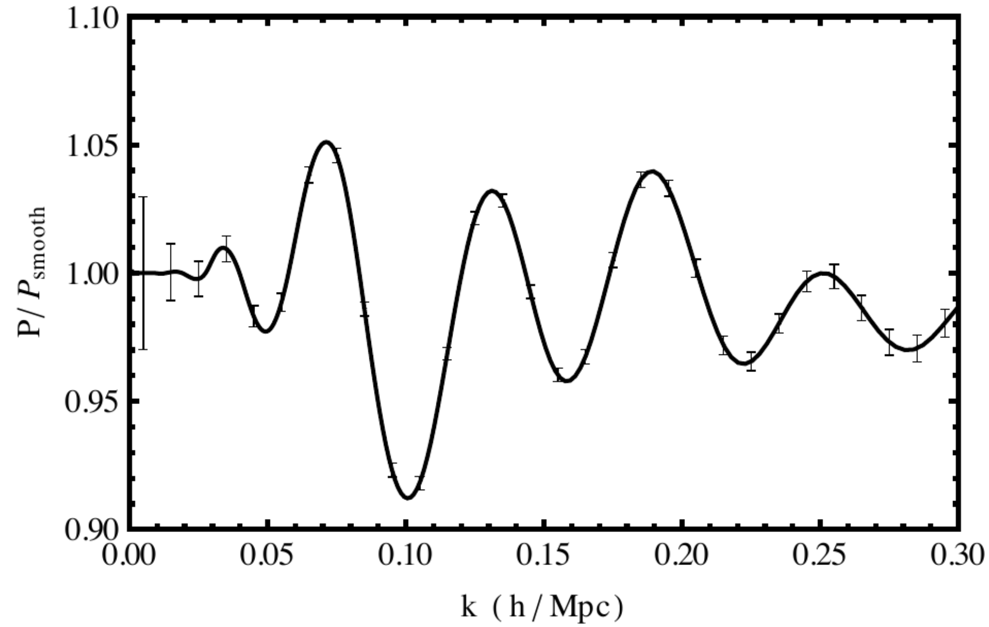

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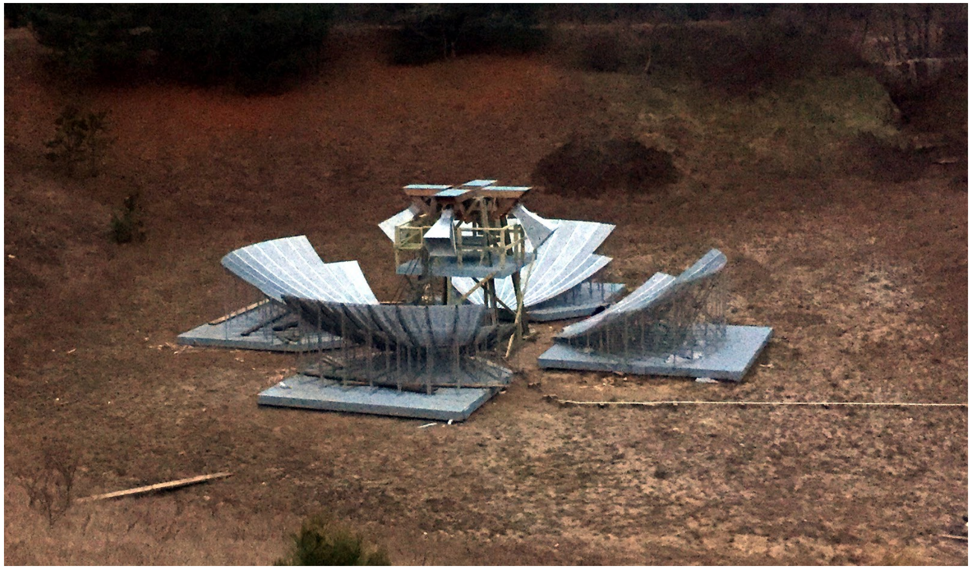


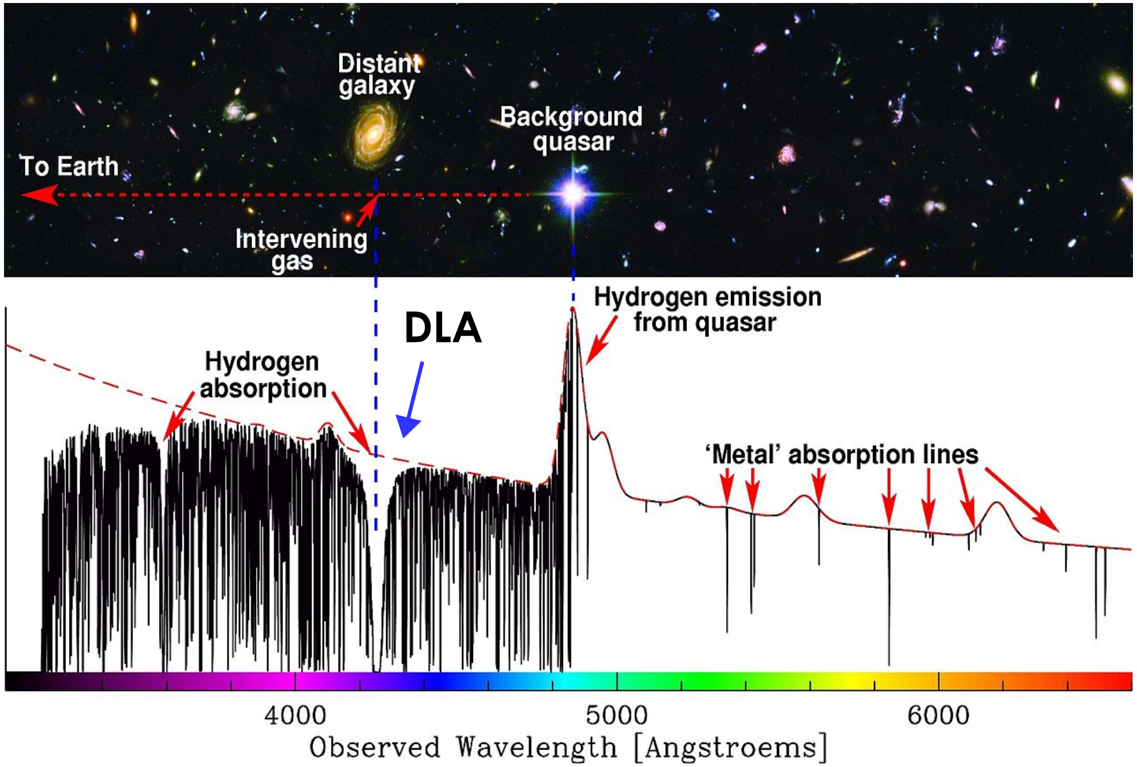
All these experiments will, in the next 5 years, demonstrate the promise of the technique.

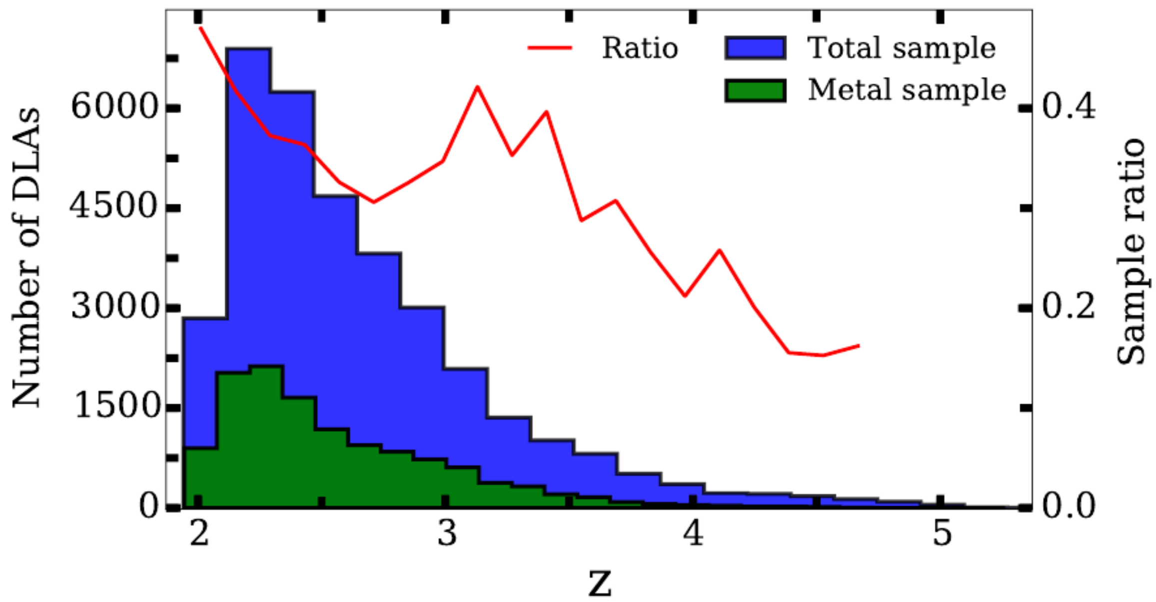
The 21 cm cosmological signal

The HI distribution post-EoR

Strong absorption in QSOs spectra reveals the presence of high concentration of HI,

Damped Lyman-alpha (DLAs) systems contain >90 % of the HI in the Universe





Almost 30k DLAs have been detected in BOSS at z<3.5, hundreds in QSOs at high z

$$\Omega_{\rm HI}(z=2.3) = 0.83 \times 10^{-3}$$

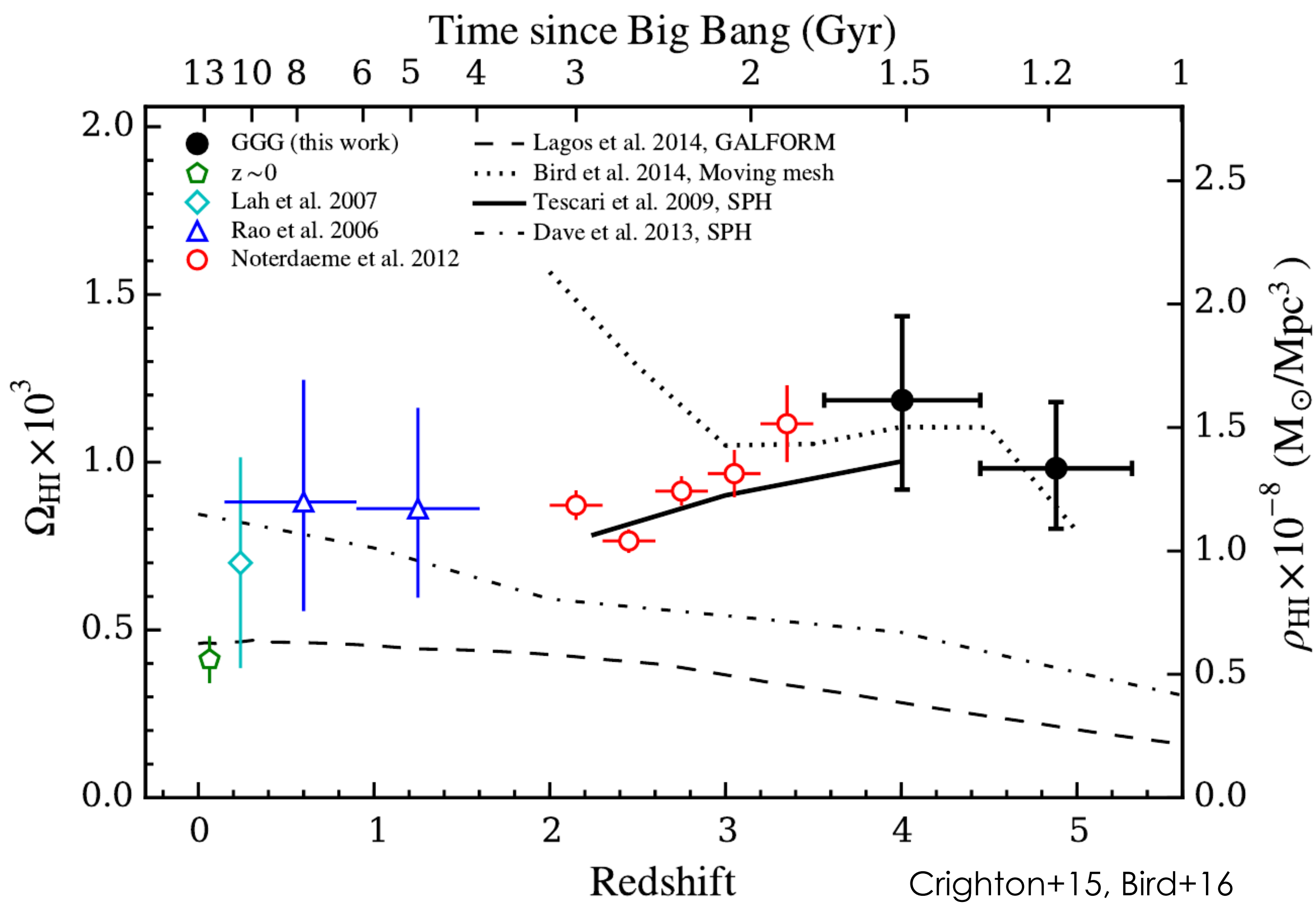
$$b_{\rm DLA} = 2.00 \pm 0.1$$

Mas-Ribas+16

Cosmological abundance

Limited by sys at low z and by stat a high z. (today)

No strong evidence for evolution over time at z > 1.



