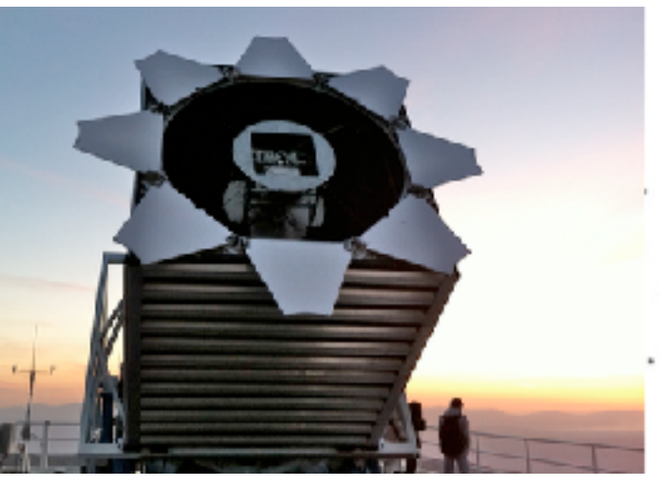
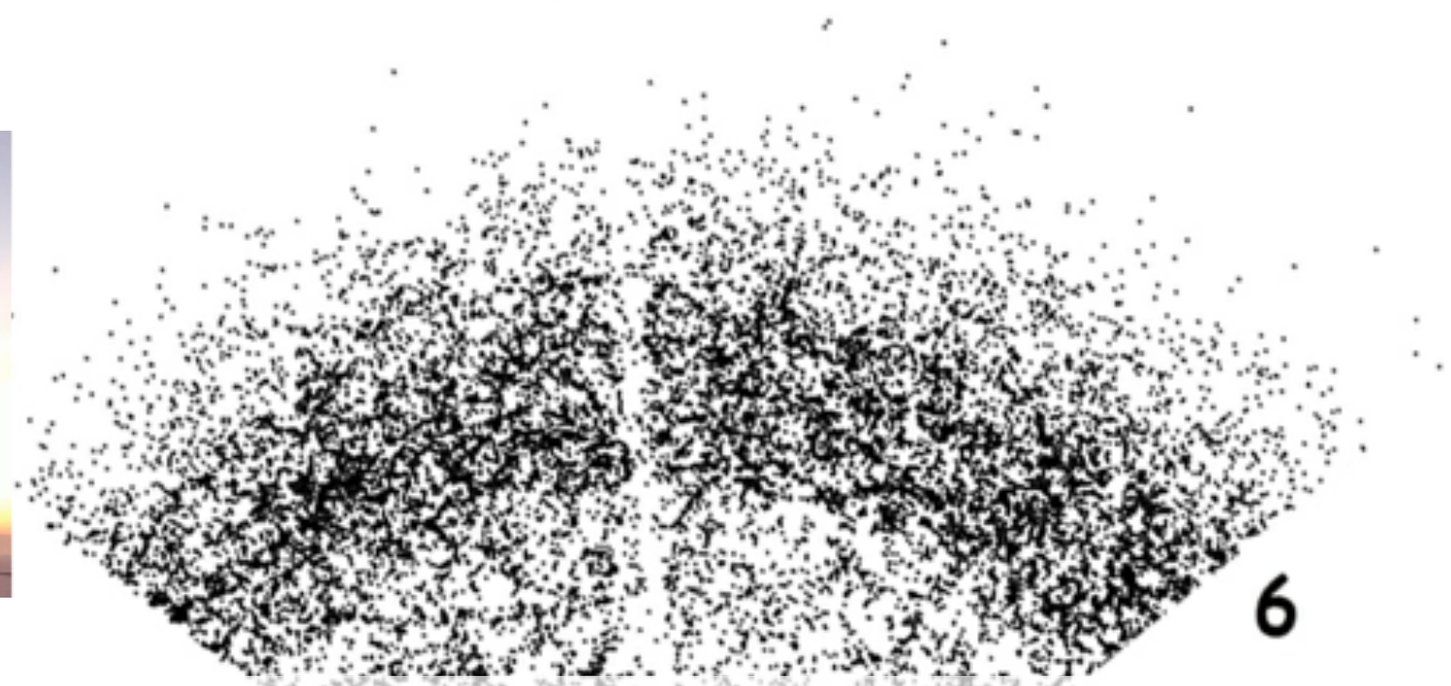
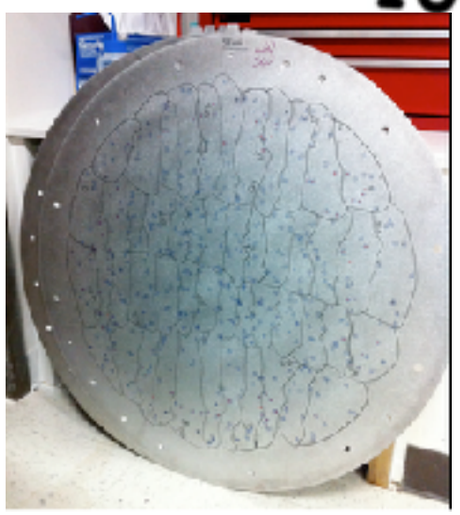
eBOSS

From the initial idea to the cosmo results







Jean-Paul KNEIB

EPFL, Switzerland/Marseille, France

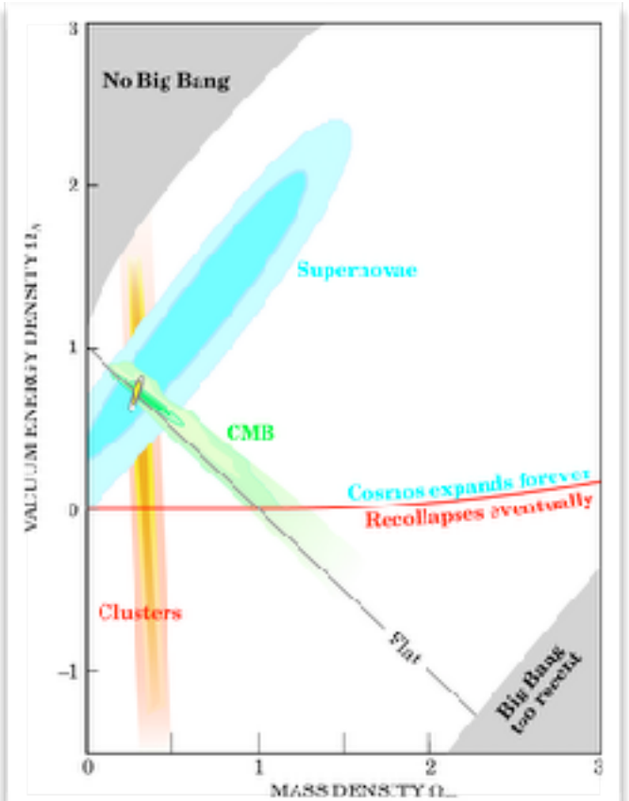
e-BOSS collaboration

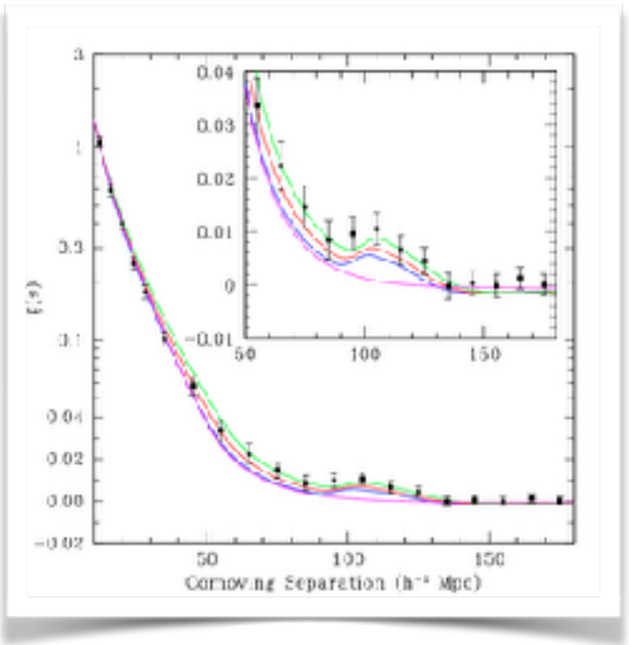
Graphic: Anze Slozar

Outline

- Why the eBOSS survey?
  - Historical and Scientific Context
  - eBOSS targeting
  - What did not work !
- eBOSS in a nutshell
- Some of the eBOSS results
- What's next?

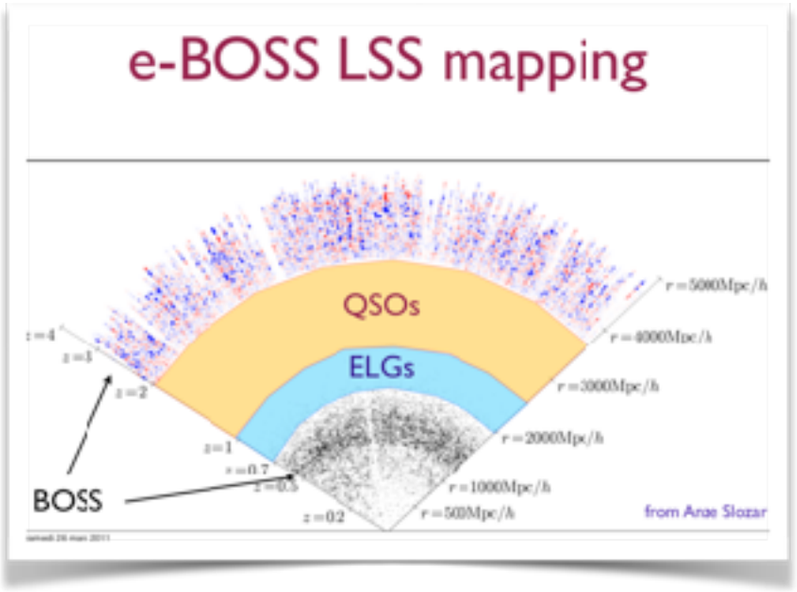
Key Milestones before eBOSS

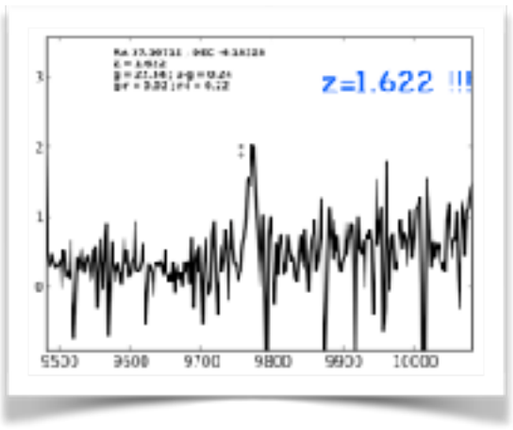


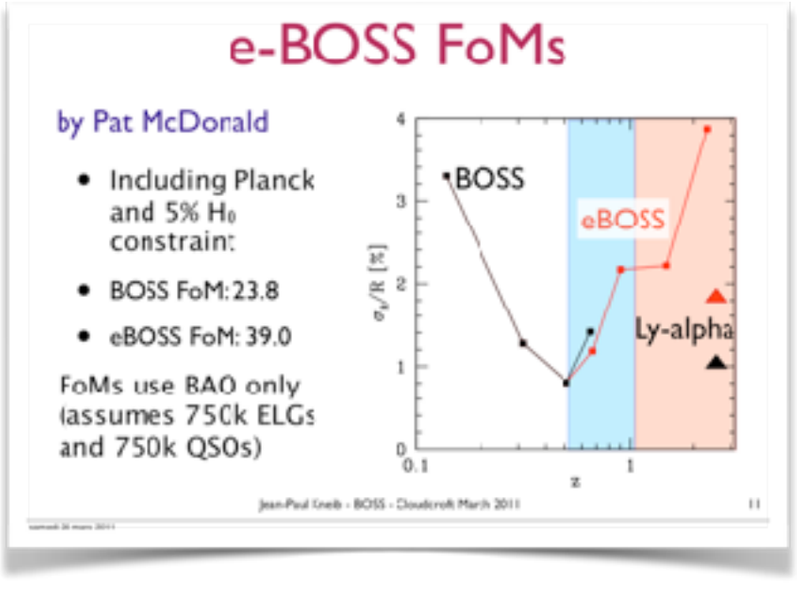


- 1998/98: SNIe suggest **acceleration of the expansion of the Universe** => *first evidence of Dark Energy - Lambda-CDM becomes the standard cosmological model*
- 2000+: Balloon born experiments measure the first acoustic peak in the CMB => flat universe
- 2001: 2dF matter density is 0.3
- 2003: WMAP - First Data Release and Results
- 2005: SDSS LRG first detect the BAO peak at z~0.3
- 2006: Dark Energy Task Force - strategic planning for DE measurements - stage II (current), III (DES, BOSS), IV (SNAP … DESI, Euclid) experiments
- Fall 2009: Start of the SDSS-III/BOSS survey [distance at 1% precision]
- Oct 2011: Selection of *Euclid* - accelerated expansion gets the Nobel Prize

Start of eBOSS



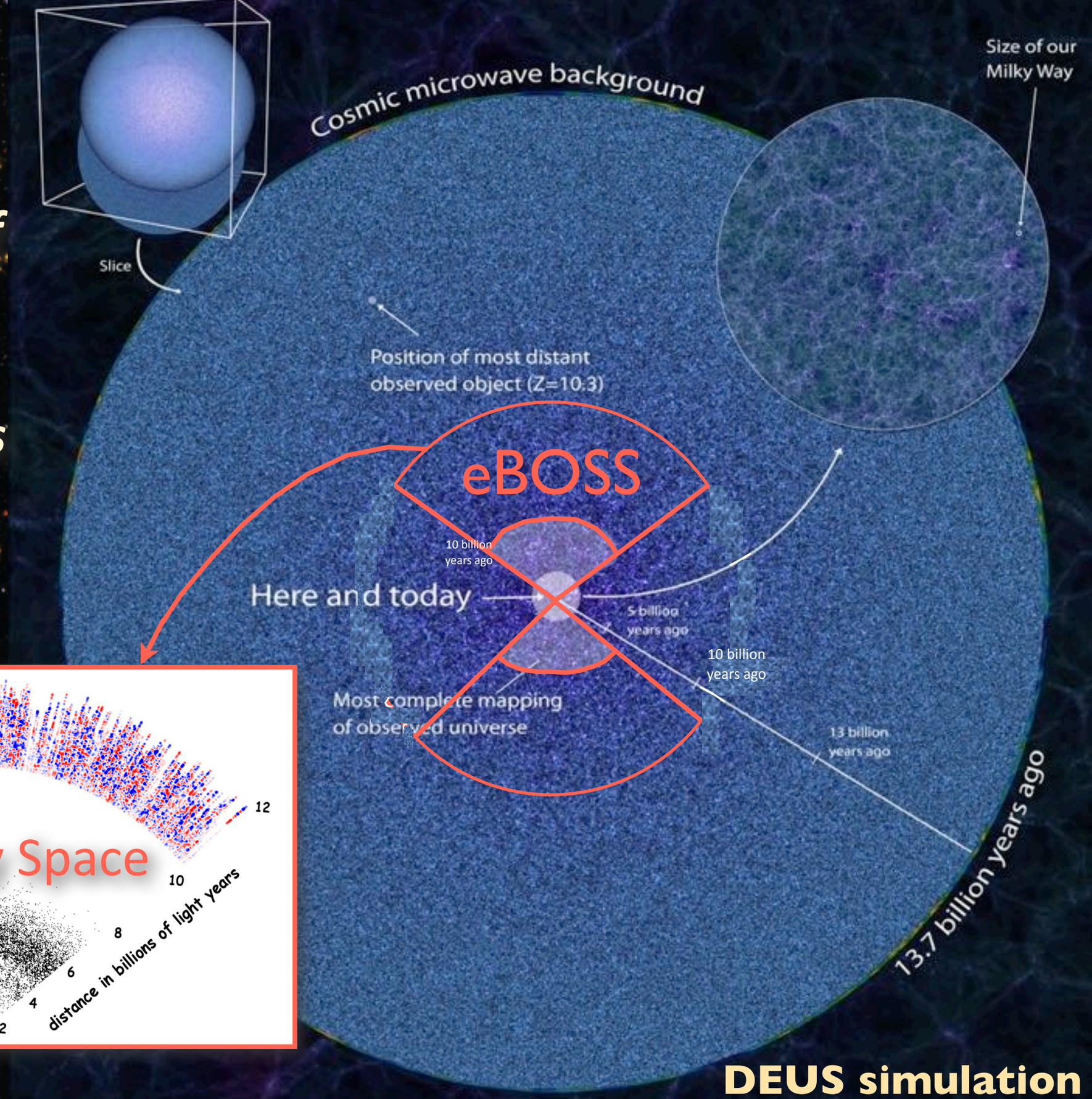


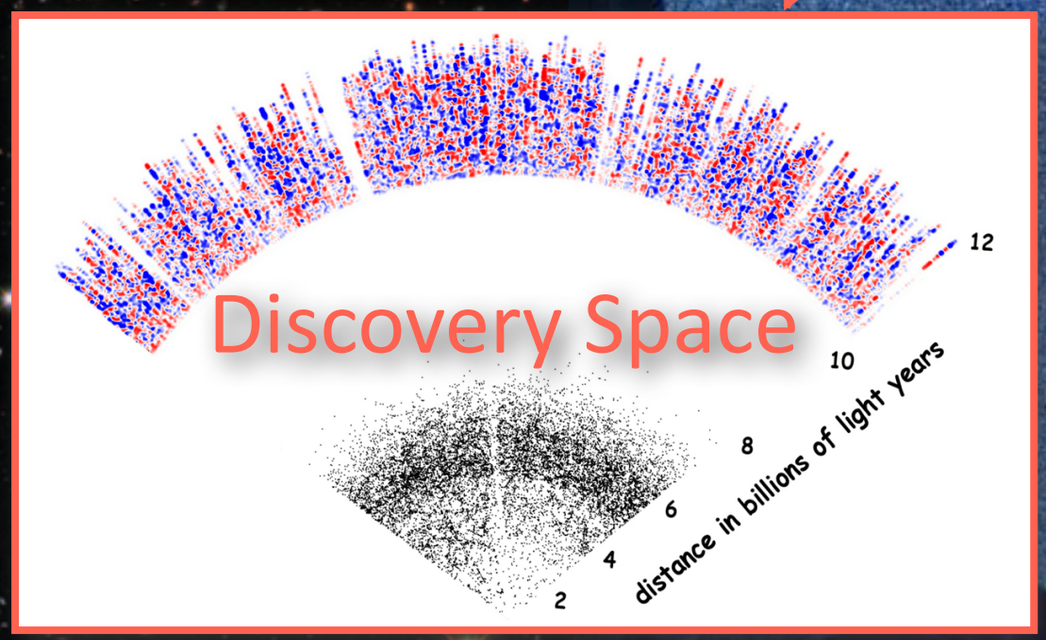


- 2002-2008: The SNAP saga => JDEM (2009) => WFIRST (2011)
- 2009: start of the BigBOSS project (former name of DESI) - DE from BAO/massive spectroscopy
- June 2010: BOSS ancillary proposals to targets ELGs for the BigBOSS project.
- Feb 2011: First results from the BOSS ELG projects - z=1.62 from *[OII]* doublet, presented at the BigBOSS meeting
- March 2011: eBOSS: a proposal idea for After-Sloan-3
- Sep 2011: eBOSS proposal submitted (ELGs+QSOs focussed)
- Nov 2011: **eBOSS recommended for implementation** (adding SPIDERS and TDSS in), *if imaging data can be secured before survey start.*

eBOSS:

Measuring the Expansion History of the Universe between 7 and 11 billions of light years with Galaxies & Quasars





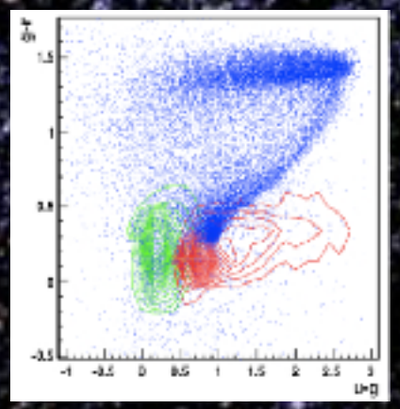
eBOSS

Gas that falls into a black hole settles into a so-called accretion disk. Friction and magnetic fields in the disk cause the gas to heat and emit UV and X-ray light.

