The extended Baryon Oscillation Spectroscopic Survey (eBOSS)

Cheng Zhao
L'Ecole polytechnique fédérale de Lausanne (EPFL)
eBOSS Collaboration

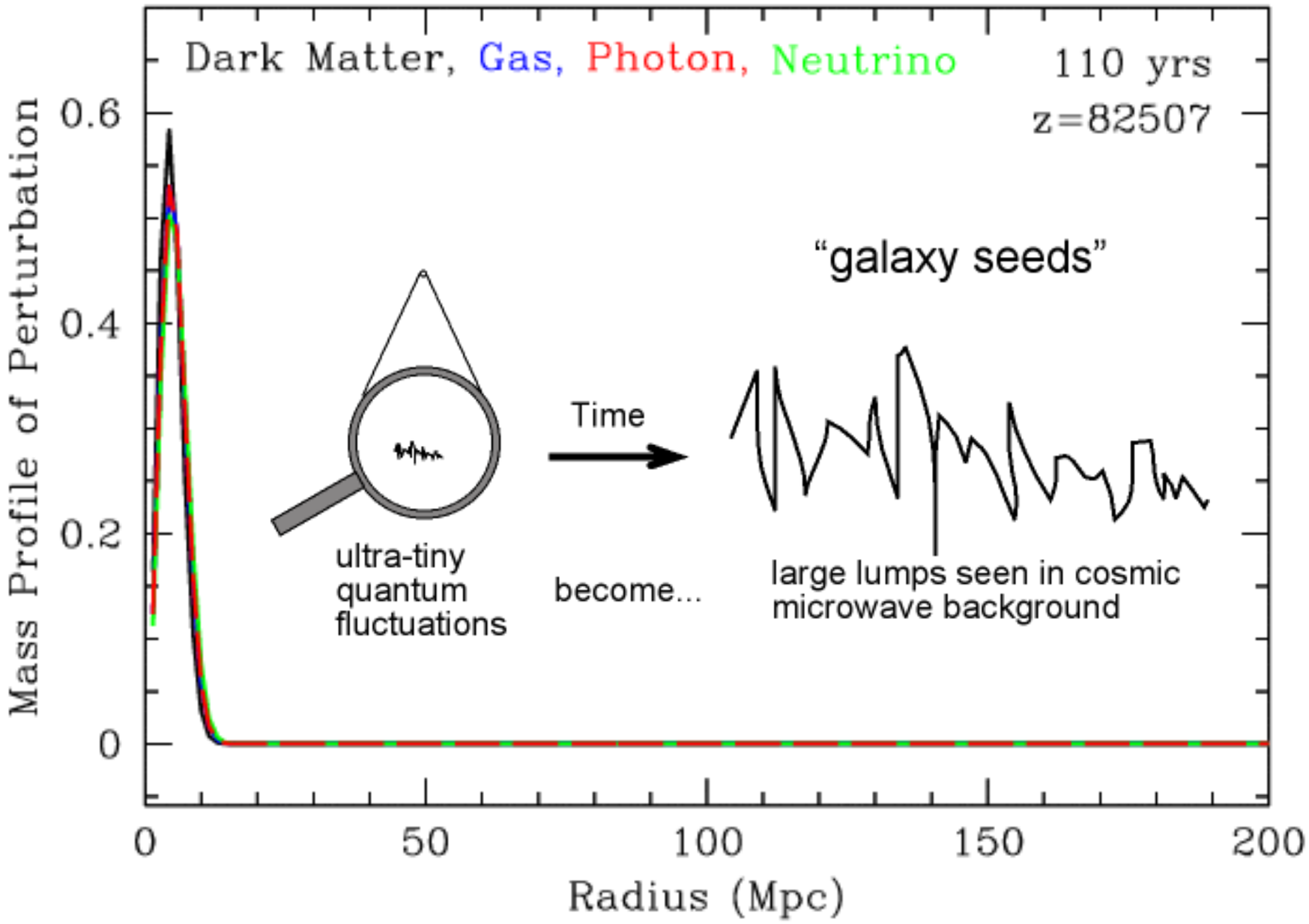
Cosmology, 15th Rencontres du Vietnam, Quy Nhon
Aug 13, 2019

Outline

- Introduction to BAO & RSD
- Introduction to SDSS-IV/eBOSS
- Data description
- LSS catalogue creation
- Massive mock production
- Data analysis & results

