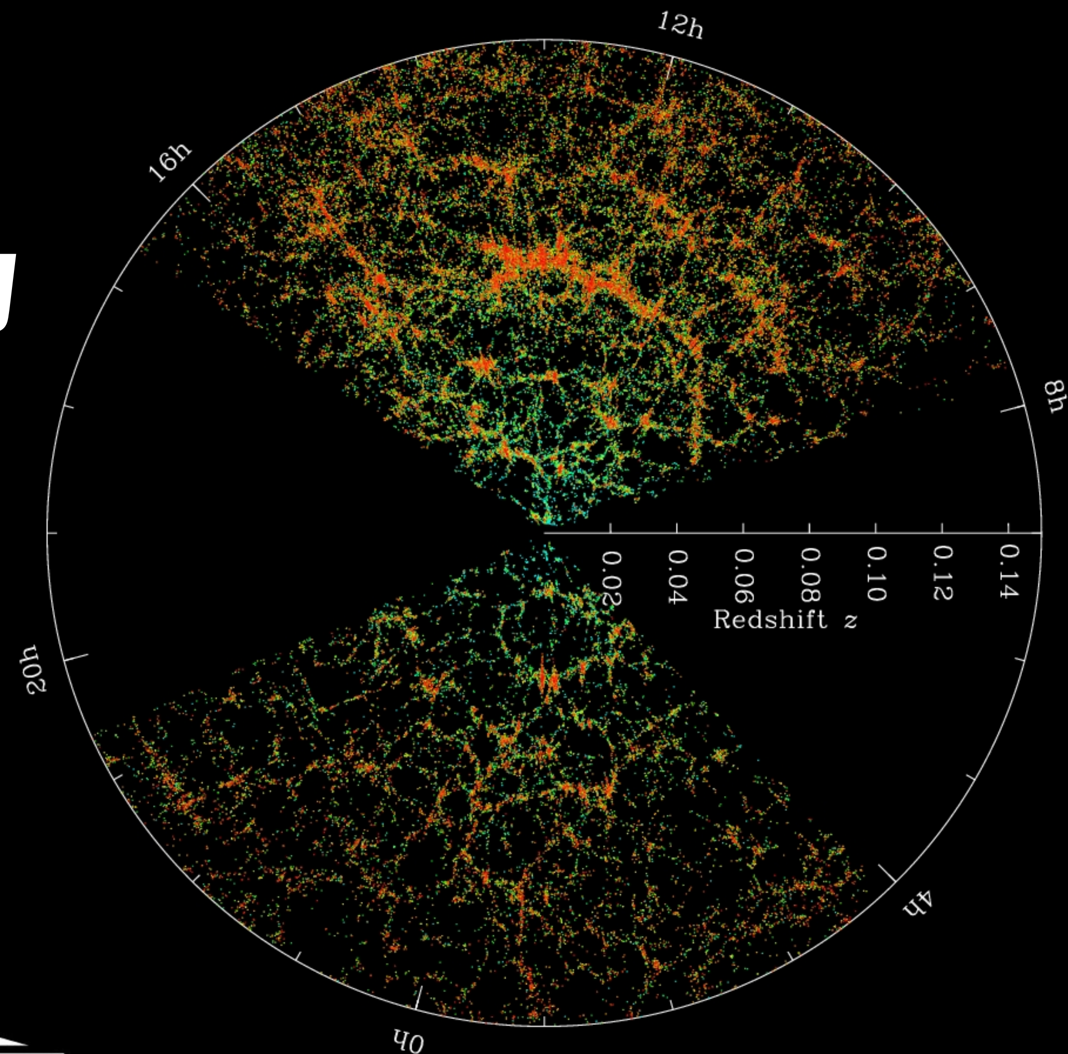
Spectroscopic
Future of ^ Galaxy Surveys

Will Percival

Waterloo Centre for Astrophysics



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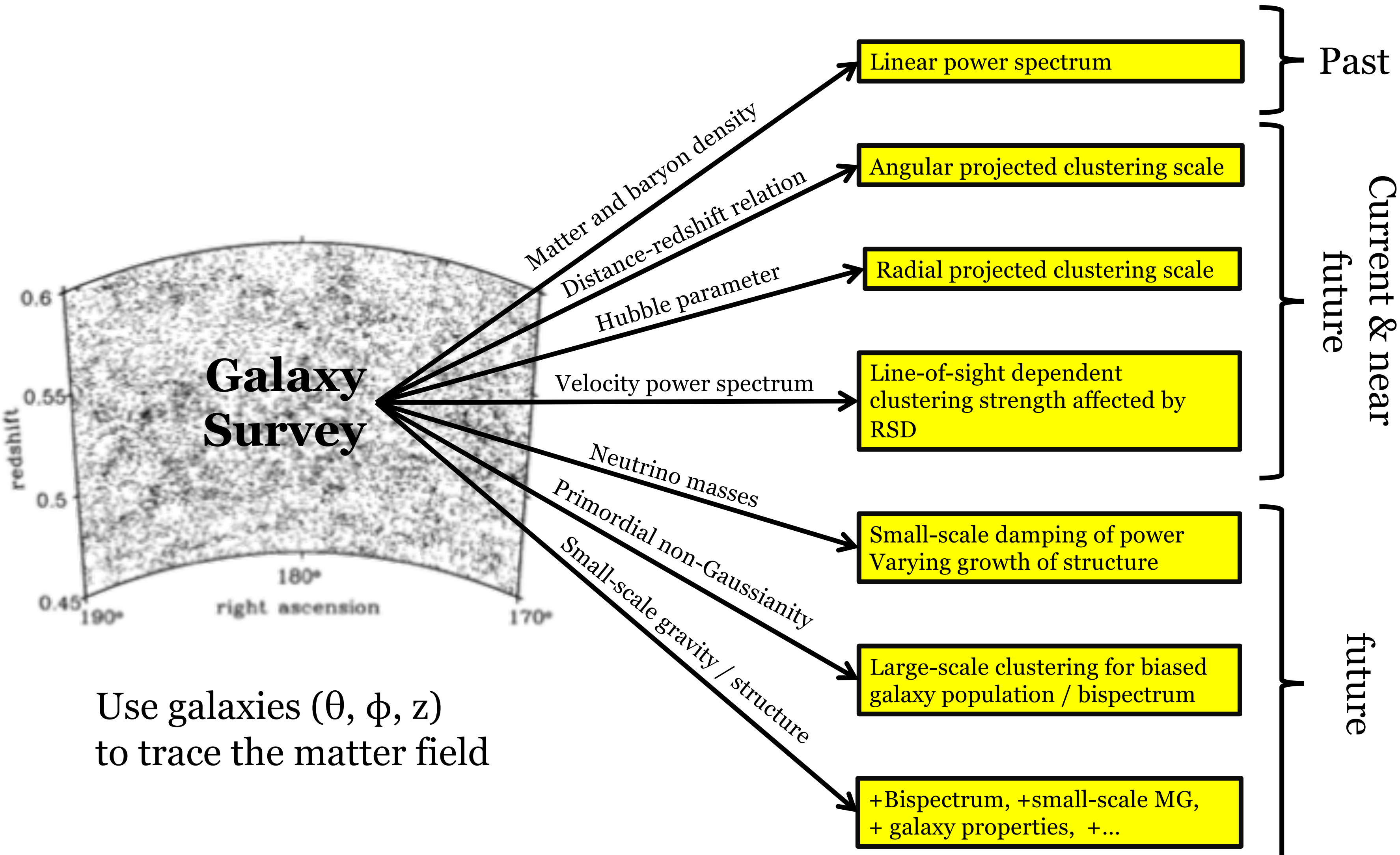
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Cosmology from spectroscopic galaxy surveys

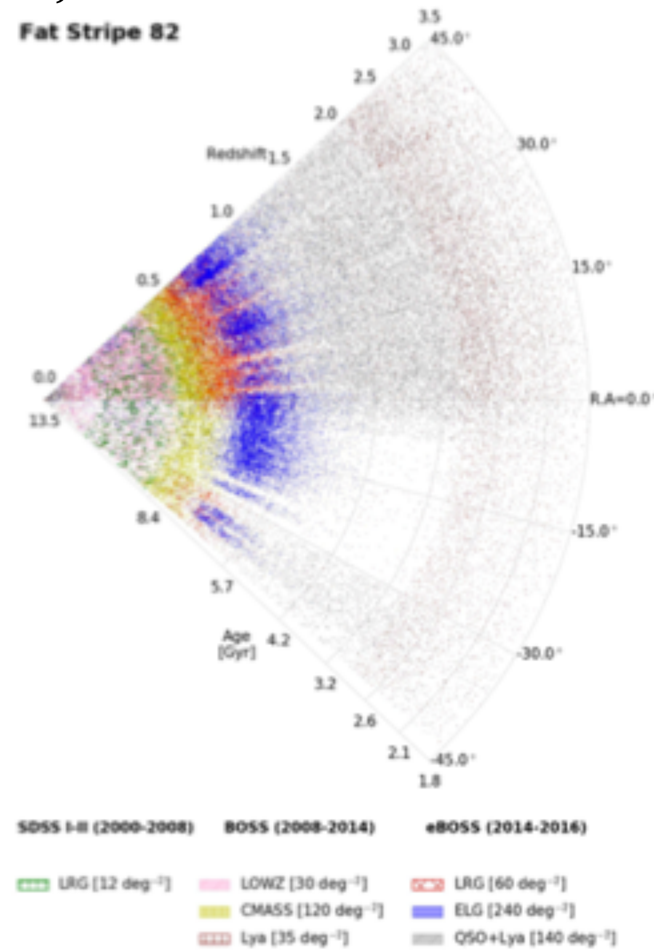


Use galaxies (θ, φ, z)
to trace the matter field

Recent progress

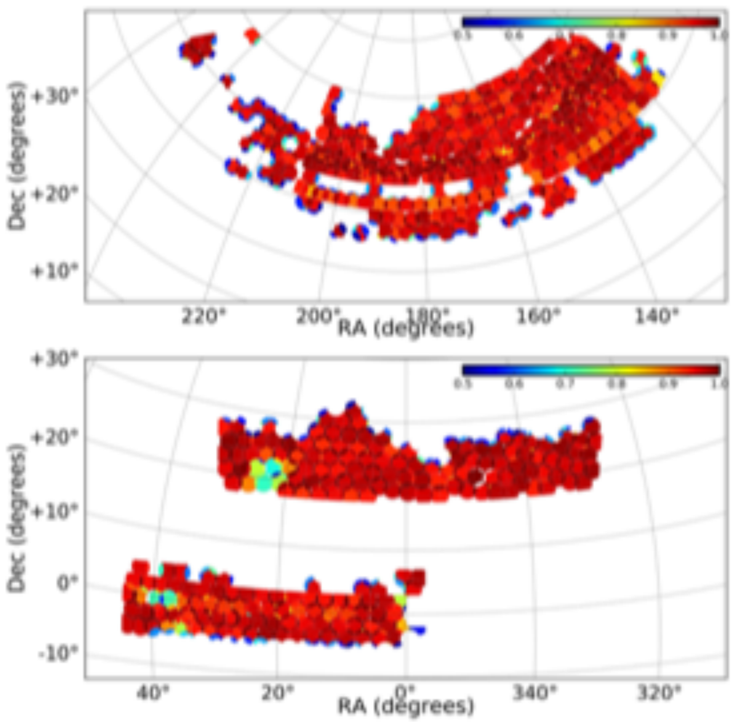
extended BOSS / SDSS-IV

- Ongoing cosmological galaxy survey within SDSS
- Use the Sloan telescope and MOS to observe to higher redshift than BOSS
- Basic parameters (cmpr BOSS 10,000deg^2, 1.1M galaxies)
    - Ω = 1,500deg^2 – 5,800deg^2
    - 230k 0.6<z<0.9 LRGs (direct BAO, RSD)
    - 210k 0.8<z<1.0 ELGs (direct BAO, RSD)
    - 340k 0.9<z<2.2 QSOs (direct BAO, RSD)
    - 60k QSOs (BAO, RSD from Ly-α forest)
- Survey 2014-2019