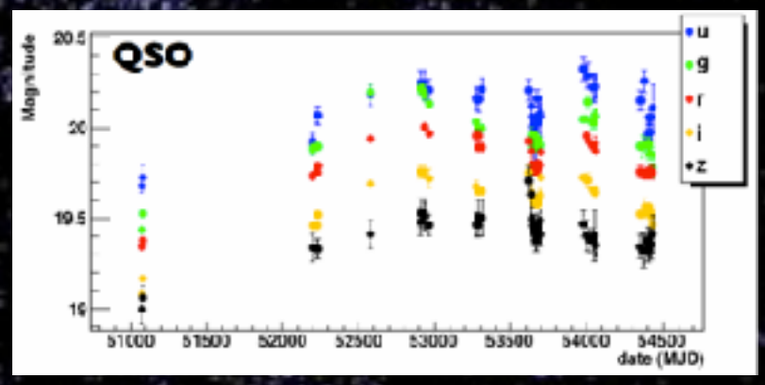
How ?
with a QSO survey

Measuring the distribution of MOST known QSOs (~1 million) using different detection techniques (UV excess, WISE, variability, X-ray)

eBOSS **TDSS** **SPIDERS**



SDSS+WISE



PTF PanSTARRs

eROSITA

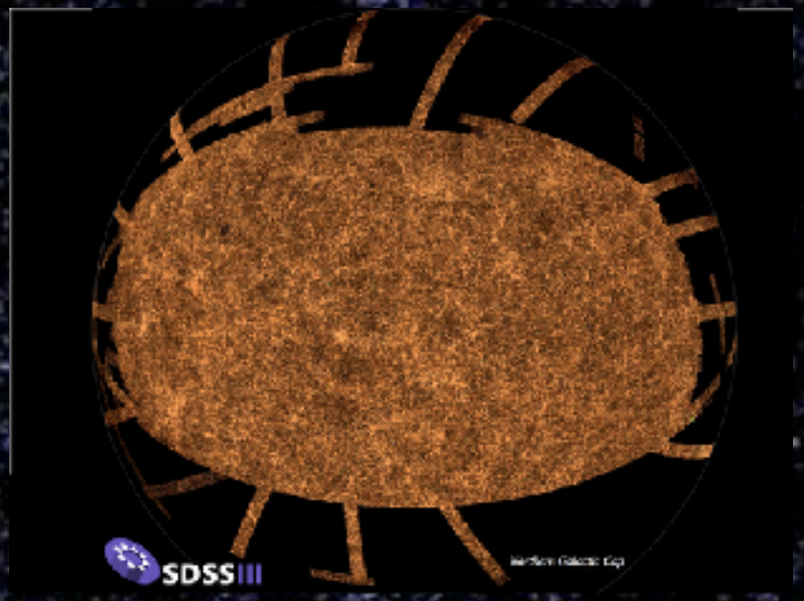
eBOSS

How ?
with a Galaxy survey

Measuring the distribution of ~half a million 0.6<z<1 LRGs and ELGs building on new imaging surveys:

- WISE for LRGs

- SCUSS and DES for ELGs



SDSS imaging

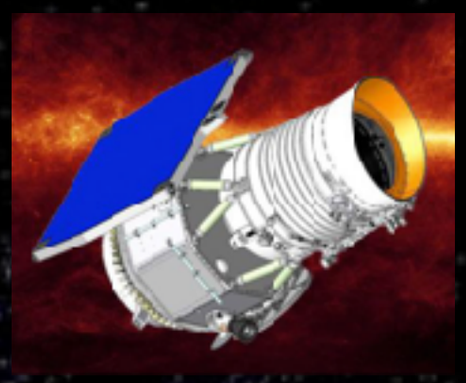
ELG

SCUSS U-band
+ SDSS gri

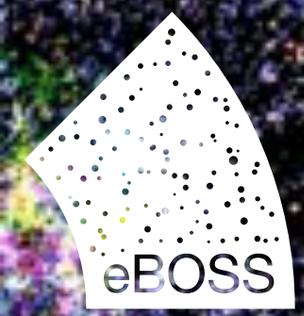
?

DES
grz selection

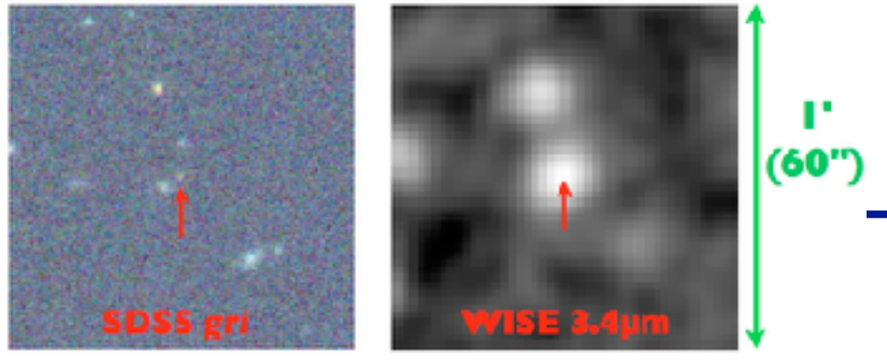
LRG



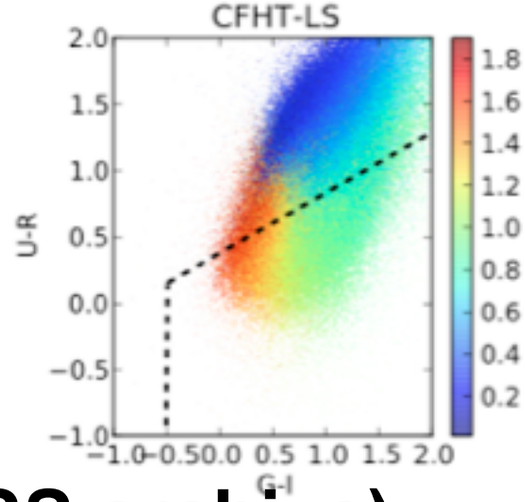
WISE



Target Selection



1. 375k (50 deg^{-2}) Luminous Red Galaxies
- Selected at 0.6< z <0.8 with SDSS+WISE
- Efficient BAO tracers due to large bias



2. 270k (170* deg^{-2}) Emission Line Galaxies (ELGs)
- Selected at 0.6<z<1, when star formation rates were high with SDSS+U-band or DES+U-band

3. 700k (90 deg^{-2}) "Core" QSOs (1 million including SDSS archive)
- Target ***all*** we can, most 1 < *z* < 2.15 with SDSS+U-band+WISE

4. 150k (20 deg^{-2}) Lyman-alpha QSOs (z > 2.15)
- 3-D density map from Ly-a forest, selected from variability (PTF/PS1)

5. ~30k TDSS
- variability objects from PannSTARRS-1 (3PI data)

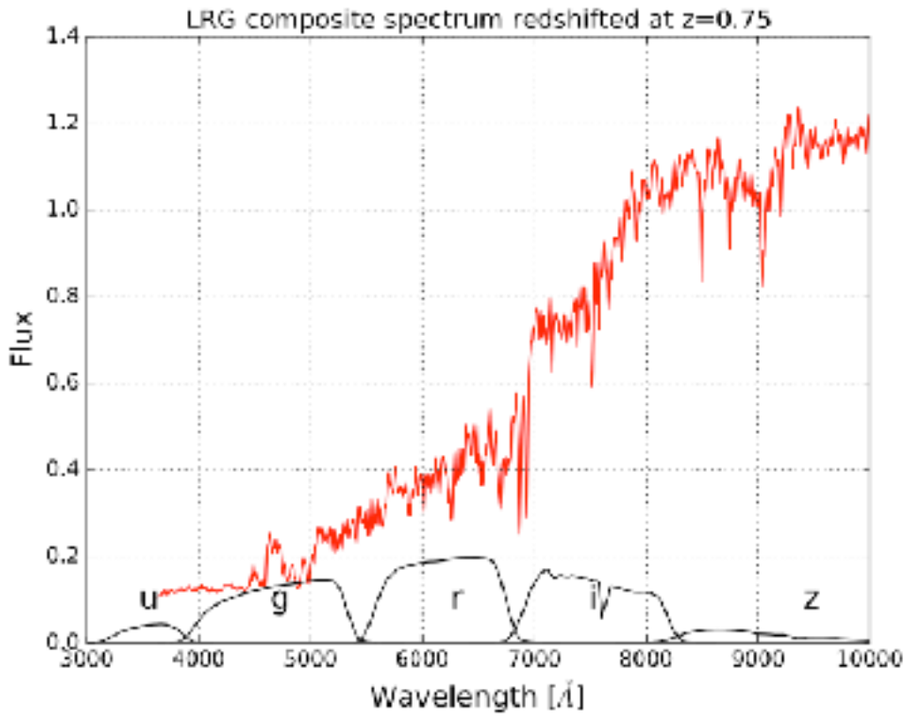
6. ~30k eROSITA sources (mainly AGN and a few cluster members)

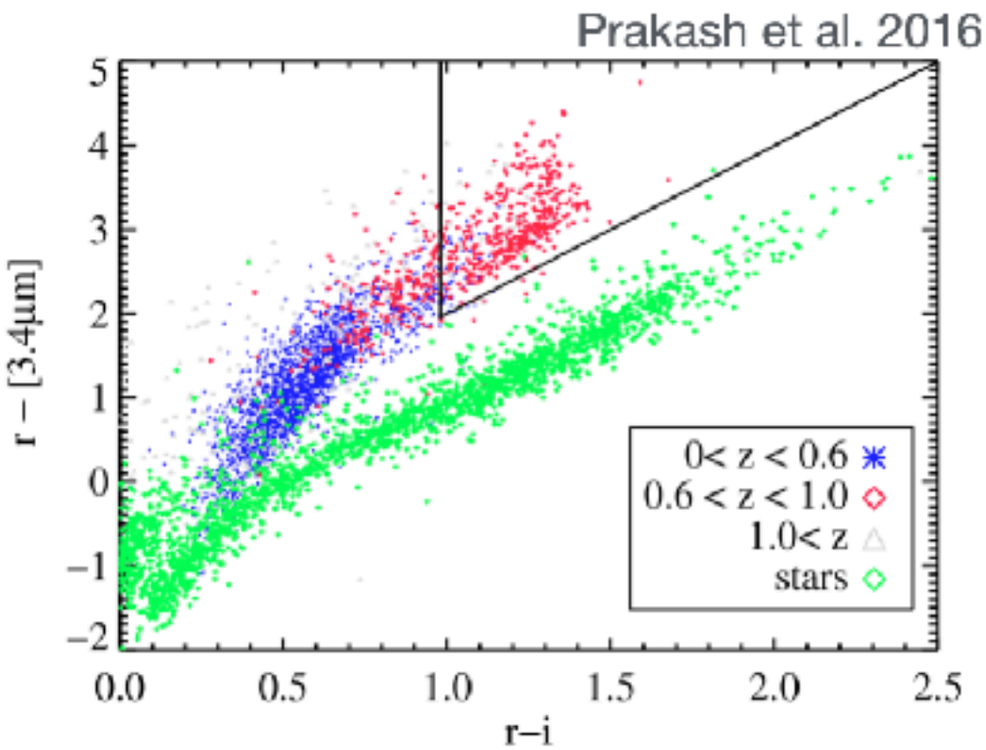
ELG sample over 1500 deg^2; LRGs & QSOs over 7500 deg^2