Crighton+15, Bird+16

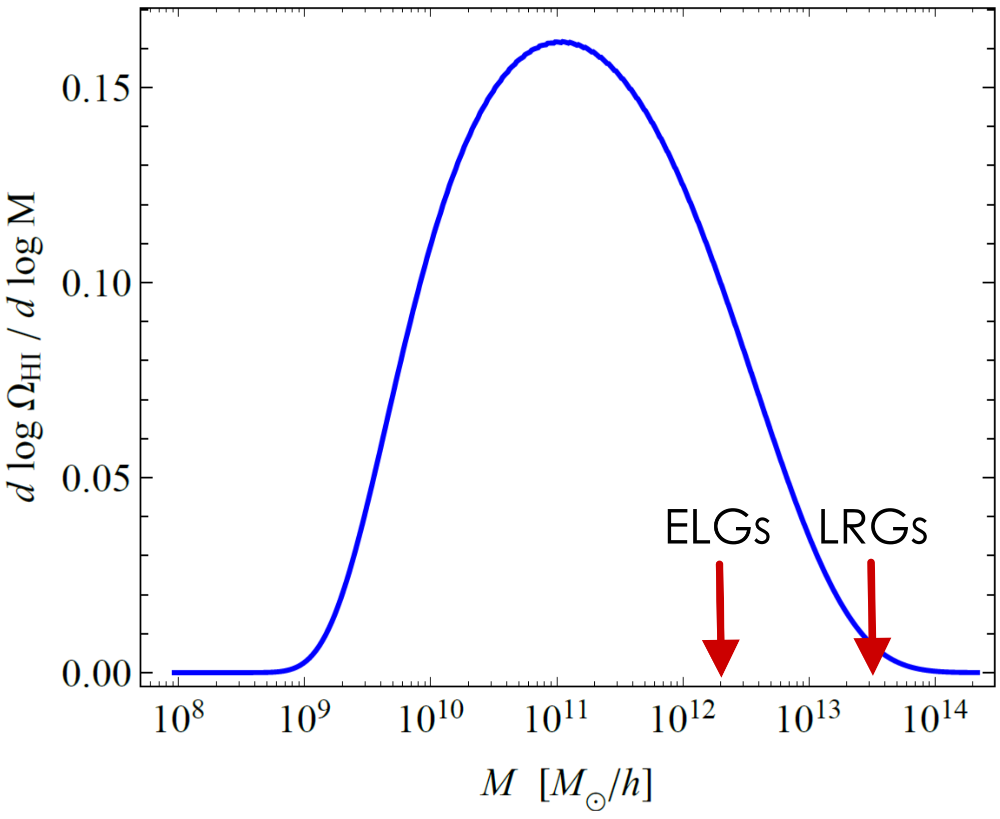
arXiv:1609.05157

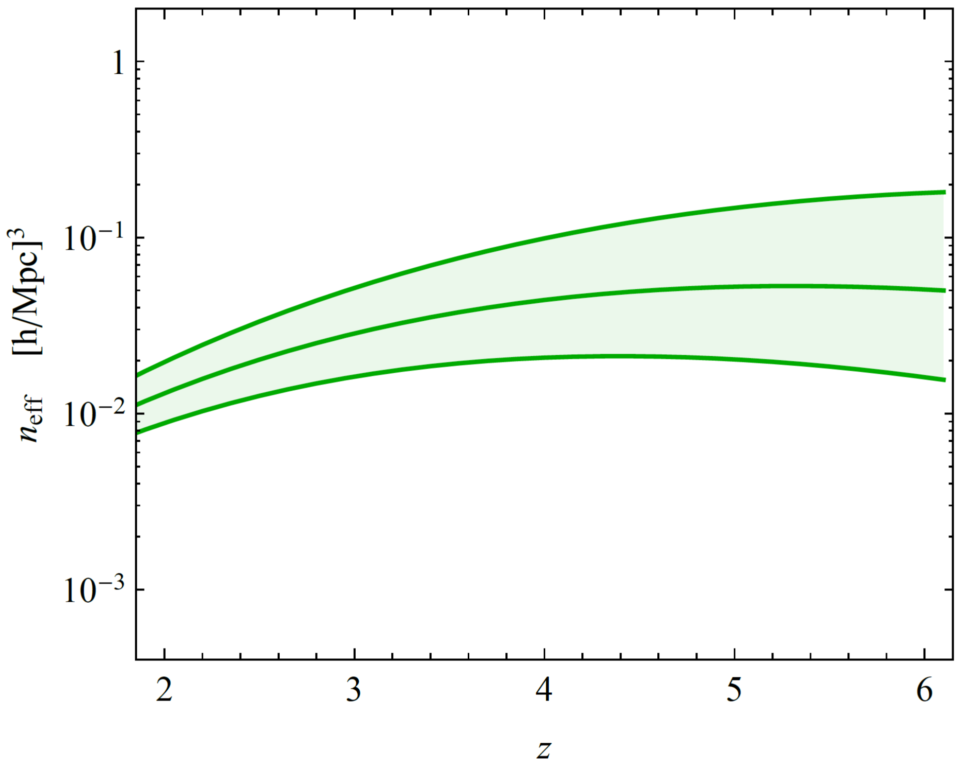
HI is everywhere

Physical models of N_HI distribution function, HI abundance, and bias of DLAs.
First time we can account for all observations.

HI resides in halos above Msun/h ~ few 10^10 at z=2.3. **Very low shot noise**.

Very conservative assumptions lead to $n_{\rm eff} > 10^{-2}({\rm Mpc}/h)^3$

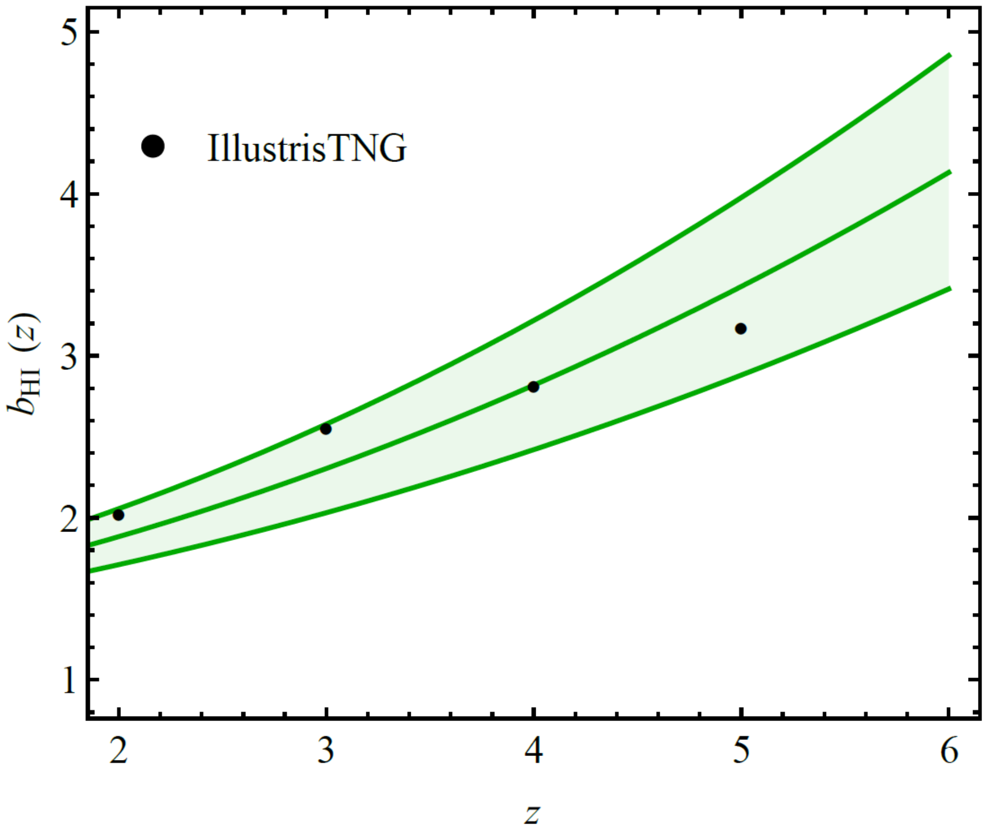


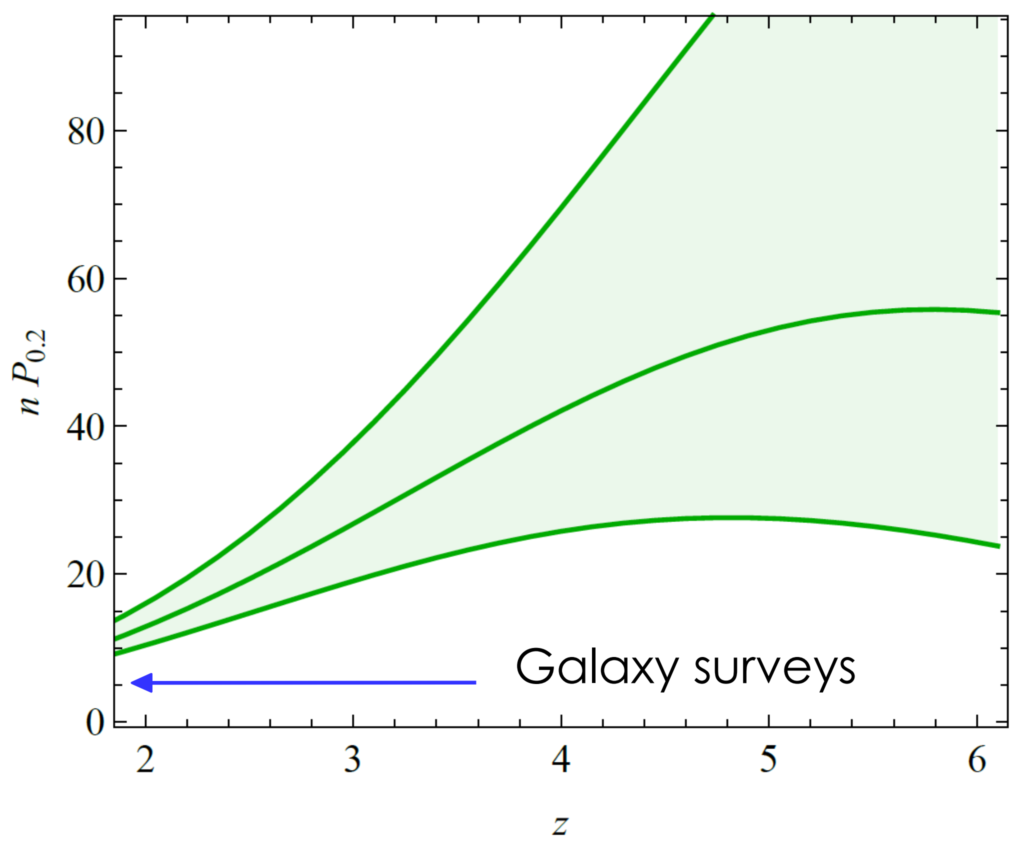


arXiv:1609.05157

HI clustering : no modes left behind

Higher redshift is easier to model, less non linear, but only if you have low mass halos



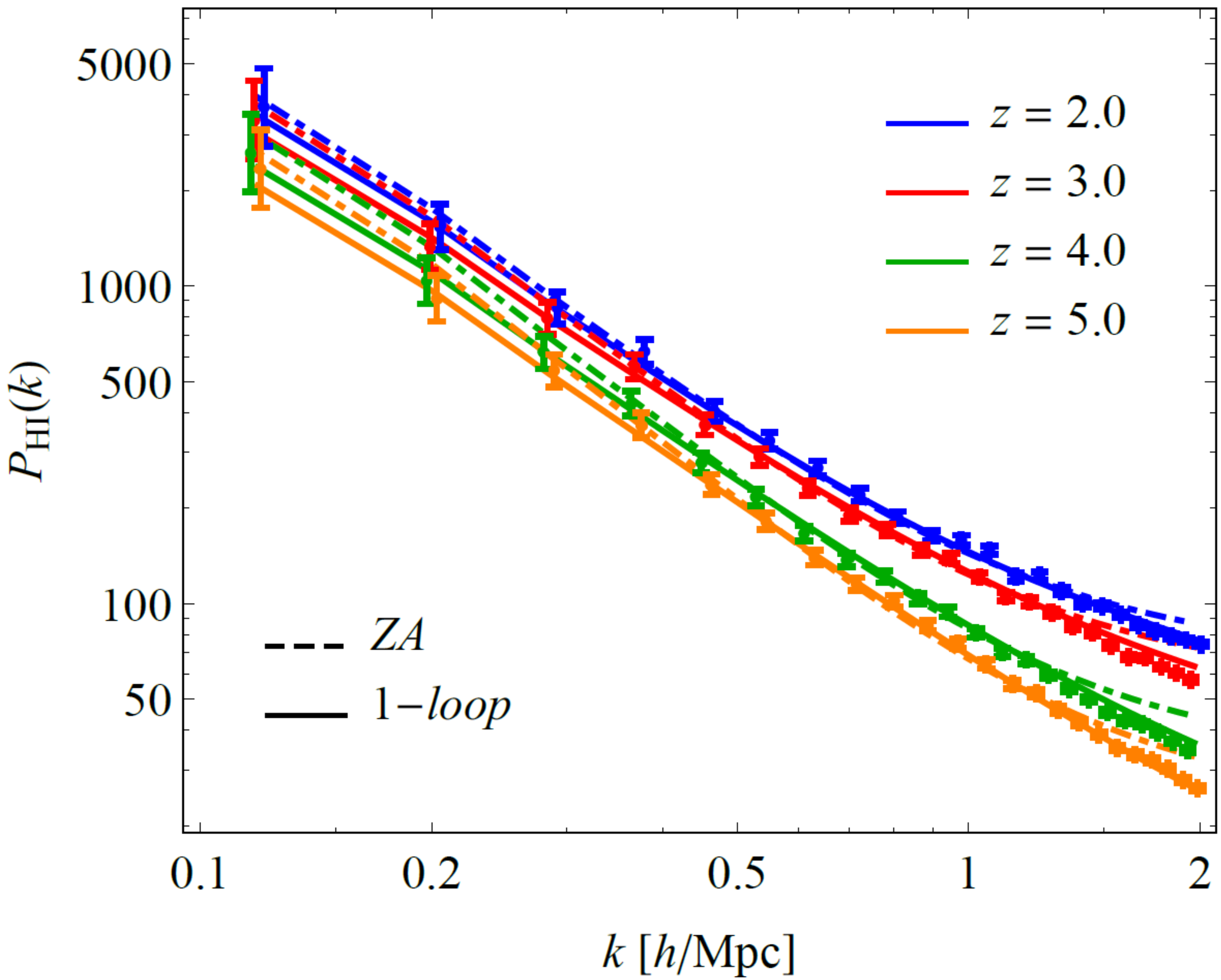


→ **Cosmological S/N is always large**.
It will go down with instrumental noise

HI clustering

In galaxy surveys surveys non-linearities in the bias limit the analysis to k~0.2(3) Mpc/h.