Baryon Acoustic Oscillations

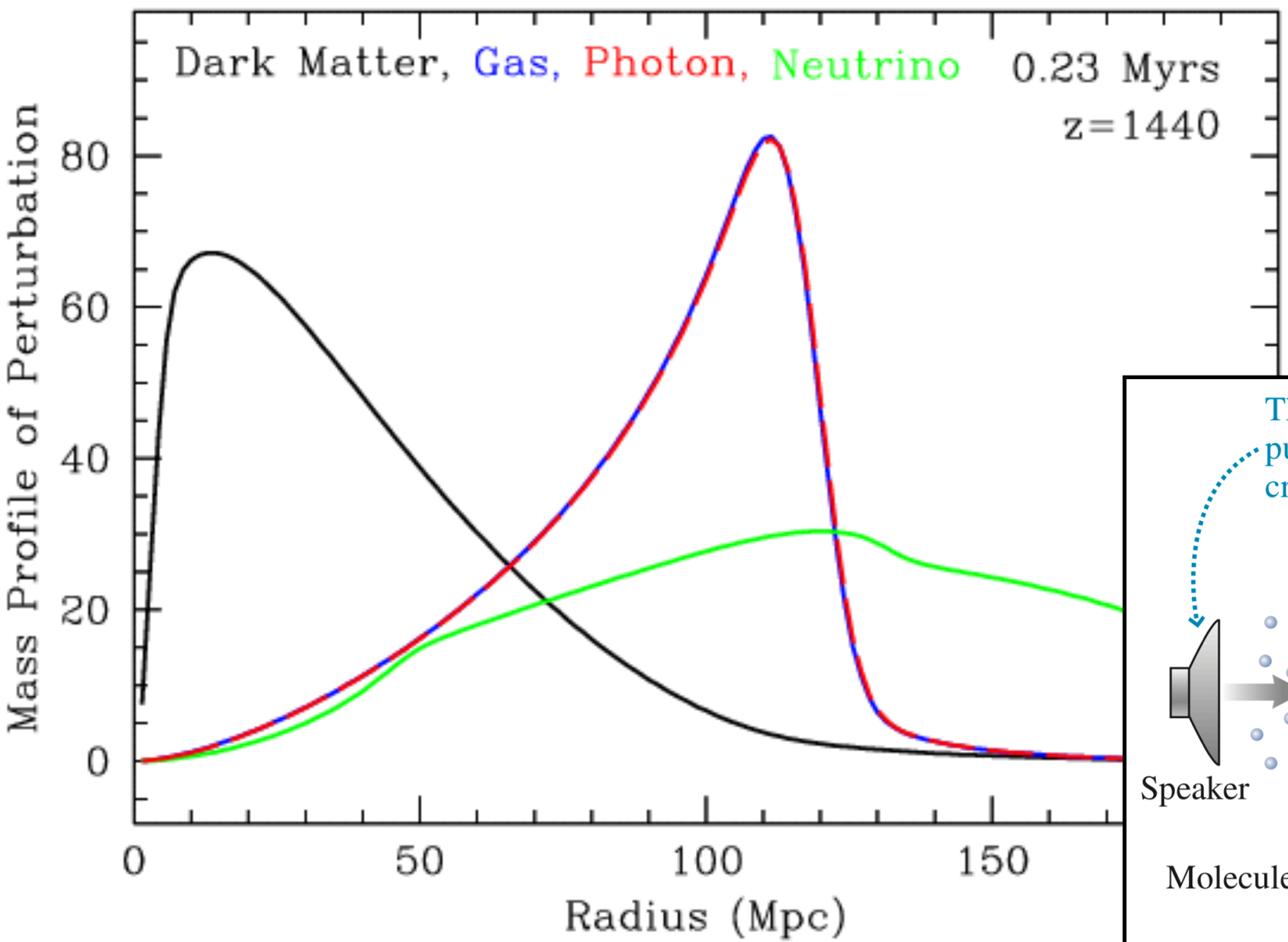
Standard ruler

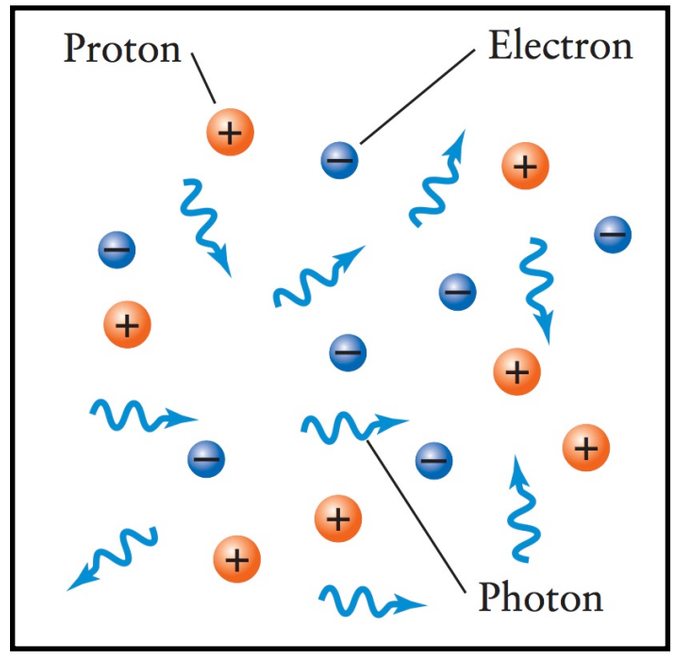


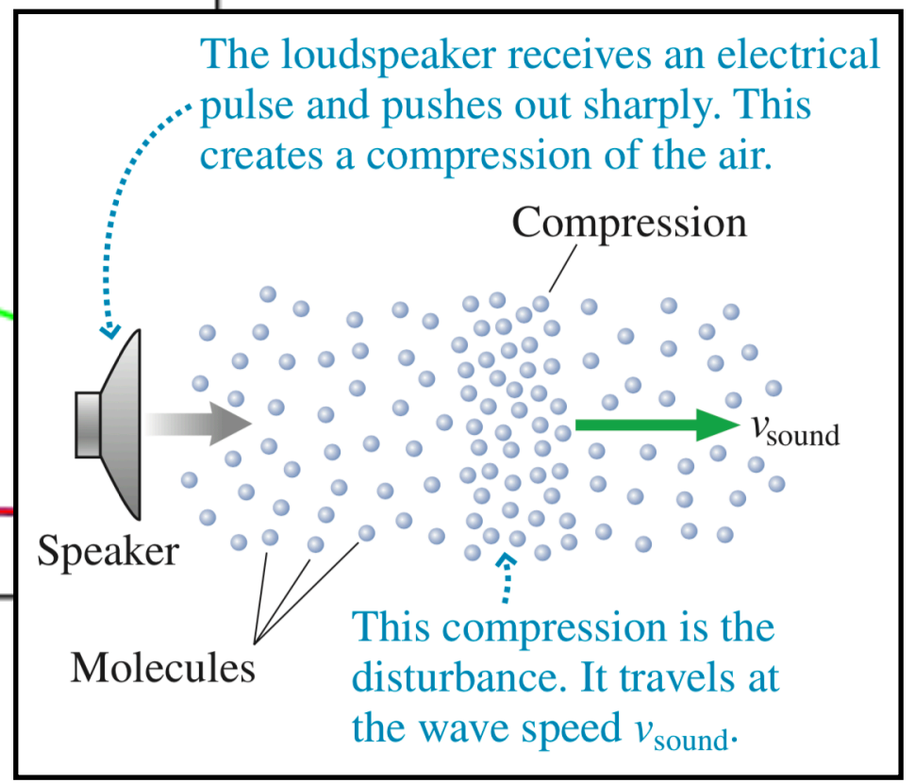
Credit: Eisenstein's web & Nick Strobel's Astronomy Notes