eBOSS

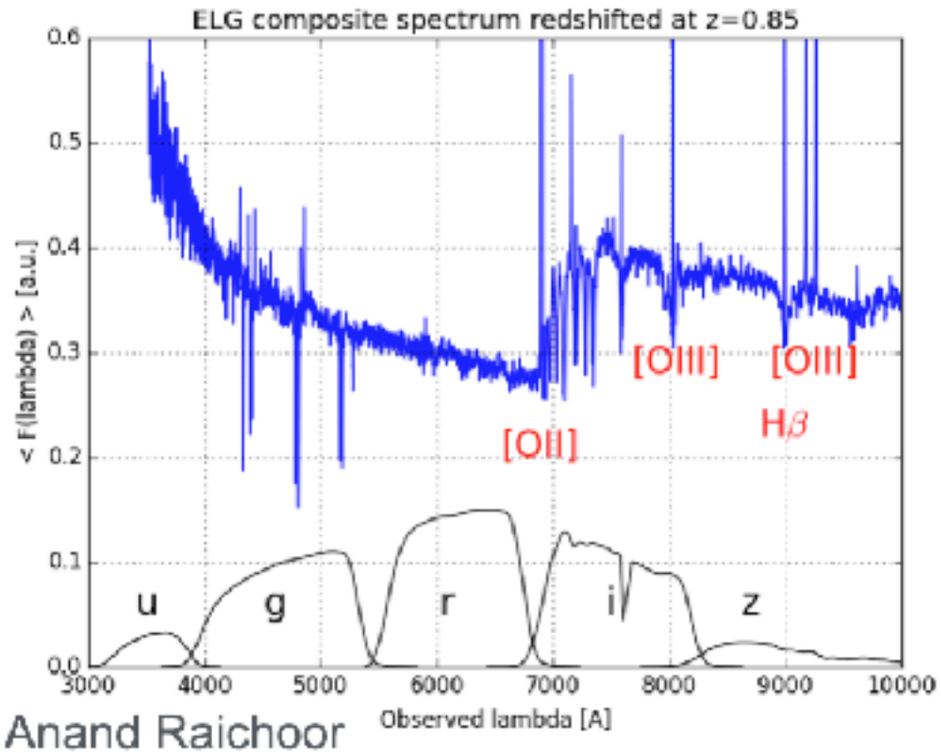
eBOSS galaxy selection

LRG: luminous red galaxy

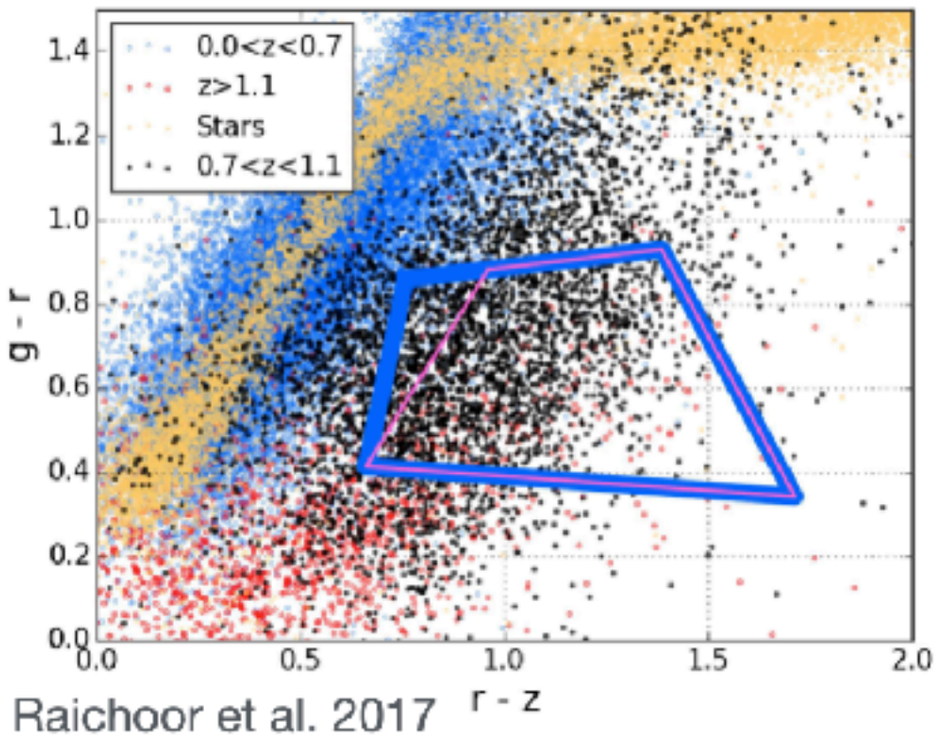




ELG: emission line galaxy



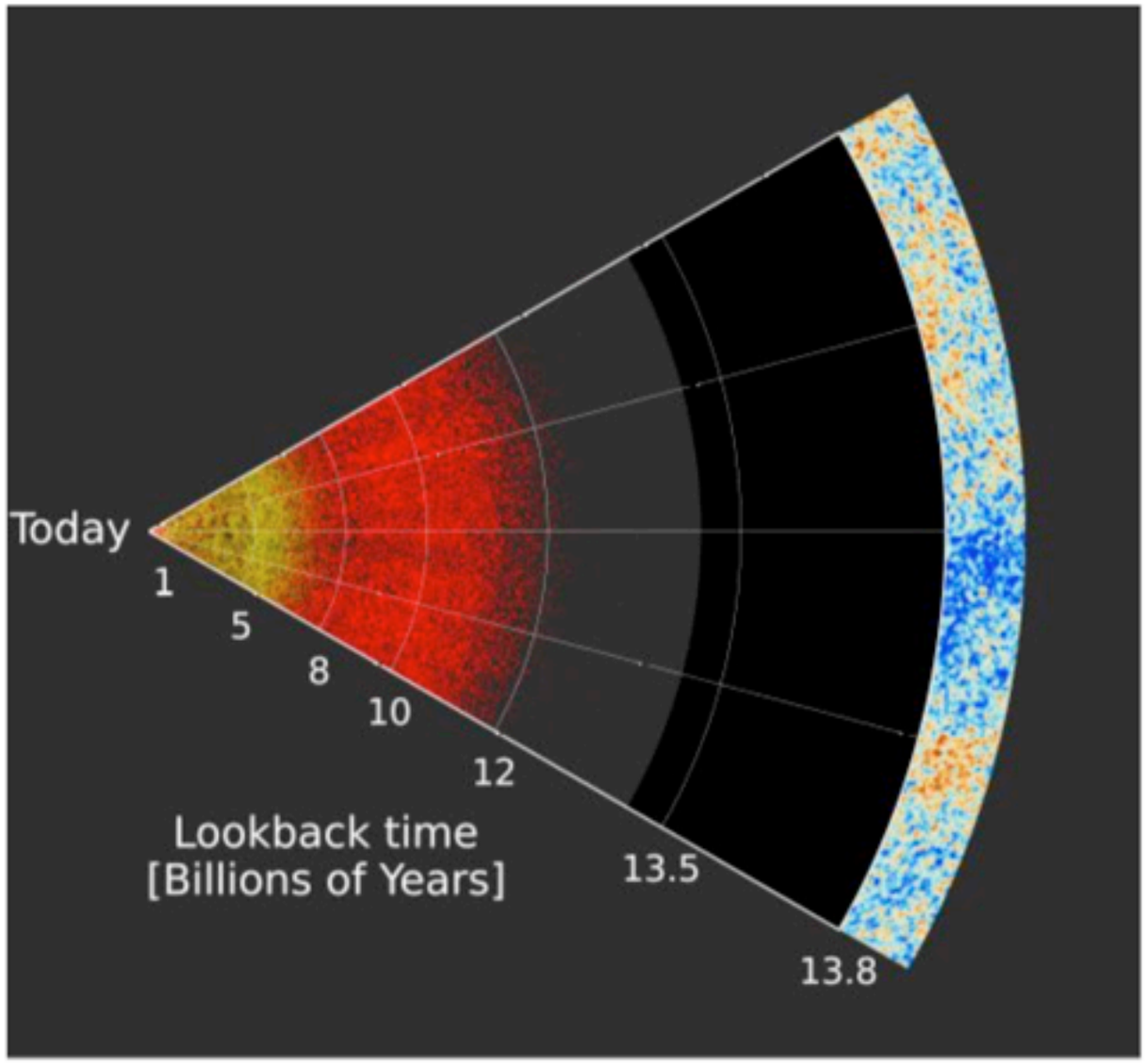
Credit: Anand Raichoor



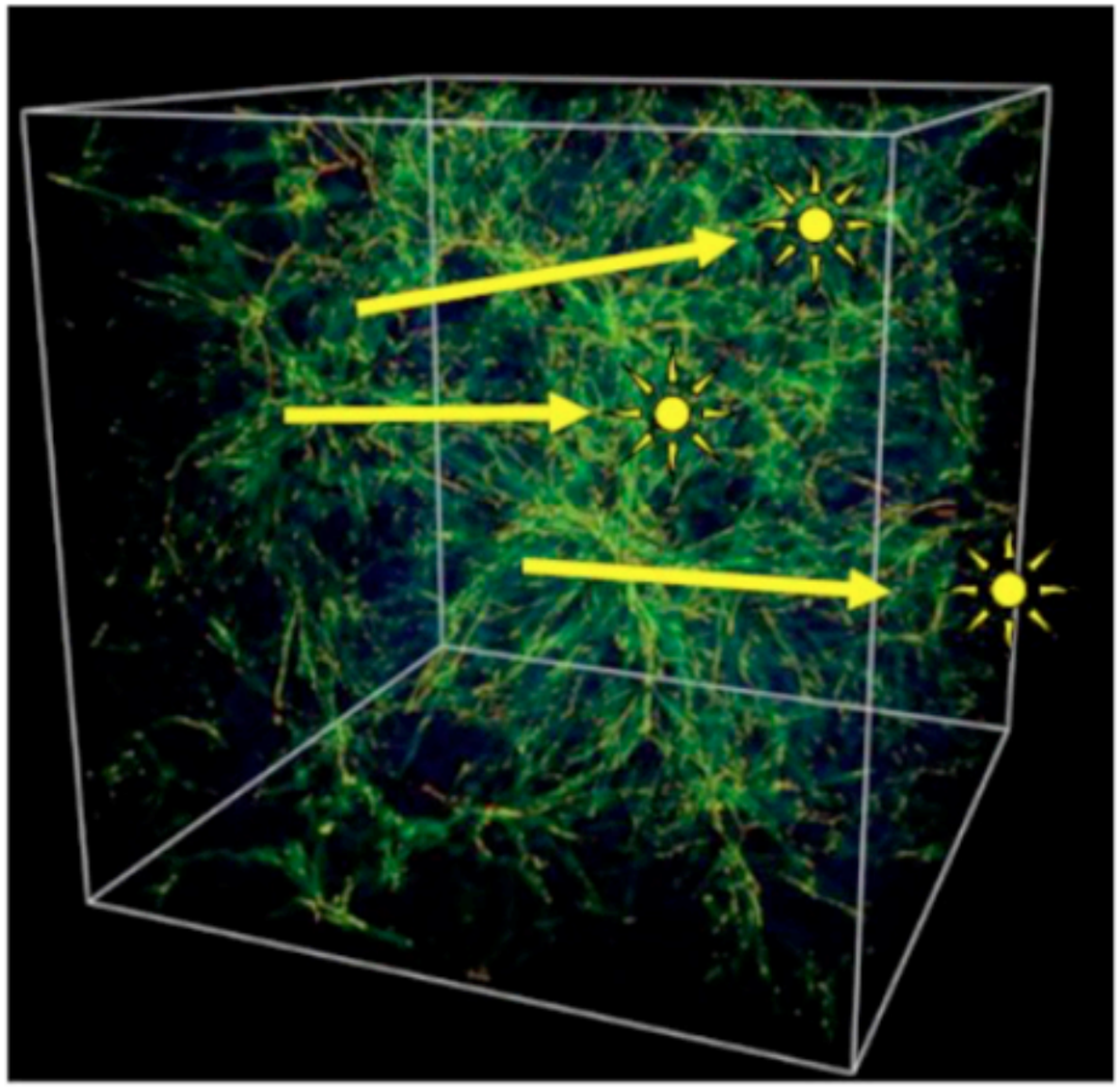
Raichoor et al. 2017

eBOSS clustering techniques

Direct tracers
Galaxies and quasars (z<2.1)



Absorption in quasar spectra by
foreground Lyman-alpha forest (z>2.1)

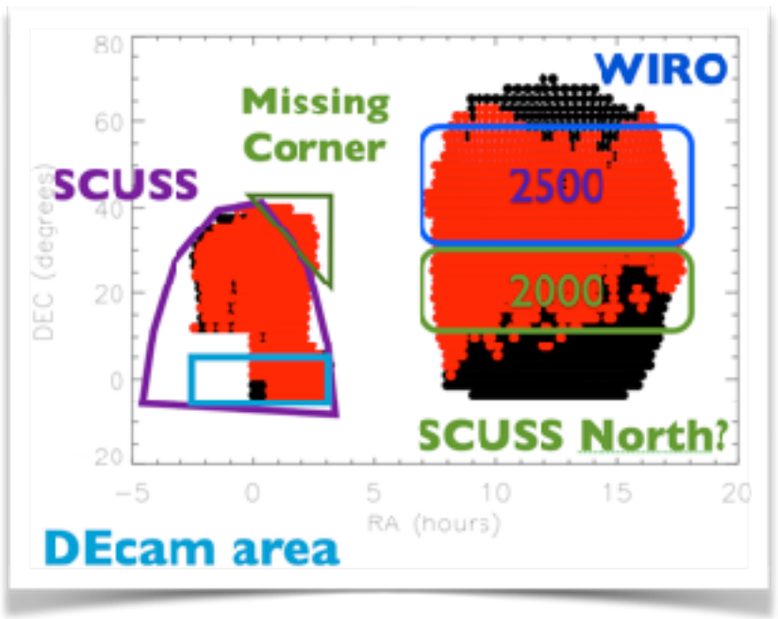


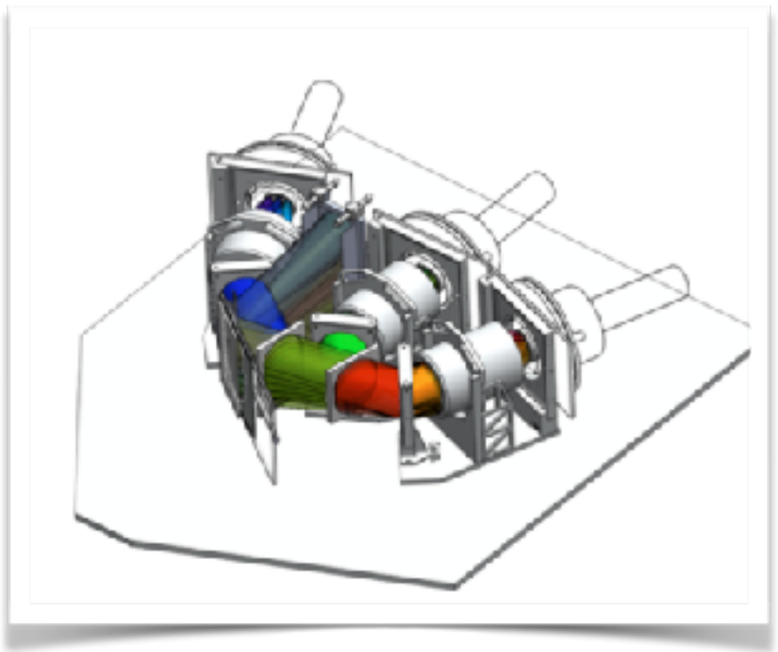
BAO cosmology forecast

	Redshift range	N_{gal}	BAO measurement
LRG	z>0.6	350k	0,9 %
ELG	0.6<z<1.0	190k	2 %
QSO	0.9<z<2.2	510k	1,8 %
QSO Ly-alpha	2.15<z<3.5	50k	1,1 %

- eBOSS will observe multiple samples, covering a wide redshift range
- Decrease risk, enhance science return
- BAO DETF FoM increase by a factor of ~2.2 from BOSS to eBOSS (Assume Planck CMB measurements, 5% H_0 constraint)

What did not work !



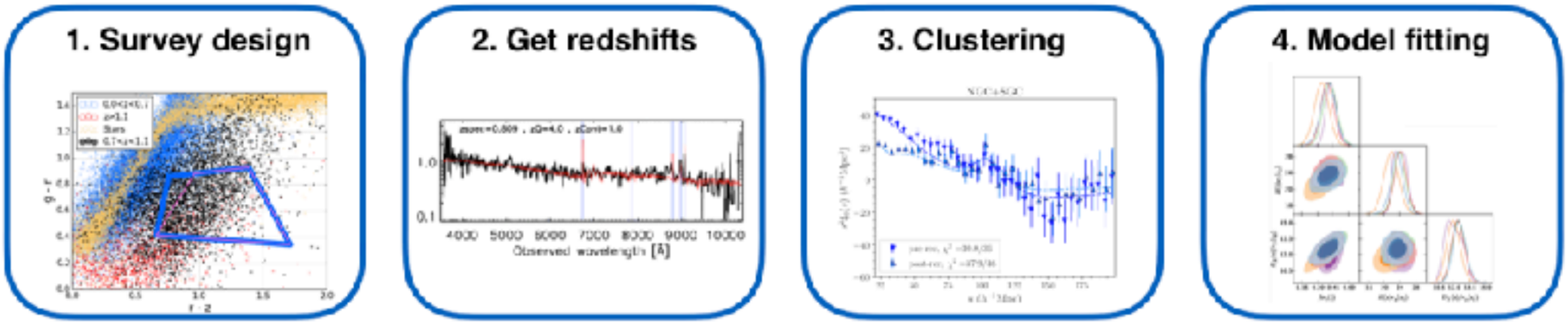


- **Proposed idea to use a robotic fiber positioner** => judge risky to develop in less than 3 years. *Now implemented for SDSS-V* => required 4 years (3.5 without COVID+expertise from DESI+MOONS)
- **Proposed ideas to collect new imaging:**
  - With CFHT: S^3 prop => *become* **CFIS**
  - With the 2.3m WIRO telescope (U-band survey) => camera not ready on time
  - With the SCUSS survey (U-band from the Bock telescope - Chinese led project) => not sensitive enough, did not improved target selection
  - With DECam Survey => *ultimately used for the ELG survey postponing the ELG survey start*
- ***3rd Spectrograph (first BigBOSS spectrograph)***
  - Idea to go from 1'000 to 1'500 fibres => plate test validated, but procurement of a spectrograph + installation in a separate building was judge too risky

Galaxy Survey workflow

1. **Survey design**: sky footprint, imaging, target selection
2. **Get redshifts**: spectroscopic observations, 1D-spectrum reduction, redshift fitting
3. **Clustering**: LSS catalogues, correlation function
4. **Model fitting**: analysis validation, systematics estimation, cosmological parameters

- **Mock catalogues**: covariance matrix, analysis validation



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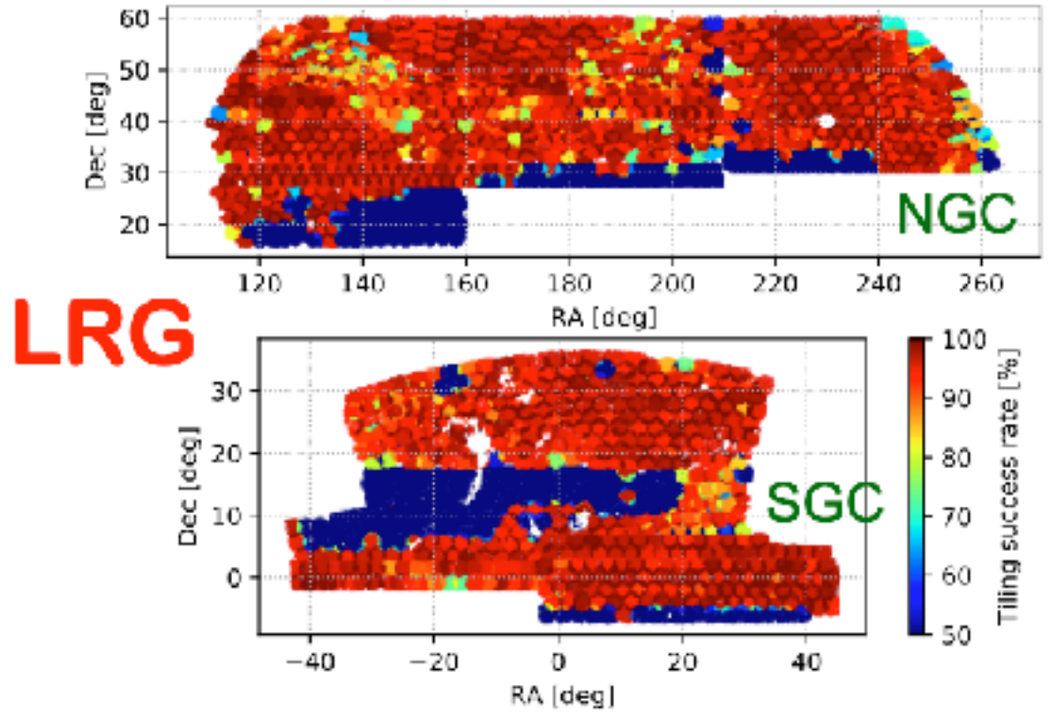
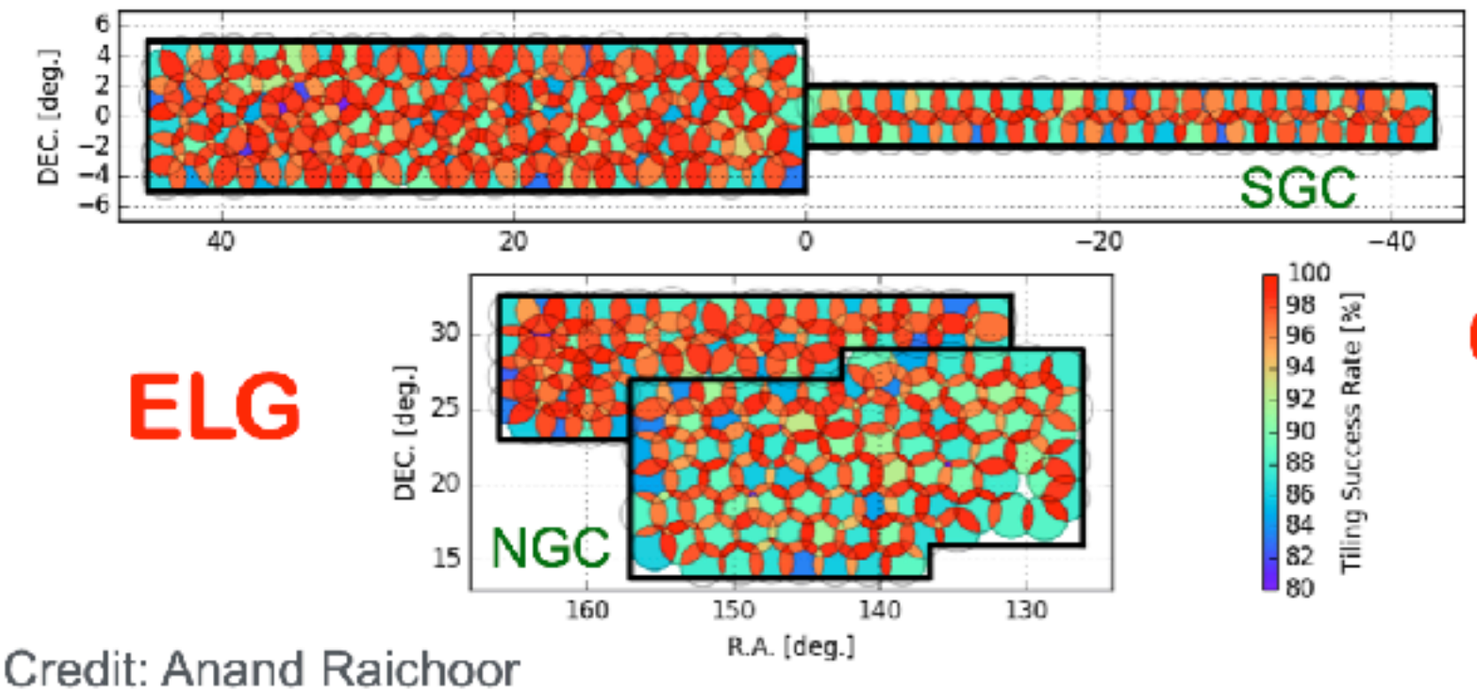
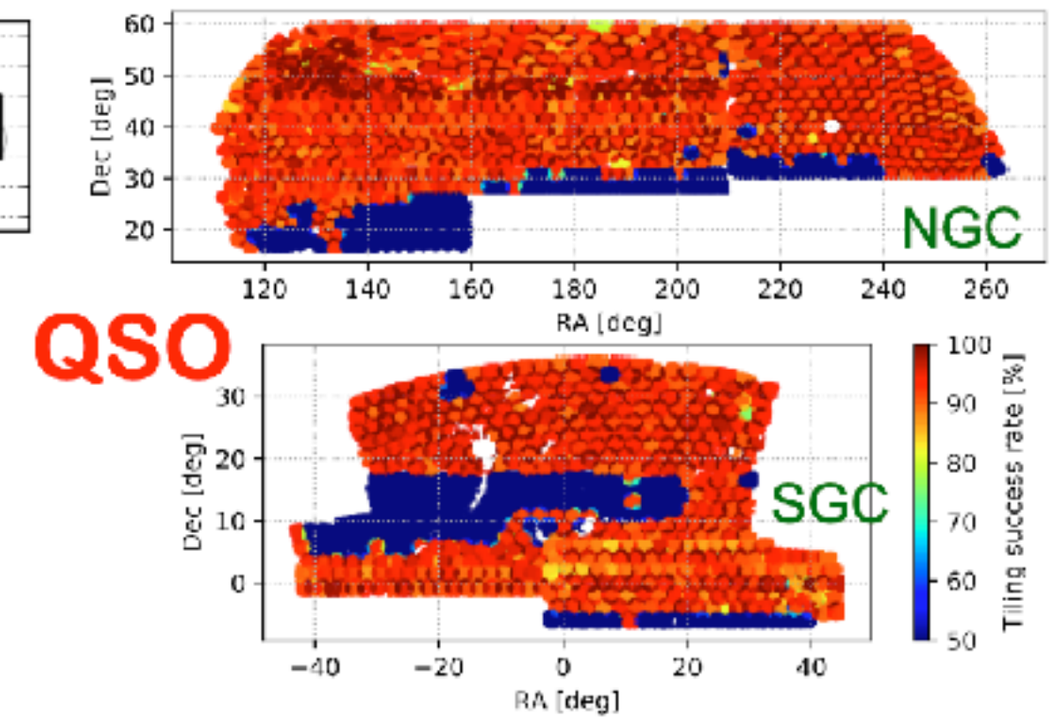
Completed eBOSS survey

- LRG (Oct. 2014 — Feb. 2019)
  - 1020 plates, ~ 260 targets per plate
- ELG (Sep. 2016 — Feb. 2018)
  - 305 plates, ~ 820 ELG targets per plate
  - 4 chunks (independent of tiling)
- QSO (Jul. 2014 — Feb. 2019)
  - 1020 plates, ~ 520 QSO targets per plate