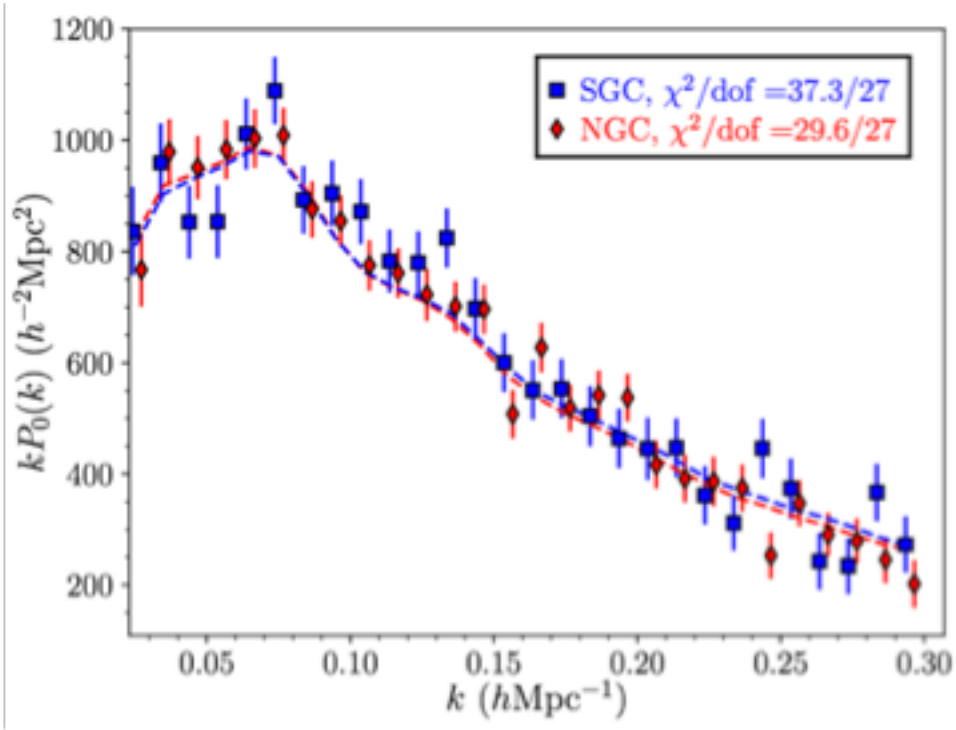


Dawson et al. 2015; arXiv:1508.04473, Zhao et al. 2015; arXiv:1510.08216

DR14 eBOSS QSO footprint (data now public)



Ata et al. 2017; arXiv:1705.06373



~2,000deg² split in the NGC and SGC regions

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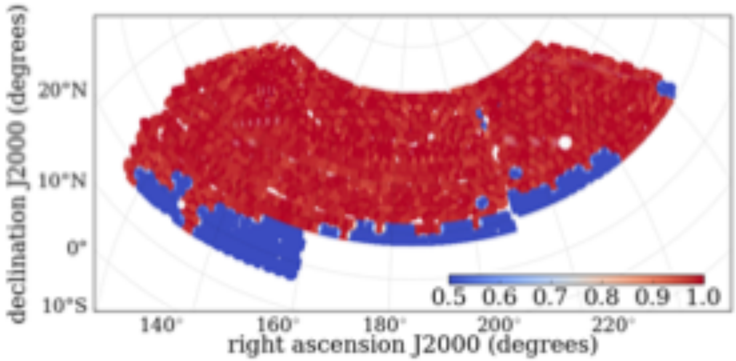
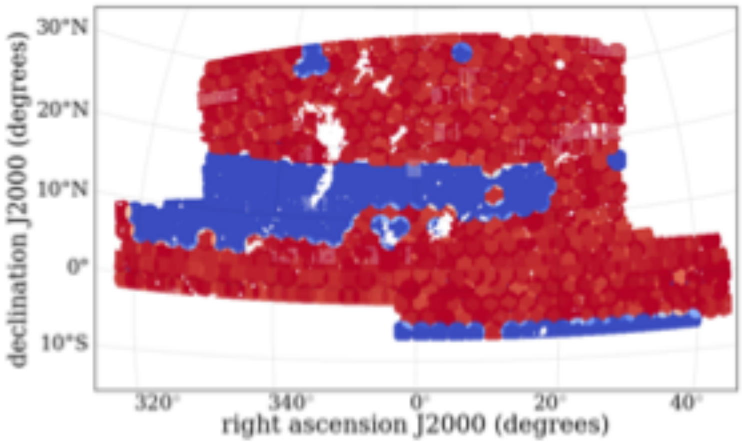
DR16 eBOSS footprint (data public early 2020)



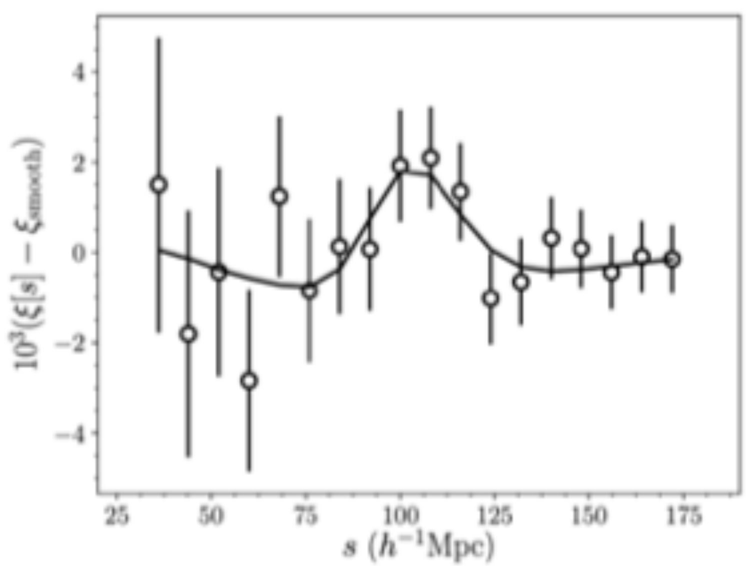


5,800deg^2 split in the NGC and SGC regions

?

Cosmological measurements will be announced at the Jan AAS meeting

BAO as an absolute ruler



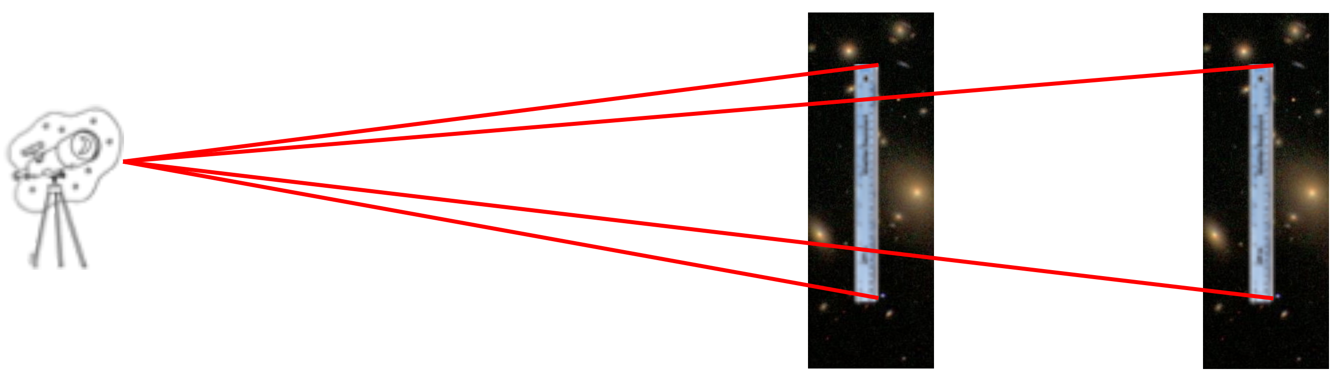
eBOSS DR14 quasars at z=1.52
Ata et al. 2017; arXiv:1705.06373

Radial direction

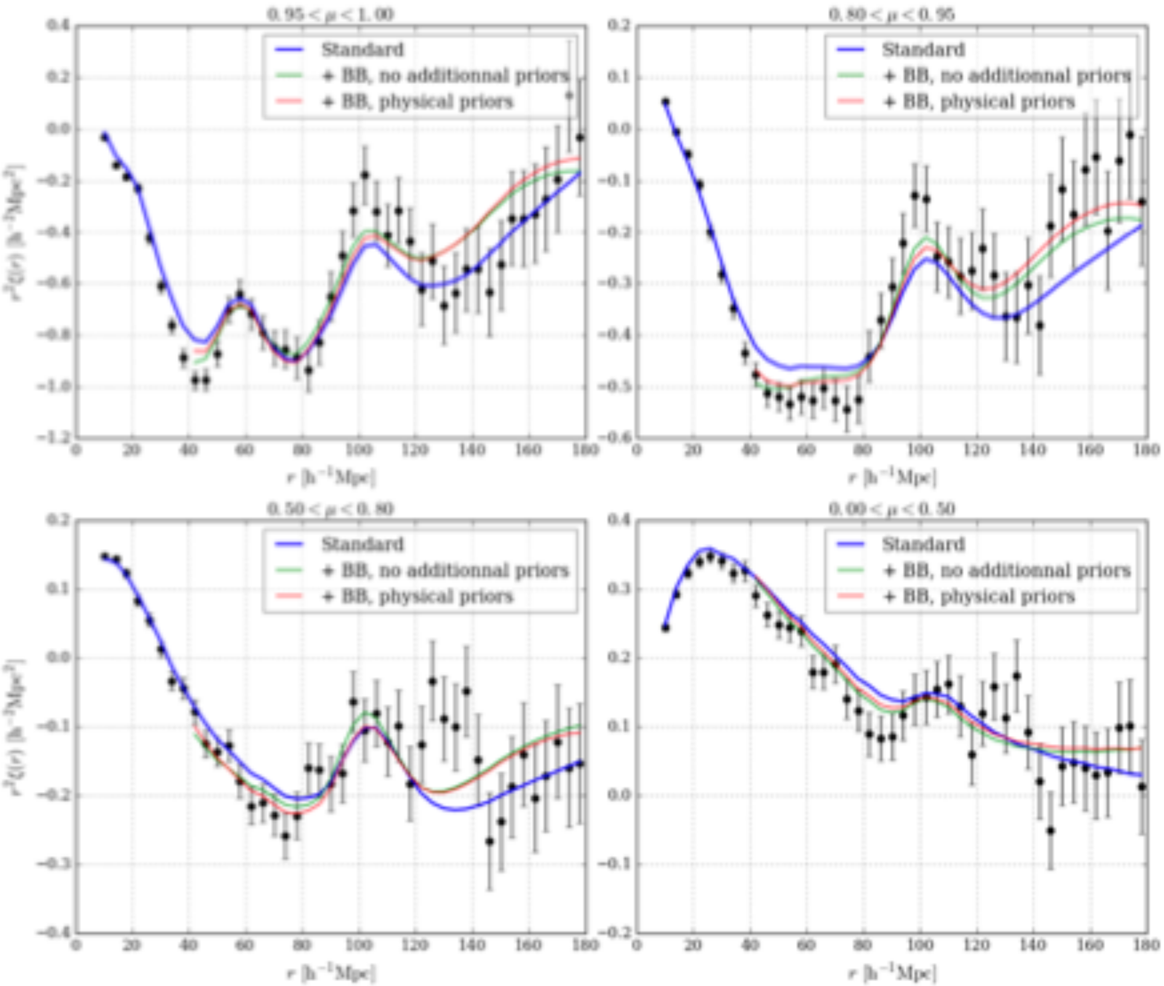
$$\alpha_{\parallel} \propto H(z) r_d$$

Angular direction

$$\alpha_{\perp} \propto \frac{D_A(z)}{r_d}$$



BAO as an absolute ruler



eBOSS DR14 Ly-alpha forest auto-correlation at z=2.35
De Sainte Agathe et al. 2019; arXiv: 1904.03400