Baryon Acoustic Oscillations

Standard ruler



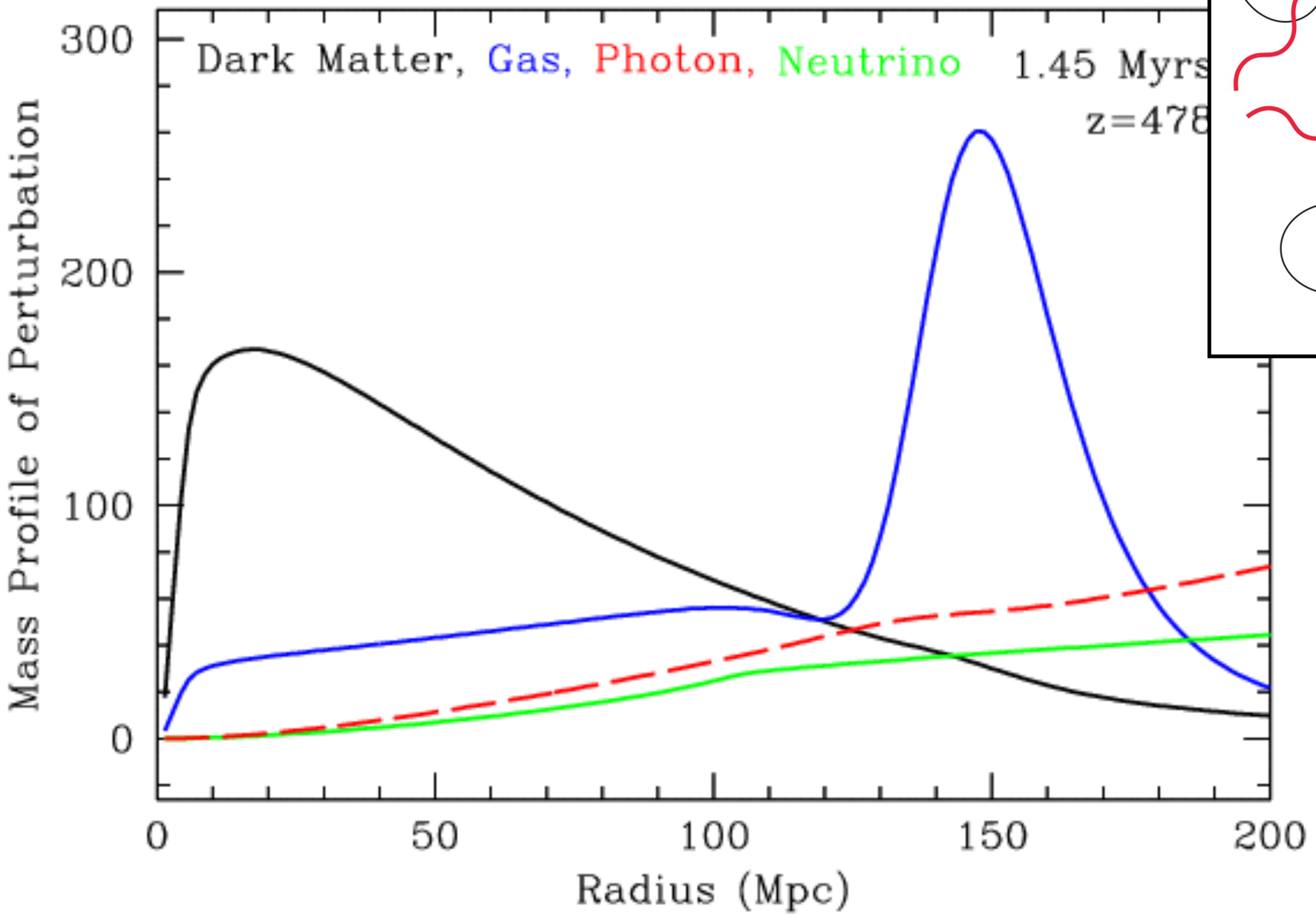


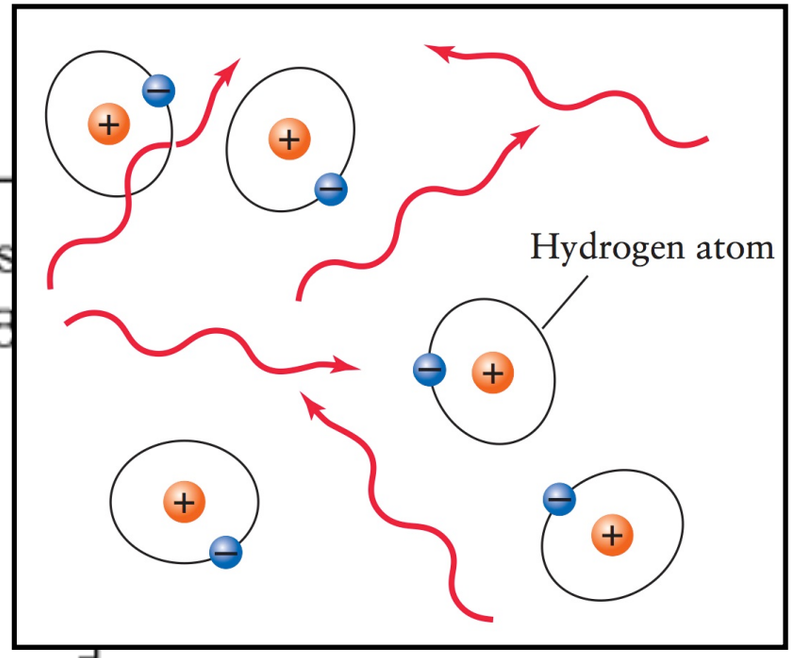


Credit: Eisenstein's web & «Universe» (Freedman et al.) & «College Physics» (Knight et al.)