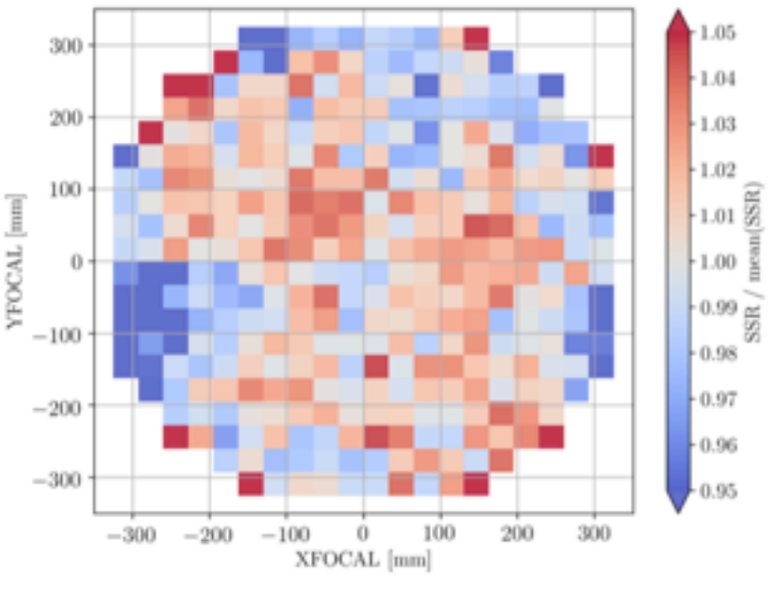


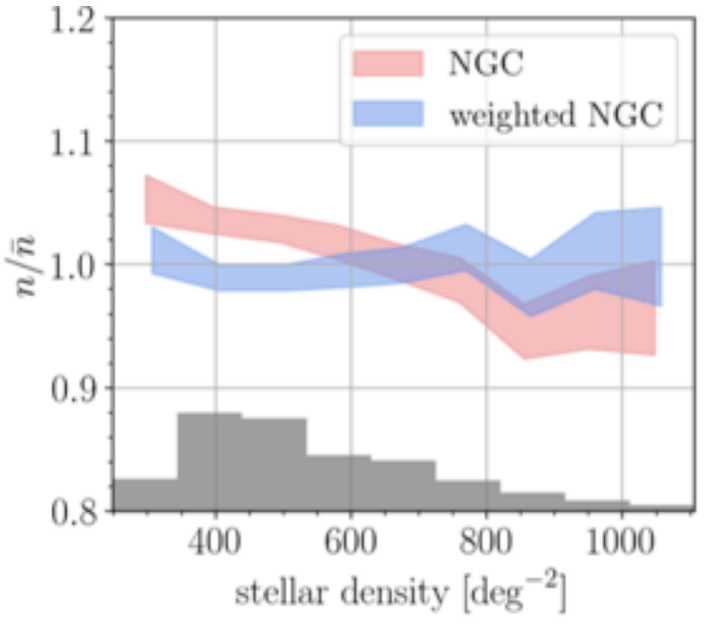
Credit: Anand Raichoor

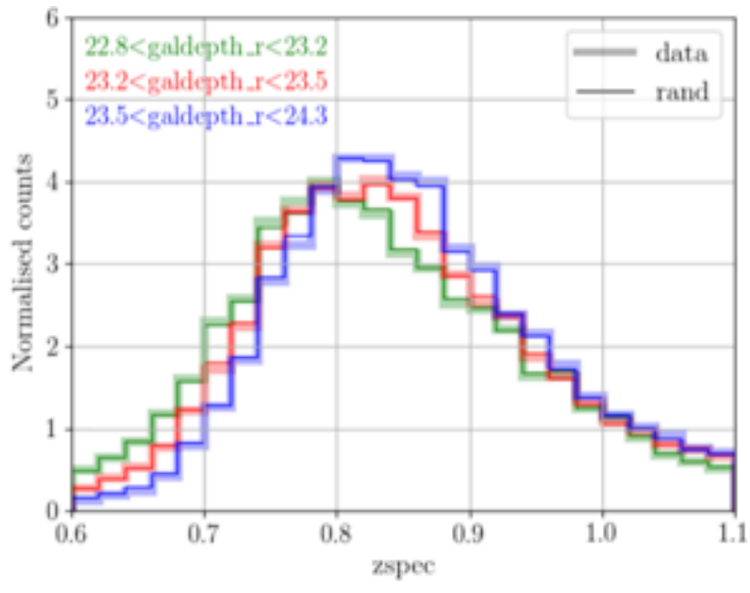
eBOSS/ELG: Large-Scale Structures Catalogues

- LSS Catalogues
  - ✓ 3D-position (R.A., Dec., zspec) for ELGs with 0.6 < zspec_reliable < 1.1
  - ✓ 3D-position of randoms with no clustering
  - ✓ Weights to correct for observational effects
  - ✓ Input for the clustering measurement

- Corrections for
  - ✓ Redshift failures
  - ✓ Systematics from target selection
  - ✓ Angular-radial correlation (ELG-specific)

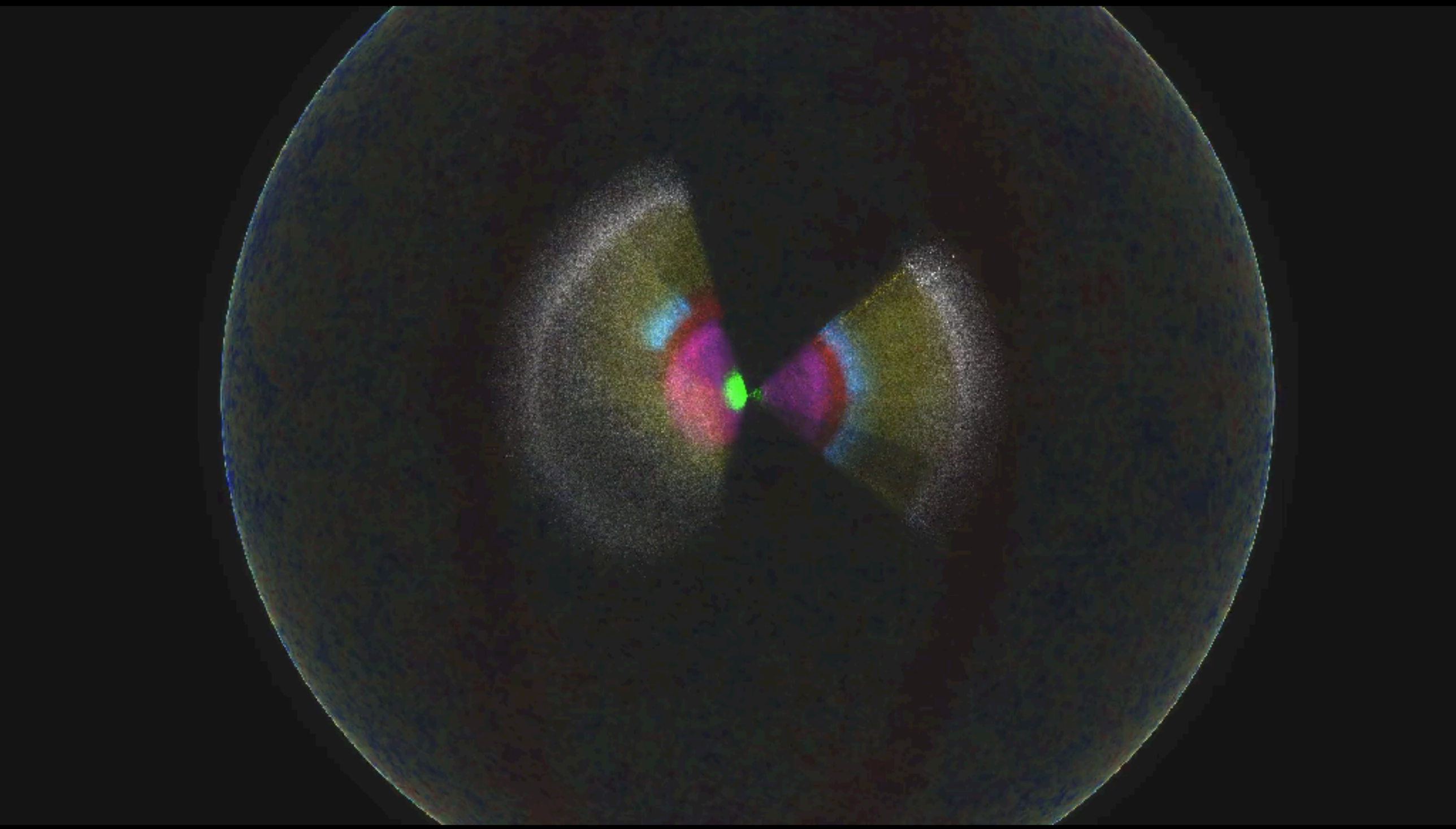






Raichoor et al 2020

20 years of SDSS mapping



Credit: Anand Raichoor

Cosmic Variance Evaluation

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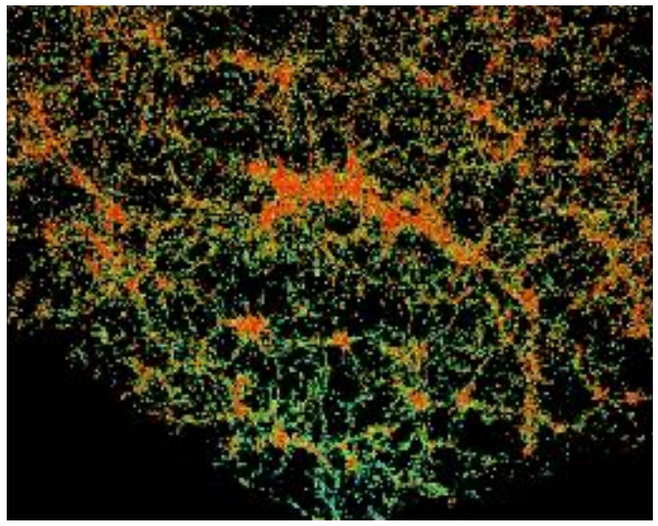
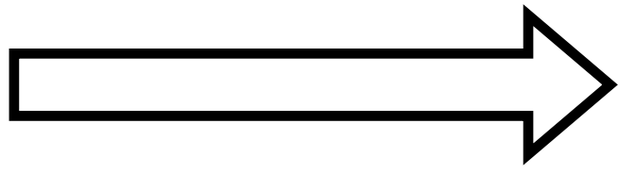
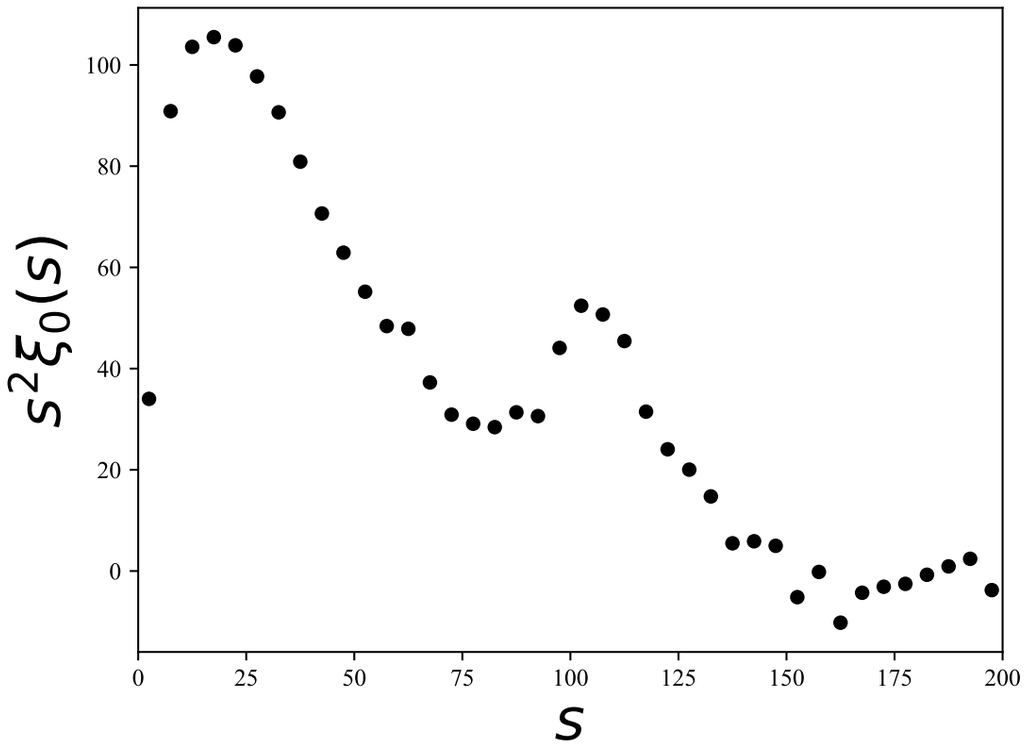
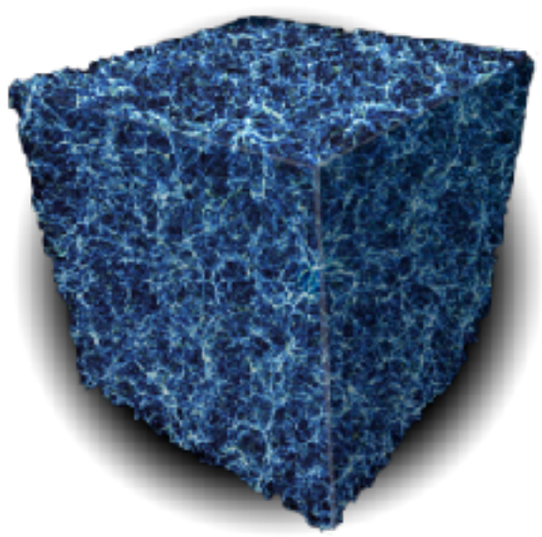


Observational data

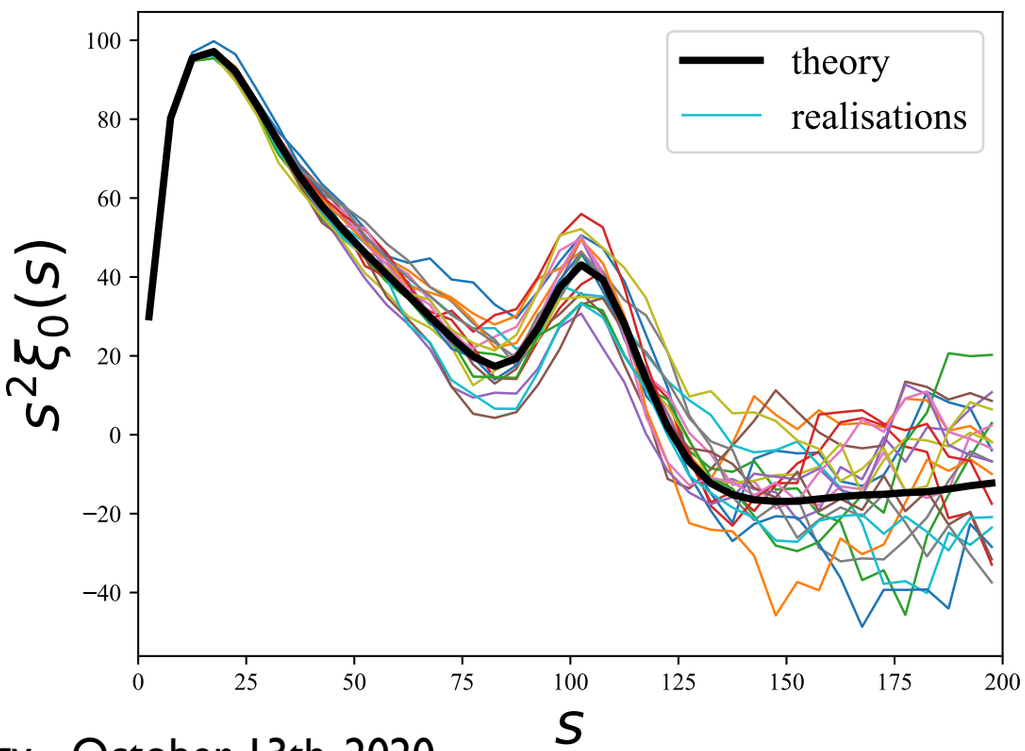






Same cosmology

different white noises



N-body simulation

EZmock: density map

eBOSS multi-tracer mocks

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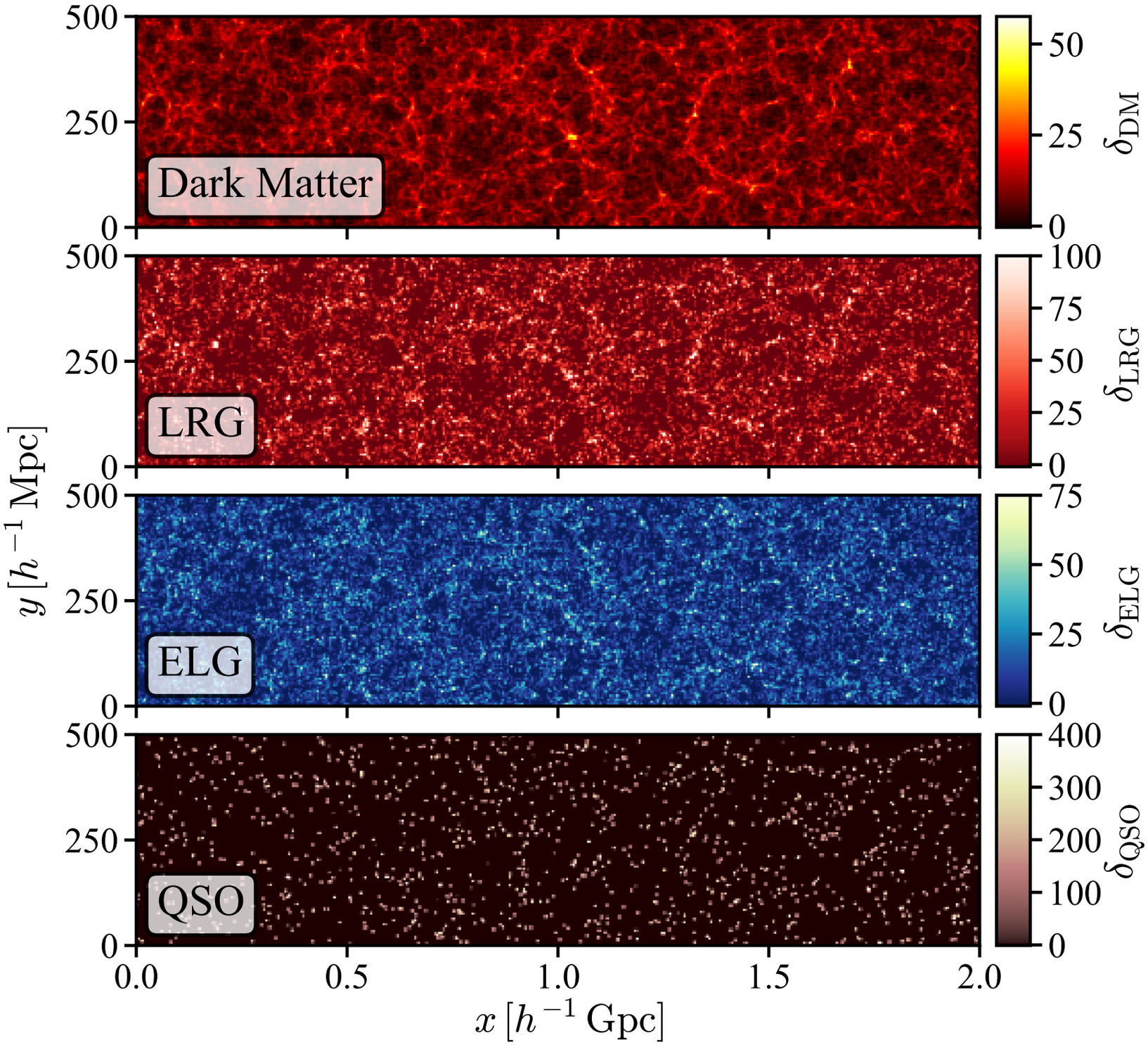
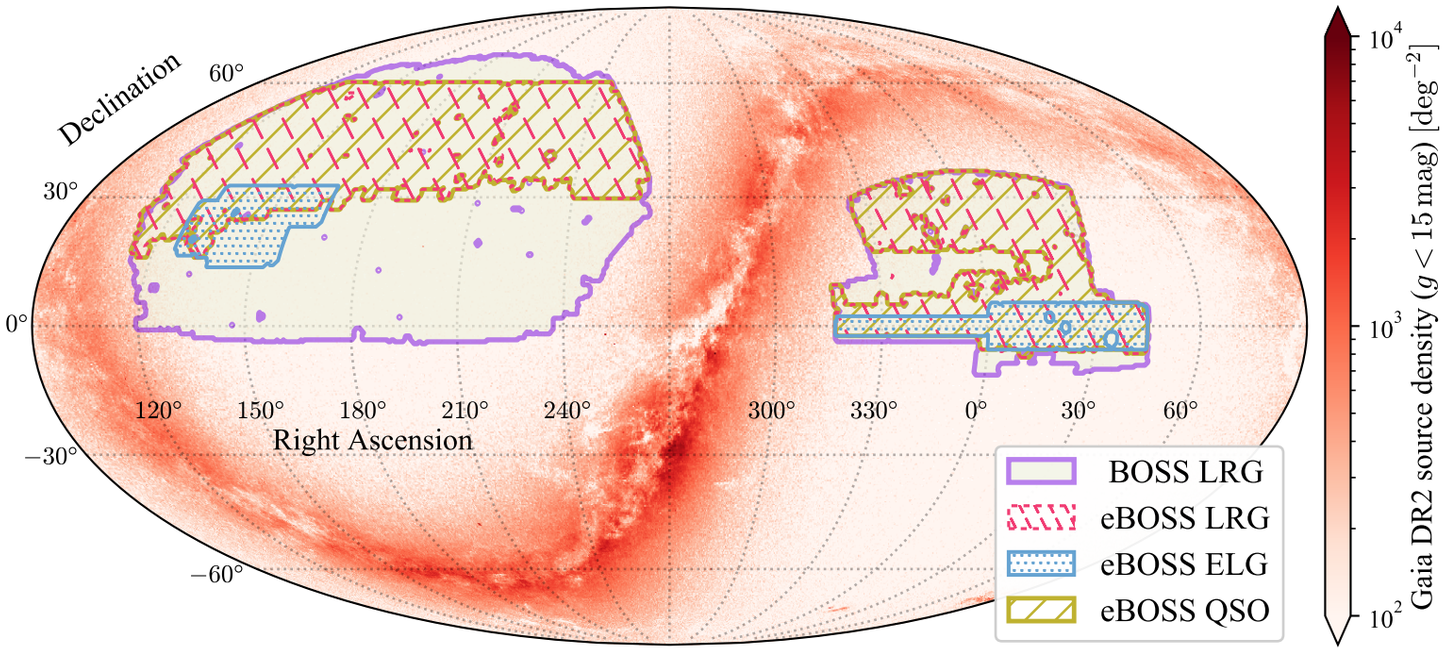