Unique of HI, as it probes very low mass halos : Non-linear bias is not an issue.
Crucial for redshift space distortions (RSD) measurements.



Simulations requirements

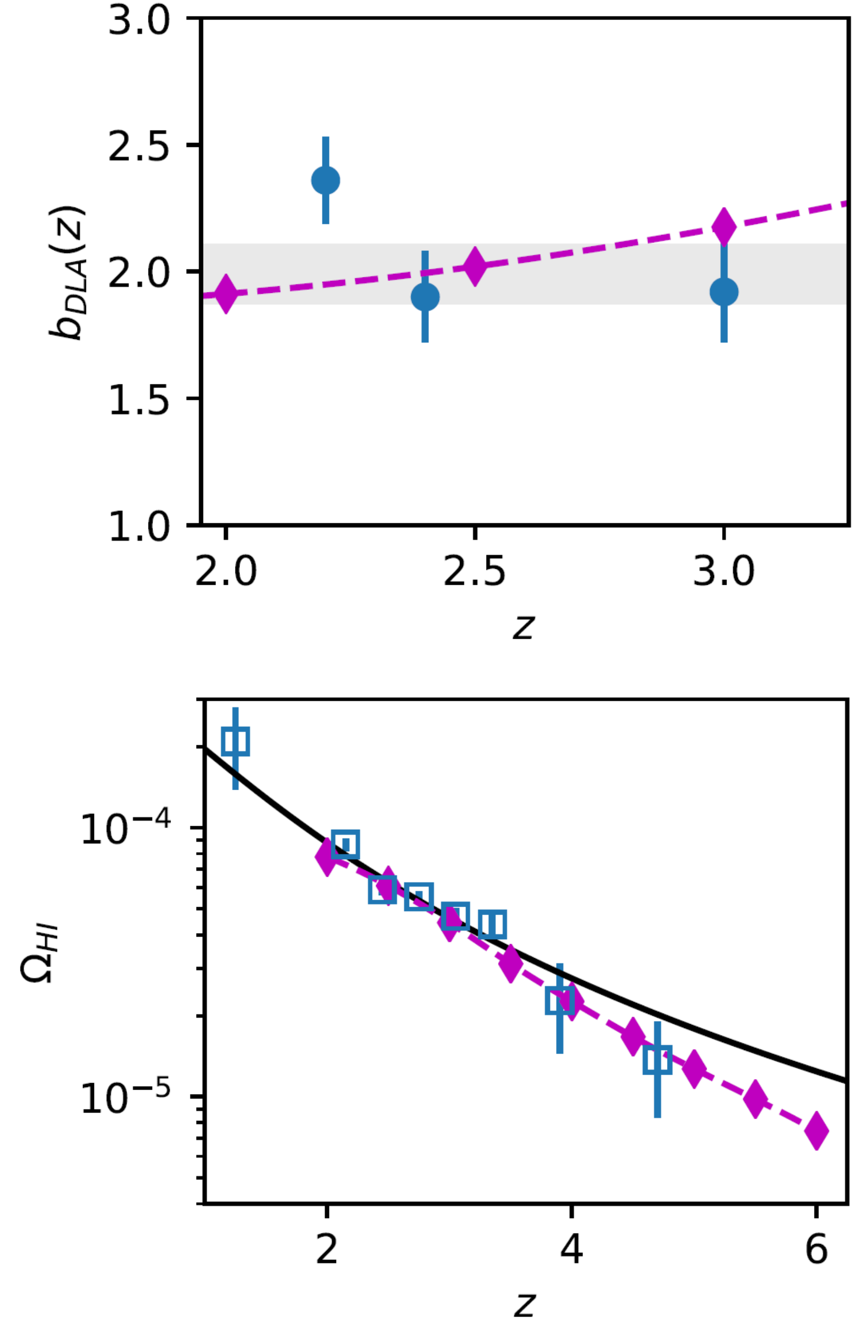
Simulating the 21 cm signal pushes the boundaries of High Performance Computing (HPC):

- Resolve very low mass halos, 100x smaller than ELGs
- Large volumes required by BAO and RSD
- Flexibility to different modeling assumptions

The Hidden Valley simulation suite (PI Feng)

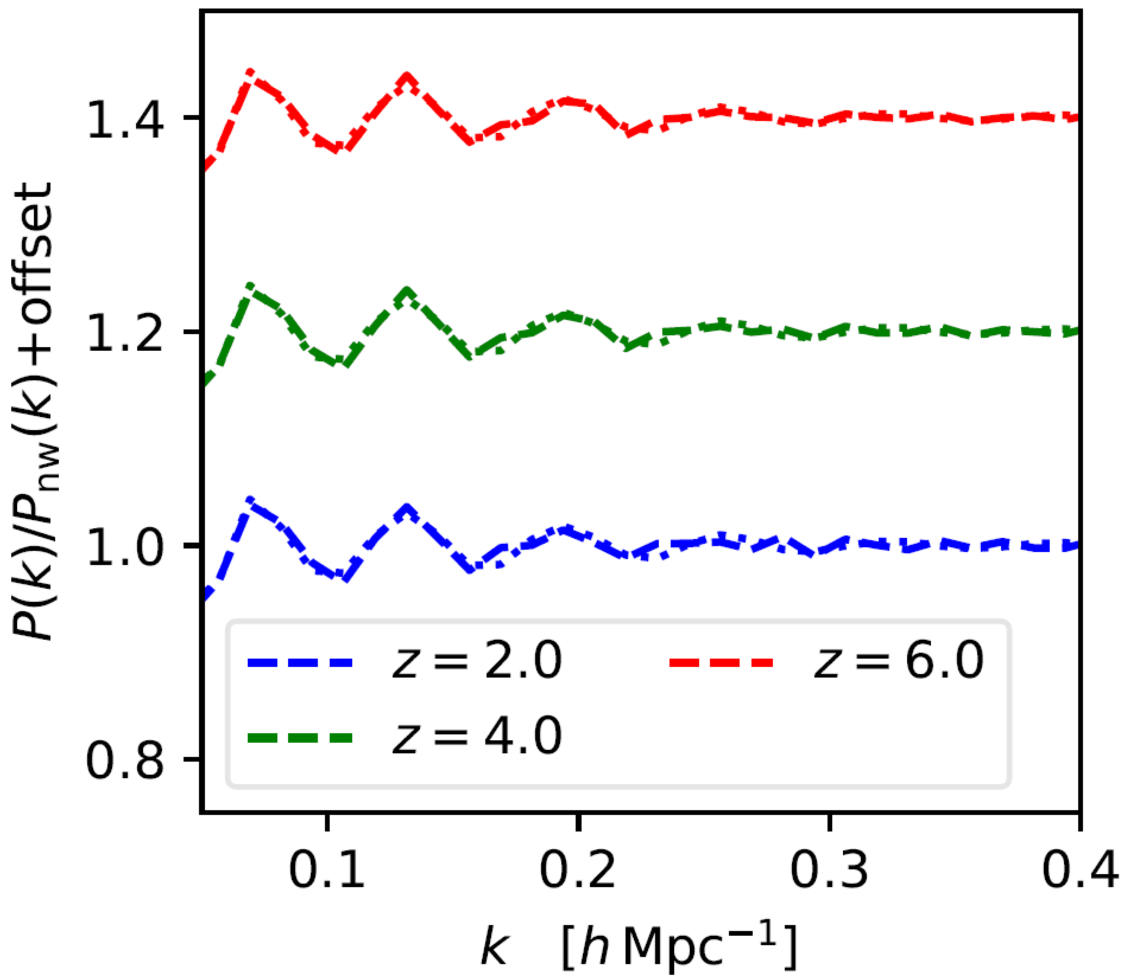
- Largest LSS simulations ever run at NERSC
- Several 1 Trilion (10240^3) particles simulations:

  9000 nodes and >500k MPI ranks
  more than 90% of Cori at NERSC



The Hidden Valley simulation suite

Undergoing effort to study BAO and RSD in more realistic setups



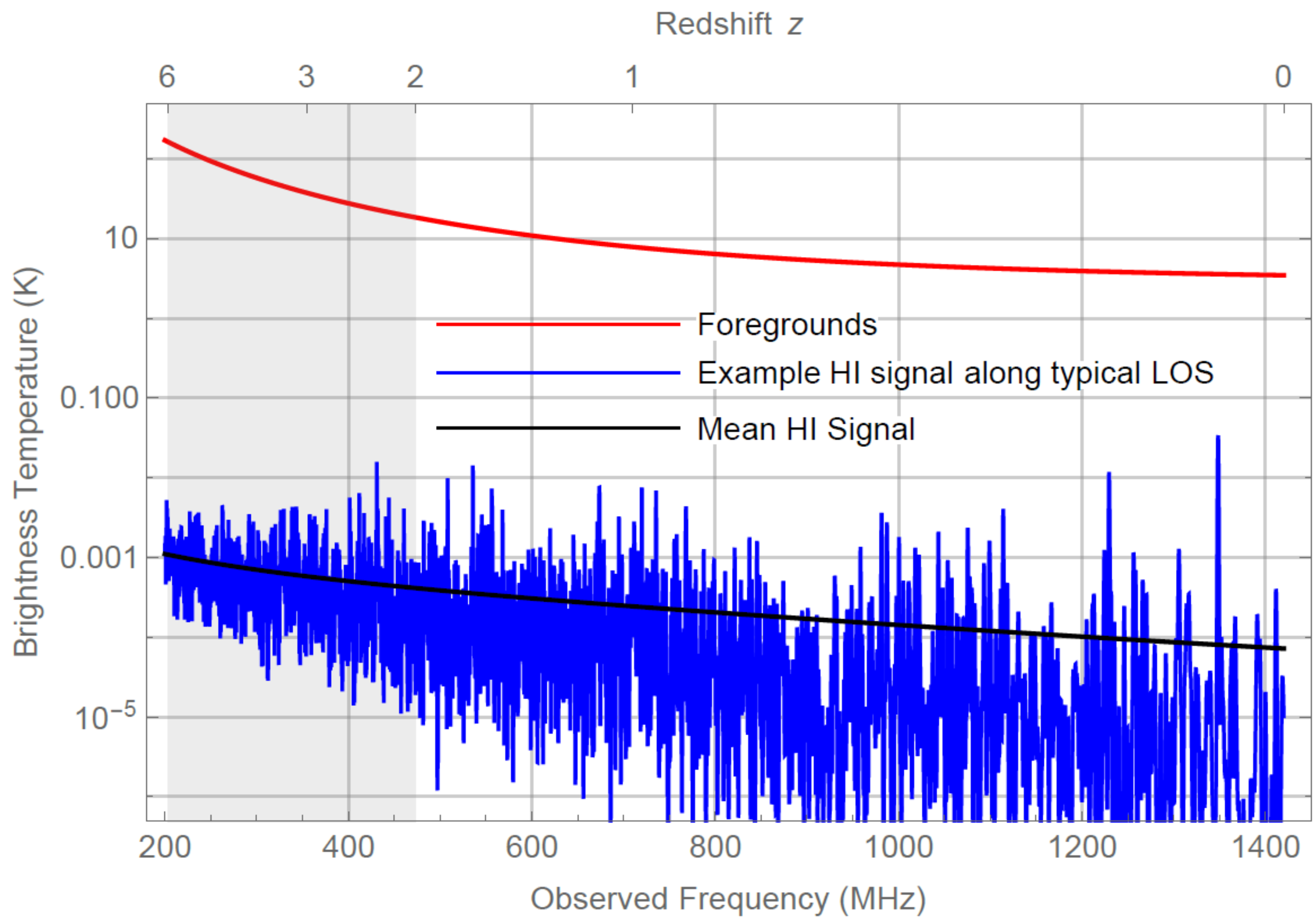
The Stage-II experiment

A Stage-II 21 cm intensity mapping experiment

Having estabilished HI as the ultimate cosmological probe...how do we measure it ?