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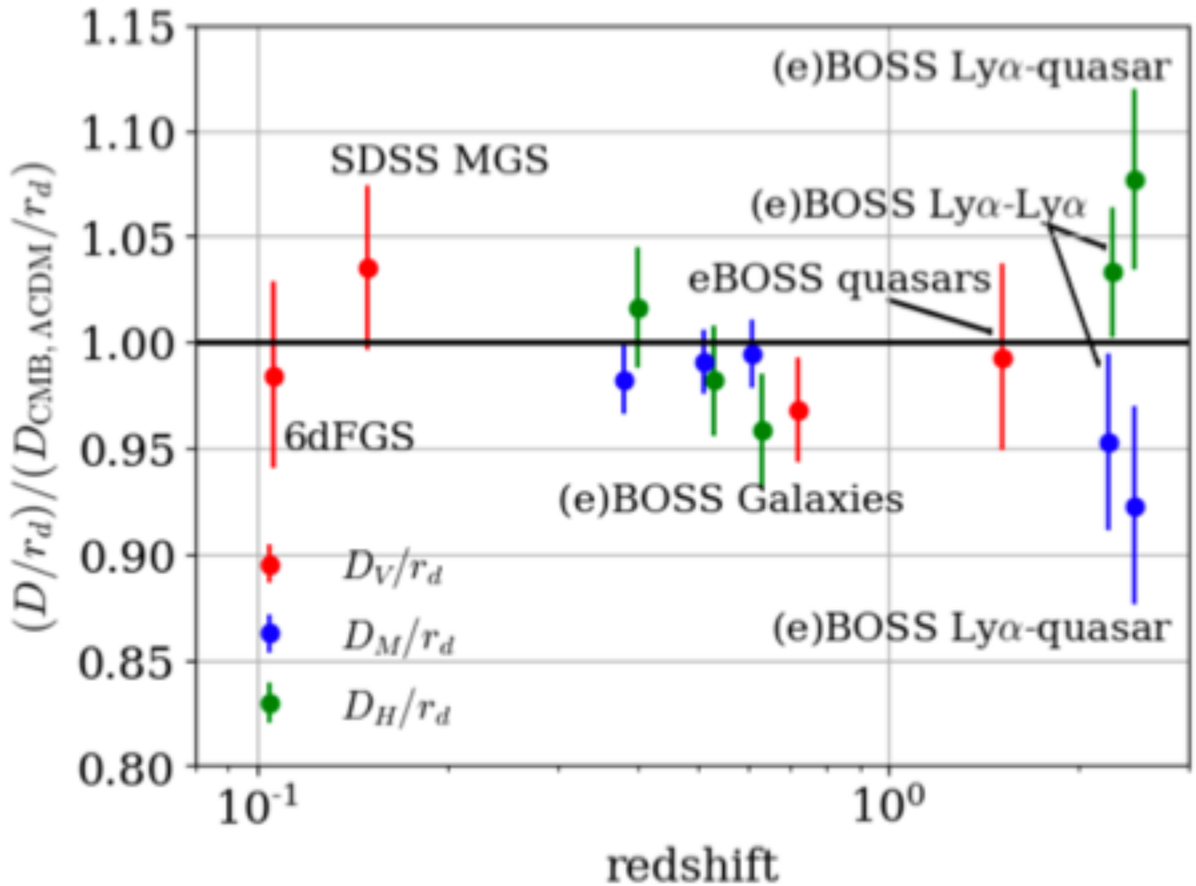
Current BAO measurements



Blomqvist et al. 2019; arXiv: 1904.03430

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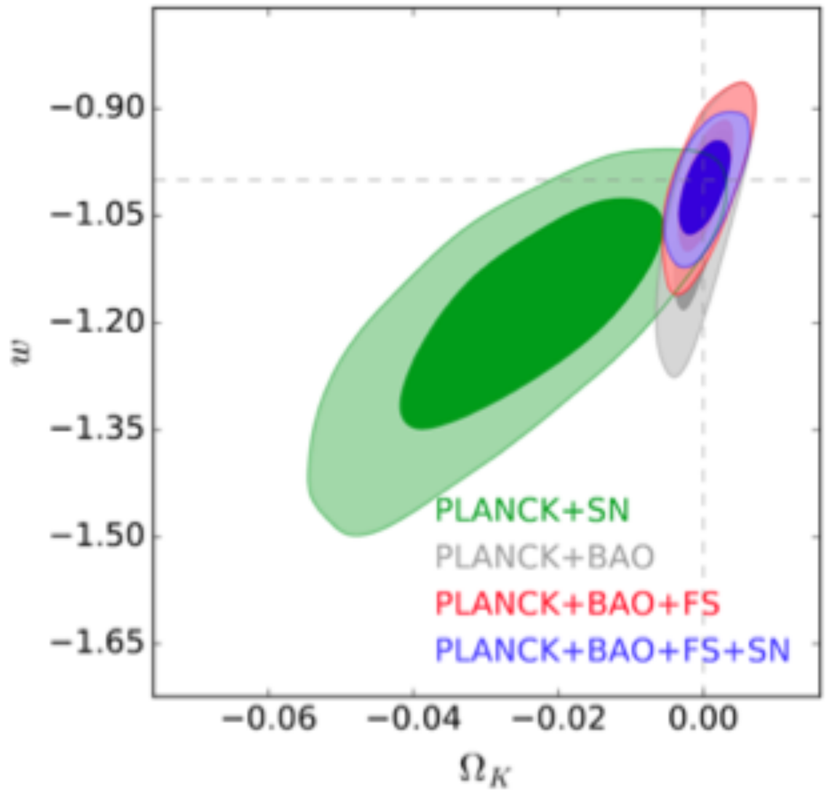
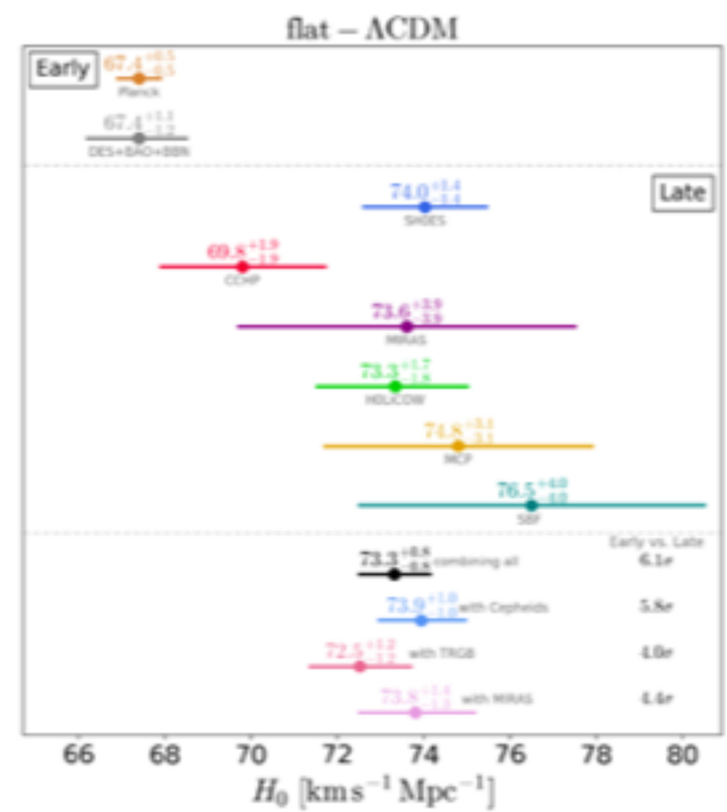
Cosmological Implications of the absolute ruler



Alam et al. 2016; arXiv:1607.03155



Verde, Treu & Riess 2019; arXiv:1907.10625

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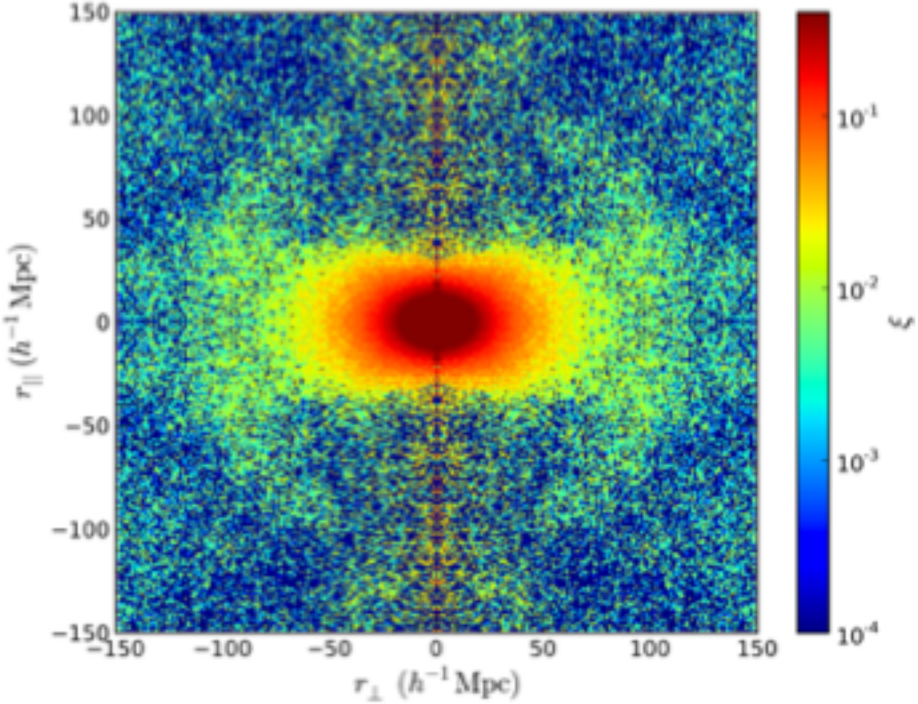
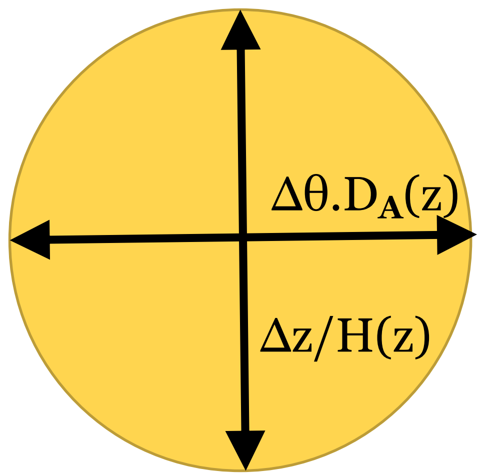
Relative BAO: position vs line-of-sight

Samushia et al. 2013; MNRAS, 439, 3504



$$\frac{\alpha_{\|}}{\alpha_{\perp}} \propto H(z)D_A(z)$$

The Alcock-Paczynski effect



STANDARD SHAPE
[Minimum scale – cosmological expansion can still be recovered]