eBOSS survey geometry



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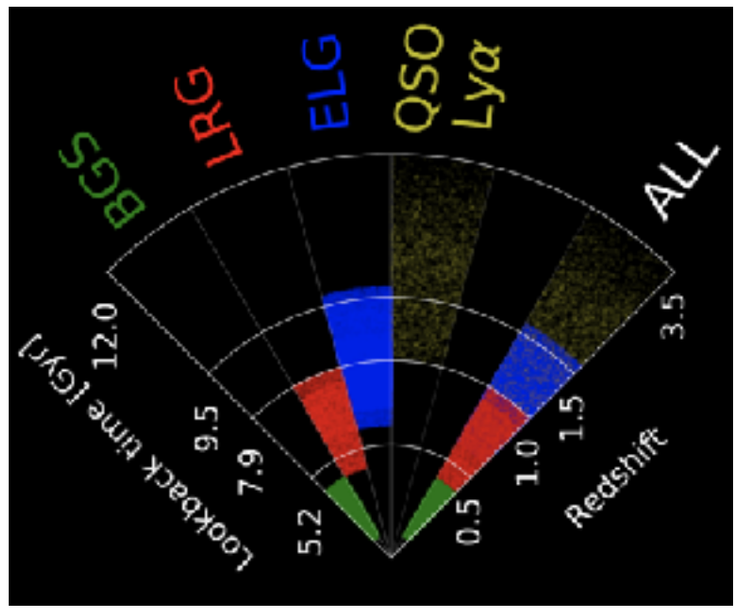
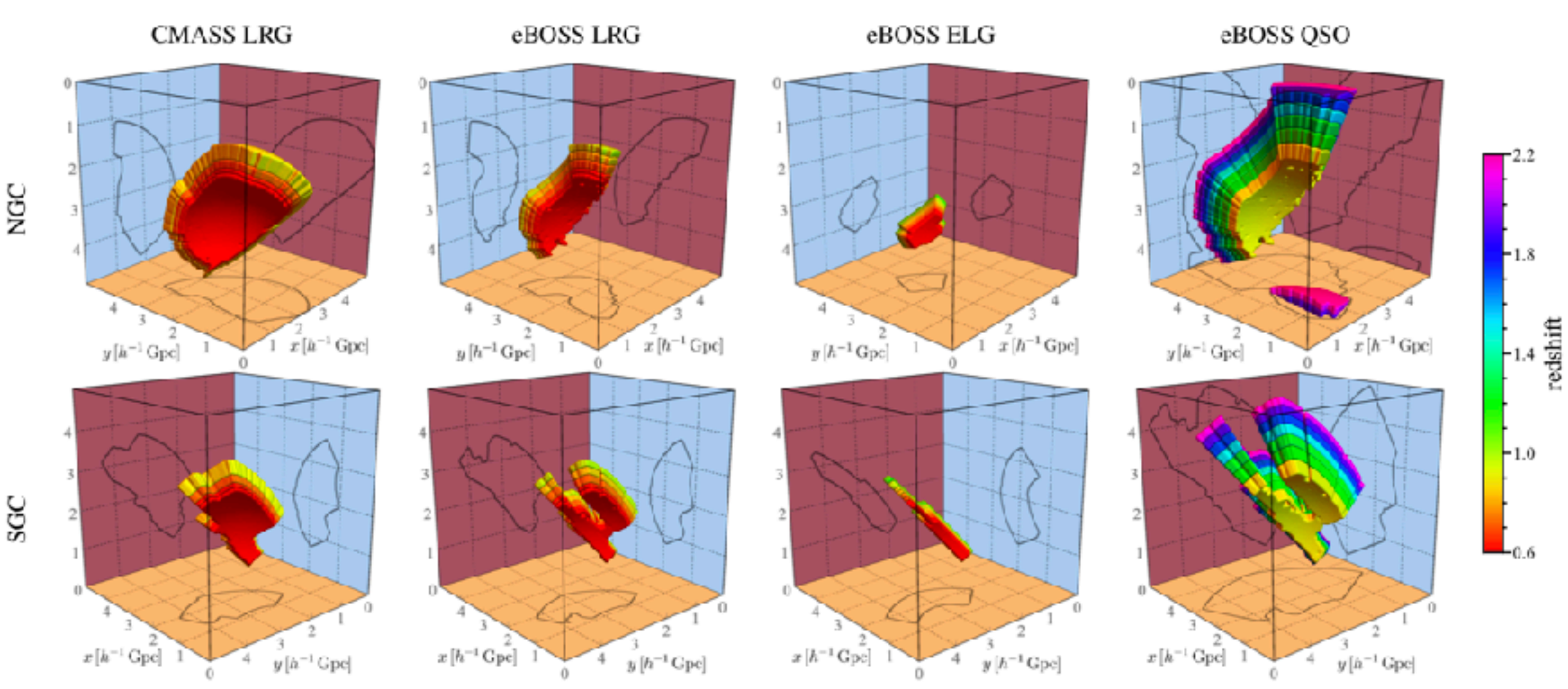
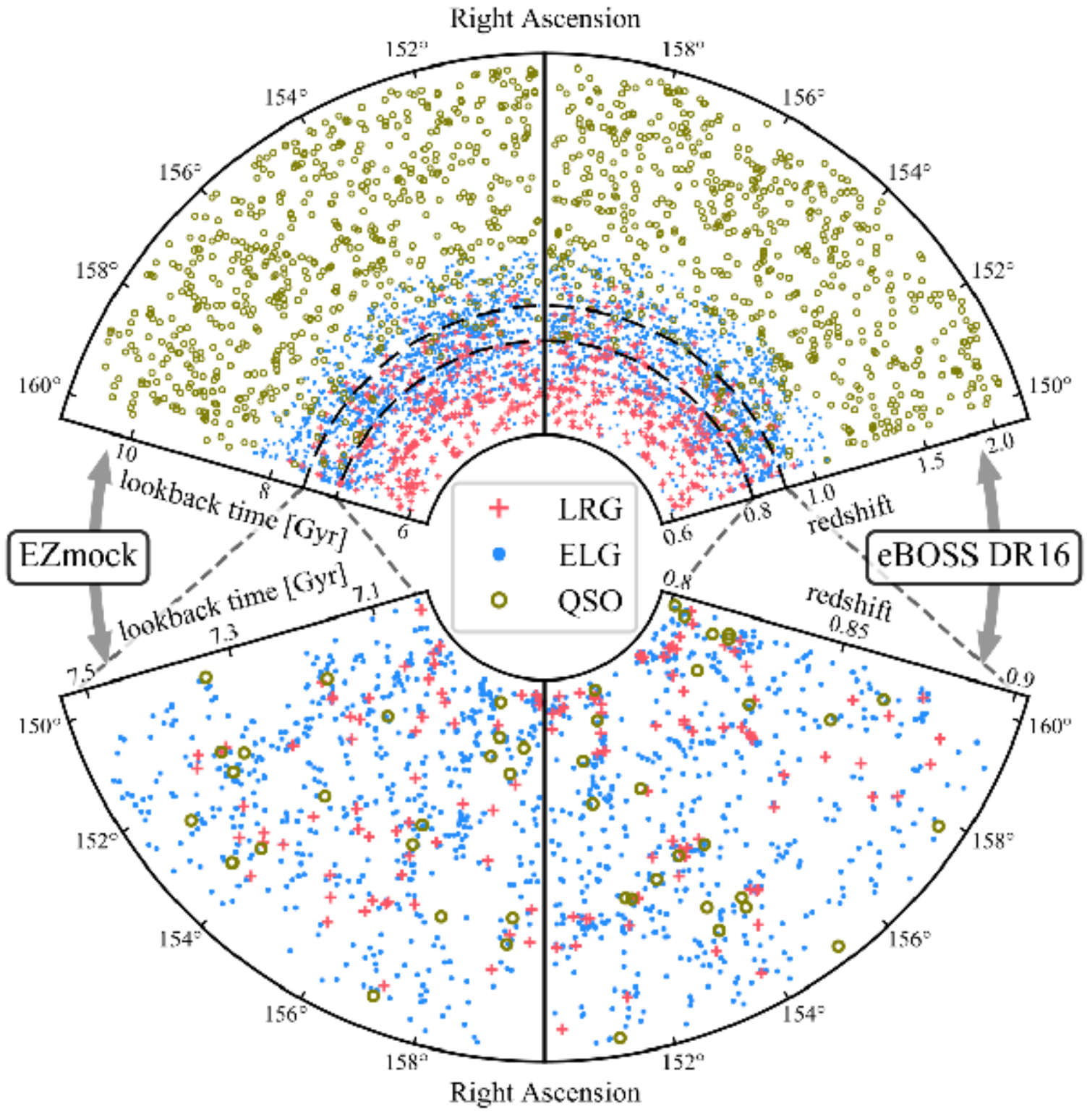




Tracer distribution comparison



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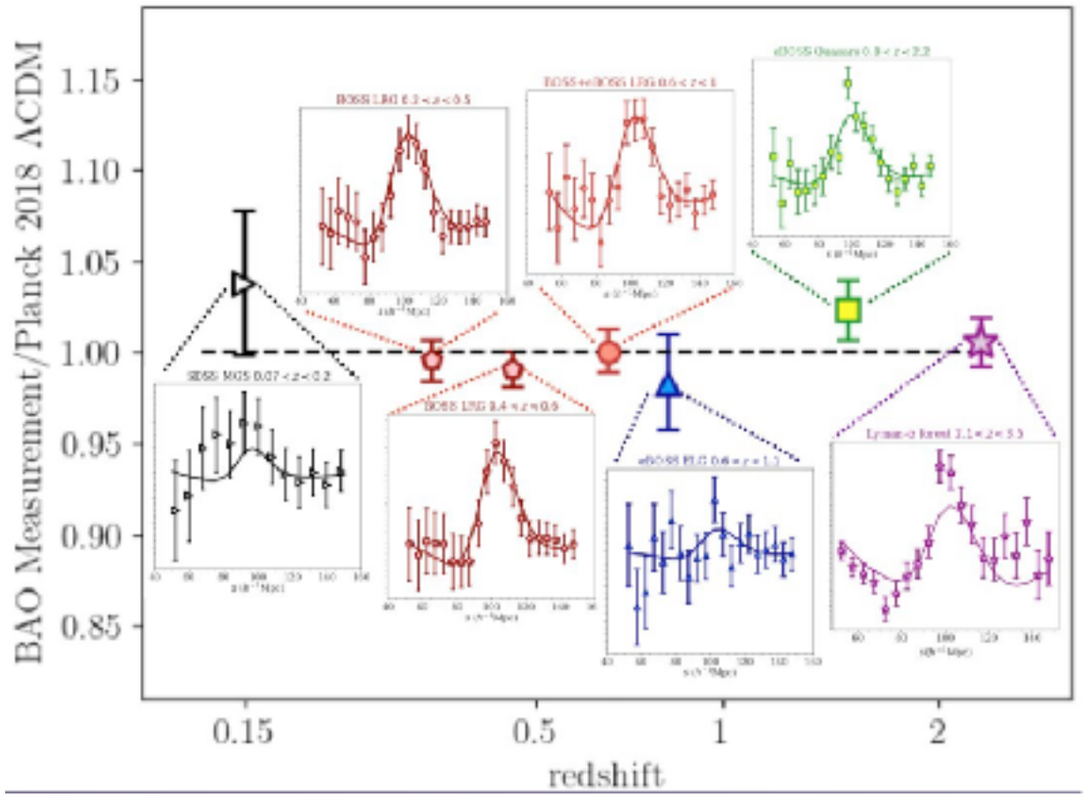
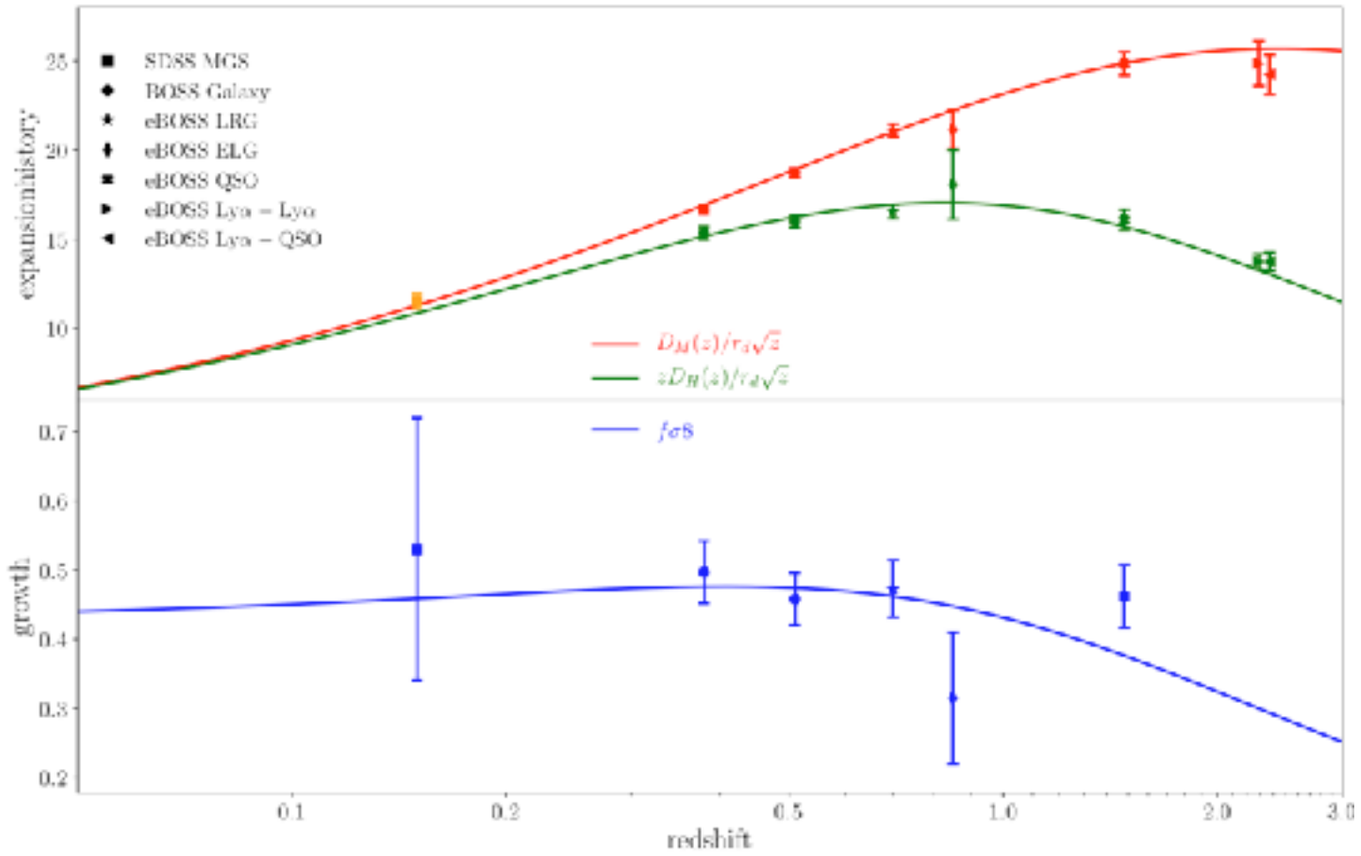
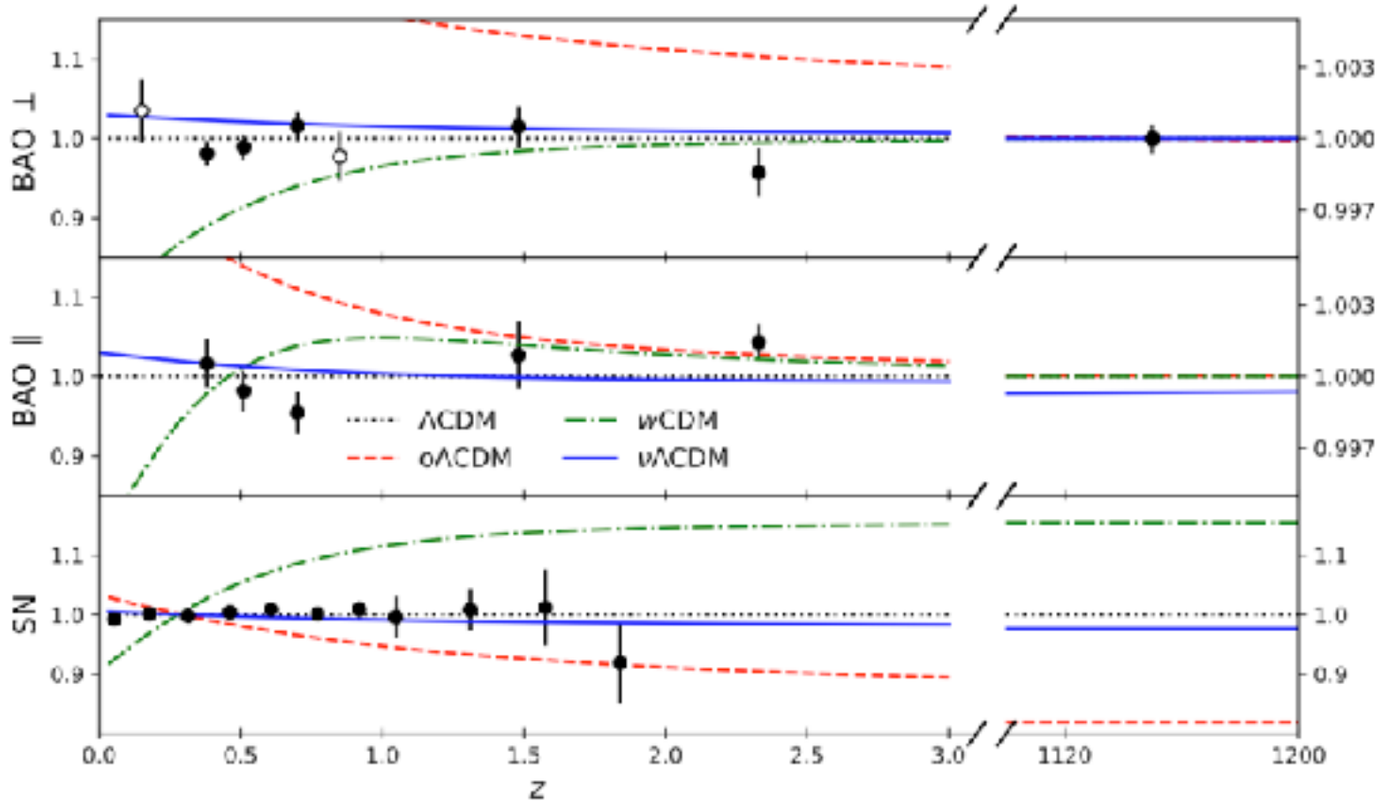
SDSS: BAO and RSD Measurements