- Dish size determines the FOV.
- Longest Baseline fixes resolution.
- Want short baselines for large scale modes.
- Survey speed favors transiting telescopes.
- Calibration/foreground removal requires compact arrays and redundant baselines.
- ~Noiseless ! $P_{\rm th} \leq P_{\rm sn} \ll P_{HI}(k)$

~~The bad news~~ The challenges

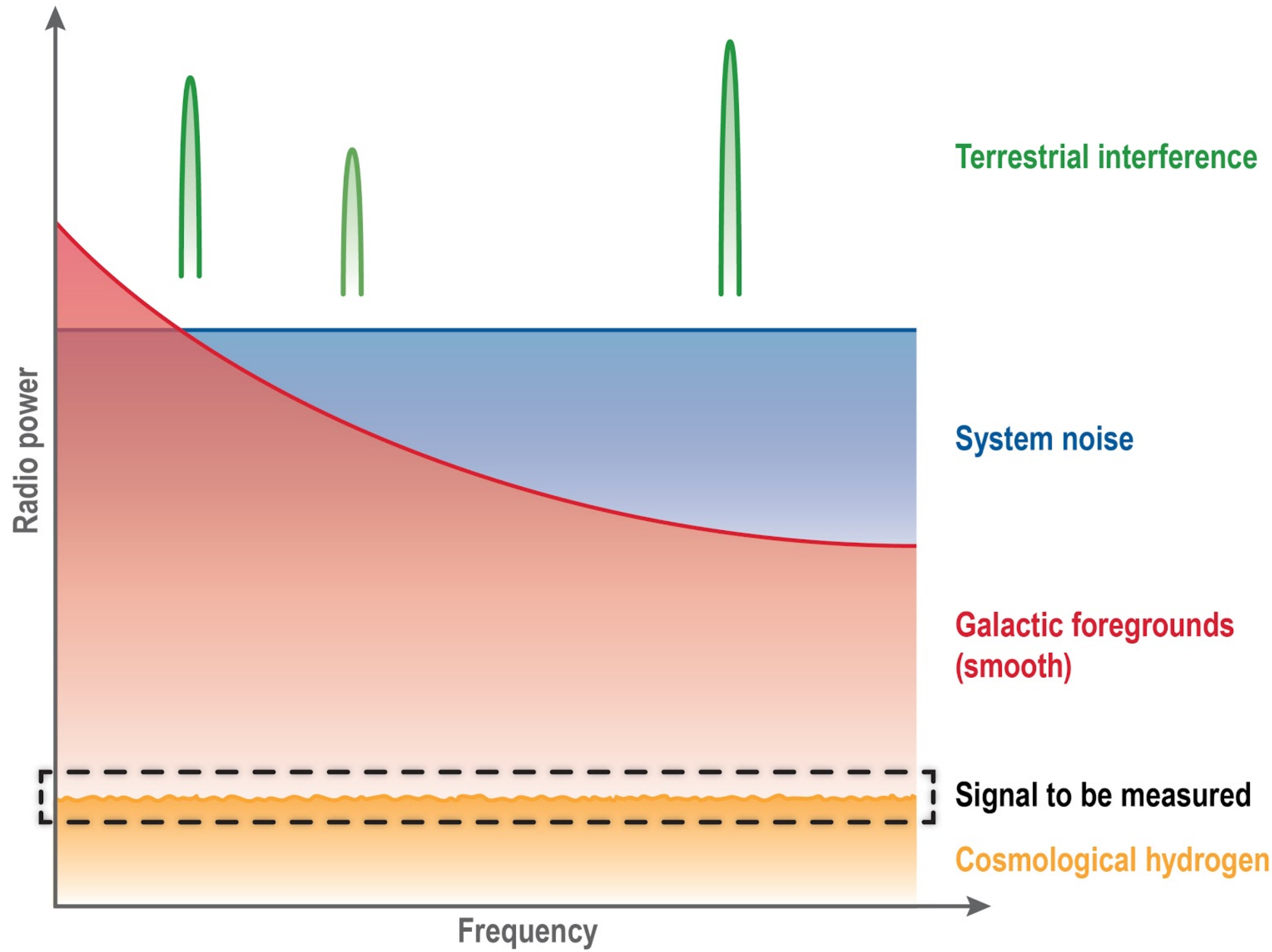


- Signal is subdominant, but the only non-smooth component.

- Of course, instrument can have non-smooth, time-varying response too!
  Not a fundamental limitation of the approach. Calibration is a purely technical challenge.

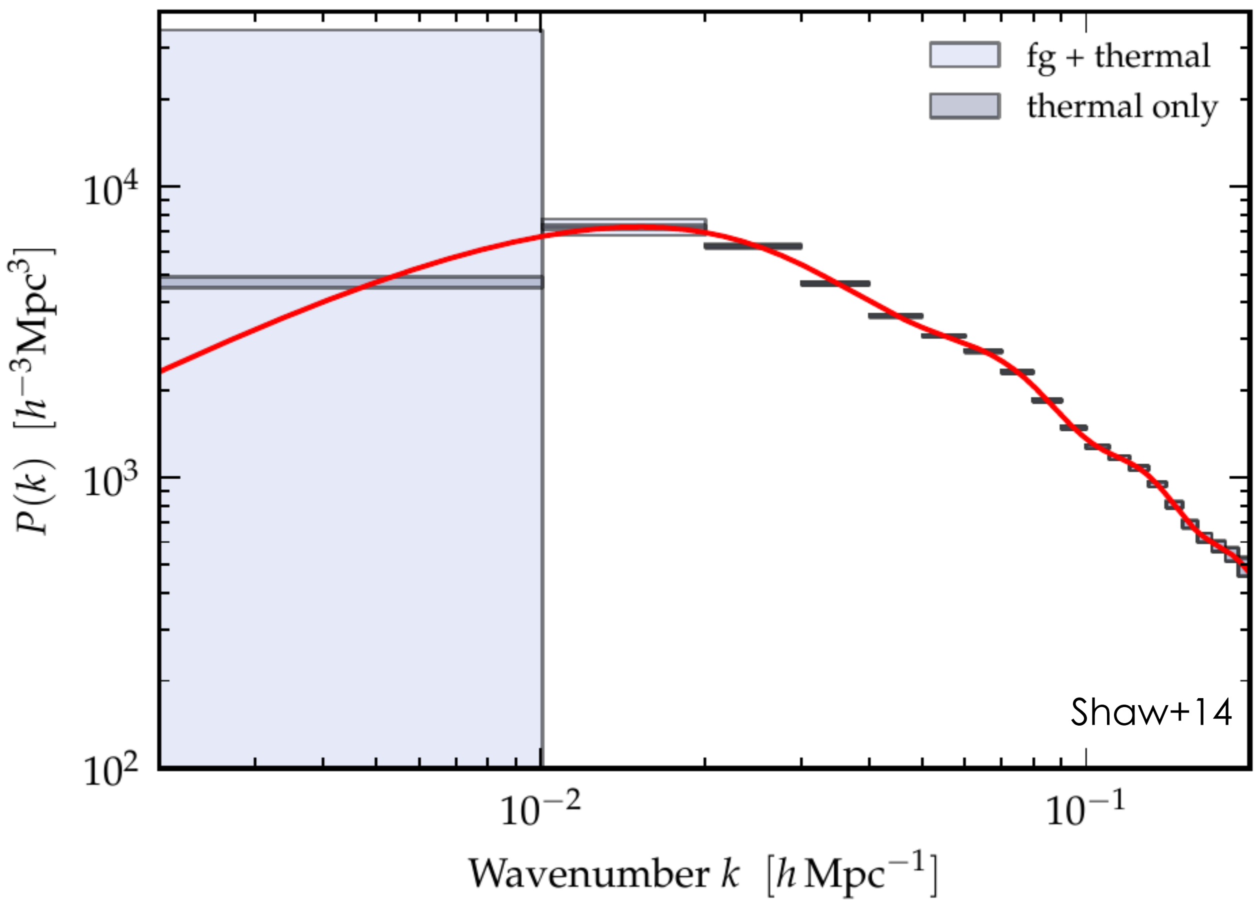
~~The bad news~~ The challenges

Terrestrial interference (RFI) taken very seriously. In South Africa a TV station has been moved from the HIRAX site and a no fly zone has been issued !



~~The bad news~~ The challenges

Smooth foregrounds in frequency space appear at low k, where signal is lost.
Foregrounds incuded in the forecast.



The Stage-II experiment

Concept described in arXiv:1810.09572, a 60+ pages white paper:

- a 256x256 compact array
- of 6 meter dishes
- operating at $2<z<6$ over half the sky.

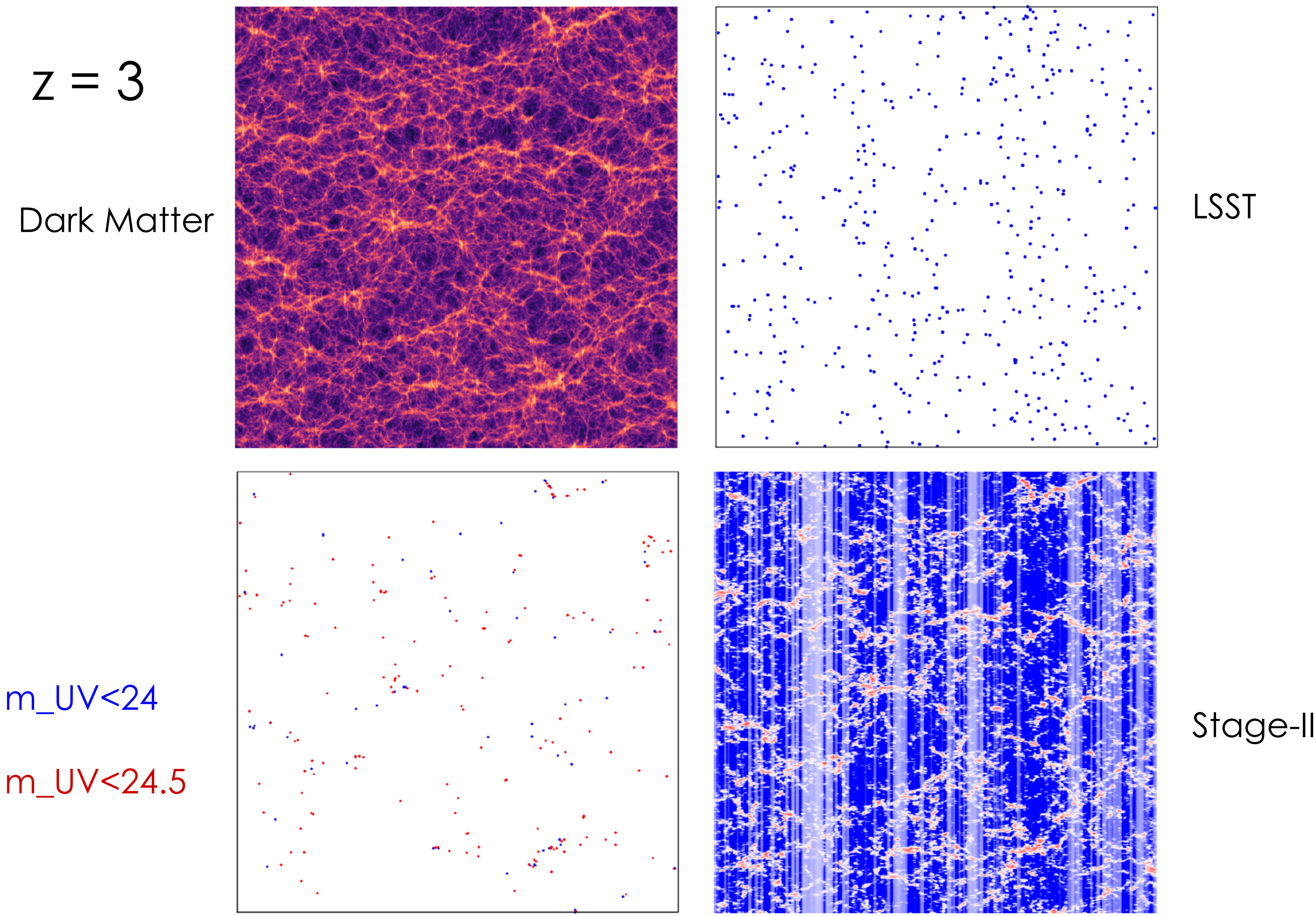
Final design TBD, work in progress for Astro2020.

Cosmic Visions Dark Energy:
Inflation and Early Dark Energy with a Stage II
Hydrogen Intensity Mapping Experiment
(Cosmic Visions 21 cm Collaboration)

Réza Ansari,[1] Evan J. Arena,[2,3] Kevin Bandura,[4,5] Philip Bull,[6,7] Emanuele Castorina,[8] Tzu-Ching Chang,[9,10] Simon Foreman,[11] Josef Frisch,[12] Daniel Green,[13] Dionysios Karagiannis,[14] Adrian Liu,[6,7,15] Kiyoshi W. Masui,[16] P. Daniel Meerburg,[17,18,19,20,21] Laura B. Newburgh,[22] Andrej Obuljen,[23,24,25] Paul O'Connor,[2] J. Richard Shaw,[26] Chris Sheehy,[2] Anže Slosar,[2,*] Kendrick Smith,[27] Paul Stankus,[28] Albert Stebbins,[29] Peter Timbie,[30] Francisco Villaescusa-Navarro,[31] and Martin White[6]

The Stage-II experiment

Concept : a 256x256 compact array of 6 meter dishes operating at 2<z<6 with f_sky=1/2.