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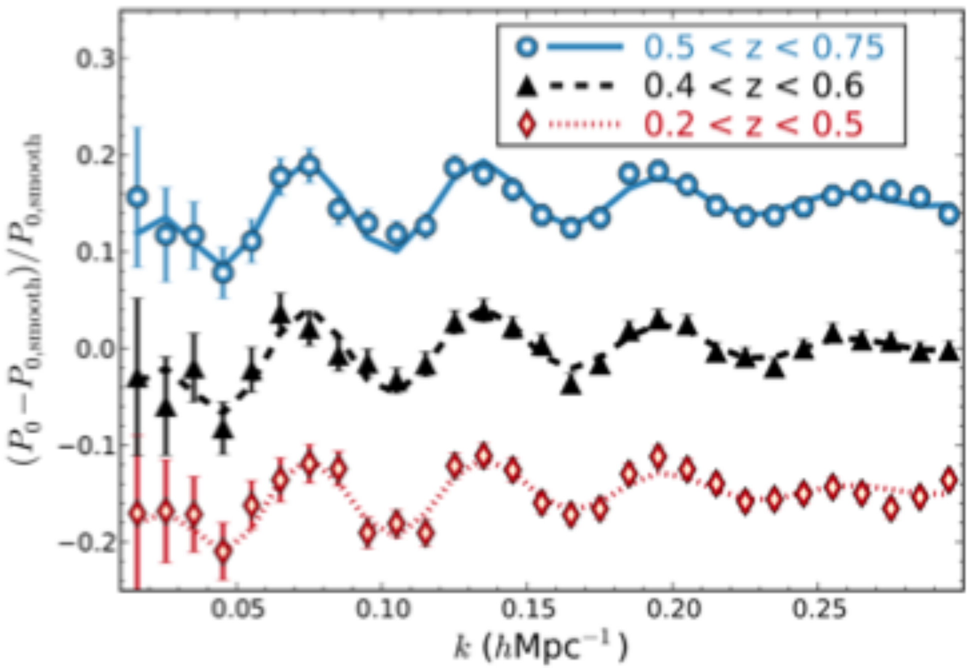
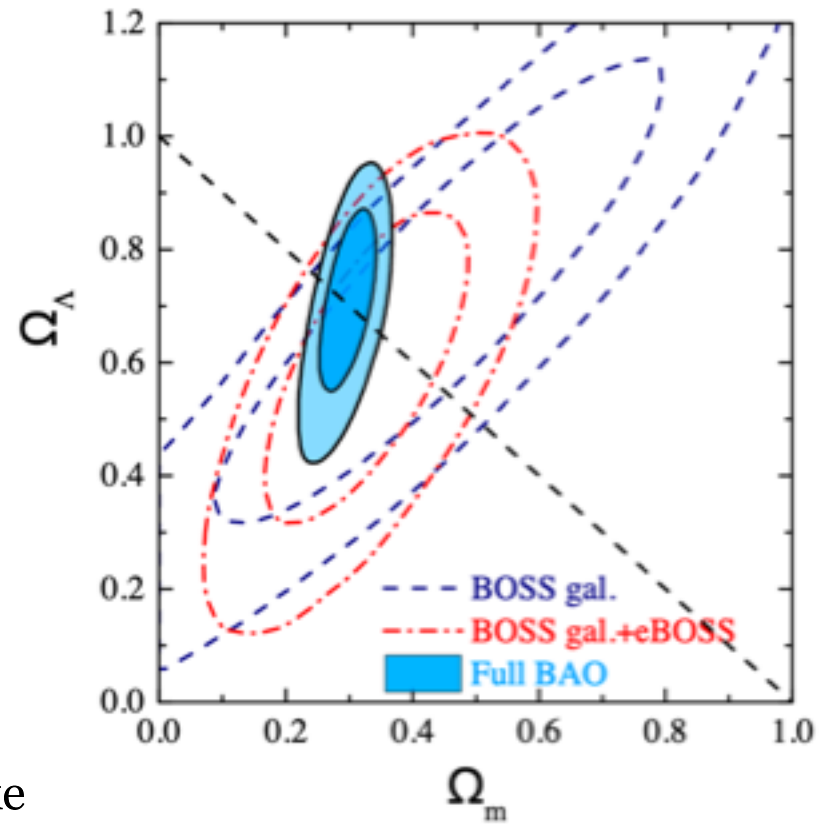
Relative BAO: evolution with redshift

Alam et al. 2016; arXiv:1607.03155



Ata et al. 2017; arXiv:1705.06373



Strong requirement that $H(z)/H_0$ looks like ΛCDM (6.6σ requirement for Λ)

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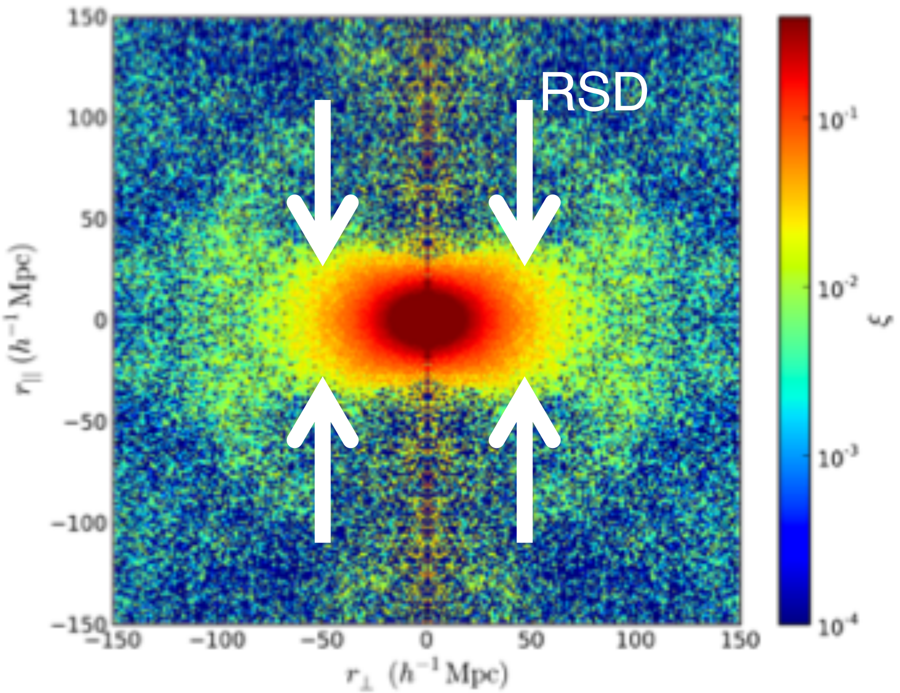
Structure growth

Linear amplitude of δ_k depends on peculiar velocities: additive term

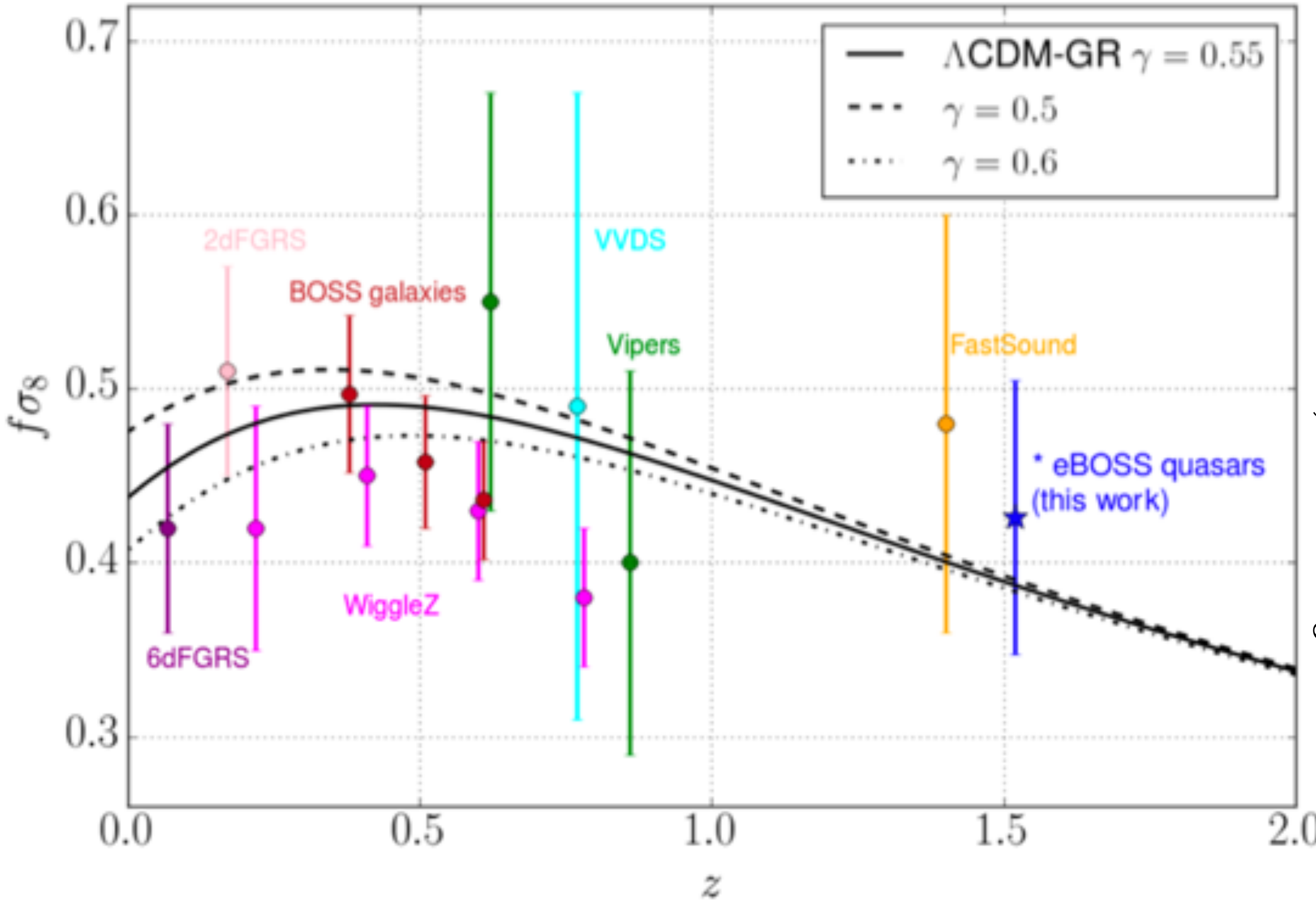
$$\mu^2 f(z)\sigma_8(z) \propto \mu^2 \frac{dG}{d\log a}$$

RMS amplitude of velocities of structure growth



Samushia et al. 2013; MNRAS, 439, 3504

Current RSD measurements from galaxy 2-point



Zarrouk et al. 2018; arXiv:1801.03062

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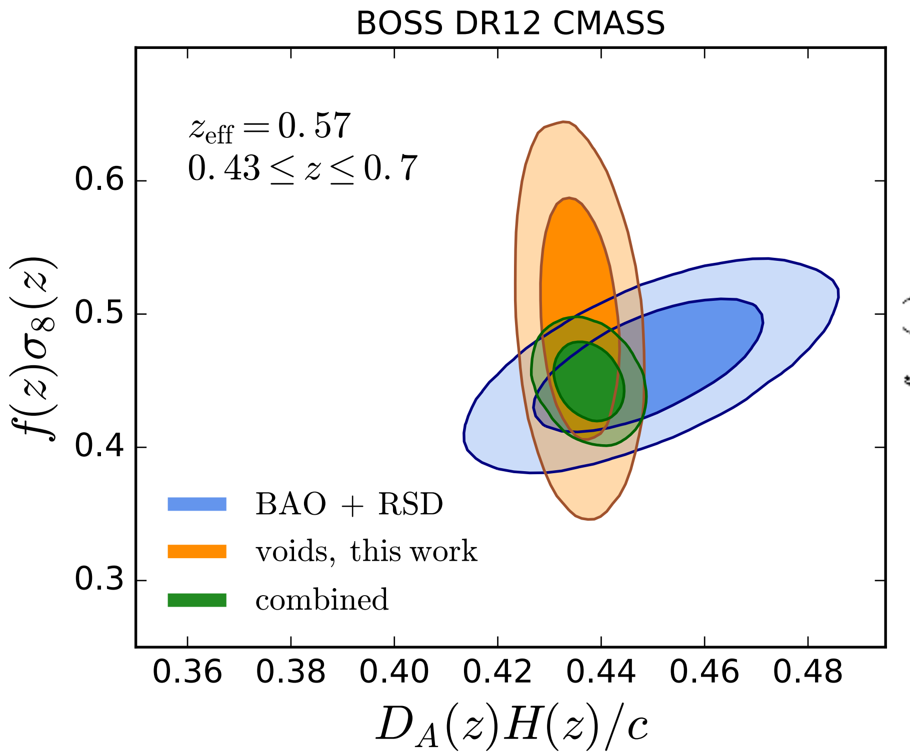
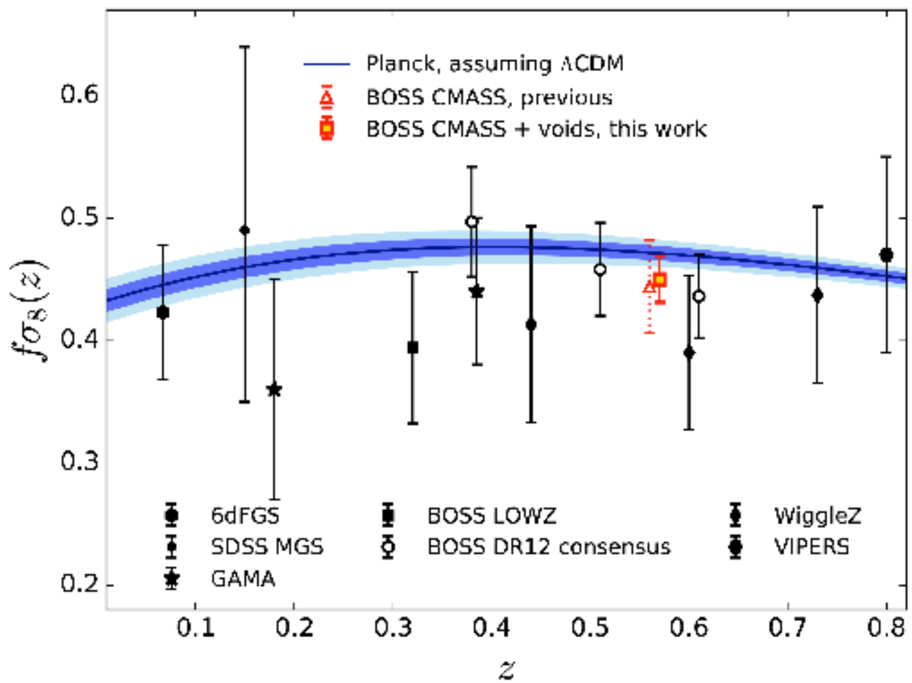
Void – galaxy cross-correlations