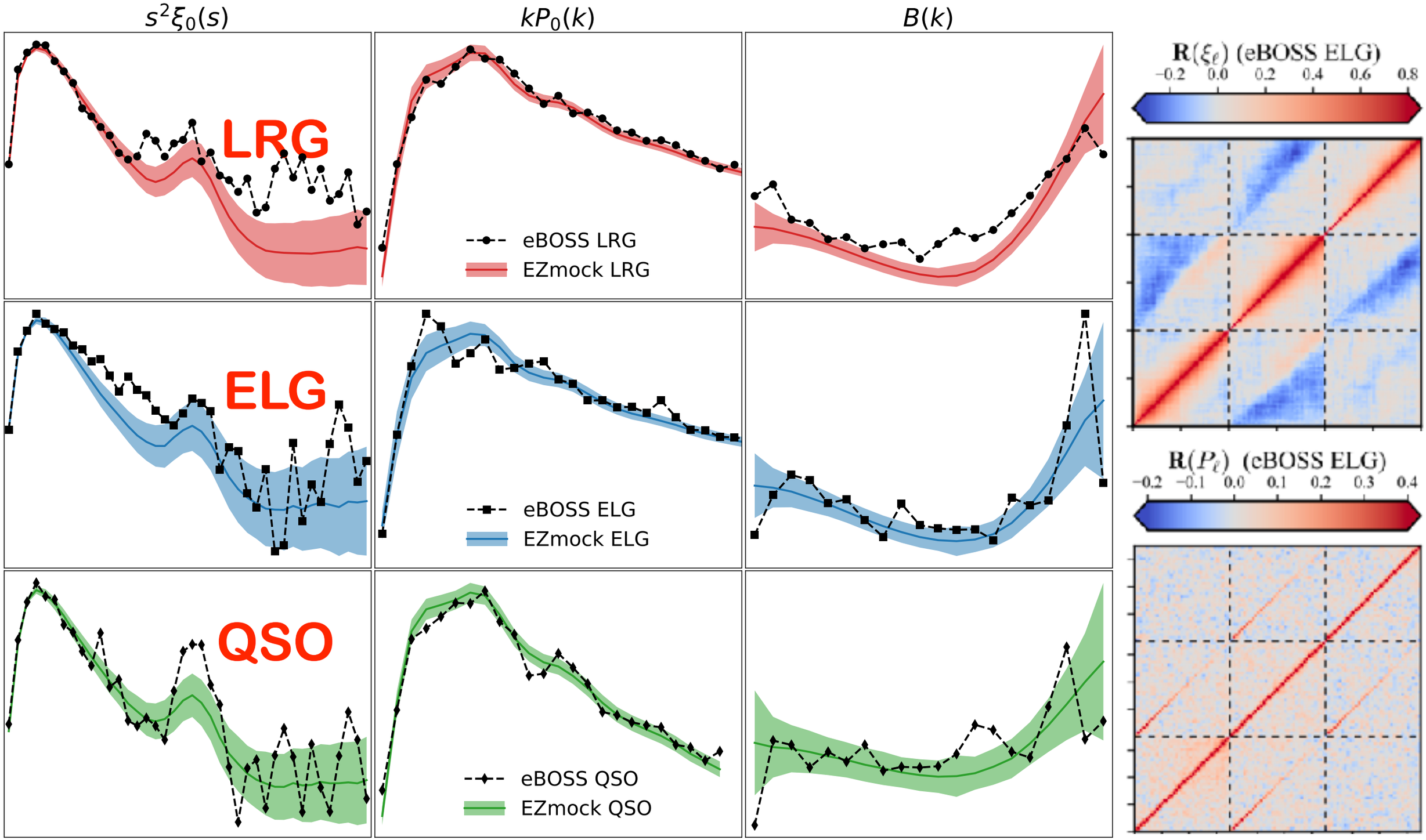


… and models comparison



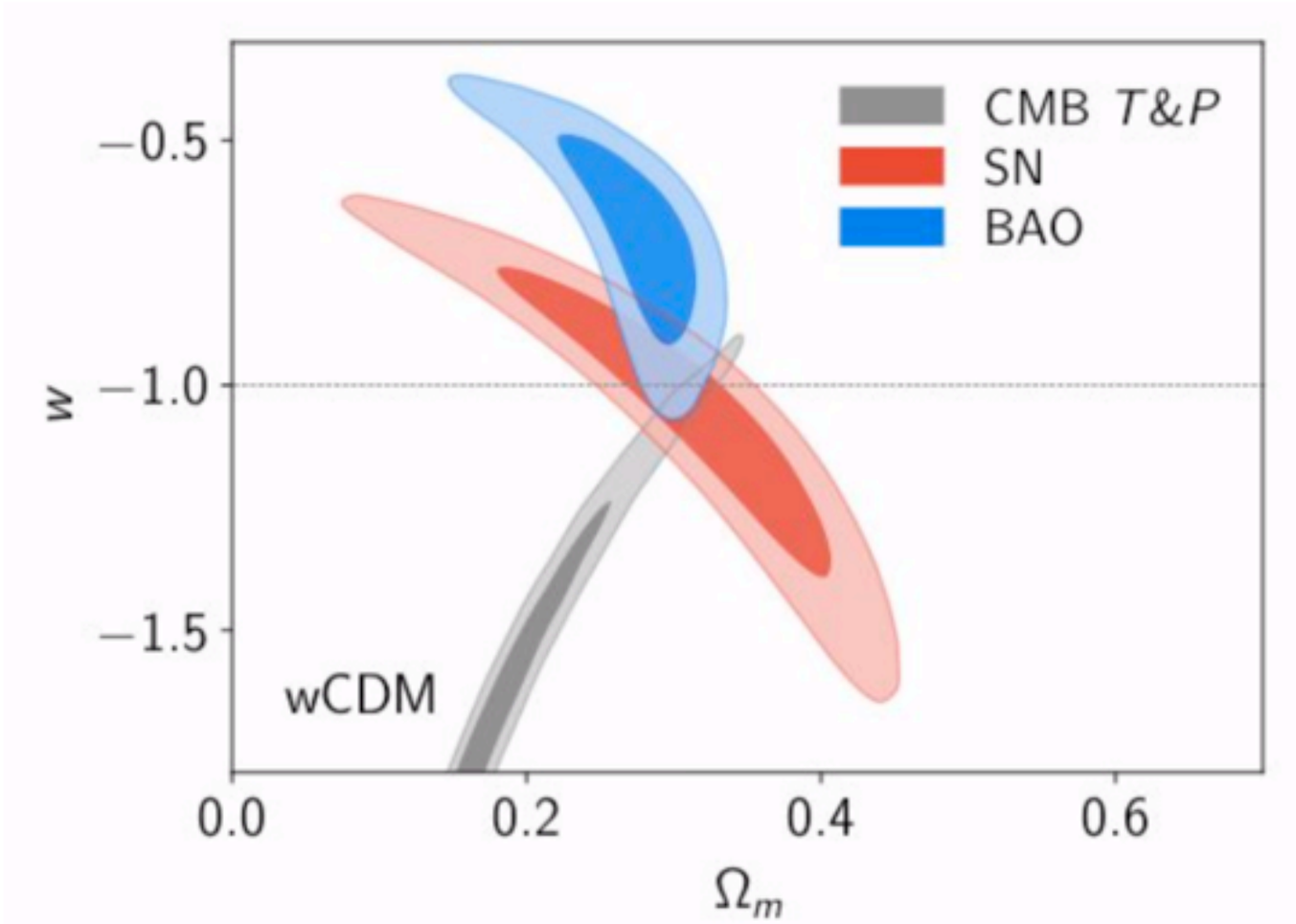
Alam et al 2020

Clustering and Covariance



wCDM cosmology

- BAO-only offer tighter constraints than SNe-only
- Degeneracies well-aligned for SNe+CMB
  - SNe+CMB vs BAO+CMB: 1.2X better in Ω_Λ; 1.5X in w

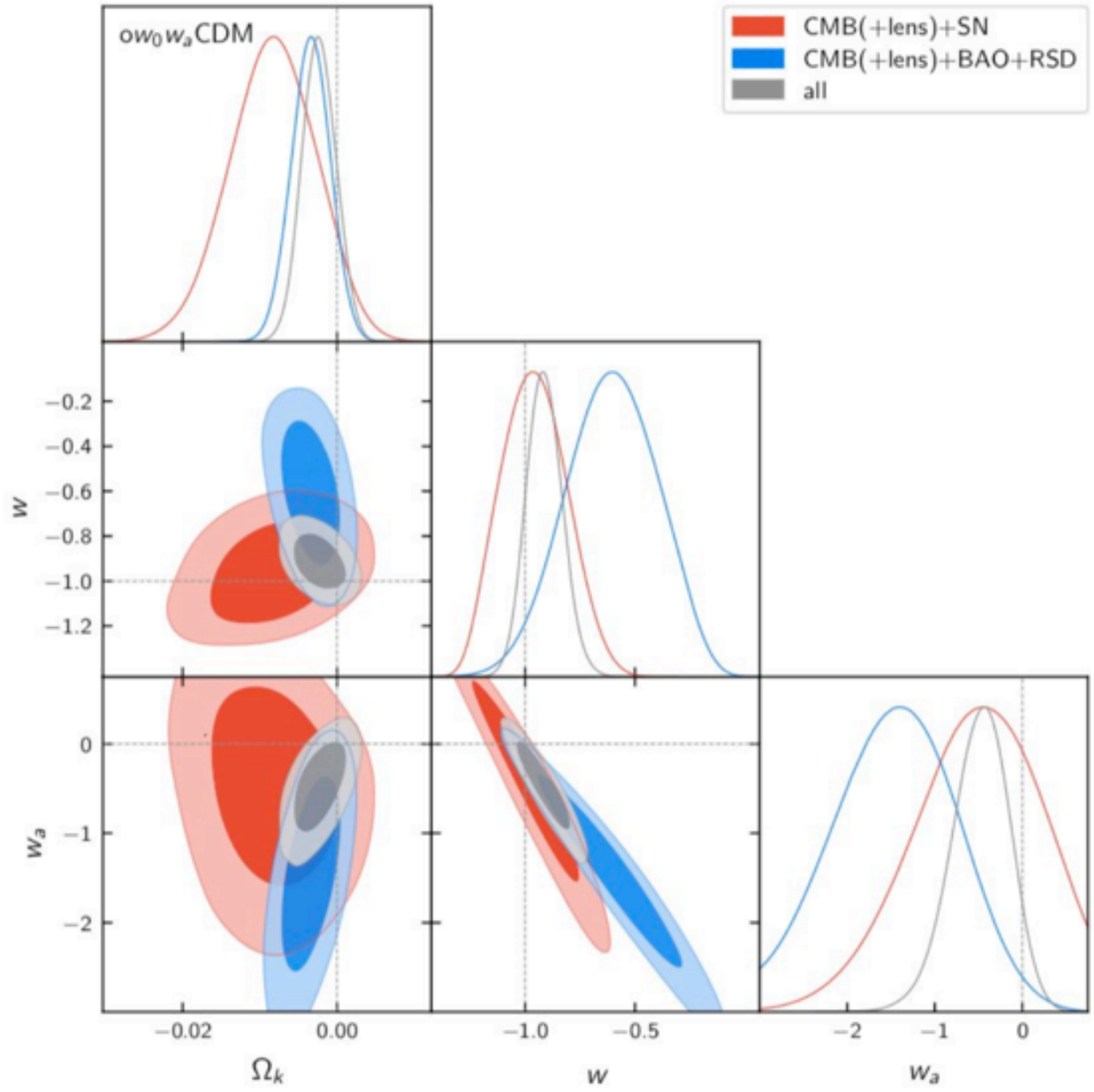


Constraints from ow0waCDM

- Complementarity of BAO and SNe Ia → tight constraints of curvature and the dark energy equation of state

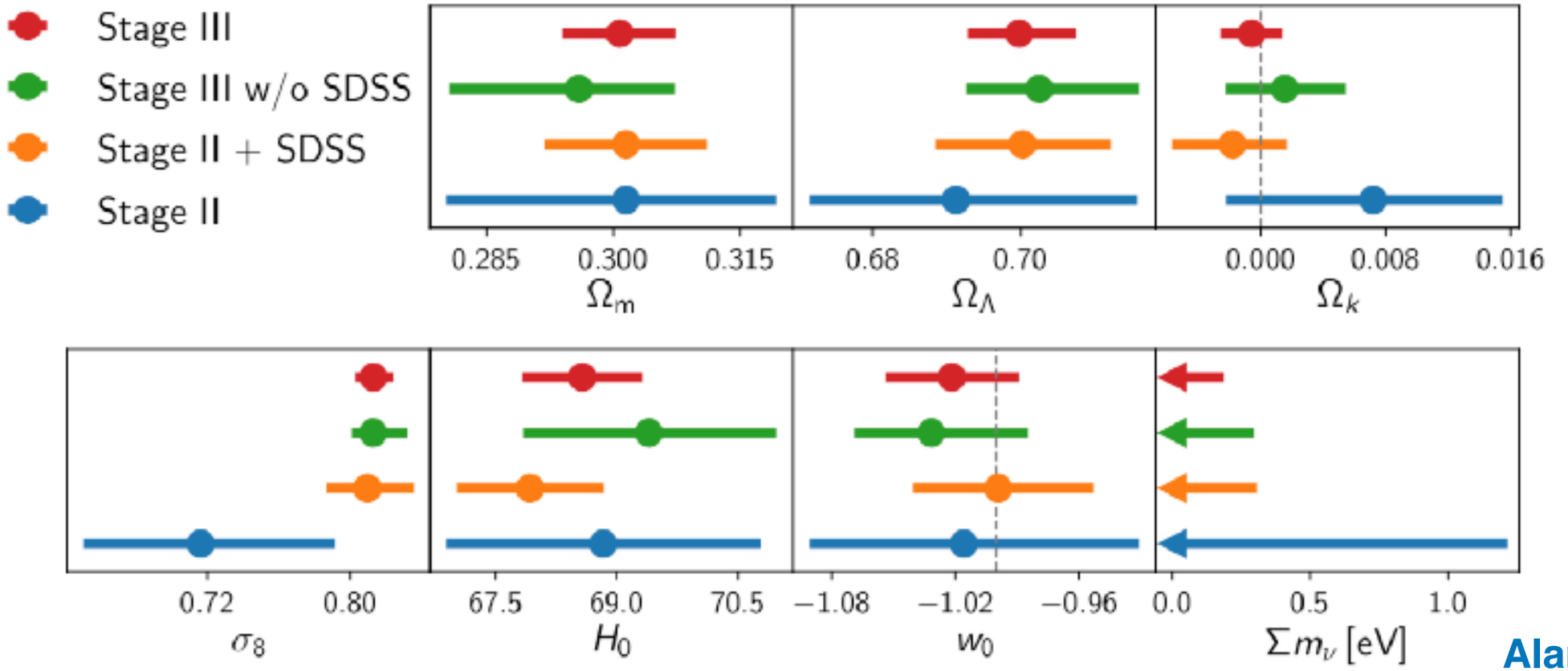
- Dark Energy Task Force Figure of Merit of 103

- FoM=150 predicted by DETF at conclusion of Stage-III



Cosmology results

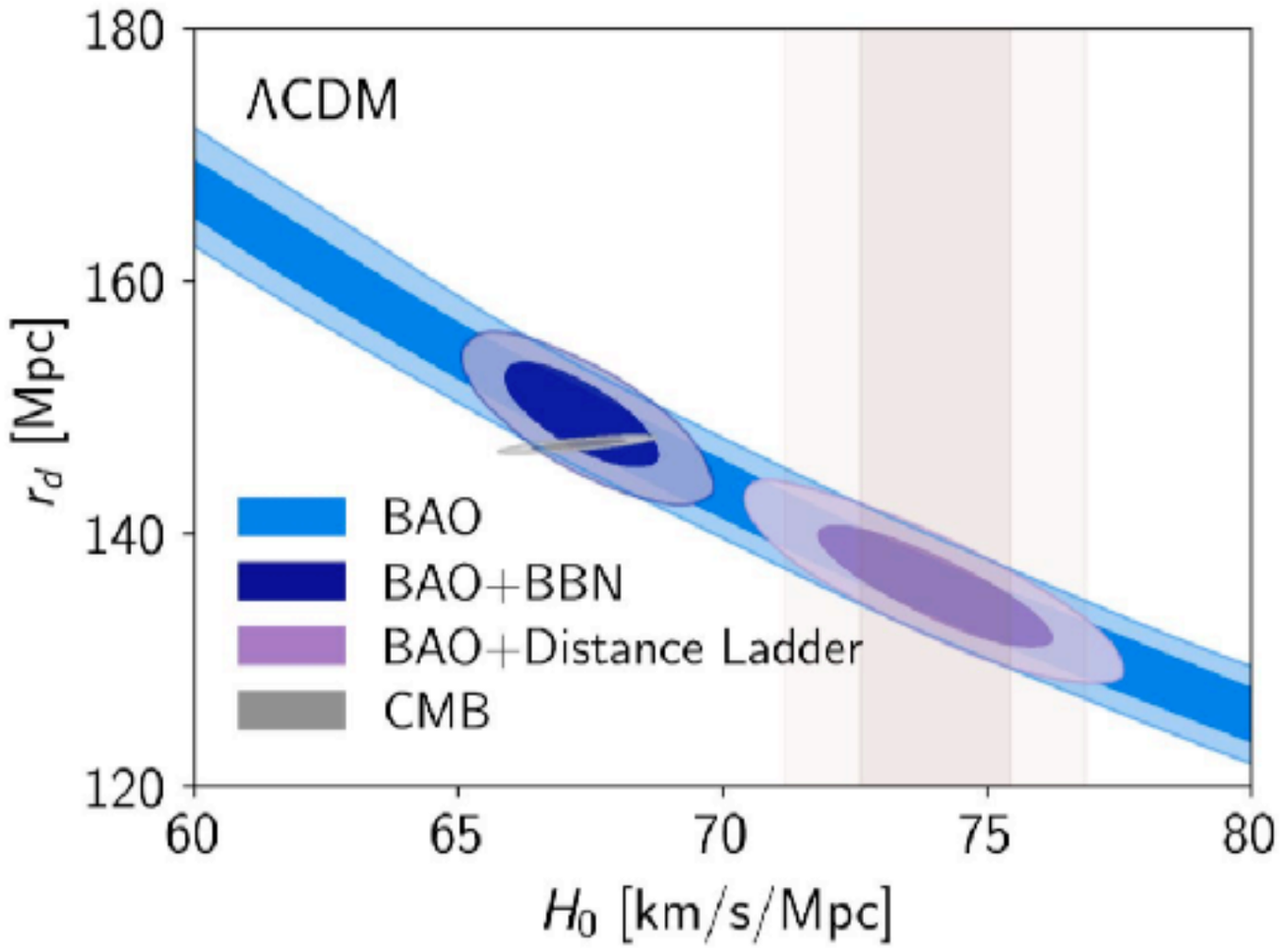
- **Stage-II** (2010): WMAP + SNe + SDSS/2dFGRS BAO
- **SDSS:** 50x improvement in curvature/H0/sigma8/w0/neutrino mass relative to Stage-II
  - largest improvements in curvature, H0, and neutrino mass precision
  - Stage-II + SDSS: H_0 = 67.6 +/- 0.9 km/s/Mpc
- **Planck+Pantheon+DES:** additional 20x improvement



Alam et al 2020

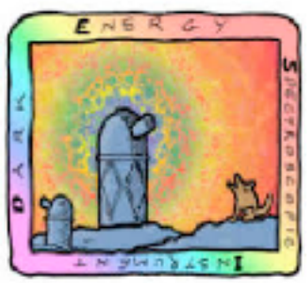
H_0 tension ?