Baryon Acoustic Oscillations

Standard ruler

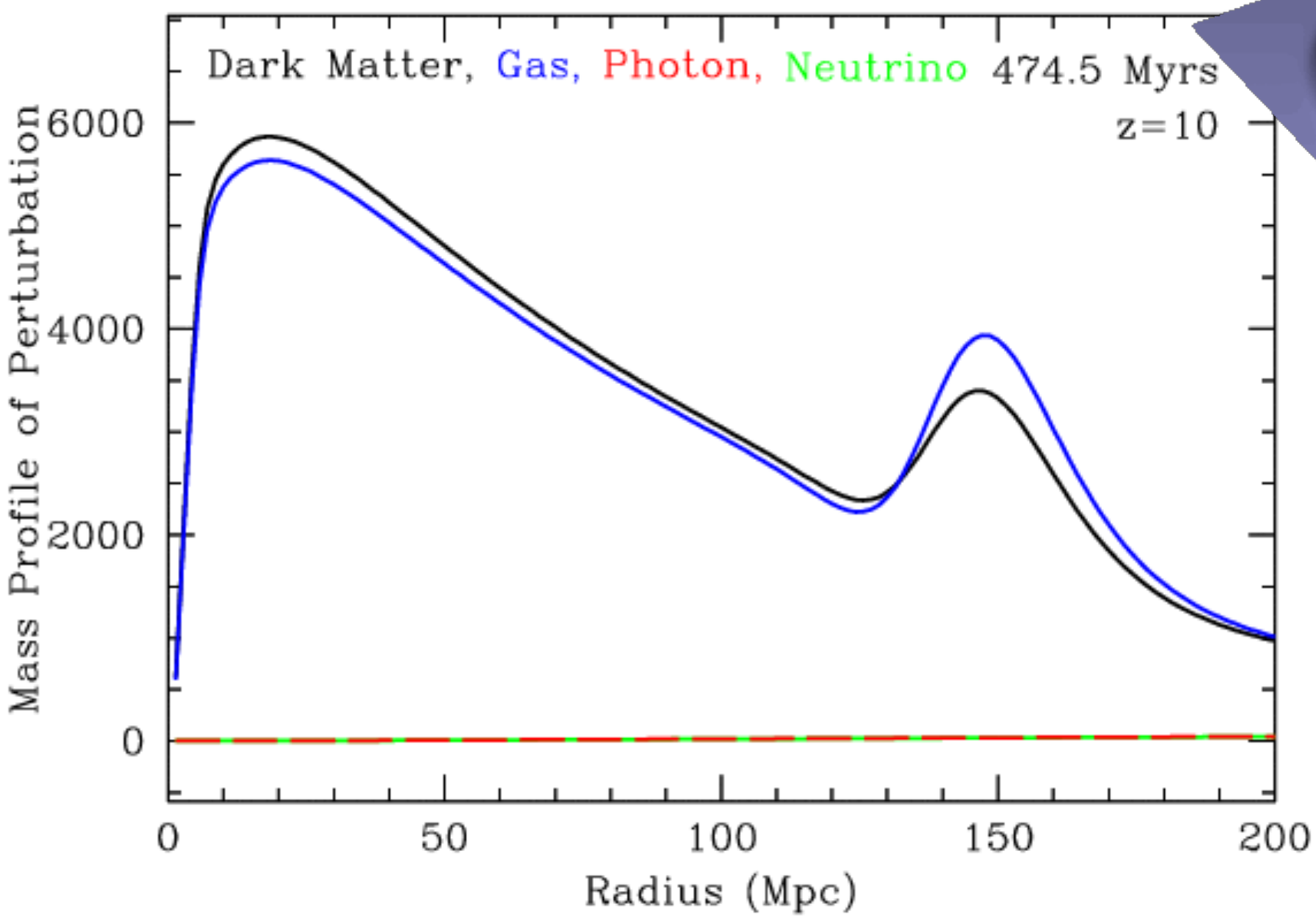


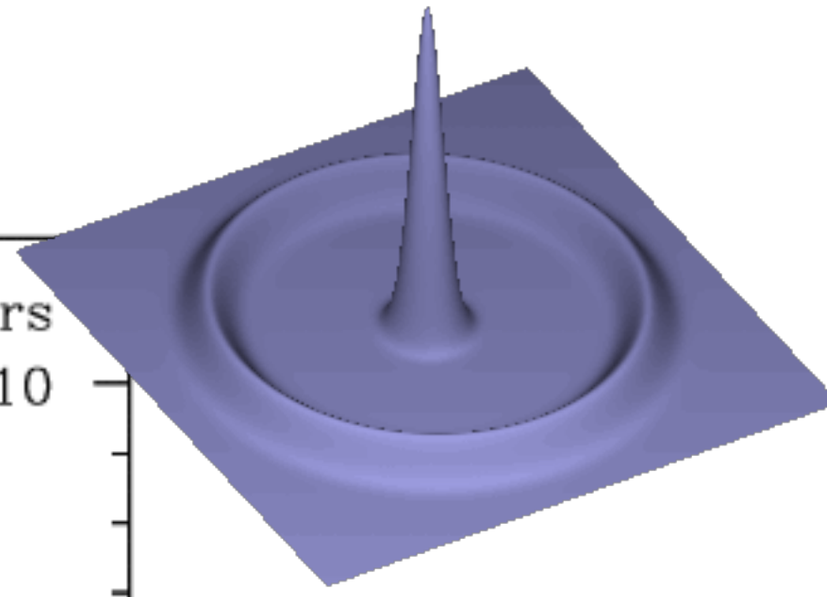


Credit: Eisenstein's web & «Universe» (Freedman et al.)