Nadathur et al. 2019, arXiv: 1904.01030

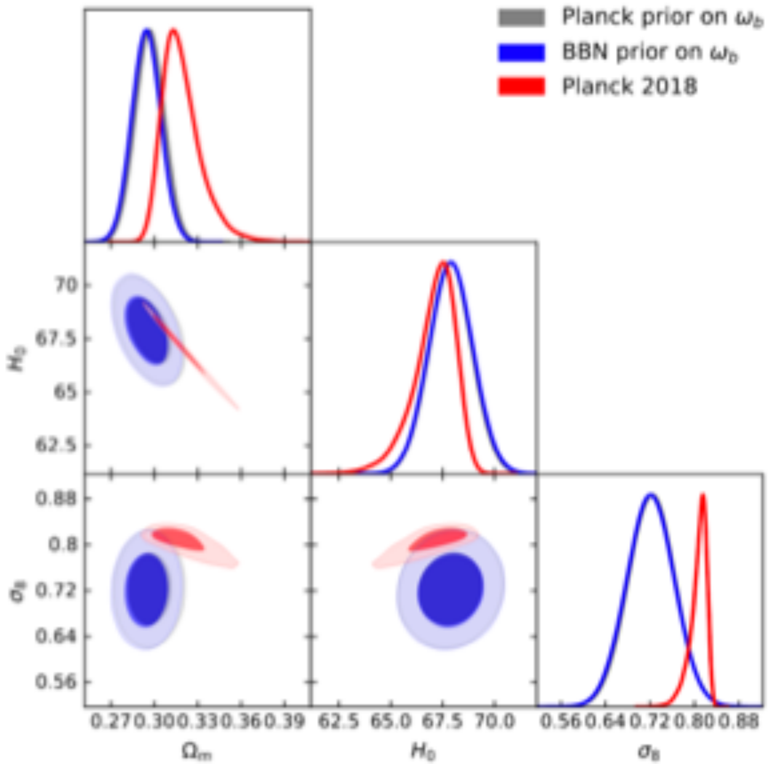
Voids: $D_A(0.57)H(0.57)/c = 0.436 \pm 0.005$

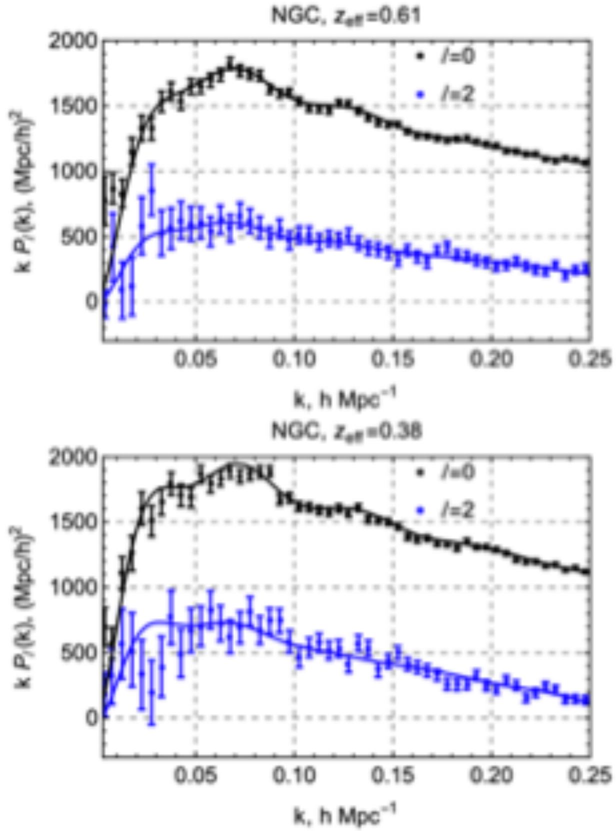
BAO: $D_A(0.57)H(0.57)/c = 0.463 \pm 0.017$

Voids+gals: $f(z)\sigma_8(z) = 0.450 \pm 0.019$

Gals: $f(z)\sigma_8(z) = 0.444 \pm 0.038$

Full power spectrum fits





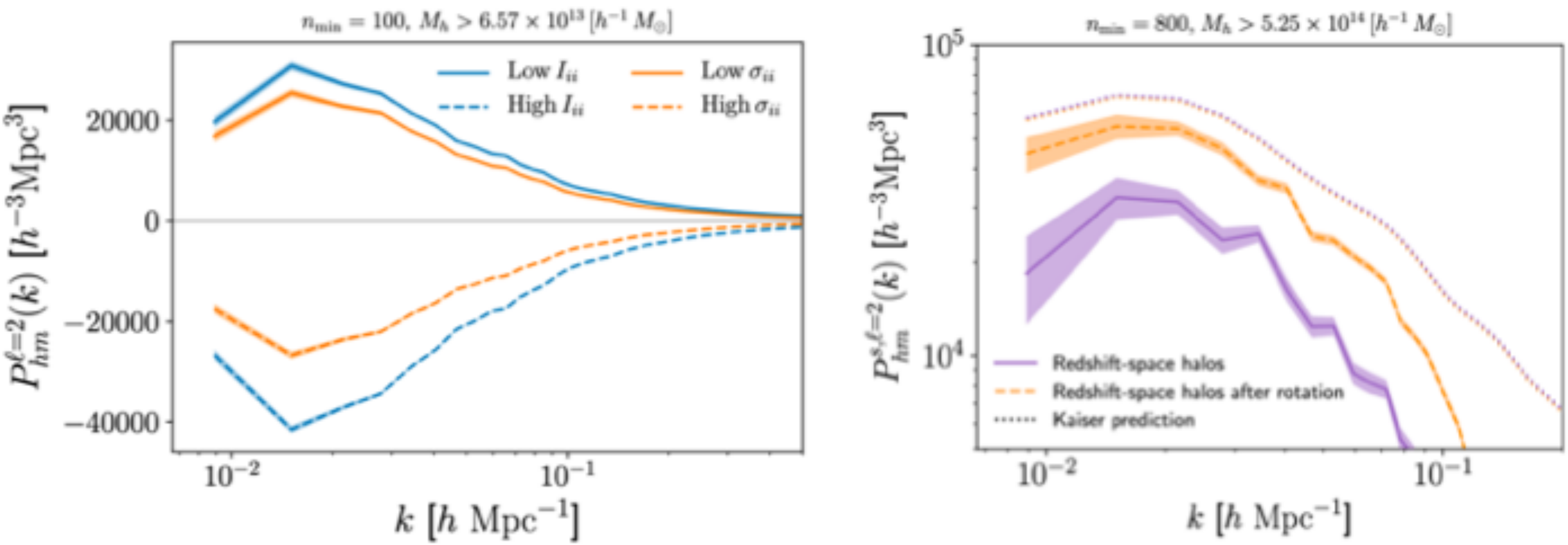
Ivanov, Simonovic & Zaldarriaga 2019; arXiv:1909.05277

"we use a complete perturbation theory model that properly takes into account the non-linear effects of dark matter clustering, short-scale physics, galaxy bias, redshift-space distortions, and large-scale bulk flows"

Future concern: Assembly bias

- Haloes align with tidal fields
- Gives biased anisotropic clustering for objects selected by shape or σ_v
- So far BOSS & eBOSS galaxy selections are ~isotropic in halo properties

- Selecting groups in redshift-space gives strong LOS clustering dependence

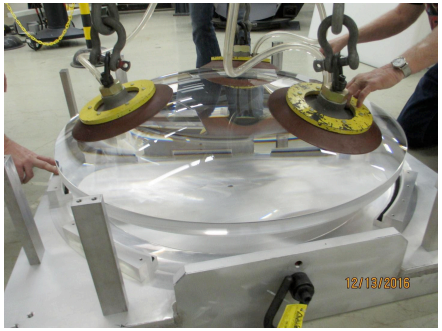


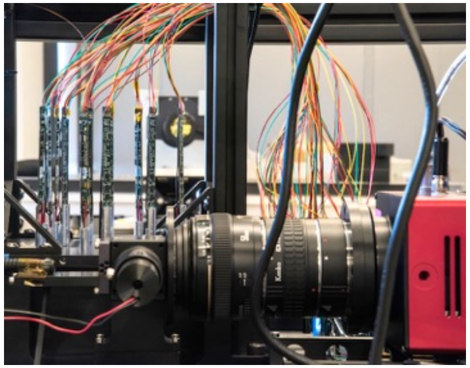
Obuljen, Dalal & Percival 2019; arXiv:1906.11823

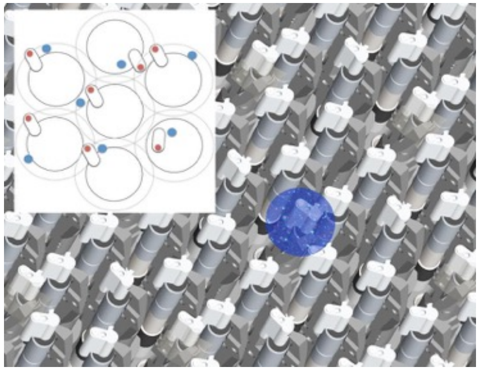
DESI (2020-2025)

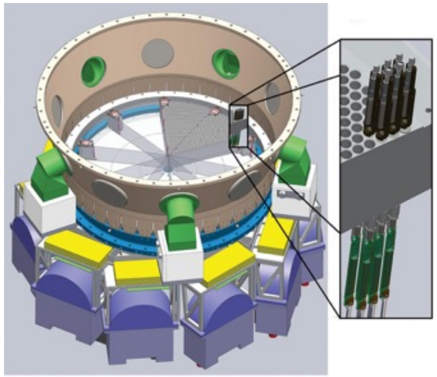
Dark Energy Spectroscopic Instrument (DESI)

- New fibre-fed MOS for Mayall
- On course for 2019 first-light and 2020 survey start
- DESI will survey
  - Ω =14,000deg^2
  - ~20,000,000 high redshift galaxies (direct BAO)
  - ~10,000,000 low redshift ($z<0.5$) galaxies
  - ~600,000 quasars (BAO from Ly-α forest)
  - Cosmic variance limited to $z \sim 1.4$
- Also WEAVE (WHT, 2020 start?) and 4MOST (VISTA, 2022 start) but fewer fibers, so less optimized for stand-alone spectroscopic galaxy surveys for cosmology