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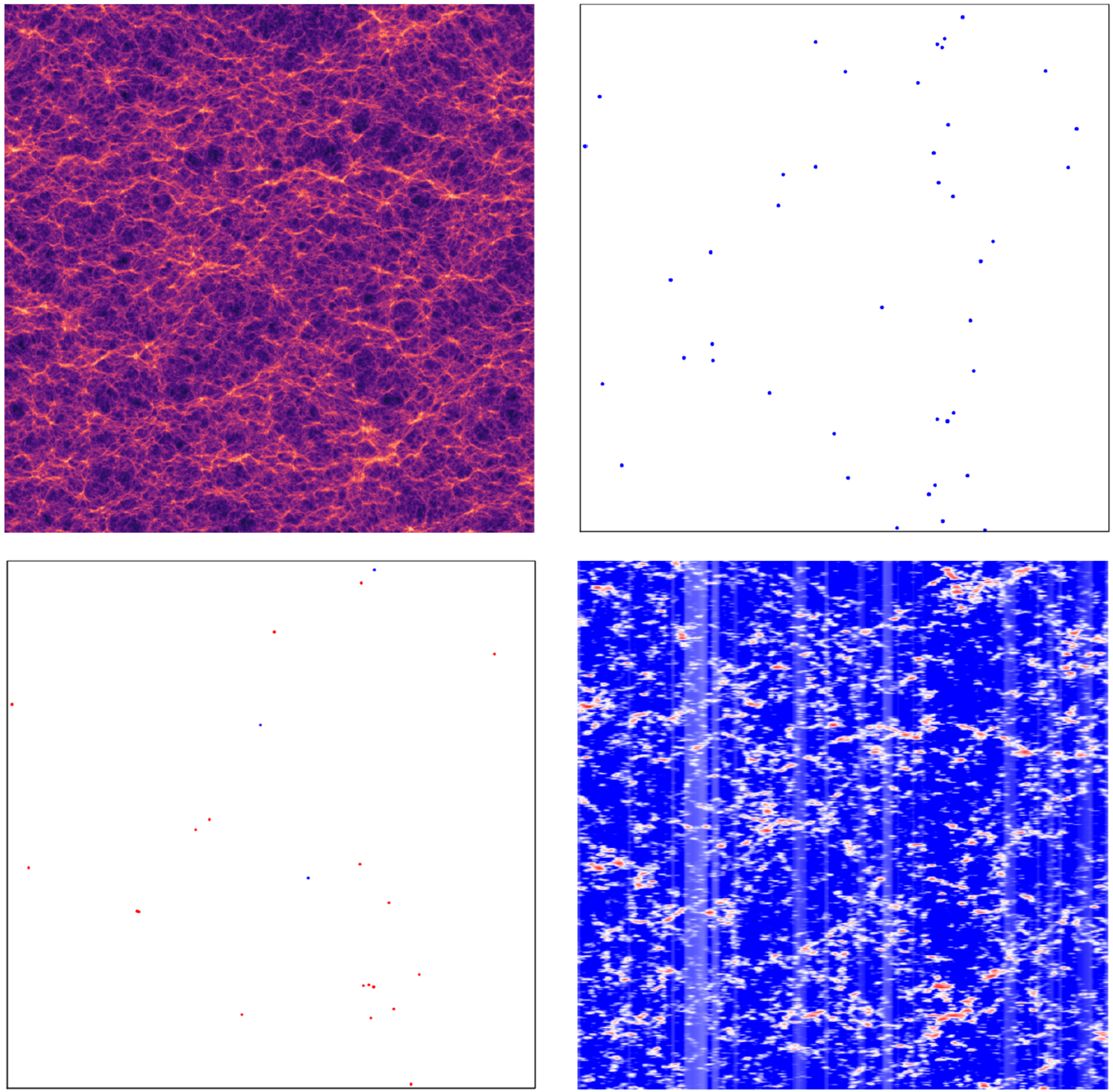
z = 5

Dark Matter



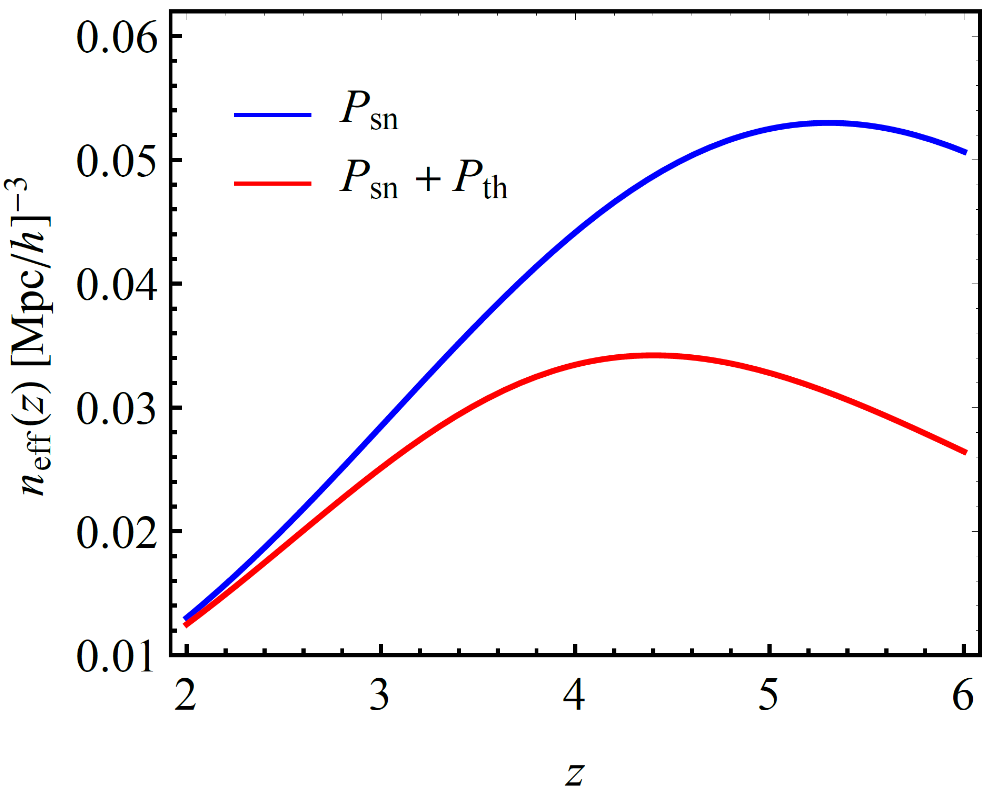
LSST

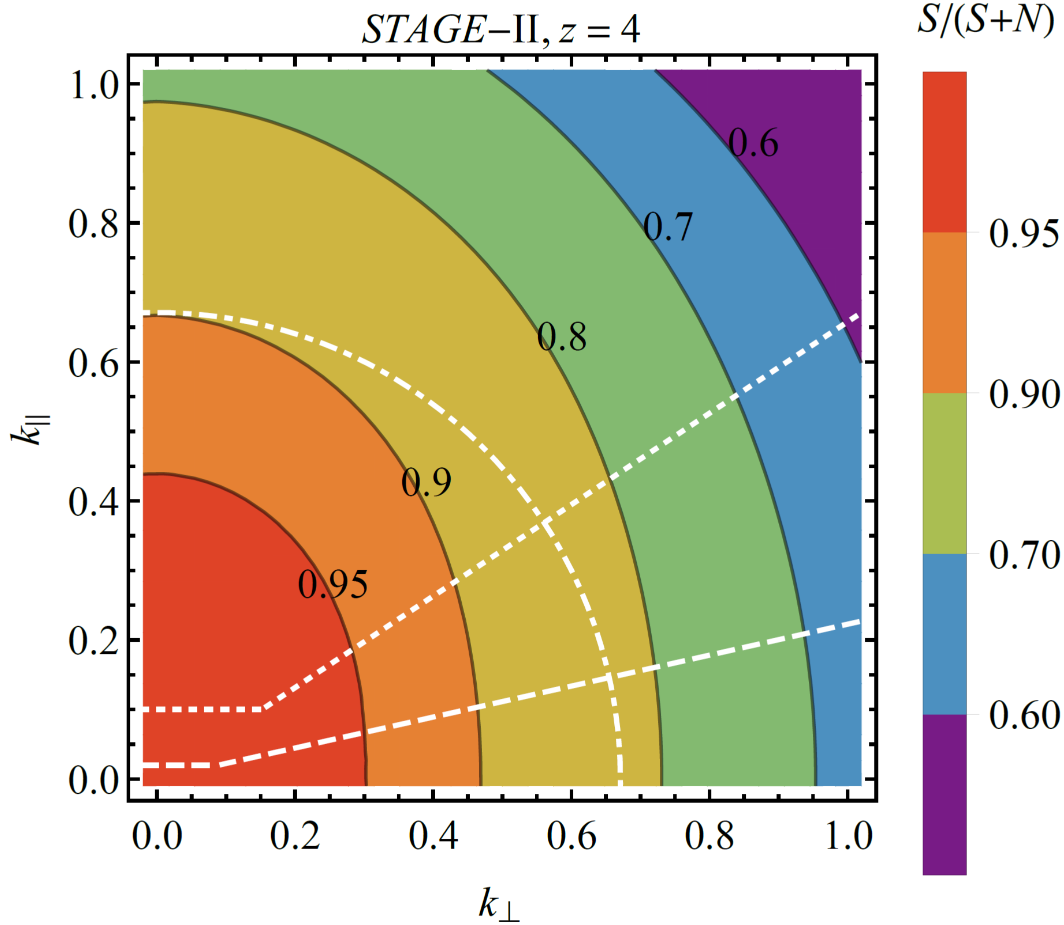
m_UV<24

m_UV<24.5

Stage-II

The Stage-II experiment: The ultimate galaxy survey





With 14000 deg² : **9 billions galaxies between 2<z<6 over >250 [Gpc/h]³**
Could be 3B, but could also be 20B !

$P_{\rm th} \leq P_{\rm sn} \ll P_{\rm HI}$ Signal dominated at all scales:

nP>15 at k=0.2 Mpc/h

nP>5 at k=0.5 Mpc/h

The Stage-II experiment: Science

Guaranteed Science:

- Expansion history in pre-acceleration era (dark energy)
- Features in the primordial power spectrum (inflation)
- Primordial non-Gaussianity (inflation)
- Redshift space distortions (RSD)
- General parameter improvements

Likely Science:

- Gravitational lensing of 21 cm maps
- Tidal reconstruction

Speculative Science:

- Fast Radio Bursts to calibrate kinetic SZ
- Direct expansion measurement at z=1
- Non linear transformation of the 21 cm field

Opens up cross-correlation science with CMB lensing reconstruction

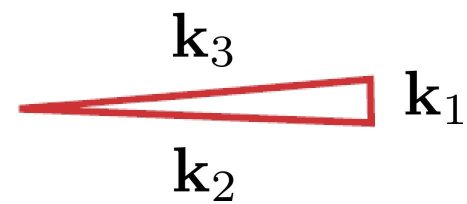
Primordial Non-Gaussianities (PNG)

The LCDM model assumes initial conditions (fluctuations) are gaussian.

PNG as an interesting signature of complex dynamics in the very early universe.

Local non-Gaussianities in the curvature perturbations

$$\zeta = \zeta_g + \frac{3}{5} f_{NL}^{\rm loc} (\zeta_g^2 - \langle\, \zeta_g^2 \,\rangle)$$



$$\langle\, \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3) \,\rangle = (2\pi)^3 \delta_D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B_\zeta(k_1, k_2, k_3)$$

Gravity cannot create such term.
A non perturbative result independent of the dynamics in single field inflation

$$\lim_{k_1 \to 0} B_\zeta(k_1, k_2, k_3) \longrightarrow 0$$

Maldacena
Creminelli&Zaldarriaga

Primordial Non-Gaussianities (PNG)

After T_CMB, by far the most accurately determined parameter in cosmology

$$\zeta = \zeta_g + \frac{3}{5} f_{NL}^{\rm loc} (\zeta_g^2 - \langle \zeta_g^2 \rangle) \qquad \zeta_g \simeq 10^{-5} \qquad f_{\rm NL}^{\rm loc} = -0.8 \pm 5$$

It implies local PNG are measured with 0.05% precision.

Detection of local PNG will rule out single field inflation.
Non detection of fnl~1 constrains multi-field models.

If we get there, we are guaranteed to learn something.

Same argument applies to other shapes (parametrization).

	$f_{\rm NL}^{\rm loc} \lesssim 1$	$f_{\rm NL}^{\rm loc} \gtrsim 1$
$f_{\rm NL}^{\rm eq,orth} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{\rm NL}^{\rm eq,orth} \gtrsim 1$	Single-field non-slow-roll	Multi-field

Primordial Non-Gaussianities (PNG): landscape

Large Scale Structure alone still far $\sigma_{f_{\rm NL}^{\rm loc}} \lesssim 25$

For local shape only :

Final eBOSS data could get close to Planck, fnl~7

DESI could reach fnl~4

LSST forecast fnl~O(few)

SphereX, fnl~0.5

Upcoming surveys won't improve other shapes over CMB.

$f_{\rm NL}$	CMB error		Stage II 21 cm error	
	Planck (current)	CMB-S4 (forecast)	FG pessimistic	FG optimistic
Squeezed (local)	5.0	2.0	0.5	0.2
Equilateral	43	21	15	5.0
Orthogonal	21	9.0	6.5	2.7

It includes foregrounds at low-k, **only k>0.01 considered**. Complementarity with SphereX for local PNG. Almost Cosmic Variance limited for other shapes.