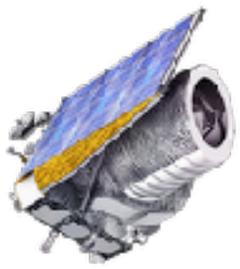
- H_0 from BAO → ~10% smaller error than those from Cepheid distance ladder + strong-lensing time delays.
- "H_0 tension" not restricted to systematic errors in Planck or to the strict assumptions of the LCDM model → *new physics?*

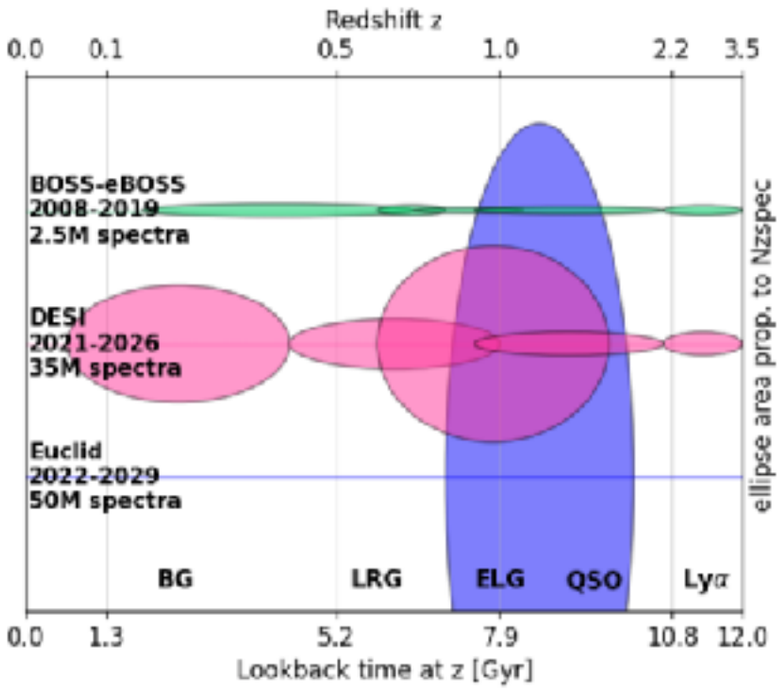


Alam et al 2020

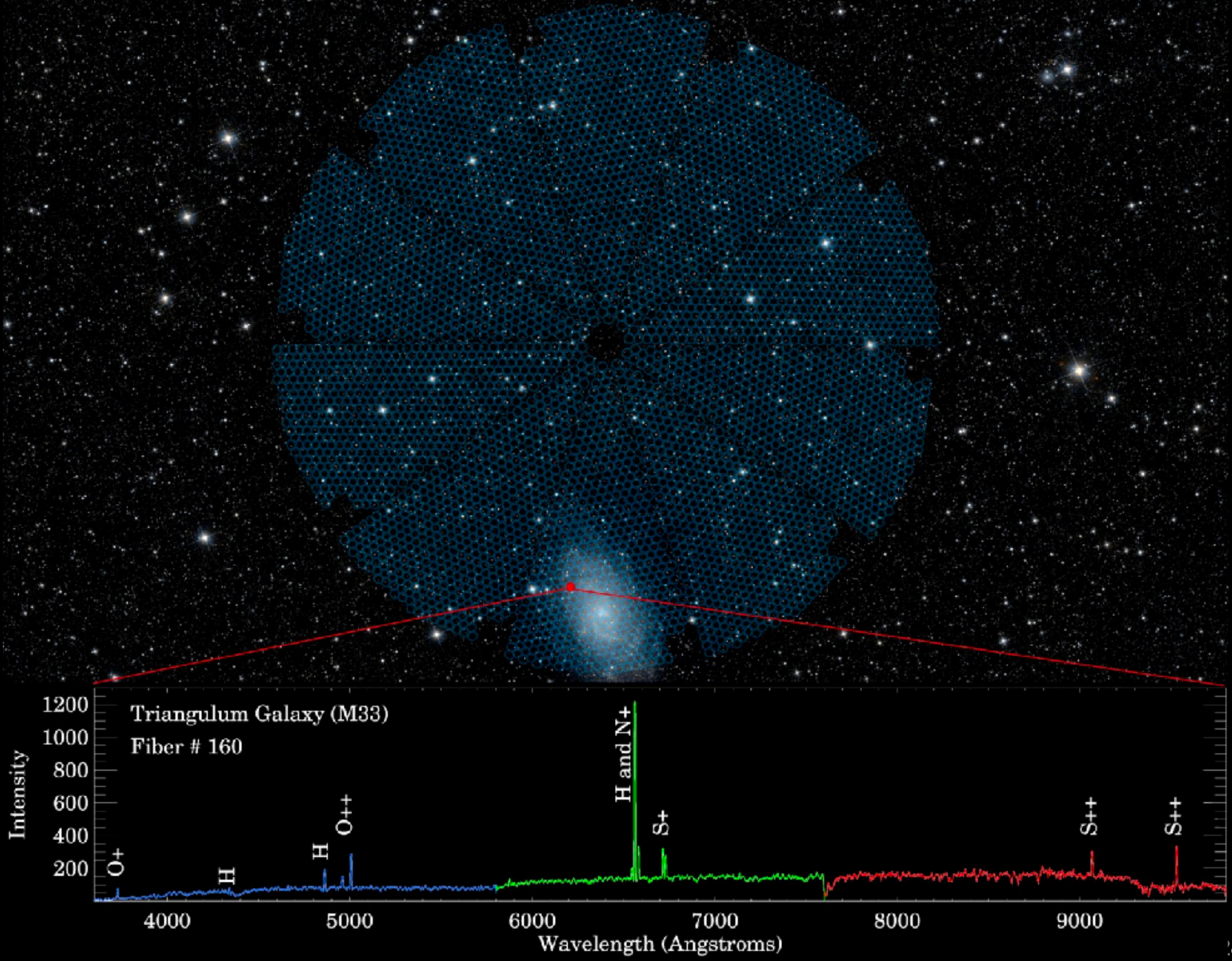
What's Next?



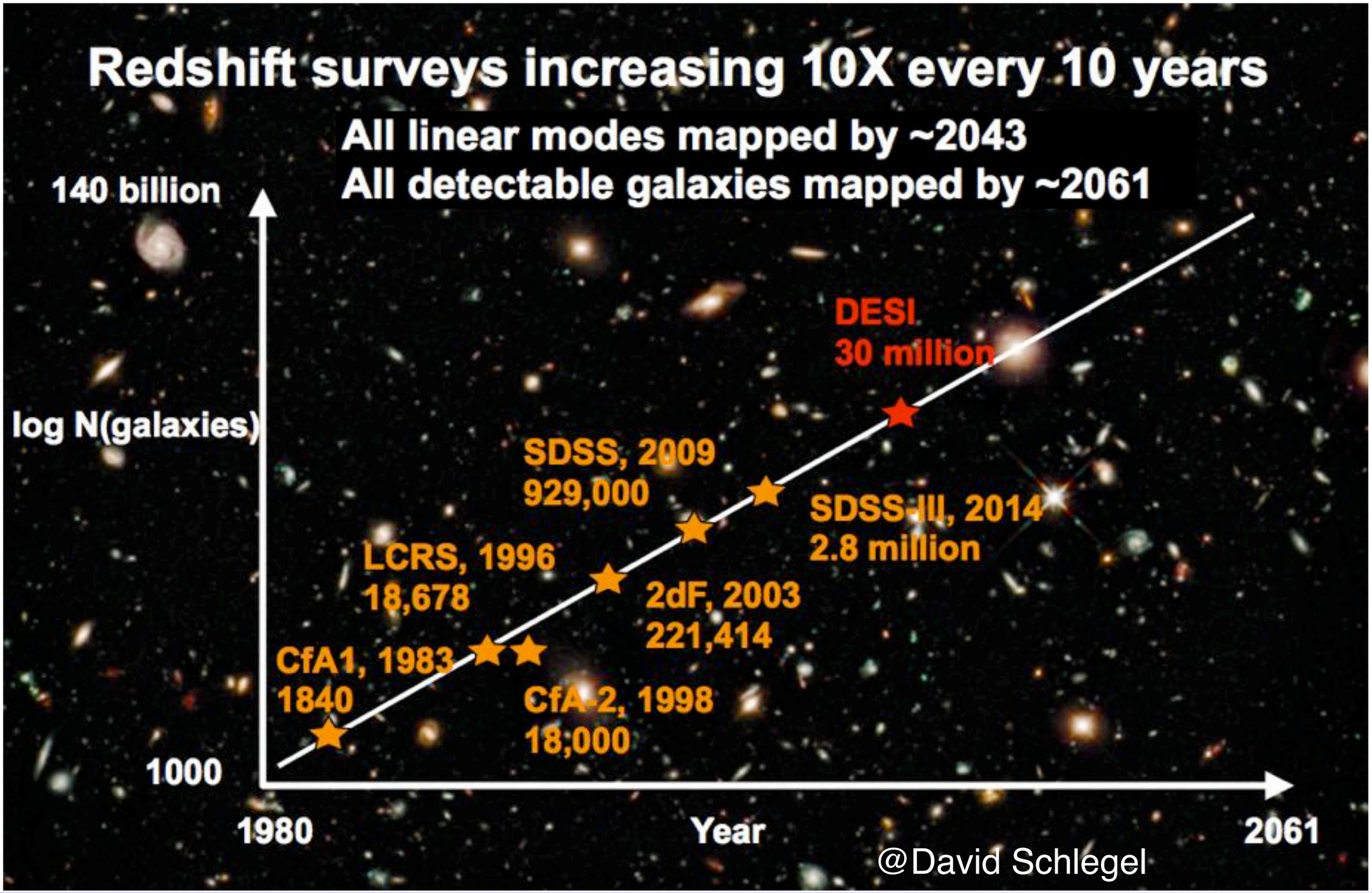




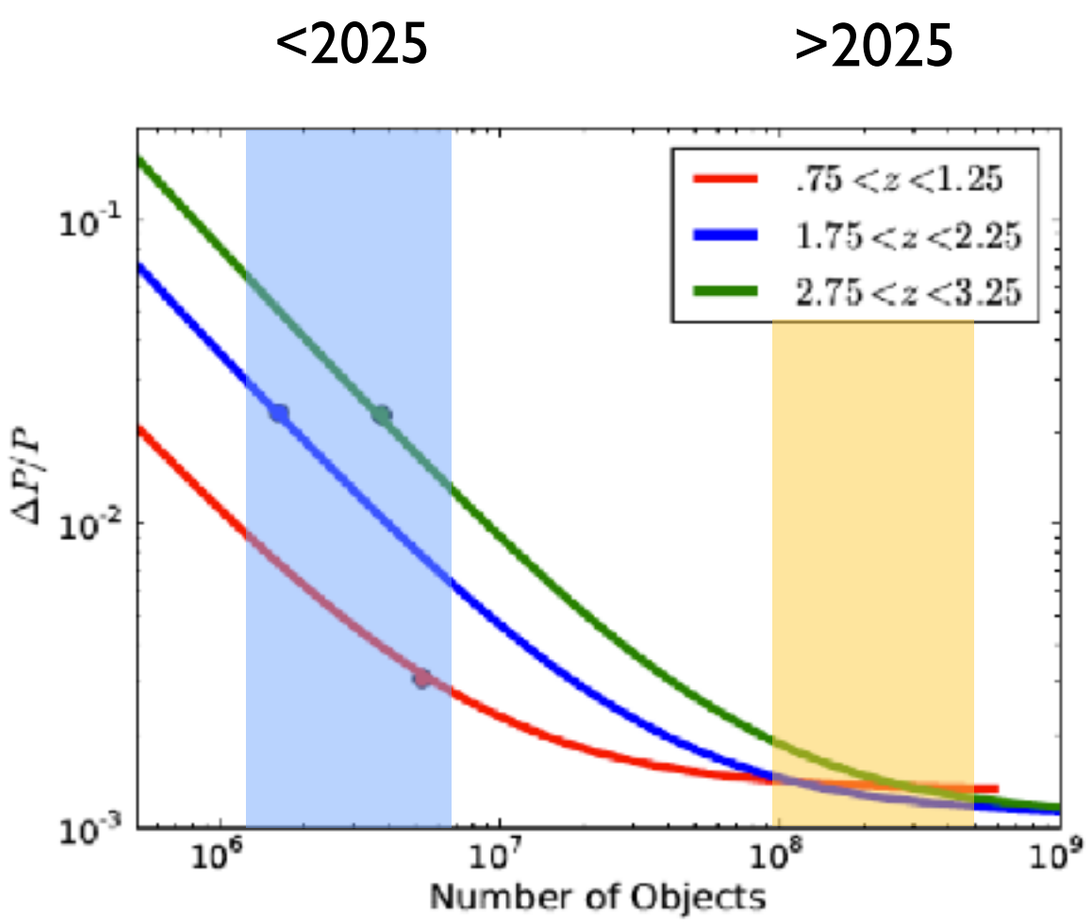
- **DESI - 35 millions redshift (0<z<1.5 + QSOs)**
  - 10x better than BOSS/eBOSS
  - back online in Nov 2020
  - Survey start in Spring 2021
  - Complete survey in 2026?
- **EUCLID - 50 million redshift (1<z<2)**
  - Low resolution infrared spectroscopy
  - Launch end of 2022?
  - End of nominal survey 2027?
- **4MOST - 10 million redshift (0<z<1 +QSOs)**
  - The "DESI" of the Southern Sky
  - First Light in 2023
  - End of nominal survey 2028


Triangulum Galaxy (M33)
Fiber # 160
Intensity
1200
1000
800
600
400
200
O+
H
H
O++
H and N+
S+
S++
S++
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)

FUTURE Massive Spectroscopic Surveys



What's Next?



Dodelson et al 2016

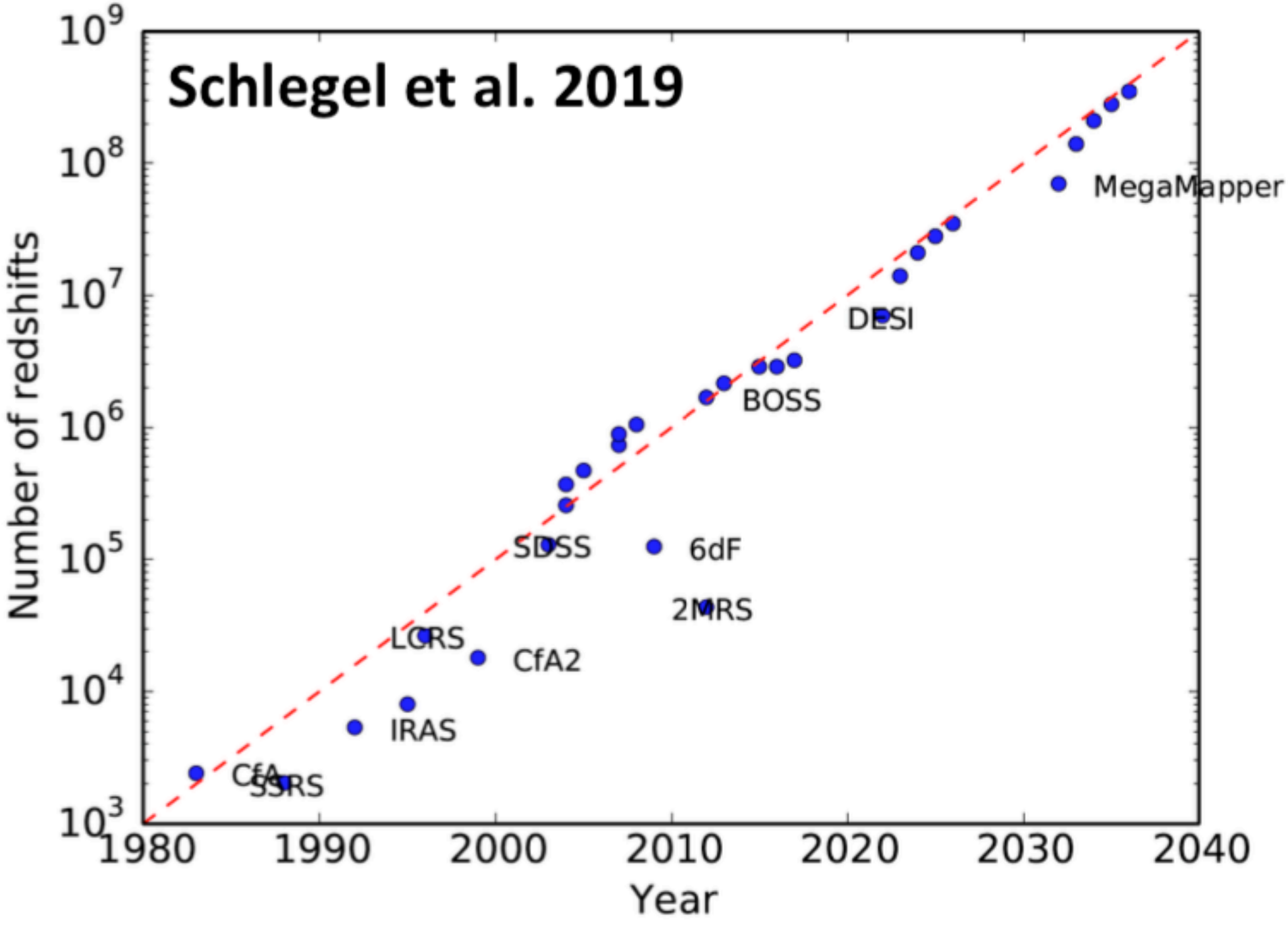
- **Then?** Dark Energy Stage V?
- What Science?
  - DE model
  - DM "temperature"
  - Sum of neutrinos mass with precision
  - Detection of primordial non-Gaussian fluctuation (f_{NL})
  - …
- **Projects:**
  - MSE - ambitious enough to gather funding?
  - ESO-SpecTel - E-ELT first!
  - Megammaper/SSST - Decadal survey/ funding?
  - SKA (HI mapping) - Big challenge!
  - GAUSS?

MegaMapper

- 6.5m telescope (2 Magellan blank mirror unused)
- Wide field corrector
- 20’000 fiber robots
- ~32 spectrographs if reusing DESI concept (16 exist)

Instrument (year)	Primary/m^2	Nfiber	Reflections	Product	Speed vs. SDSS
SDSS (1999)	3.68	640	0.9^2	1908	1.00
BOSS (2009)	3.68	1000	0.9^2	2980	1.56
DESI (2019)	9.5	5000	0.9^1	42,750	22.4
PFS (2020)	50	2400	0.9^1	108,000	56.6
4MOST (2022)	12	1624	0.9^2	15,800	8.3
MegaMapper	**28**	**20,000**	**0.9^2**	**454,000**	**238.**
Keck/FOBOS	77.9	1800	0.9^3	102,000	53.6
MSE	78	3249	0.9^1	228,000	119.
LSSTspec	35.3	8640	0.9^3	222,000	116.
SpecTel	87.9	15,000	0.9^2	1,070,000	560.