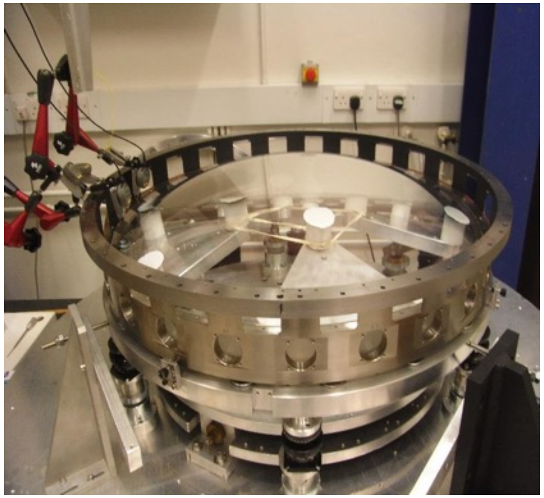








DESI – the build



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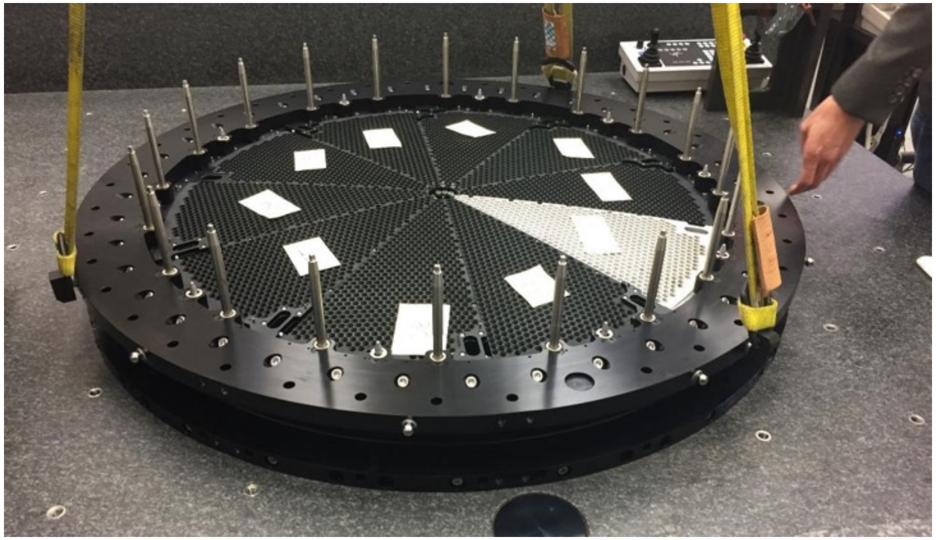
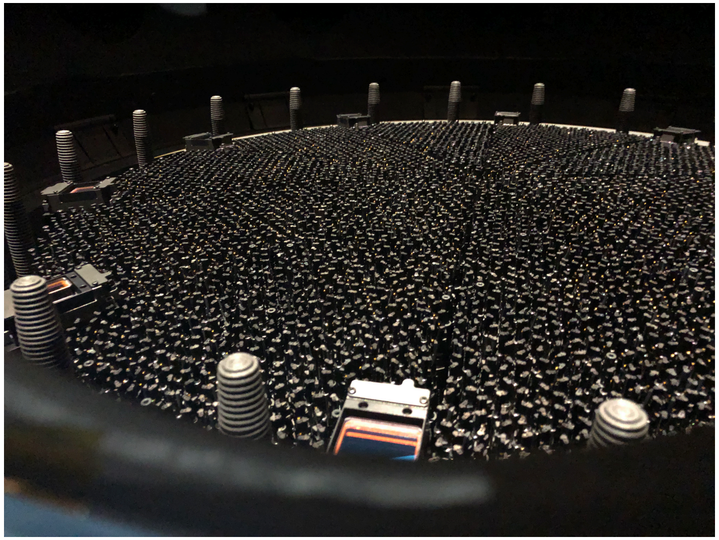
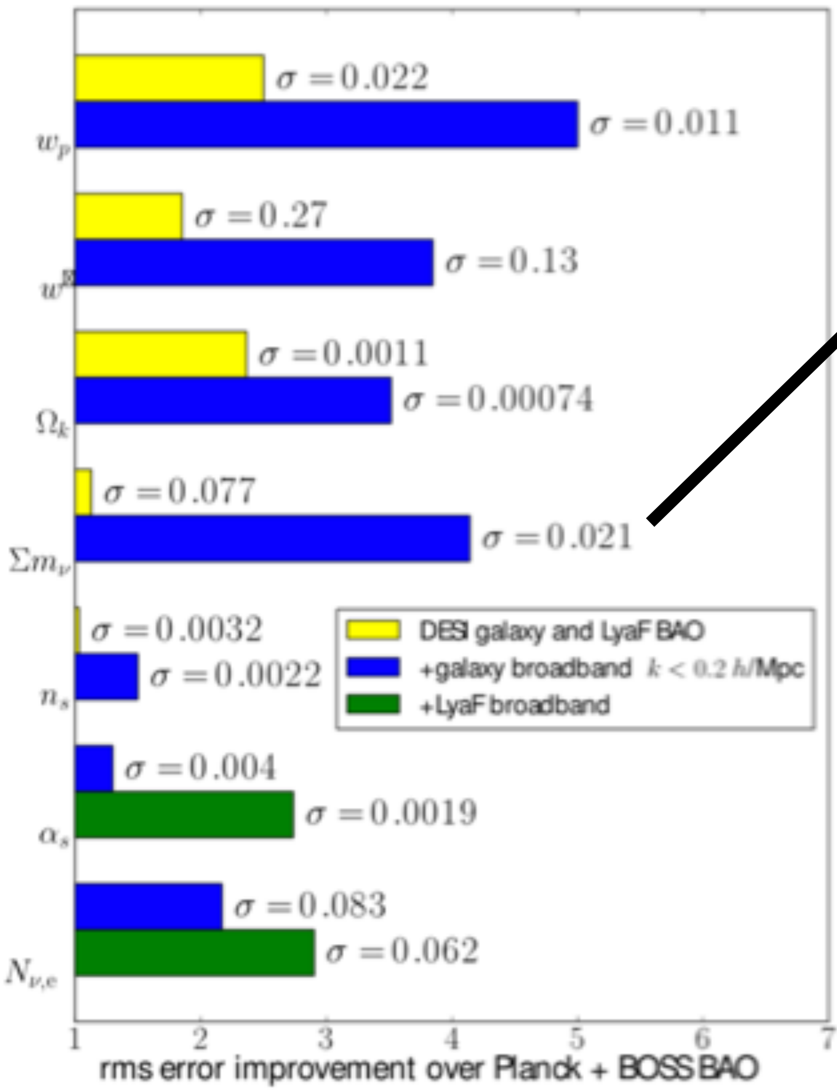
DESI – the build



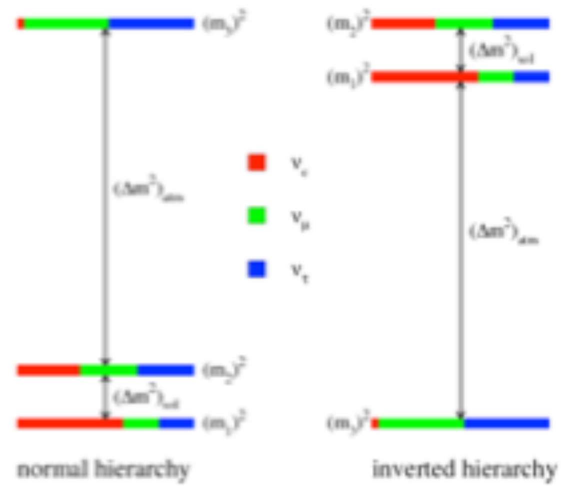


DESI cosmological predictions

DESI collaboration 2016; arXiv:1611.00036



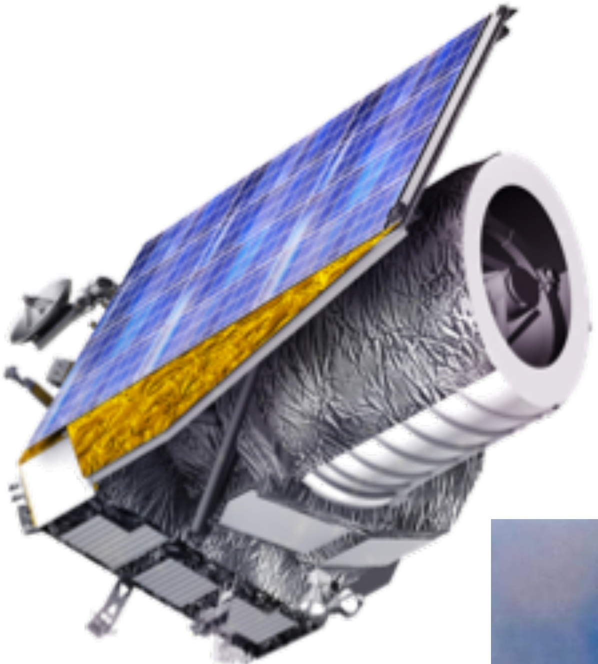
Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.56	0.19
Planck + BAO	0.087	0.18
Gal ($k_{\max} = 0.1h\,\mathrm{Mpc}^{-1}$)	0.030	0.13
Gal ($k_{\max} = 0.2h\,\mathrm{Mpc}^{-1}$)	0.021	0.083
Ly-α forest	0.041	0.11
Ly-α forest + Gal ($k_{\max} = 0.2$)	0.020	0.062



Total mass >0.059eV >0.10eV

Euclid (2022-2028)

Euclid



M2 mission in ESA cosmic visions program
due to launch 2022

Wide survey:

- 15,000deg²
- NIR Photometry
  - Y, J, H
  - 24mag, 5σ point source
- NIR slitless spectroscopy for redshifts
  - red: 1.25-1.85μm (0.9<z<1.8 Hα)
  - ~25M galaxies
- wide-band visible image for WL

Deep survey:

- 40deg²
- 12 passes, as for wide survey
- additional blue spectra: 0.92-1.25μm
- dispersion directions for 12 passes >10deg apart

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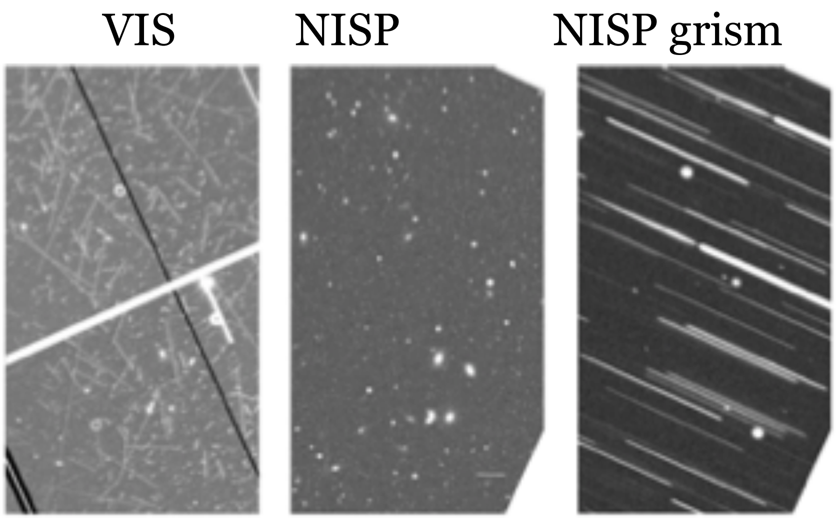
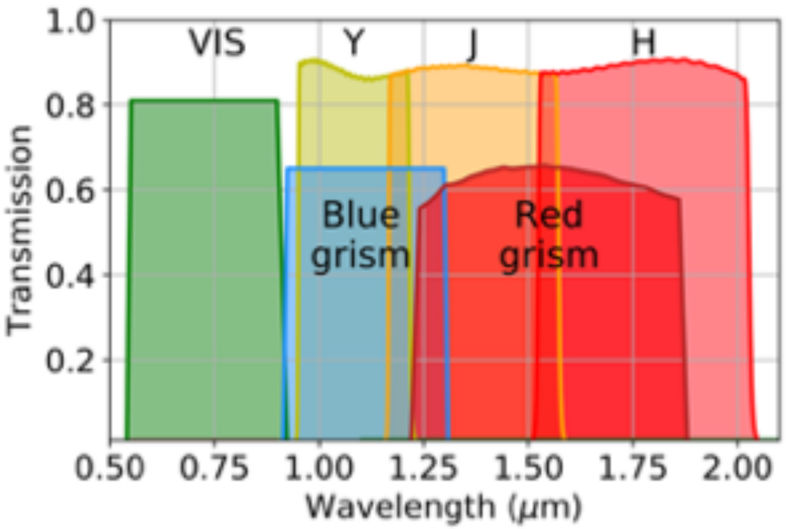
A panchromatic survey



* NISP simulation does not include cosmic rays



	VIS	Y	J	H	GRISM
Wide	24.5	24	24	24	2×10^{-16} erg/s/cm²
Deep	26.5	26	26	26	2×10^{-17} erg/s/cm²