Redshift Space Distortions (RSD)

arXiv:1902.07147

What we measure is

$$P_{21}(k,\mu) = \bar{T}_b^2[P_{\rm HI}(k,\mu) + P_{\rm sn}] + P_{\rm th}$$

In the linear regime it's impossible to constrain the amplitude of the power spectrum

$$P_{21}(k,\mu) = \bar{T}_b^2[(b_{\rm HI}\sigma_8 + f\sigma_8\mu^2)^2 P_m(k)/\sigma^2_{8,\,\rm fid} + P_{\rm sn}] + P_{\rm th}$$

Three possible ways out :

- External prior on brightness temperature. Hard to get better than 5 % (Obuljen, EC+)
- Cross correlations with QSOs, LBGs, etc. (Chan, EC+)
- Use information in the mildly non linear regime.

Redshift Space Distortions (RSD)

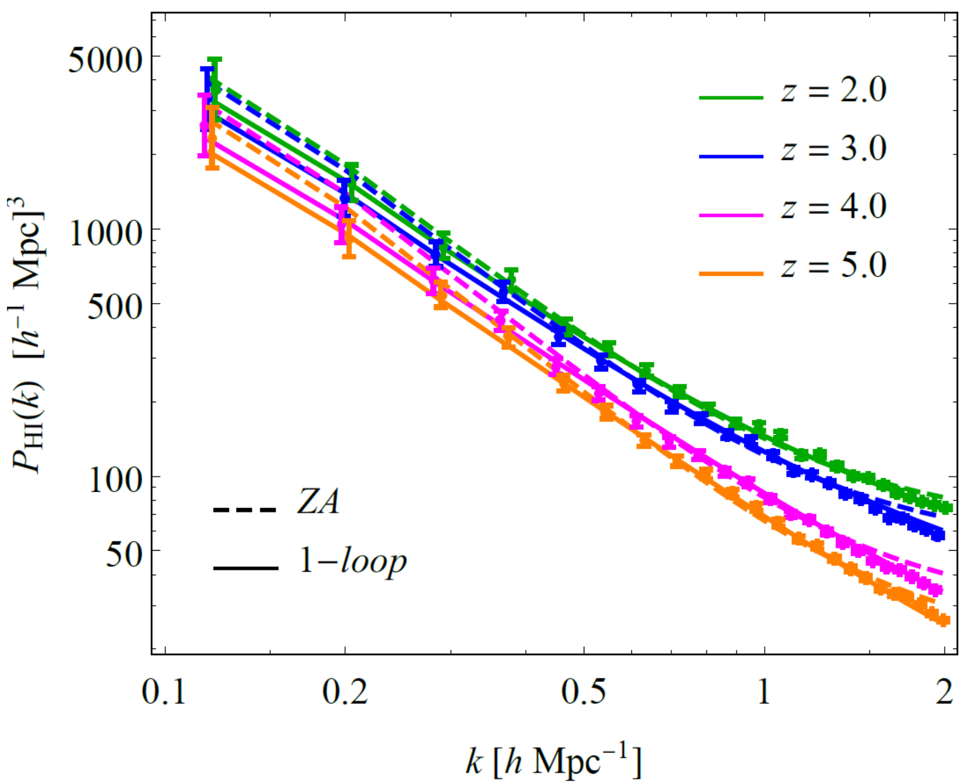
arXiv:1902.07147

In the perturbative regime

$$P_{21}(k,\mu) = \bar{T}_b^2 P_{\rm HI}(k,\mu) + {\rm Noise} = \bar{T}_b^2[\mathcal{O}(P_L(k)) + \mathcal{O}(P_L(k)^2) + ...] + {\rm Noise}$$

$f\sigma_8,\ (f\sigma_8)^2$ $\quad$ $(f\sigma_8)^2, (f\sigma_8)^3,\ (f\sigma_8)^4$

It turns out HI is the ideal tracer for PT: high-z, low mass halos, small satellite fraction



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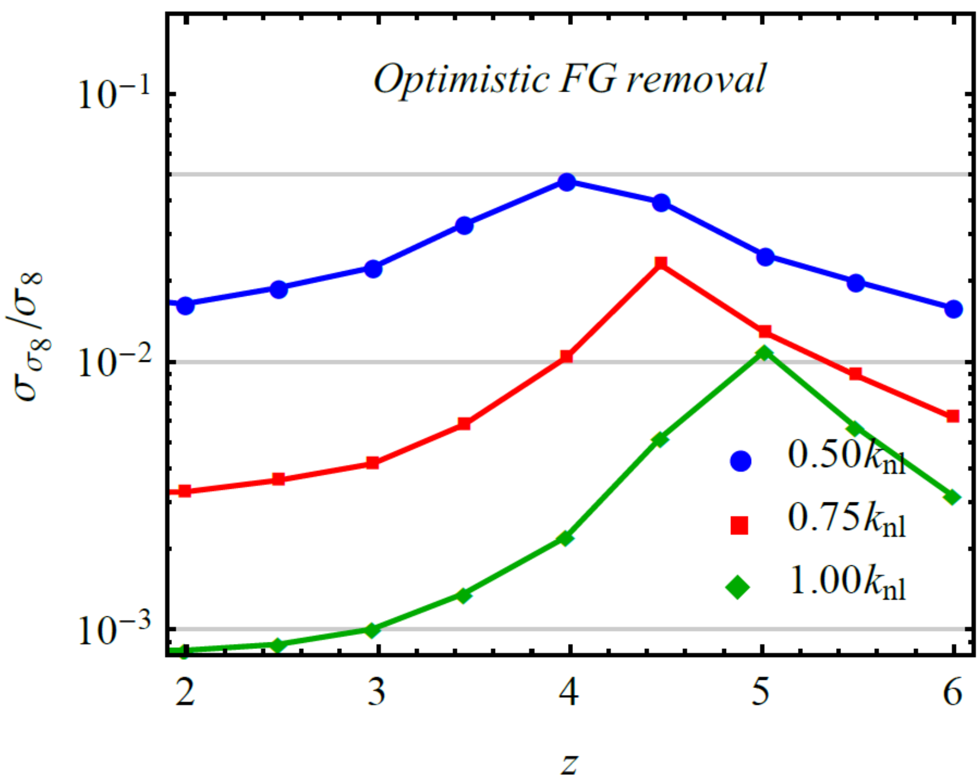
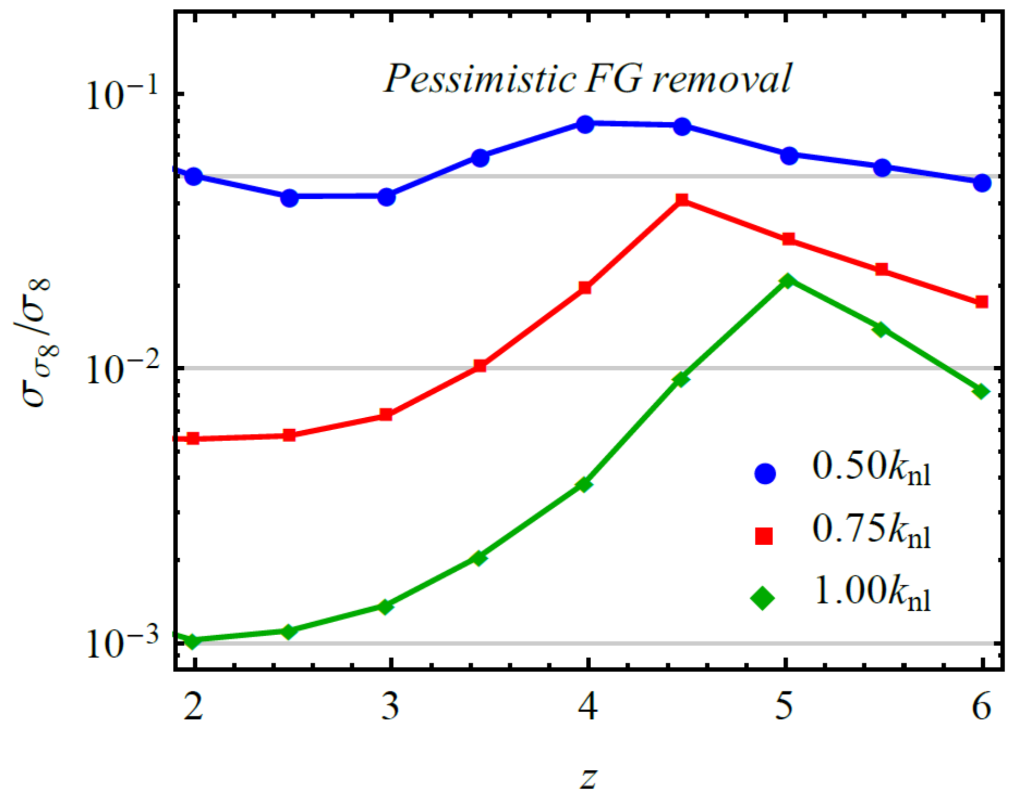
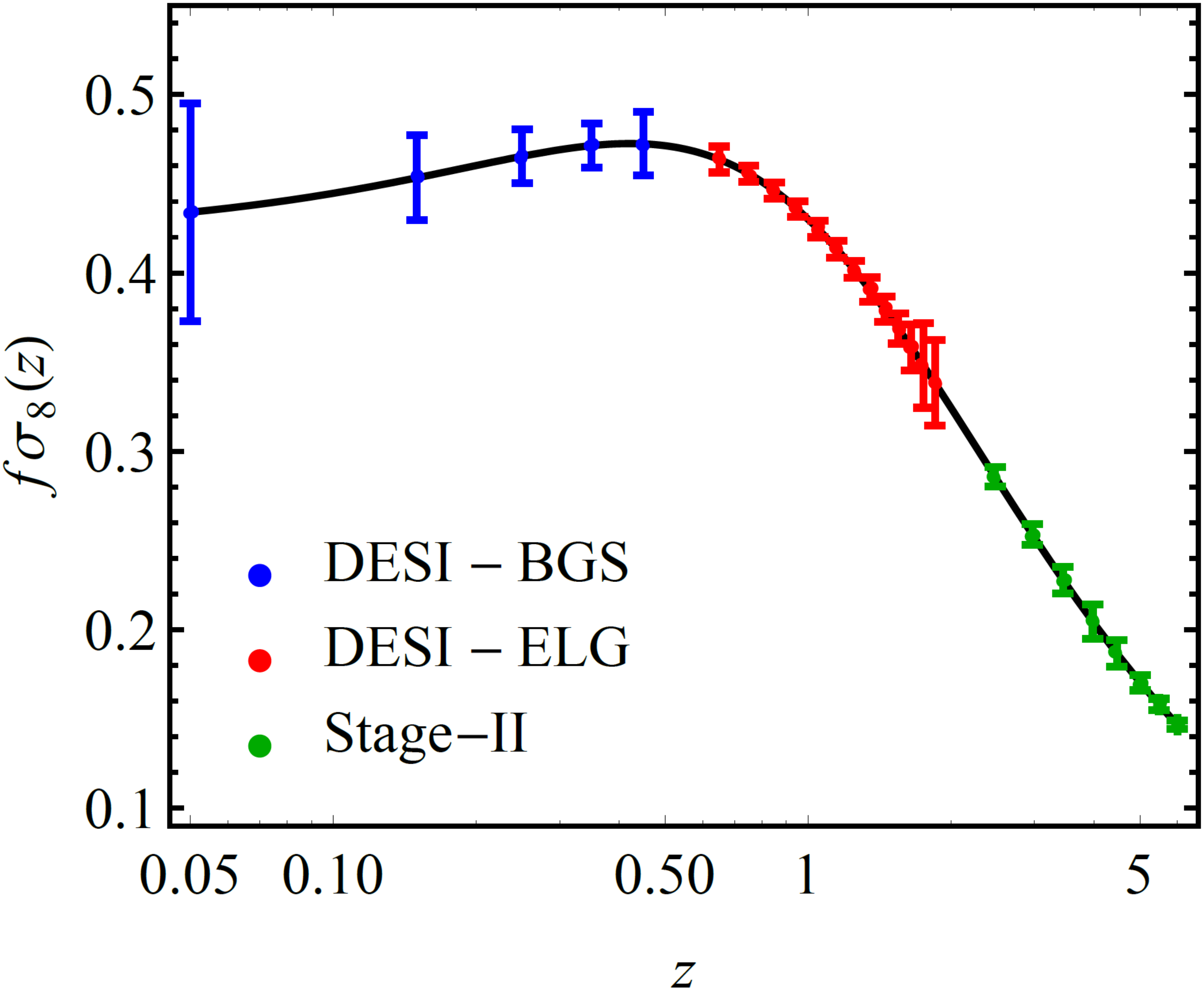
≳1% measurements of growth of structure up to z<5