MegaMapper


Schlegel et al. 2019
MegaMapper
DESI
BOSS
SDSS
6dF
2MRS
LCRS
CfA2
IRAS
CfA
SSRS
Number of redshifts
Year
10^9
10^8
10^7
10^6
10^5
10^4
10^3
1980
1990
2000
2010
2020
2030
2040

Megamapper/SSST

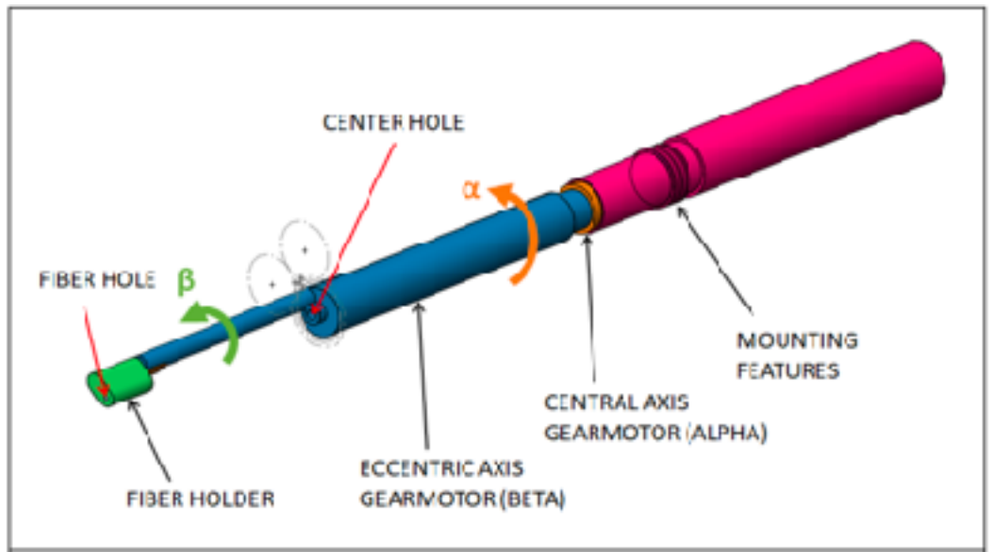
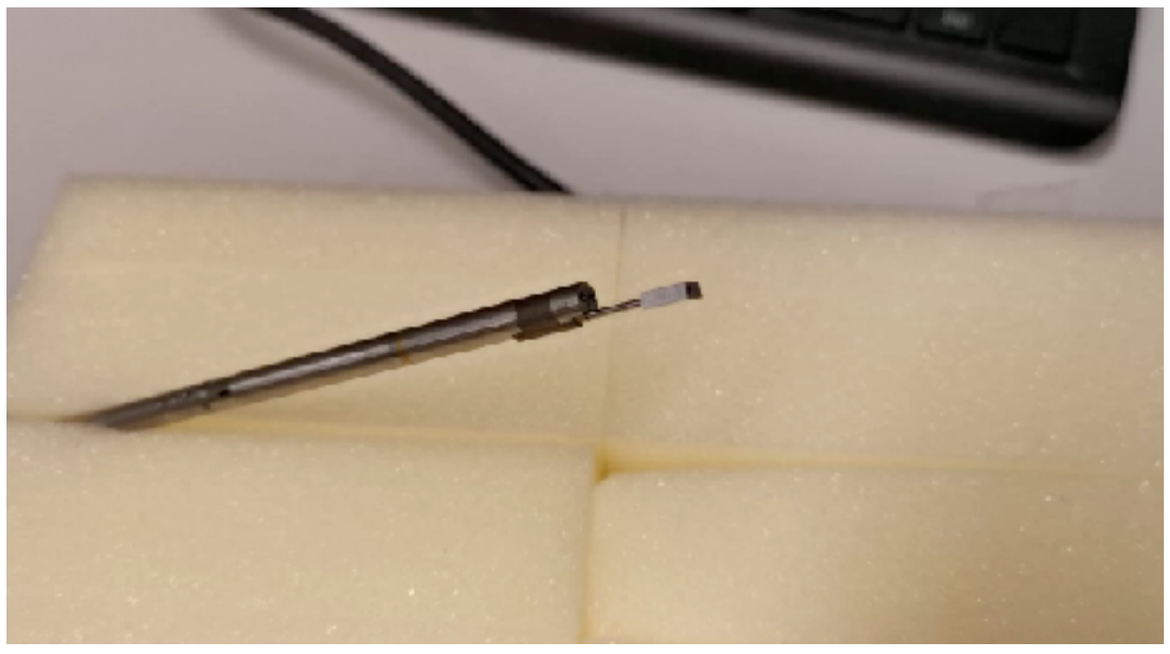


Fig 1. Cartoon of our concept for the overall robot, showing ALPHA and BETA motors.

- 6.5m telescope
- ~20'000 fiber robot positionner (6mm diameter)
- 30-40 spectrographs
- 200'000+ spectra

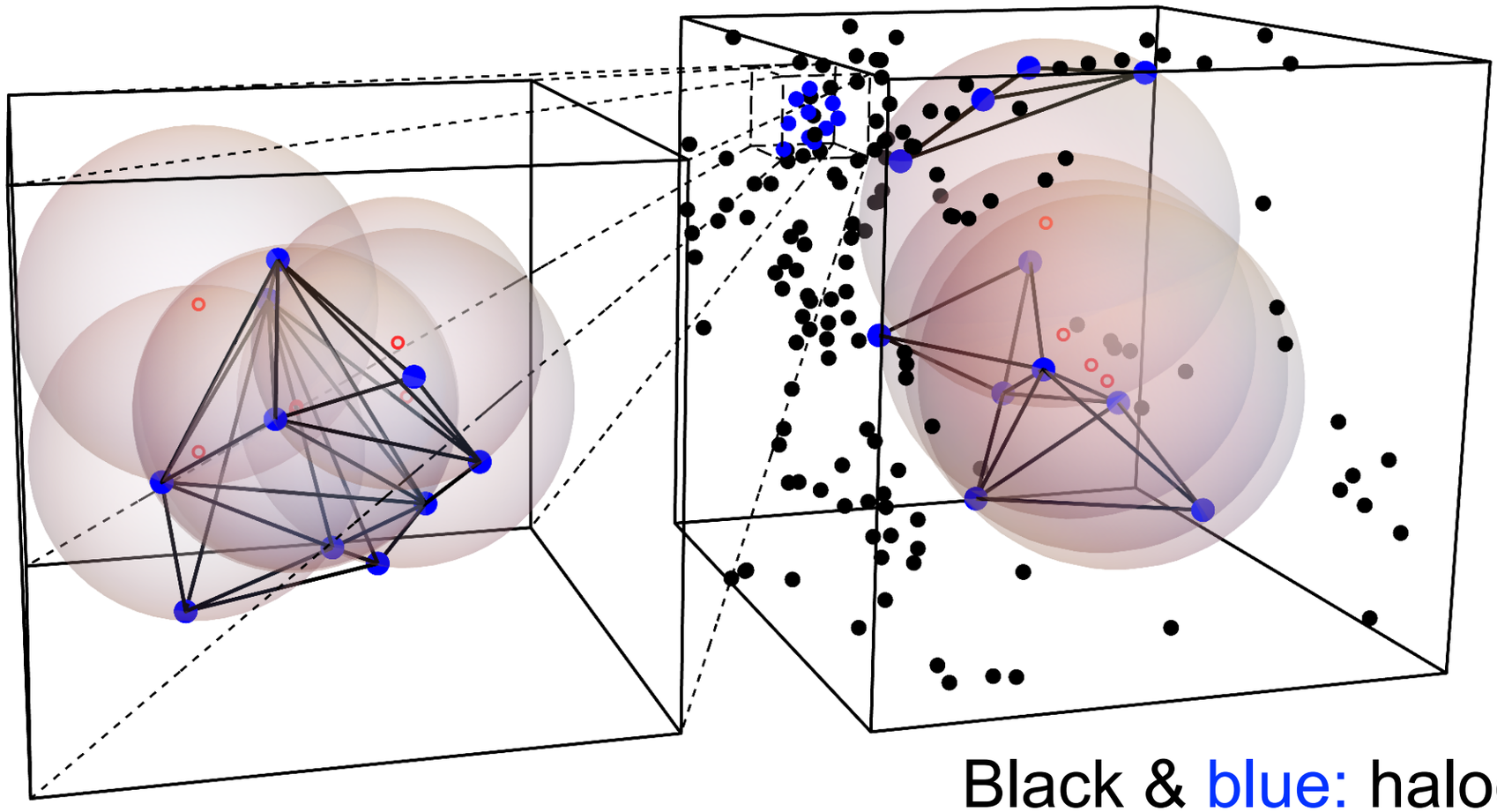


Conclusion

- eBOSS completed a 20 year legacy of SDSS redshift surveys
- Stage III Dark Energy experiment are now being finalised (still missing final DES results)
- *Cosmological model converging to Lambda-CDM*
- *But H_0 tension => sign of new physics???*
- New Stage IV about to start
- *Plan ahead for Stage V surveys?*

Beyond Galaxy Clustering?

Delaunay Tetrahedra Voids (or Spheres)



© Cheng Zhao

Black & blue: haloes
Red: centres of voids

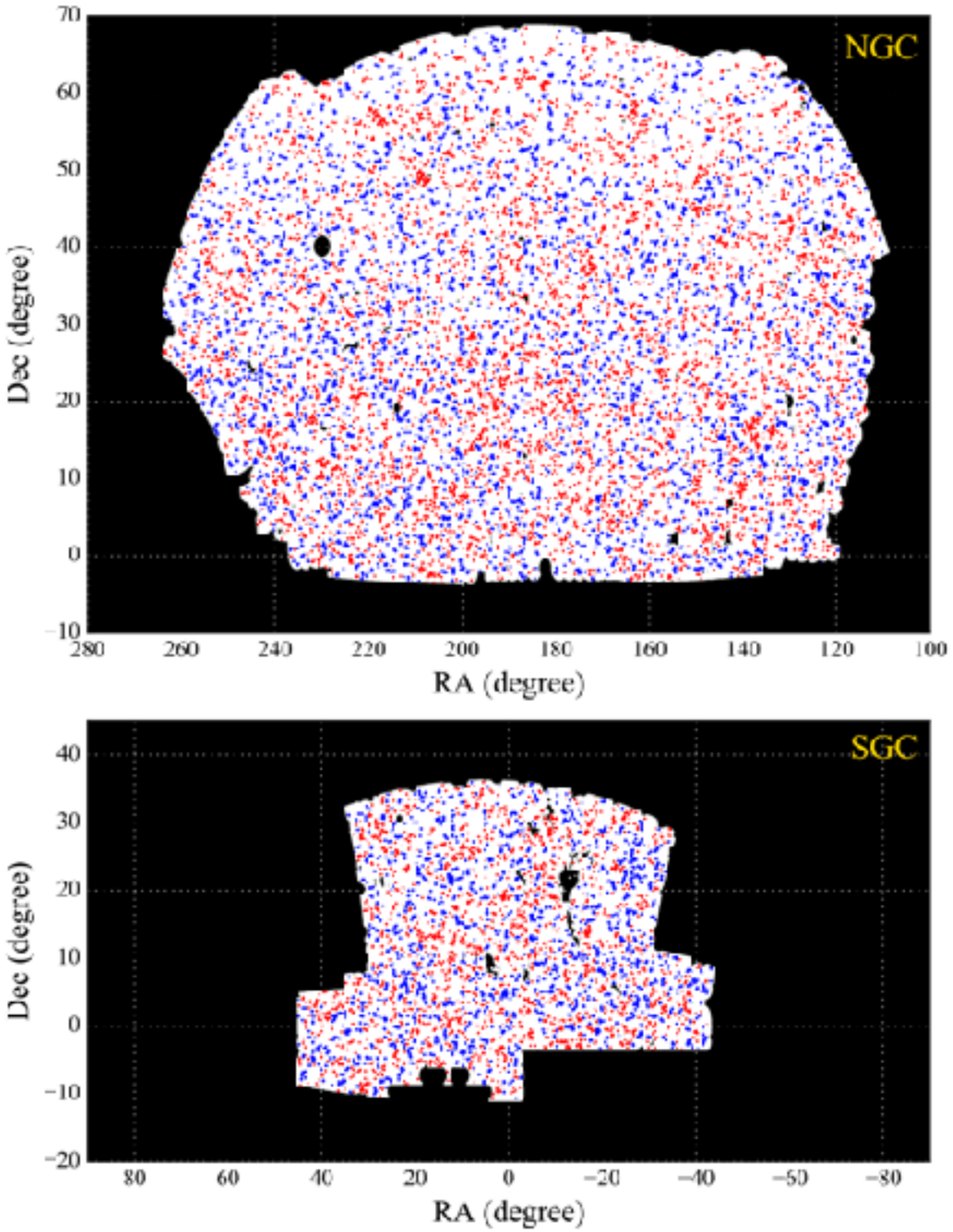
cosmology independent

~10 minutes for 5.5 million haloes with one CPU core

>1000 times faster than some traditional finders

CZ+ 2016

DT Voids in SDSS-III/BOSS



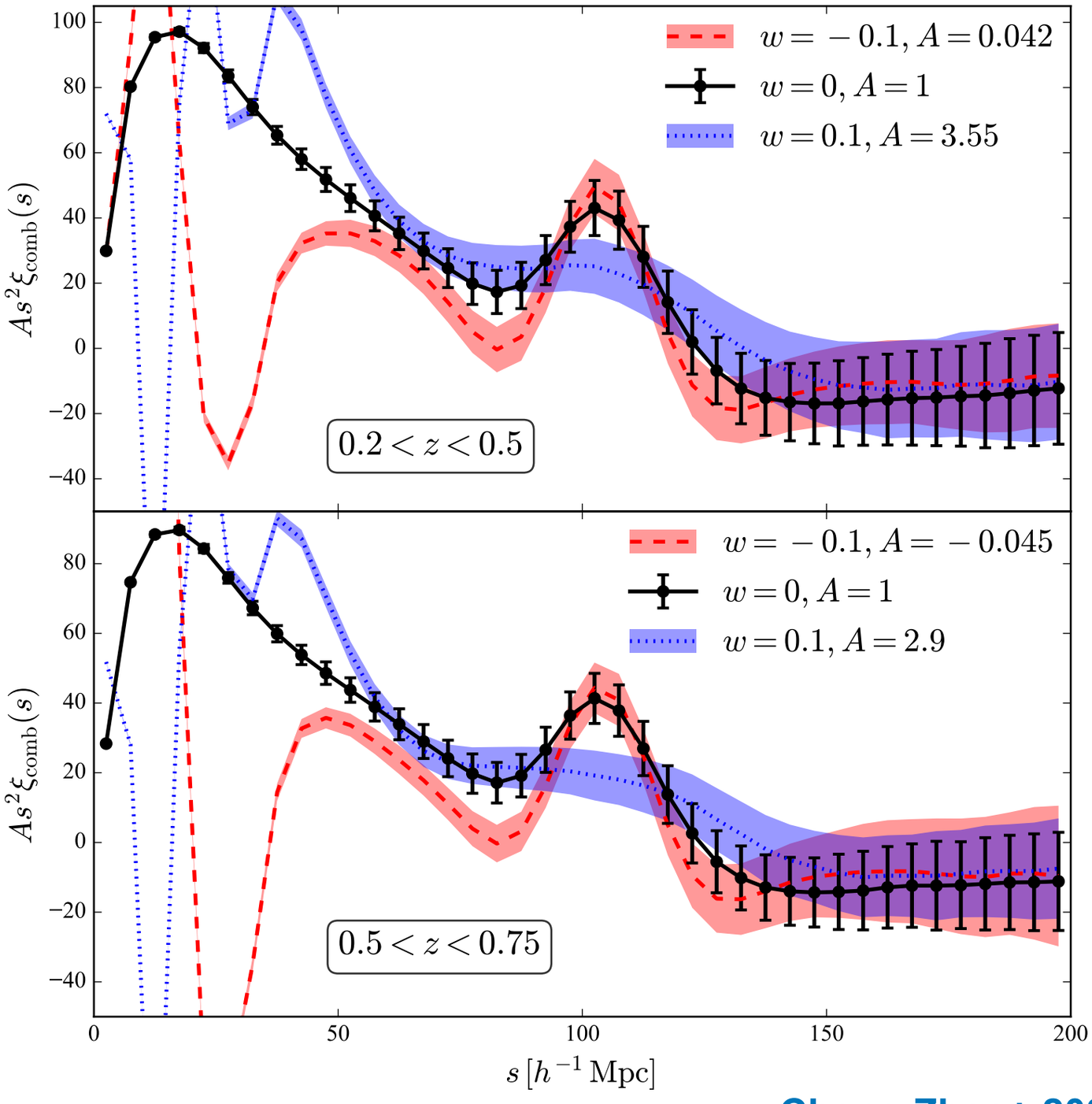
BOSS DR12 DT voids

Red: Luminous red galaxies

Blue: DT voids

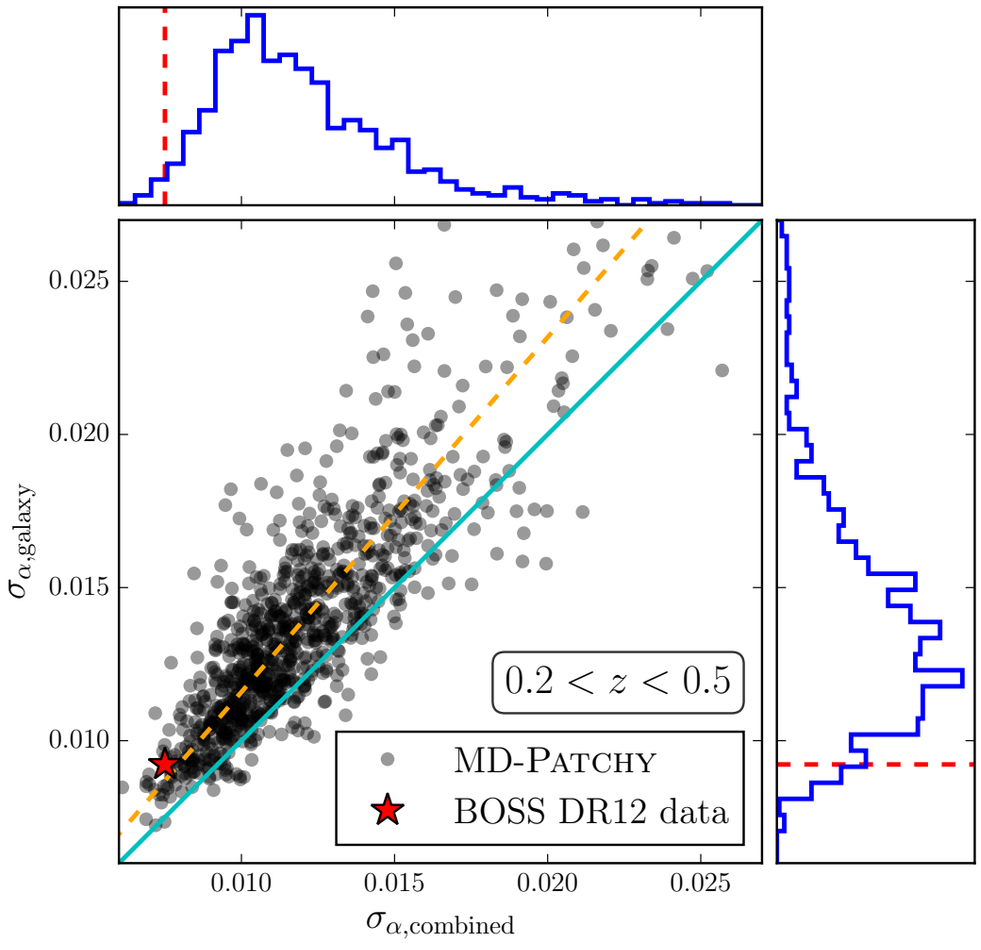
Cheng Zhao+ 2020

[Galaxy+DT Voids] Clustering



Cheng Zhao+ 2020

Stronger BAO !
~10% better



Yet to be done on eBOSS !