Baryon Acoustic Oscillations

Standard ruler

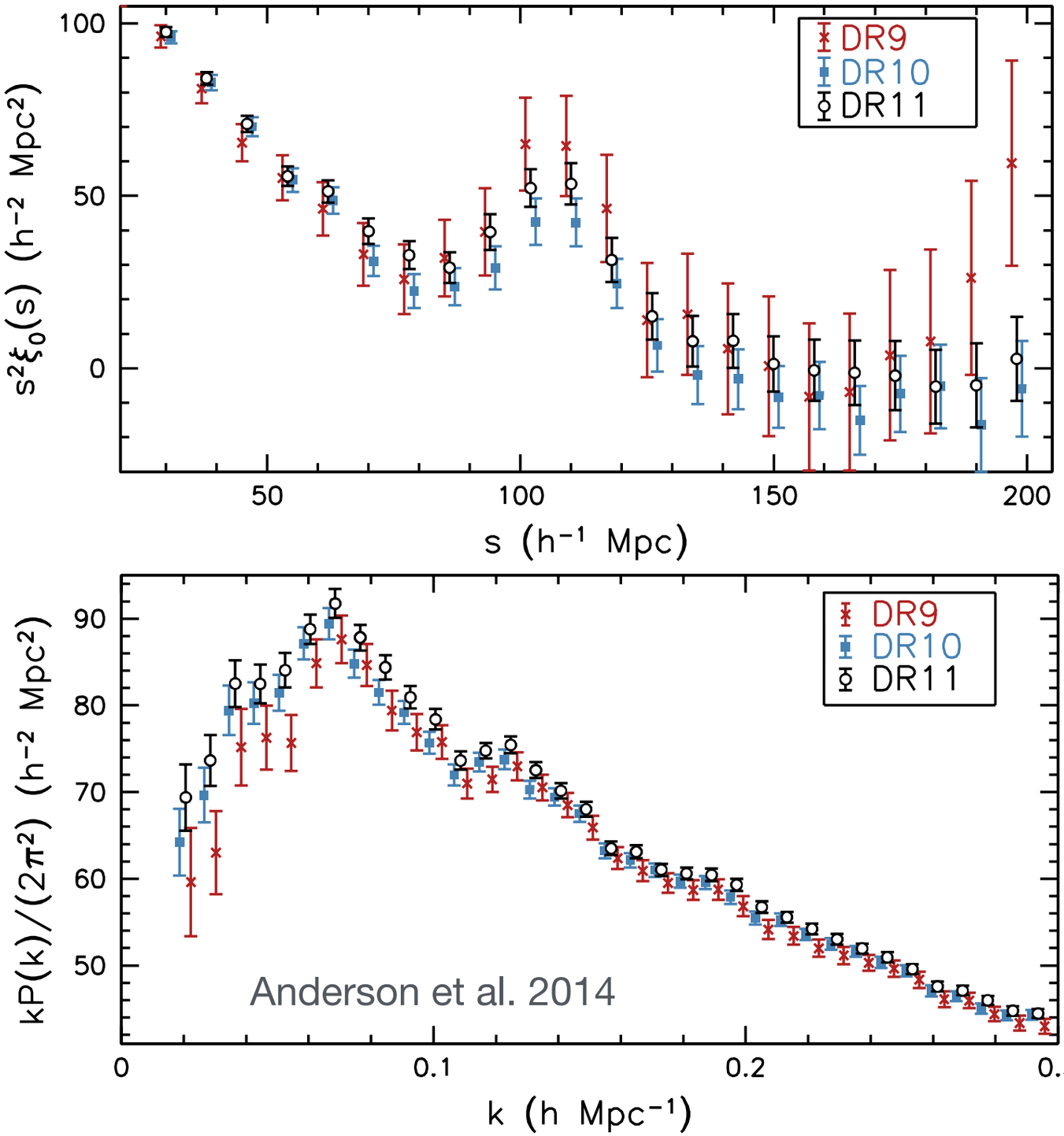


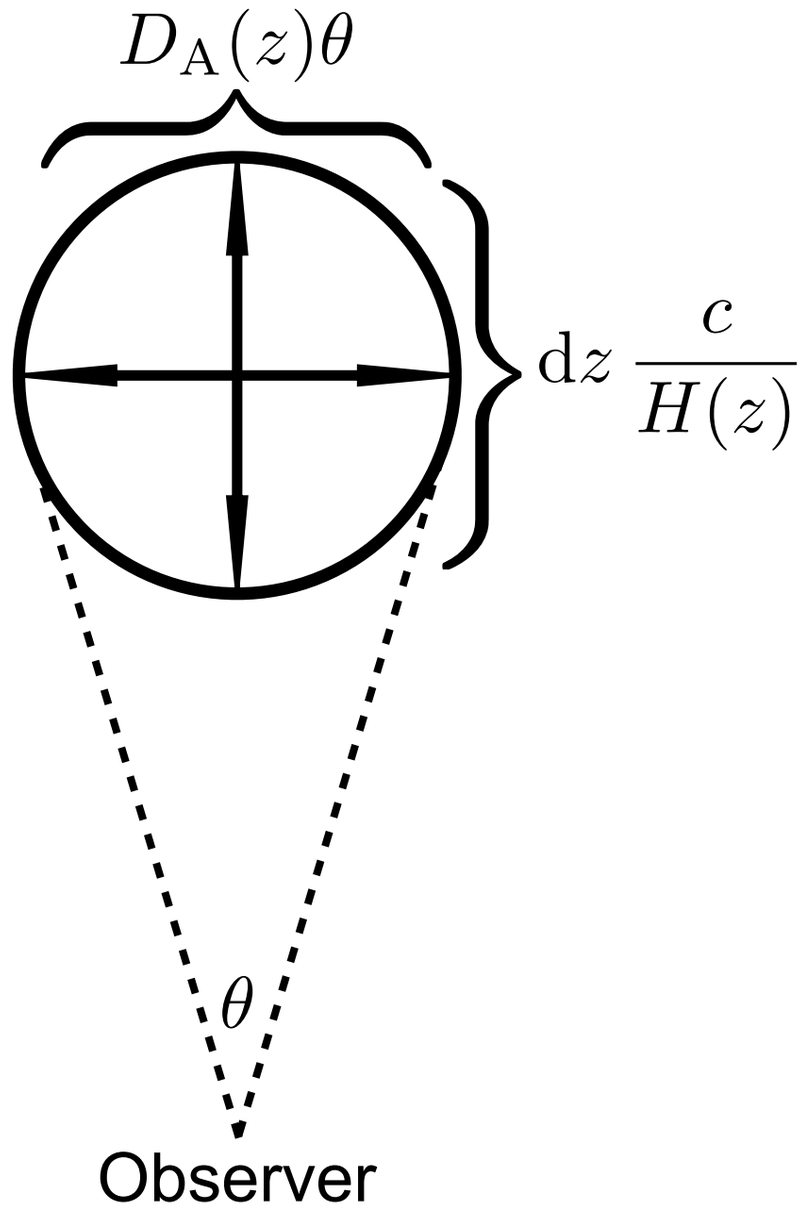


Credit: Eisenstein's web

Baryon Acoustic Oscillations