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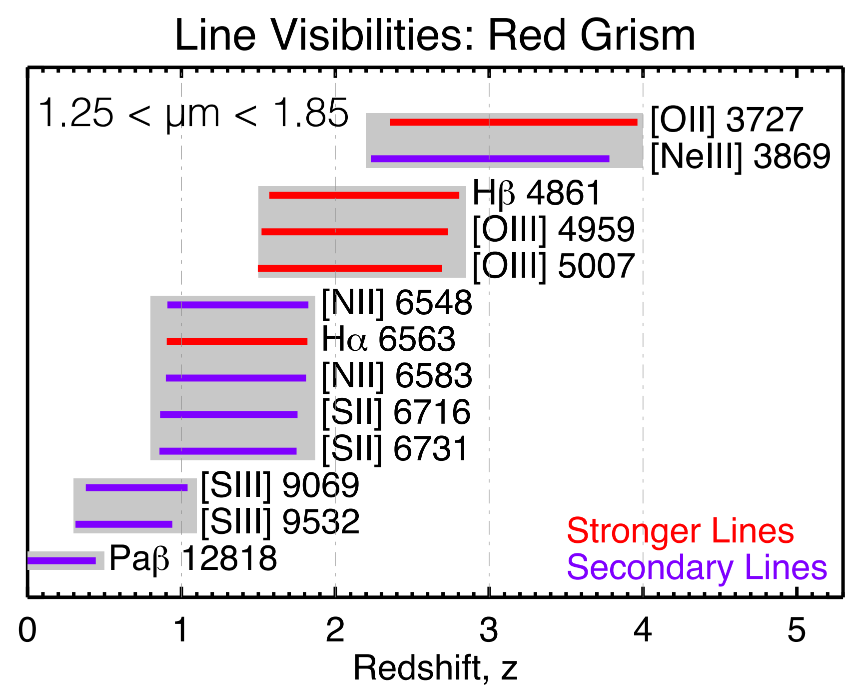
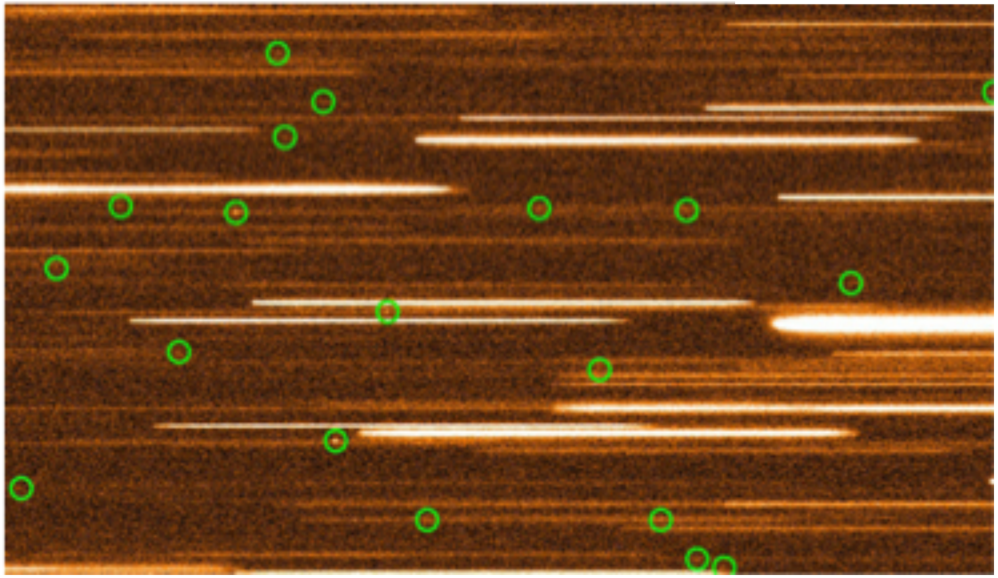
Slitless spectroscopy

Pushing the detection limit:

- Line misidentification
- Spectra confusion
- Detector persistence
- Foregrounds



Addison et al. 2018; arXiv:1811.10668



Garilli et al.

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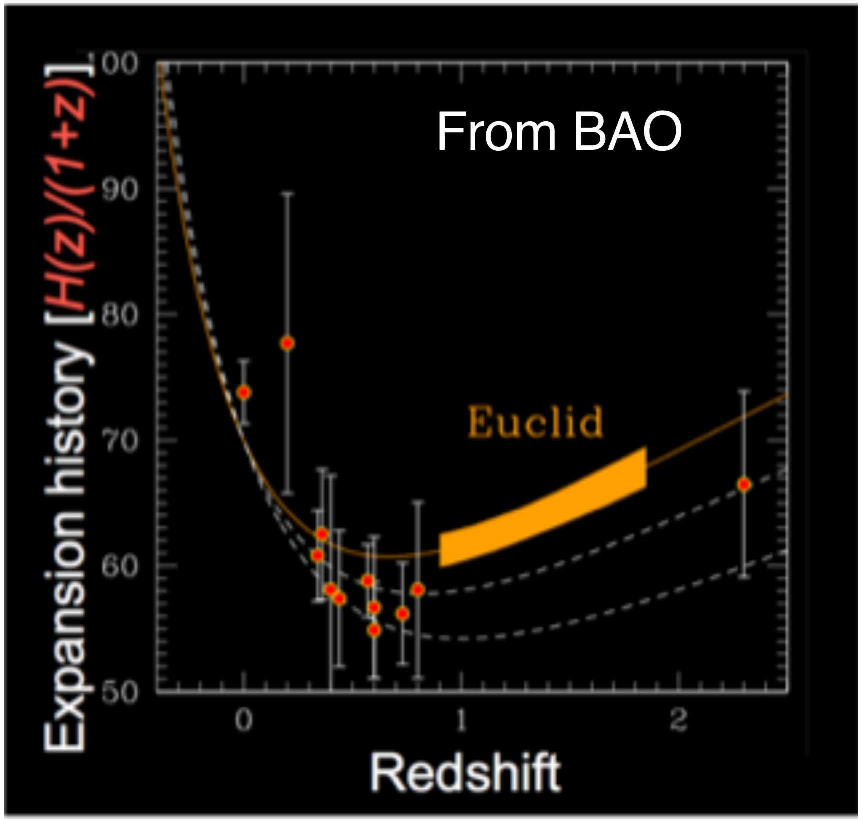
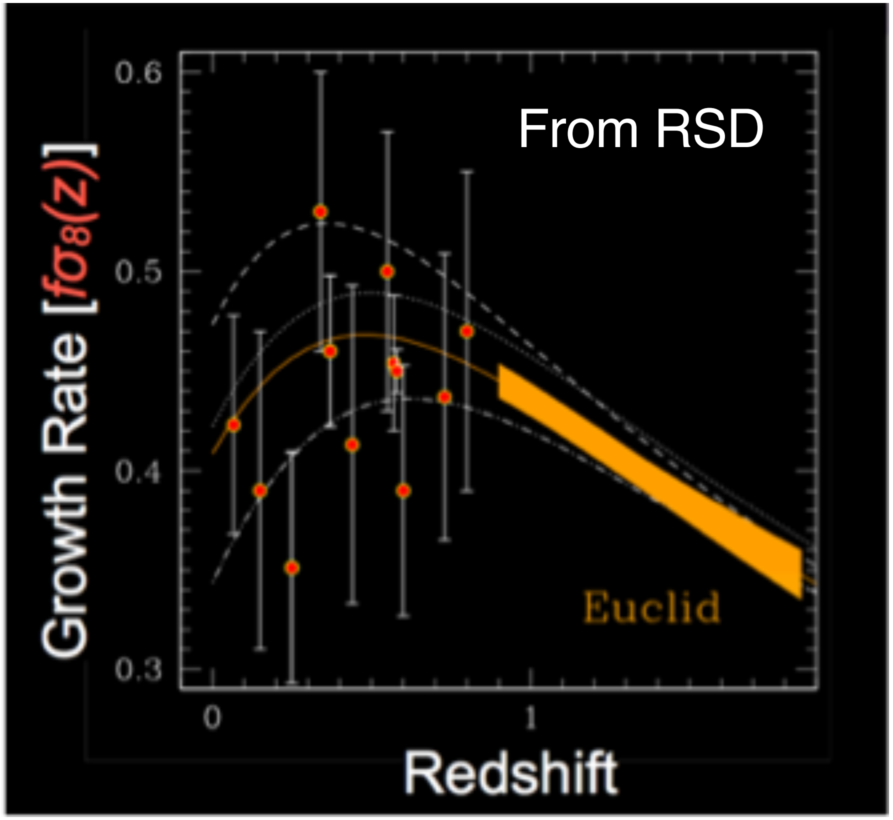
Euclid galaxy clustering predictions





The next generation ...

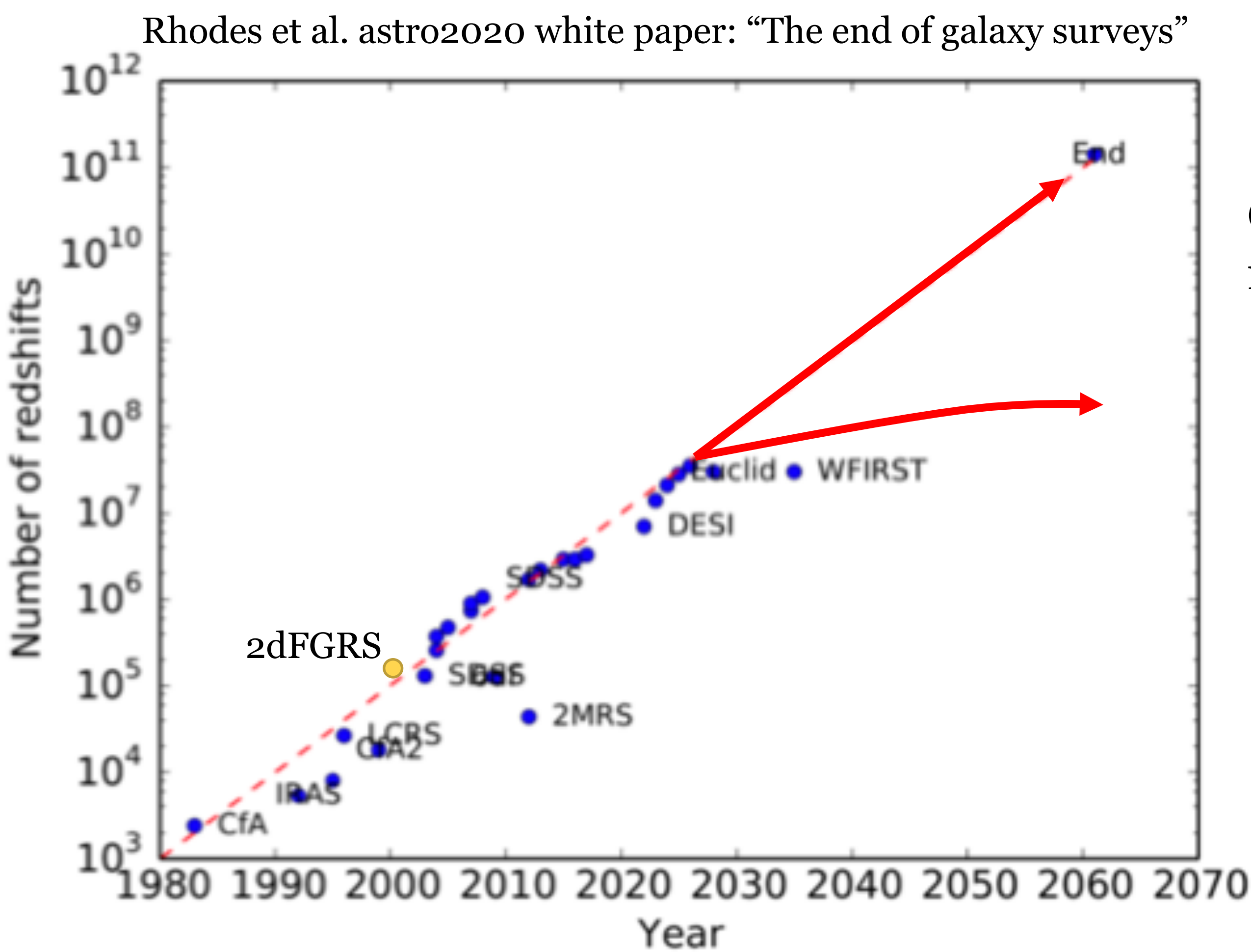
Astro2020 papers on spectroscopic surveys

- The Sloan Digital Sky Survey as an Archetypal Mid-Scale Program (Blanton et al.)
- SDSS-V: Pioneering Panoptic Spectroscopy (Kollmeier et al.)
- The Dark Energy Spectroscopic Instrument (DESI) (Levi & Allenet al.)