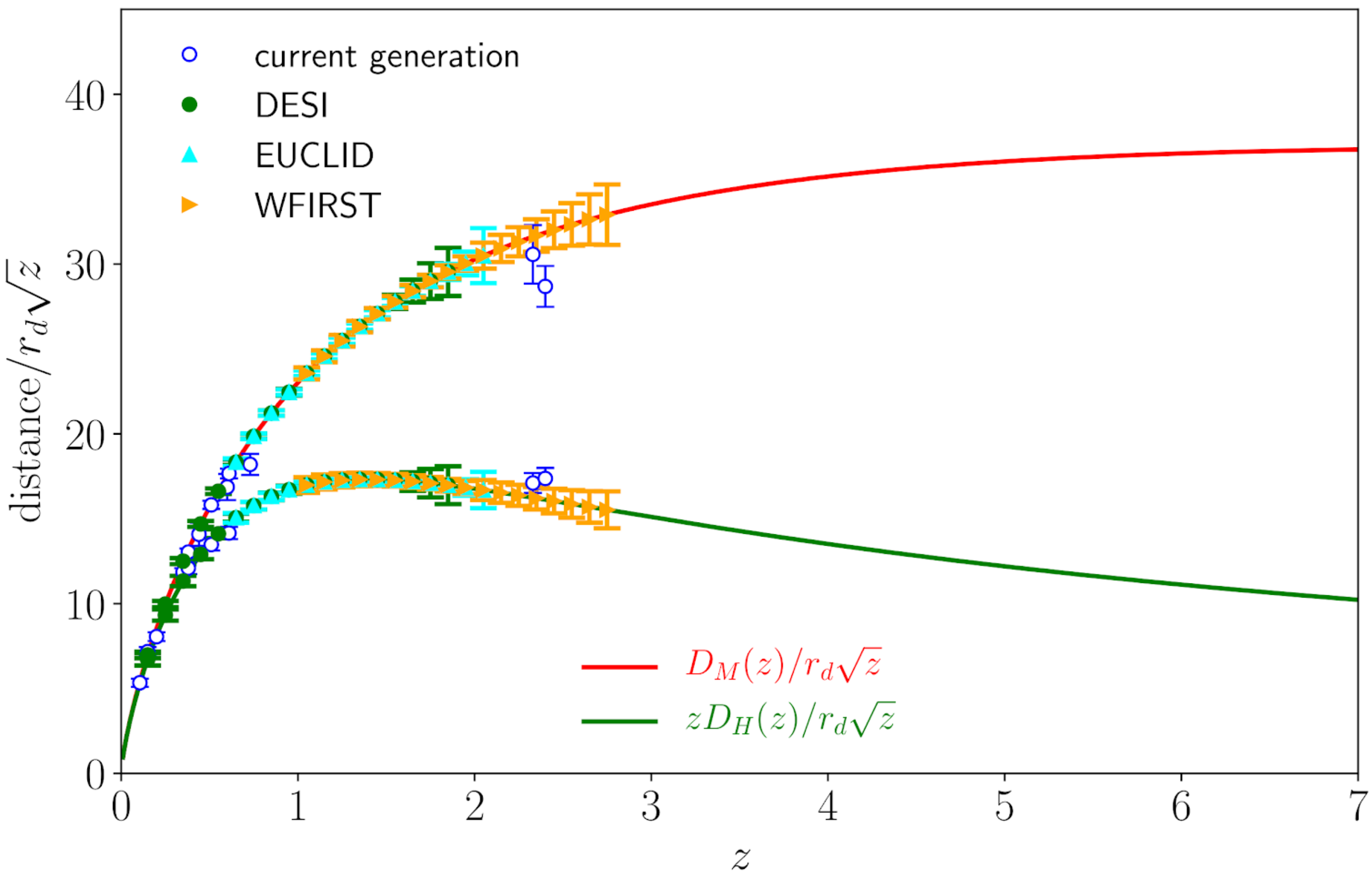


arXiv:1902.07147

≳1% measurements of growth of structure up to z<5

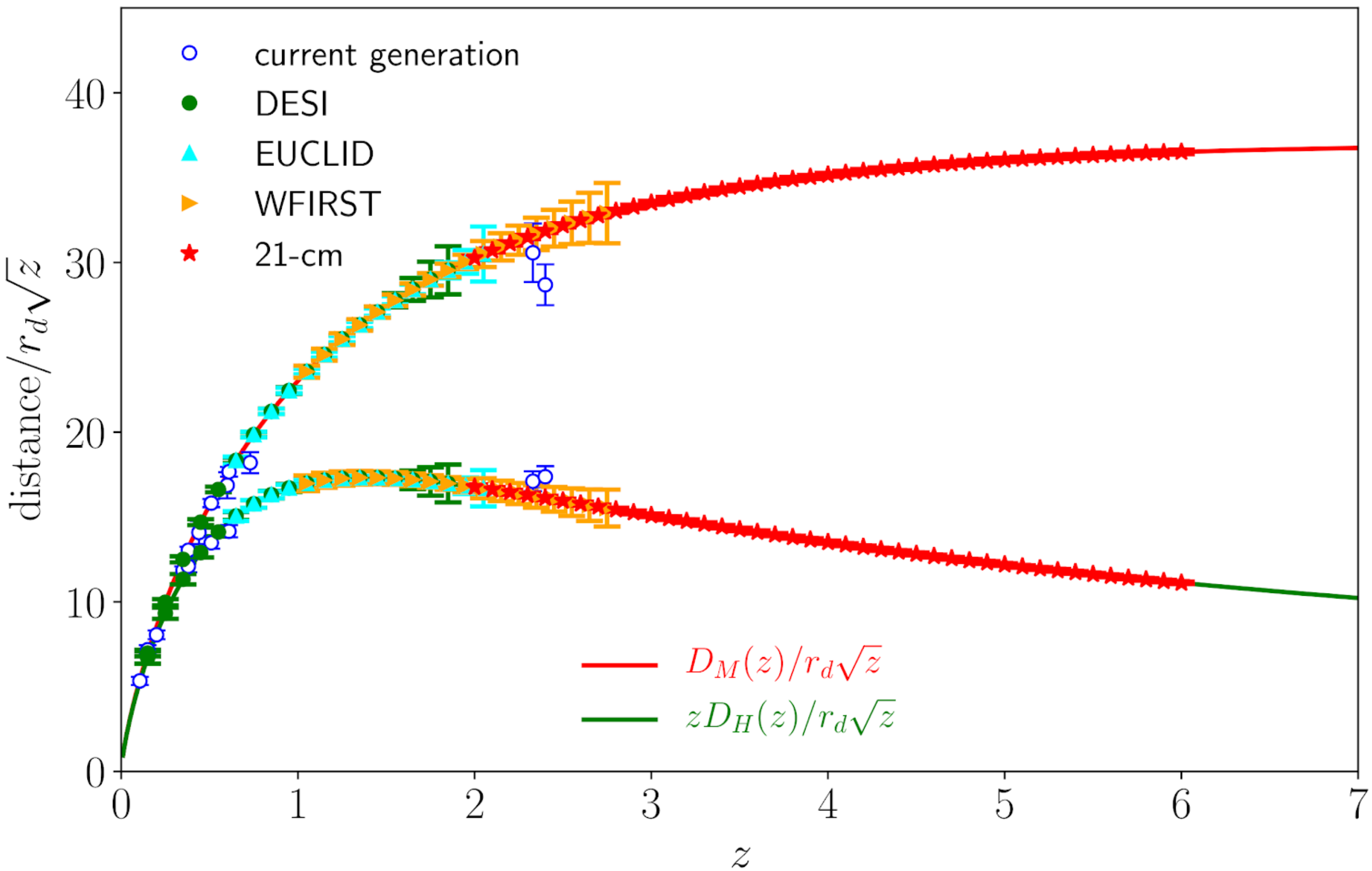


Expansion history measurements: 2025



- Expansion history is a basic cosmological quantity
- There is a big picture argument that we should complete our program of measuring the expansion history
- Currently planned experiments reach to z~3.

Expansion history measurements in the 30's



- Expansion history is a basic cosmological quantity
- There is a big picture argument that we should complete our program of measuring the expansion history
- Currently planned experiments reach to z~3.
- 21 cm gets to z~6 at the sub % level
- No reconstruction used

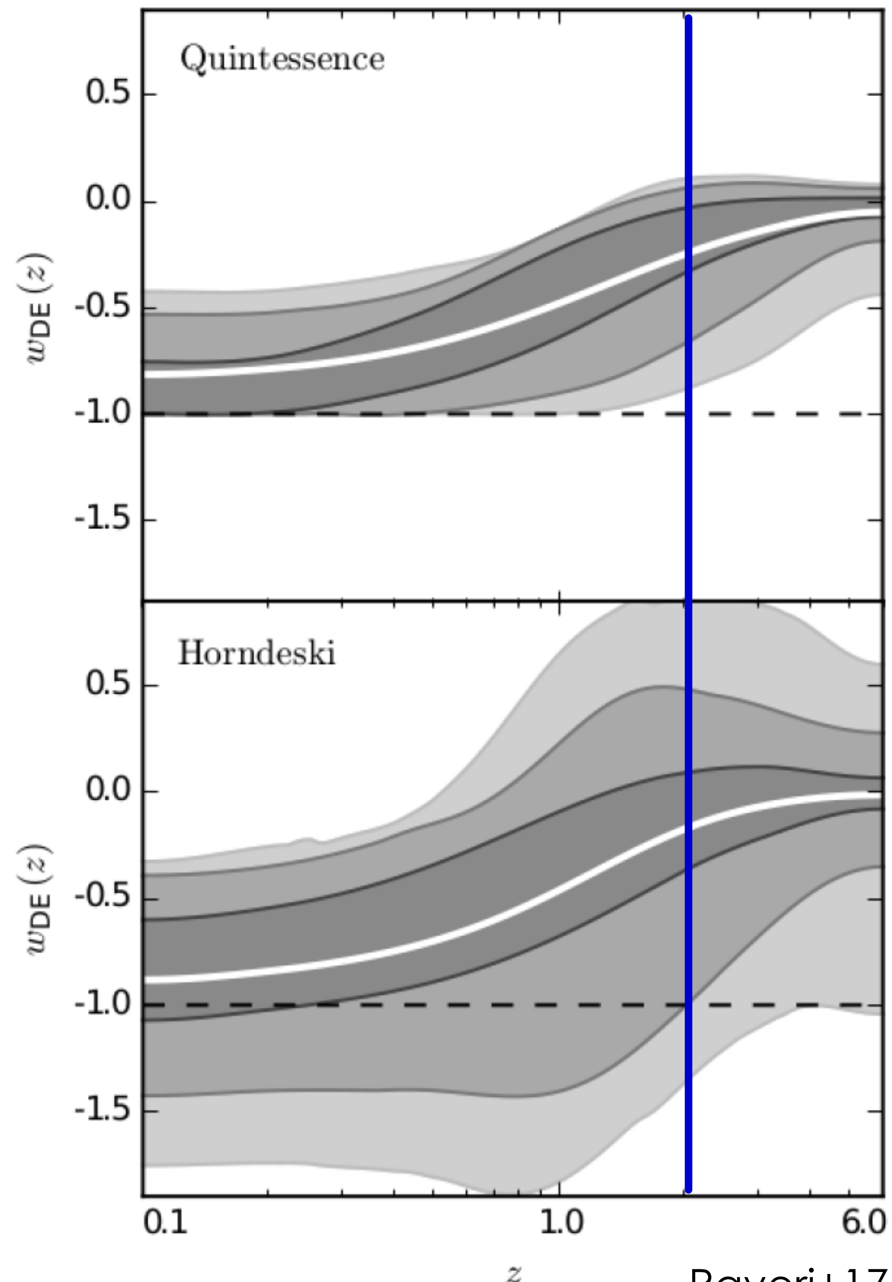
Expansion history measurements: implications for Dark Energy

Several models are still allowed by current data

Upcoming surveys will lock down DE at z<2
but Early Dark Energy (EDE) still alive and well

High-z is the natural place to look at, lacking theoretically motivated priors.