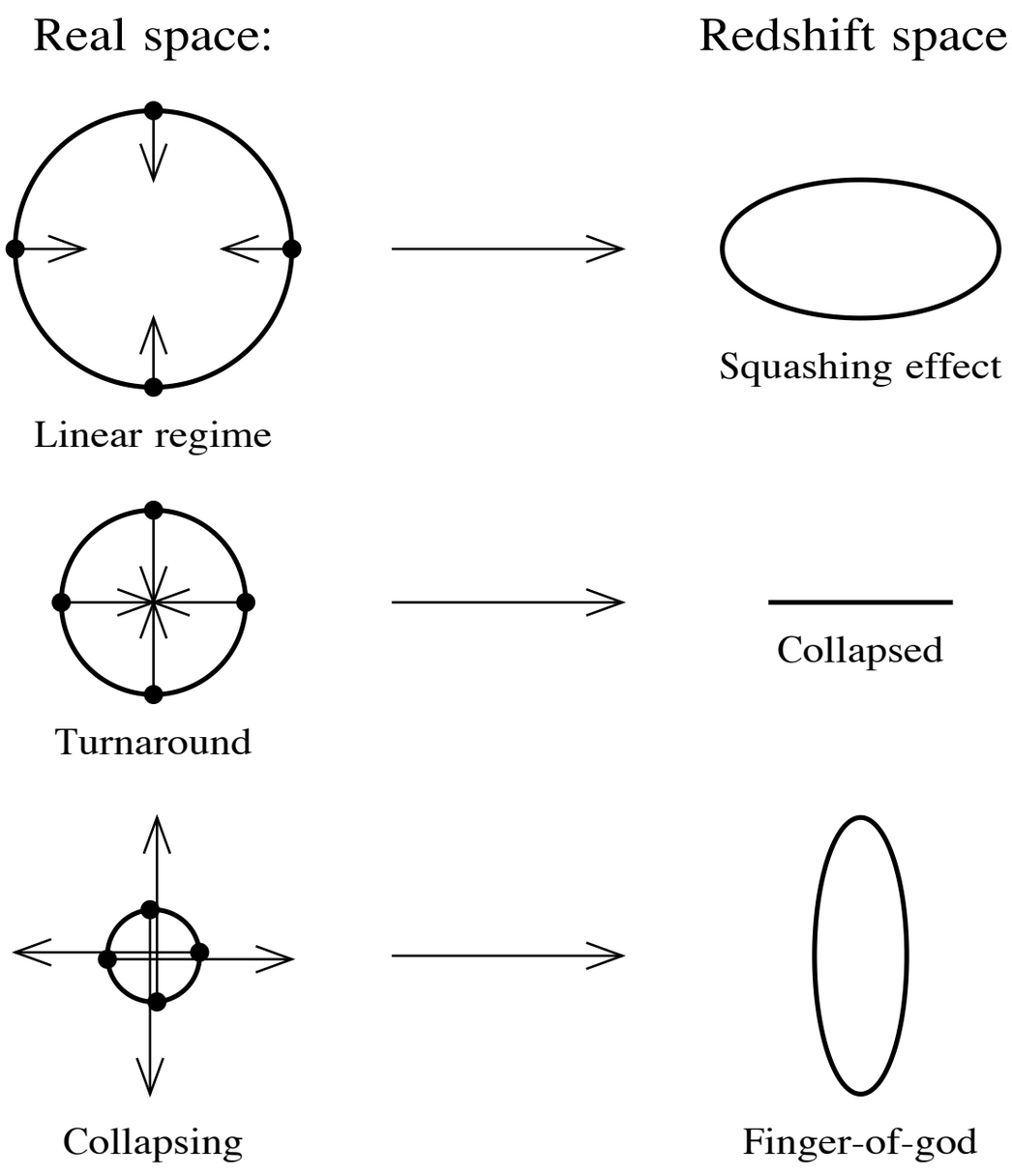
Standard ruler



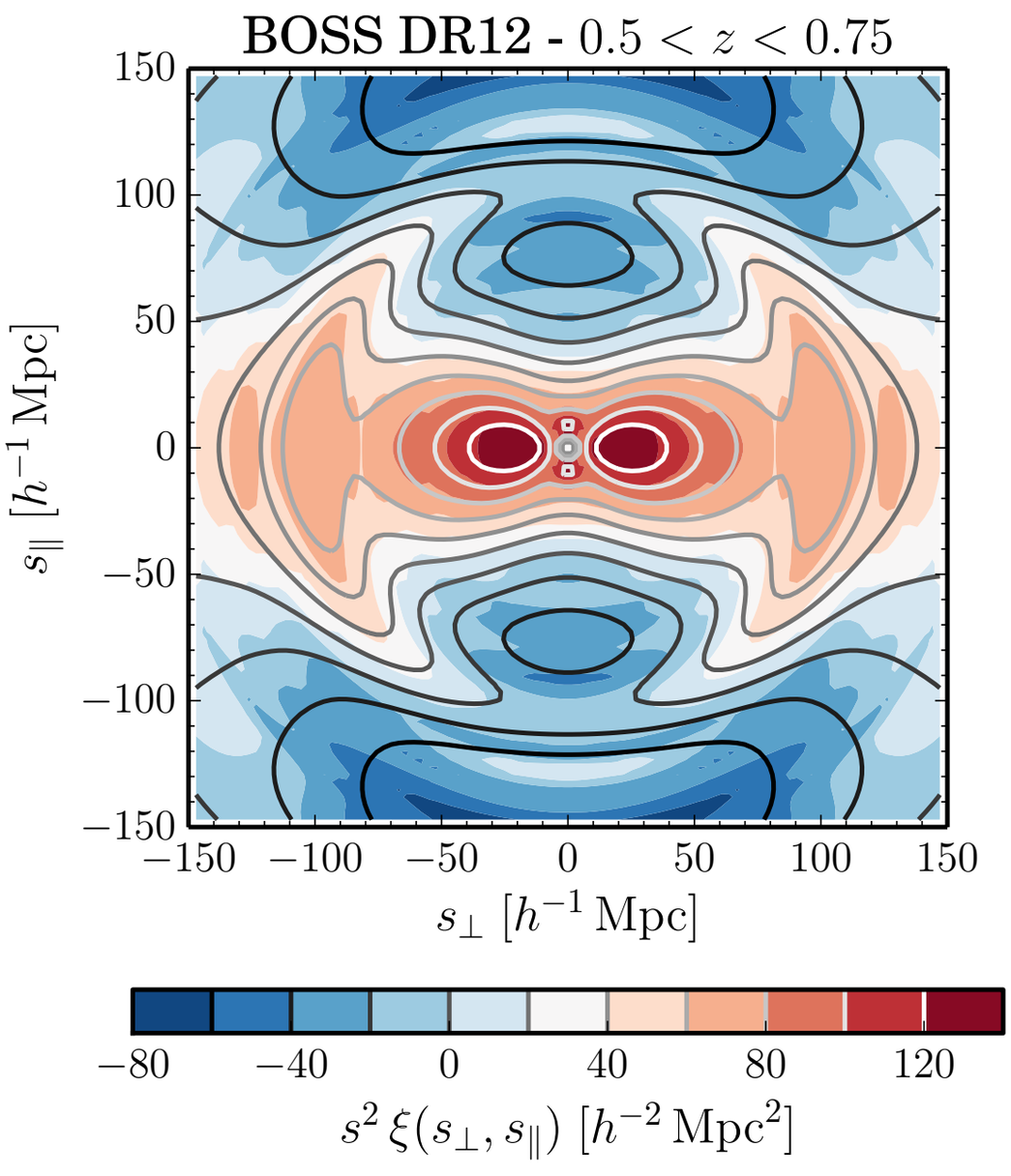


Redshift Space Distortions

Growth of structures

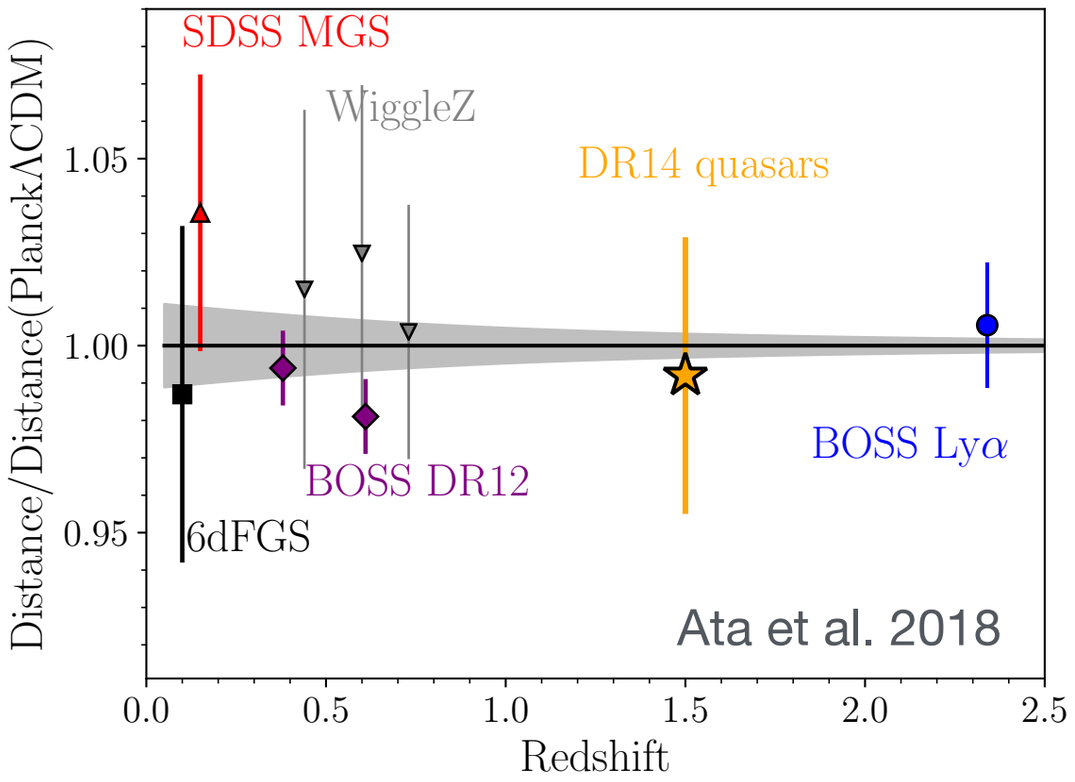


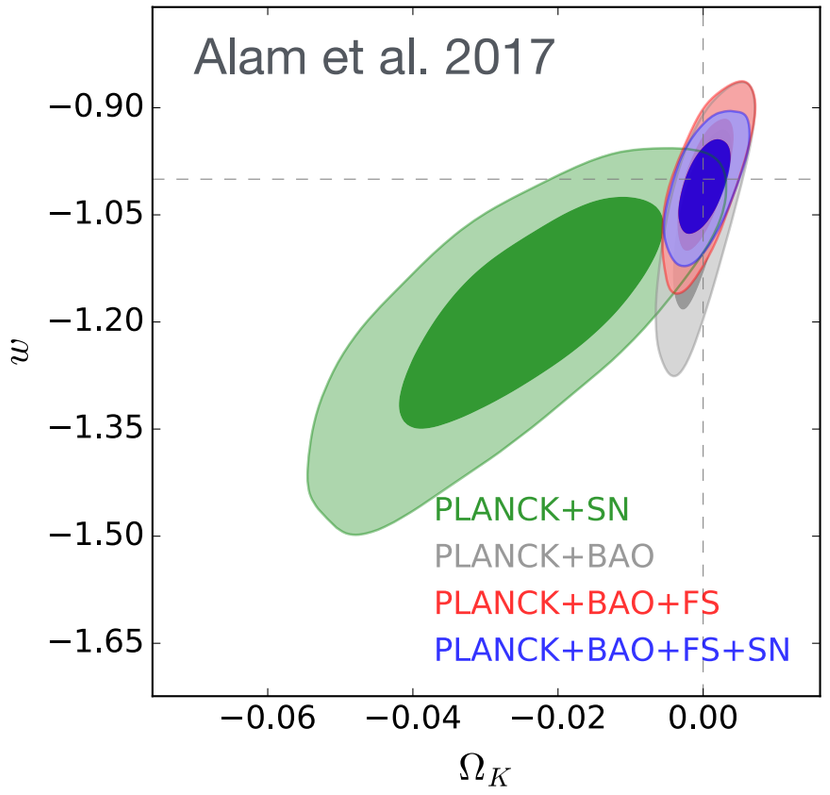