- The MegaMapper: a z > 2 Spectroscopic Instrument for the Study of Inflation and Dark Energy (Schlegel & Kollmeier et al.)
- Next Generation LSST Science (Jha et al.)
- FOBOS: a Next-Generation Spectroscopic Facility (Bundy et al.)
- The Maunakea Spectroscopic Explorer (Marshall et al.)
- SpecTel: A 10-12 Meter Class Spectroscopic Survey Telescope (Ellis & Dawson et al.)
- HD GRS: Illuminating the dark universe with a very high density galaxy redshift survey over a wide area (Wang et al.)

- Towards a Spectroscopic Survey Roadmap for the 2020s and Beyond (Abbott et al.)
- The End of Galaxy Surveys (Rhodes et al.)

Survey improvement



Goal: all of the information

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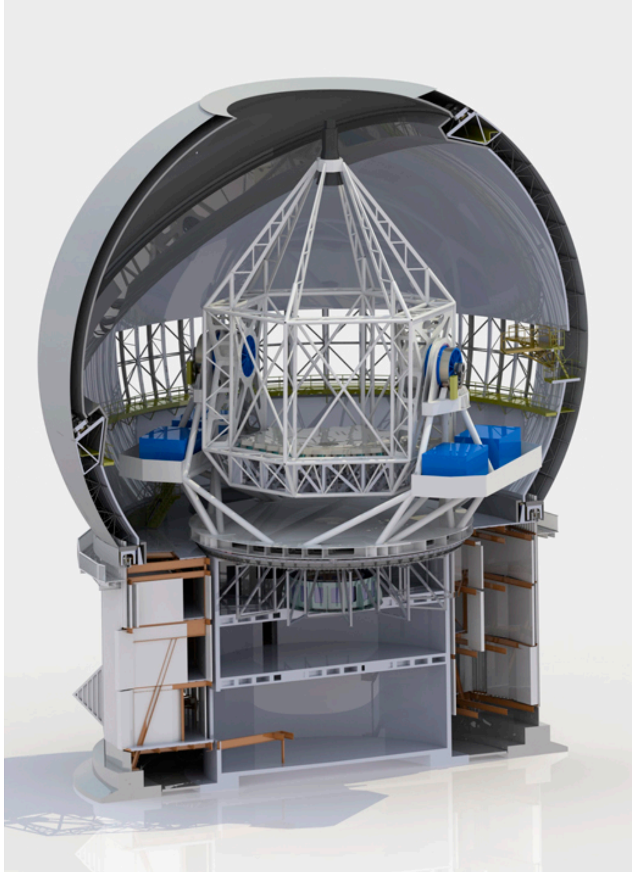
The Maunakea Spectroscopic Explorer

Maunakea Spectroscopic Explorer

- Proposed as replacement for CFHT
- New 11.25m telescope (similar profile dome to CFHT!)
- 4332 fibres, 1.5deg² FOV, current design has Echidna style positioner
- 3249 fibres
    - R~2500 (optical, J, H)
    - R~6000 spectroscopy (optical)
- 1083 fibres
    - R~20,000 – 40,000 optical windows)
- Many science cases from stars to cosmology

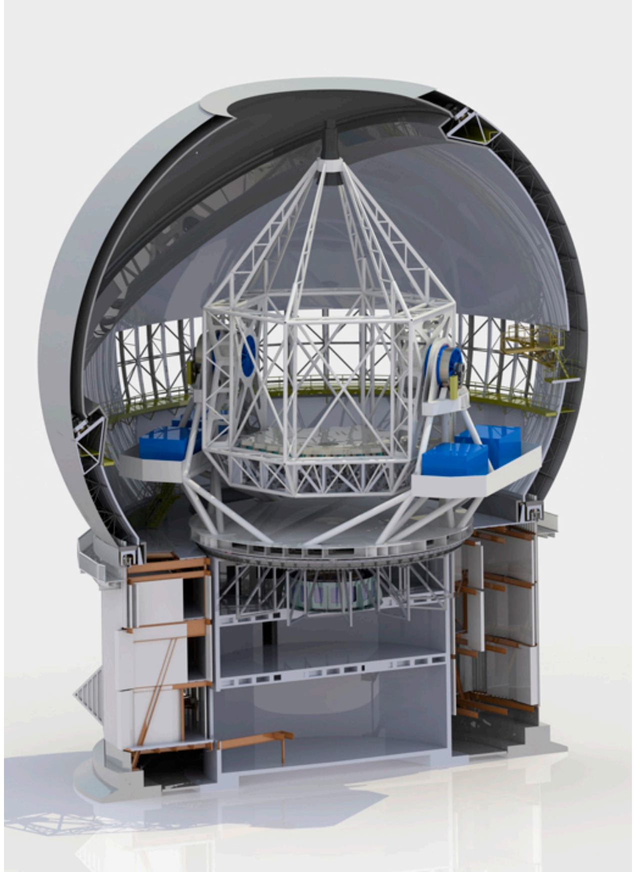


https://mse.cfht.hawaii.edu

Why do we need MSE for cosmology?

- Focus on:
  - neutrino mass
  - Inflation (the very early Universe)
  - Cosmology survey case: arXiv:1903.03158

- Other ideas for surveys with cosmological aims:
  - A deep survey for LSST photometric redshift training
  - Pointed observations of z=1 galaxy clusters
  - An IFU-based peculiar velocity survey
  - Low redshift very dense (& faint) survey



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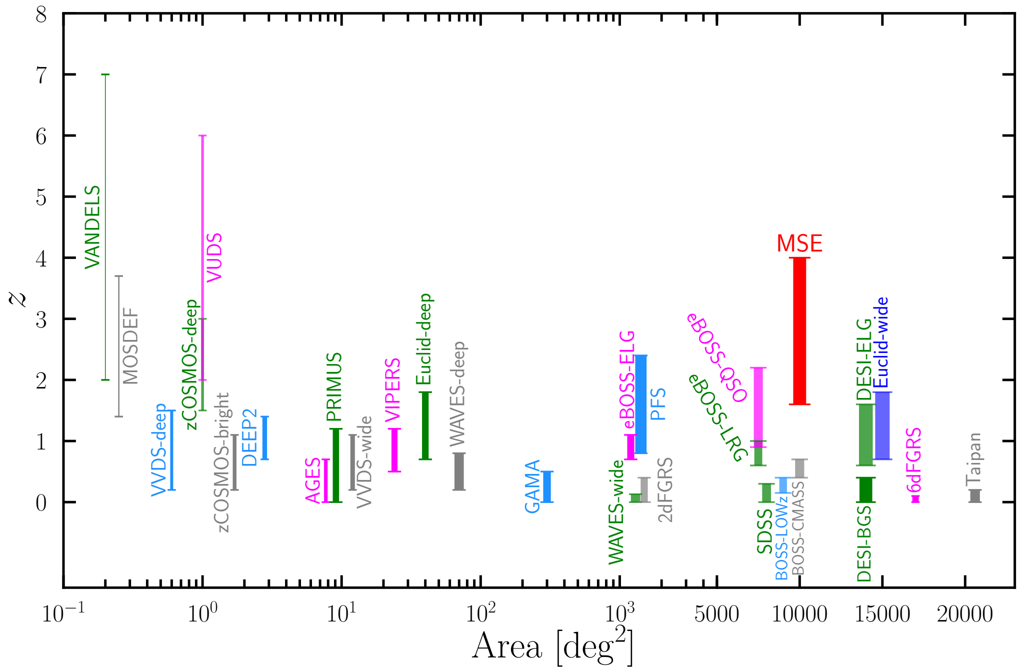
The High-z Cosmology Survey



Probing primordial Universe with SF galaxies and quasars

- Primordial non-Gaussianity and neutrino masses
- Wide survey: 10,000 deg^2
- Emission Line Galaxies: 1.6<z<2.4, Lyman Break Galaxies: 2.4<z<4.0
- Covering a volume 280 Gpc^3
- 8000 pointings with 30 minute exposure
- 100 nights per year for a 5-year MSE program

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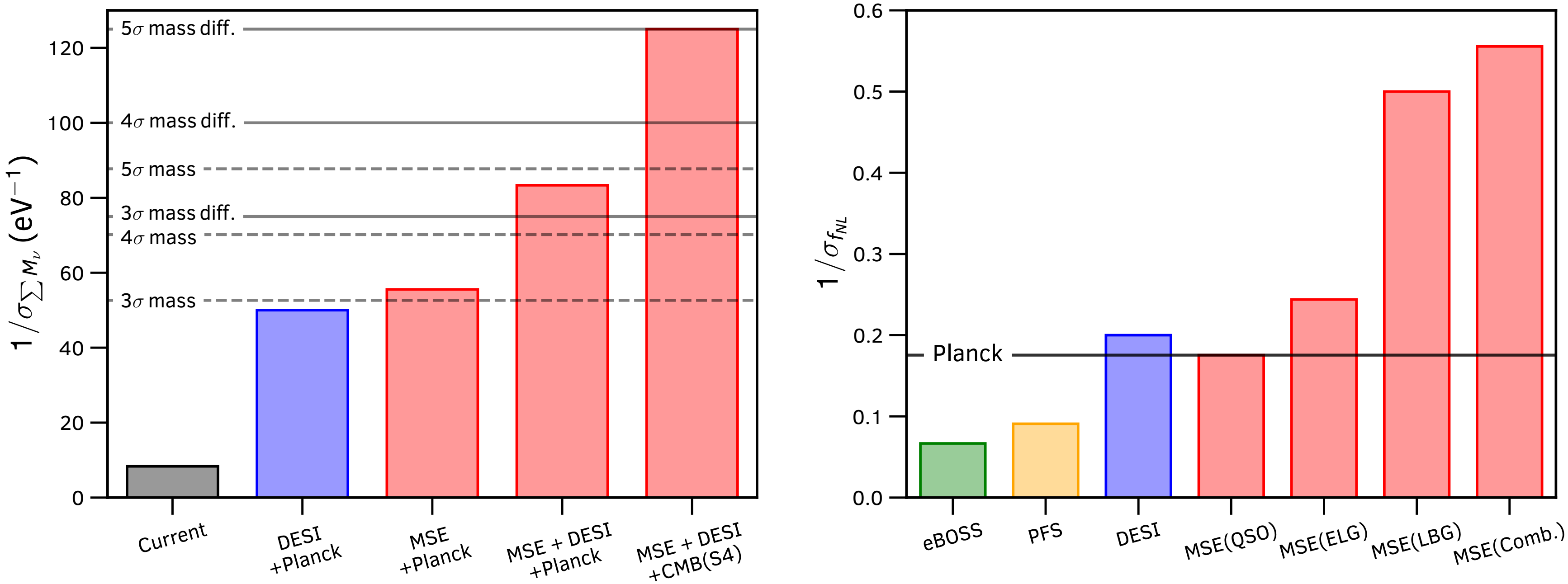
Forecast for f_{NL} and $\sum m_\nu$



A picture of primordial Universe

- f_{NL} : 3 tracers (ELG, LBG, QSO), each significantly better than CMB alone
- Total accuracy $\sigma(f_{NL})$~1.8
- With CMB(S4), accuracy on neutrino masses $\sum m_\nu$ ~8 meV
- Neutrino mass hierarchy at 5σ as precise as DUNE (ν beams)

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Discussion

- Current large-scale structure observations agree with the Planck ΛCDM model

- Future projects will push further out in redshift, number of galaxies and volume covered
  - Next generation of surveys (DESI, Euclid) will get ~20x more galaxies
  - Factor ~4 improvement on fundamental physics measurements
  - More BAO, more relative expansion measurements, but lots more beyond BAO as well
  - Continue to focus on confirming ΛCDM / finding late-time deviations

- Next step after this – MOS on 10m class telescope
  - Science more focused on inflation, neutrinos (large volume)
  - Many other science cases, including a possible extension to high density low redshift sample (MOS with large number of fibres)