It requires very accurate measurements since DE is subdominant to CDM

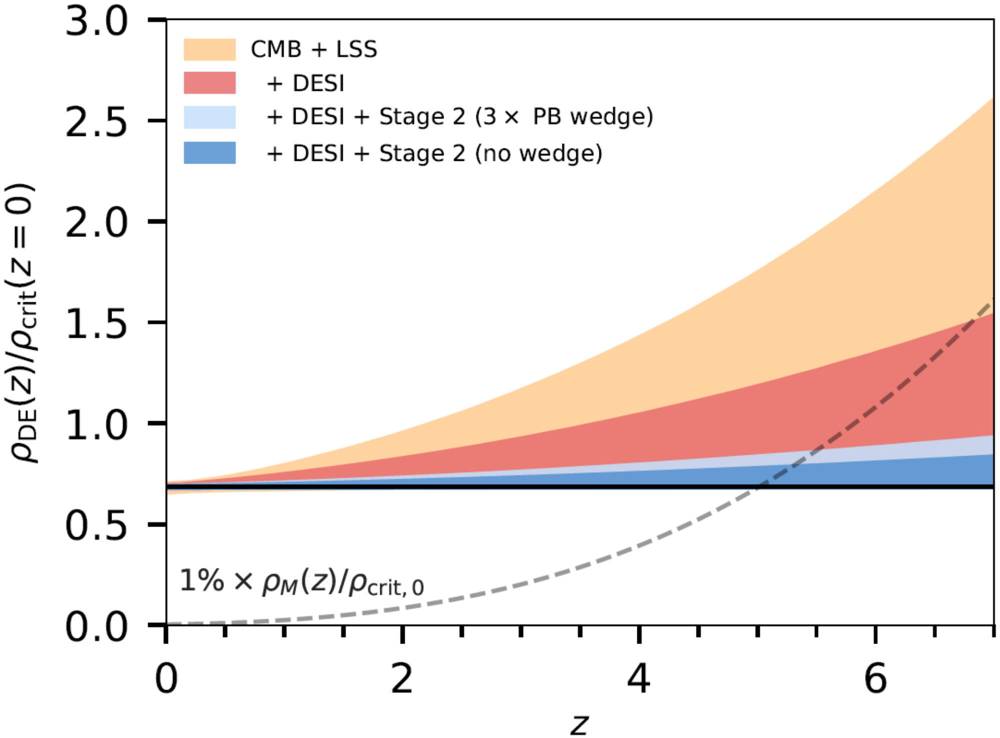


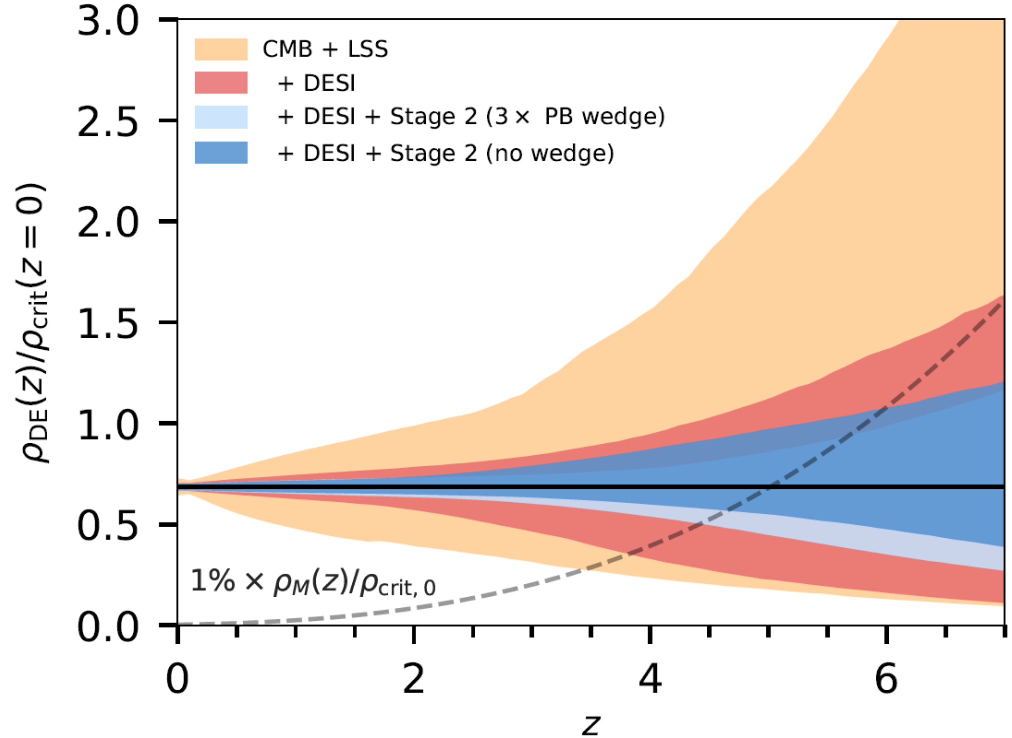
Raveri+17

Expansion history measurements: implications for Dark Energy

Stage-II is able to constraint EDE to sub- % all the way to z=6.

DE known to the same accuracy we know neutrino masses





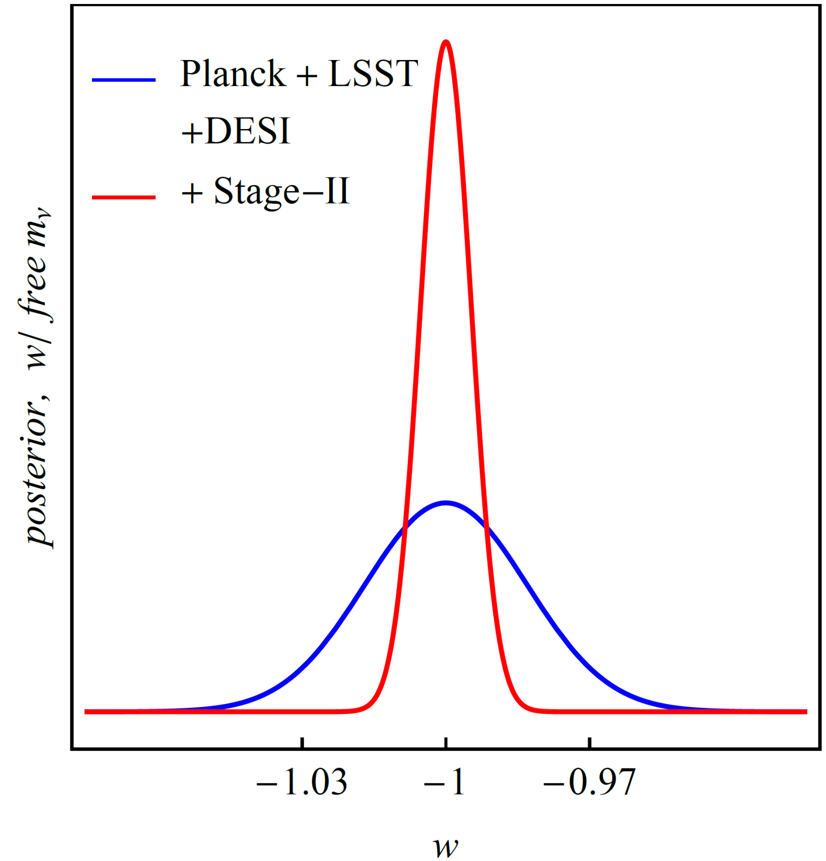
General parameters improvement

Parameter / combination	LSST + DESI + Planck	CMB S4	Stage II+ Planck	LSST + DESI + Stage II + Planck	CMB-S4 + Stage II	Everything bagel
$\sum m_\nu$ [meV]	38	59	35 / 29	27 / 23	25 / 23	16 / 15
$\sum m_\nu + 3\%\ \tau$ prior [meV]	—	15	—	—	14 / 13	10.6 / 10.3
$\sum m_\nu$ [meV] (free w)	50	—	37 / 33	27 / 22	—	—
$N_{\rm eff}$	0.050	0.026	0.045 / 0.038	0.034 / 0.031	0.015 / 0.013	0.012 / 0.011
w (free $\sum m_\nu$)	0.017	—	0.0075 / 0.0061	0.0053 / 0.0042	—	—

- Stage-II plus CMB-S4 constrains neutrino masses to 24meV, with no tau prior. Adding Planck T/P, DESI and LSST gets so 16meV.

- Neff improves by more than a factor of two compared to CMB-S4.
  x5 LSST+DESI+Planck

- EOS of DE with free neutrino masses to sub-% accuracy



Why DOE?

- Science goals directly in line with P5 science (Cosmic Frontiers)

    - Understand cosmic acceleration: dark energy and inflation
    - Physics of neutrinos

- The theory is clean, with connections to standard methods of HEP.

- The challenges lie primarily in the instrumental, computing and management realms.

- Stage II must be built and operated like an HEP experiment.

    - Small signals and hard systematics ⇒ large program.
    - Sustained development and collaboration.
    - Optimized and custom built instrument.
    - Thorough understanding of the detector by the analysis team.

- Pushing the boundaries of HPC
    - Tight coupling of experiment with simulation.
    - Specialized hardware and software infrastructure.

Why DOE?

Stage II must be built and operated like an HEP experiment

	Example: LSST	Stage 2 21-cm experiment	Core DOE competencies
Science	Will characterize dark energy, constrain inflation, measure neutrino mass.	Will characterize dark energy at higher redshift, improve all basic cosmological parameters, inflationary physics, baryon-dark matter coupling, test modified gravity paradigms	DOE Cosmic Frontier does P5 science. Focus on fundamental physics. Small signals and hard systematics require large collaborations. Particle physics developed appropriate collaborative culture. Traditional radio astronomy community is focused on PI-led astronomy projects.
Dedicated long-term Research & Development	First astronomical project of this scale. Dedicated read-outs, optical design, dedicated data-pipe from Chile, photon-level system simulation	Current designs rely on off-shelf amplifiers, digitizers and GPUs for correlations. Next gen will require dedicated low-power on-chip solutions from sustained R&D.	DOE is capable of focused long-term development in anticipation of future projects. Direct transfer of know-how from accelerator experiments: RFI technology, massive data throughputs.
Large-scale hardware replication	21 rafts, 189 CCDS total	65,000 receiving elements, 2 billion pair correlator. Elements need to be cheap and accurately replicated.	Requires professional project management not available in university settings. Semi-industrial production capabilities and QA tracking crucial.
Data rates	20 TB/night, 60 PB survey, 15PB catalog	~100 PB/day raw, ~1 PB/day real-time reduced	Beyond ATLAS/CMS instantaneous bandwidth. Require highly sophisticated triggering for Fast Radio Burst Environment. Data reduction will require HPC environment.
Instrument characterization and calibration	Cosmology side of the project reliant of weak-lensing and precise photometry, both require 10^{-4} level system understanding	Signal to foreground radiation at 10^{-4} level. Due to raw data volumes forcing real-time reduction, cannot post-calibrate.	Need sub-percent level system understanding to achieve science goals. Full system simulations and characterization well beyond what is normally done is radio astronomy. Need focused infrastructure staff doing “less glamorous” science.

US 21 cm roadmap

- Small, self-organized community

- Progress so far:
  - Summer 2018: Tremendous Radio Arrays workshop at BNL
  - October 2018: Roadmap whitepaper on arXiv (1810.09572) and submitted to DOE
  - Ongoing: talks at US institutions to raise interest
  - Notice of intent (NOI) in preparation for Astro2020

- Vigorous R&D program: (next ~5 years)
  - Research to better define science case for Stage 2 experiment
  - Data analysis of Stage 1 and testbed experiments in preparation for Stage 2
  - Technology to develop new hardware and calibration methods

- US-led Stage 2 experiment: (first light 2027-2032):
  - Follows current crop of Stage 1 experiments (led by non-US entities)
  - Most likely a collaboration between DOE and NSF
  - Notional CD0 in 2025

Summary

The high redshift Universe remains uncharted territory and it contains most of the cosmological information.

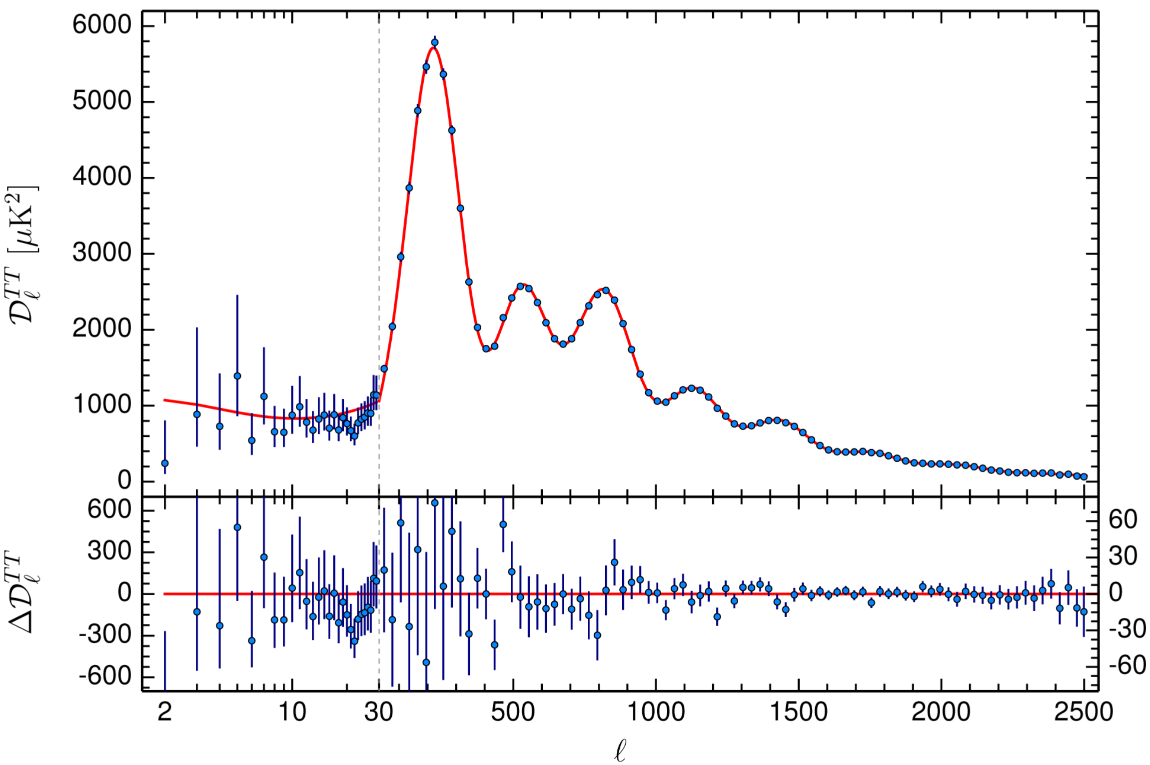
- 21 cm offers the possibility to make cheap noisless measurements up to z<6
- Signal is quite well understood, both analytically and numerically.
  - HPC opportunities in the exascale era
- Stage-II experiment could be the ultimate survey at z < 6
  - A ~10 Billions galaxies survey over V >250 [Gpc/h]^3
  - BAO and RSD for Early Dark Energy and neutrino physics
  - Primodrial non Guassianities in power spectrum and bispectrum
- Clear DOE expertise in R&D and management of large facilities.
- NOI being prepared for Astro2020.

In 1964 Penzias and Wilson (re)-discovered the CMB.

In the following years Jim Peebles and others in the US, and Zeldovich and Sunyaev in Russia predicted the presence of acoustic features in the CMB.
Both groups moved on to study the galaxy distribution on the largest scales.

Jim Peebles in Annu. Rev.Astro.Astrophys (2012) :

''….I did not continue with this (CMB), in part because I had trouble imagining that such tiny disturbances to the CMB could be detected...''



Thanks!