Hamilton 1998

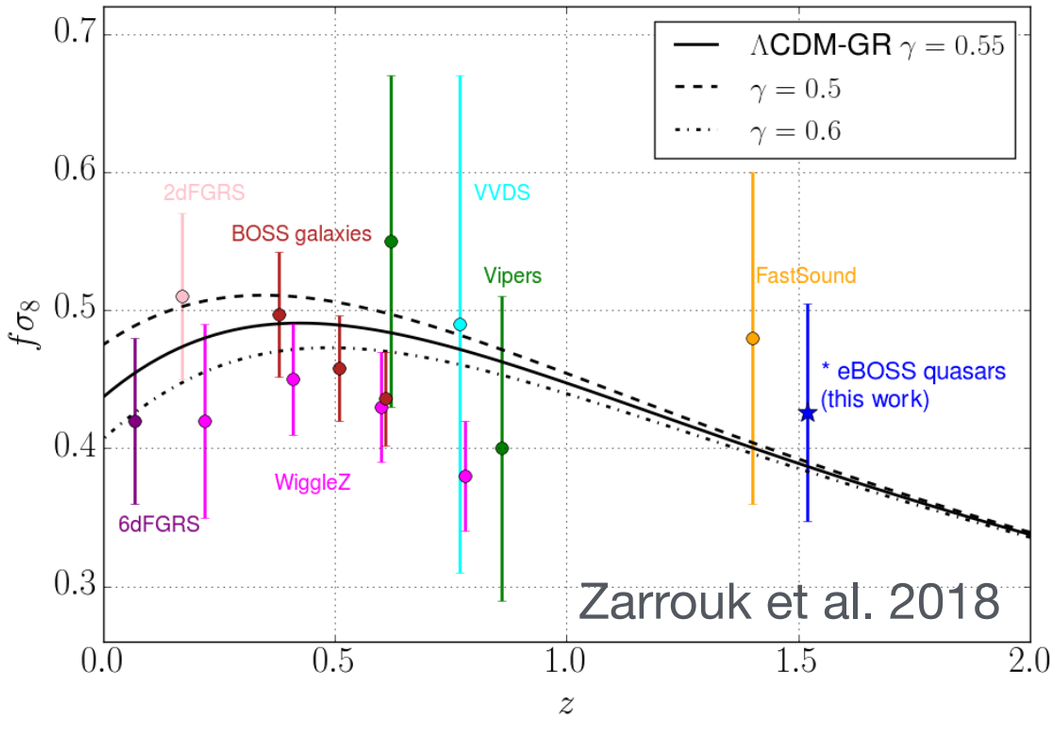


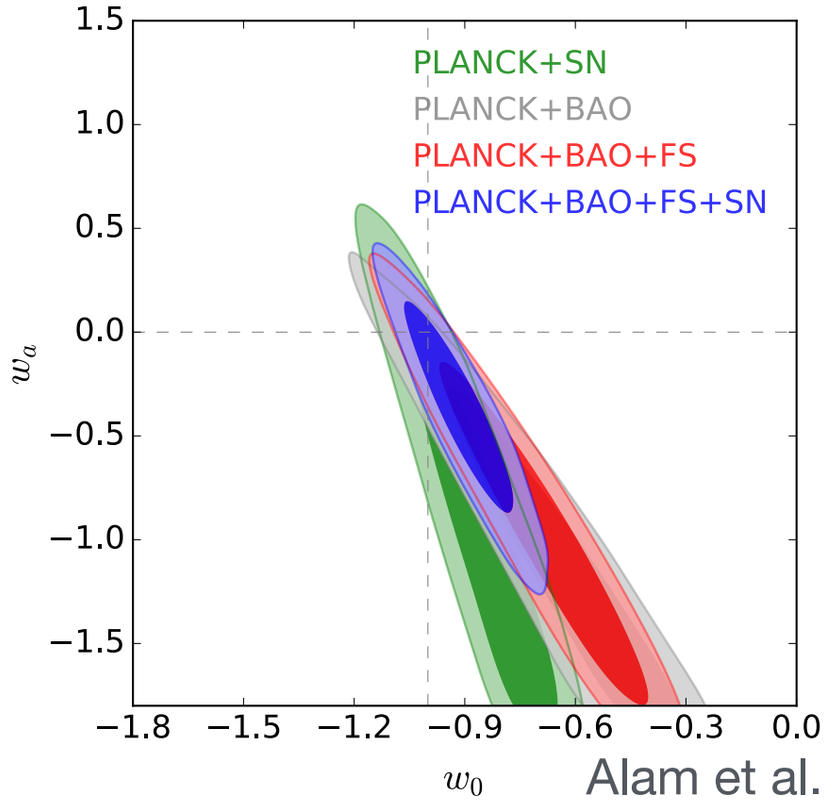
Alam et al. 2017

Key scientific goals





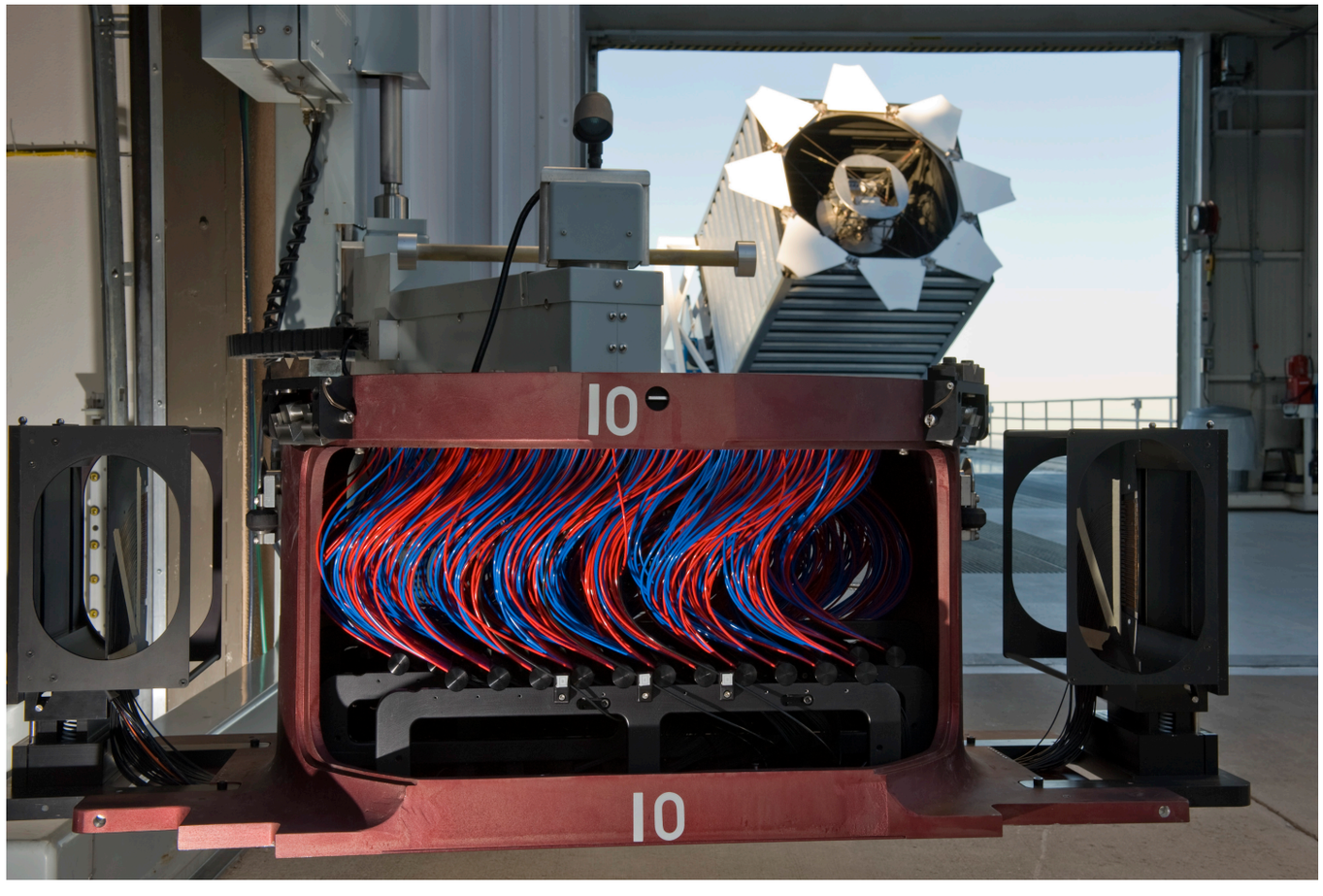


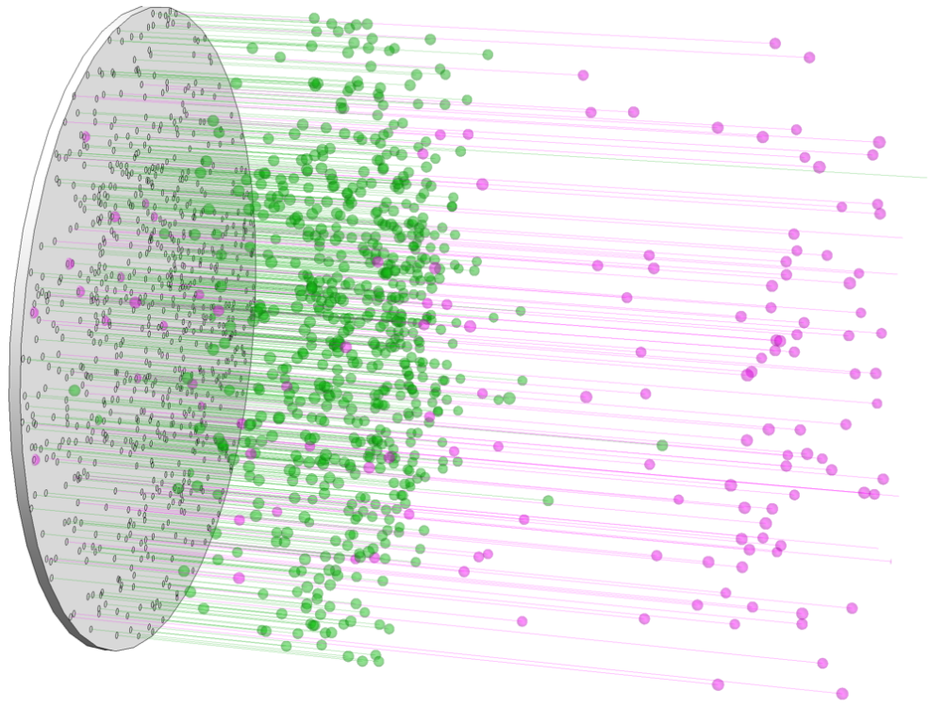


The SDSS telescope

Apache Point Observatory

- 2.5 metres, field-of-view of 7 deg^2
- SDSS spectrograph (2000-2008): 640 fibres
- BOSS spectrograph (2008-): 1000 fibres



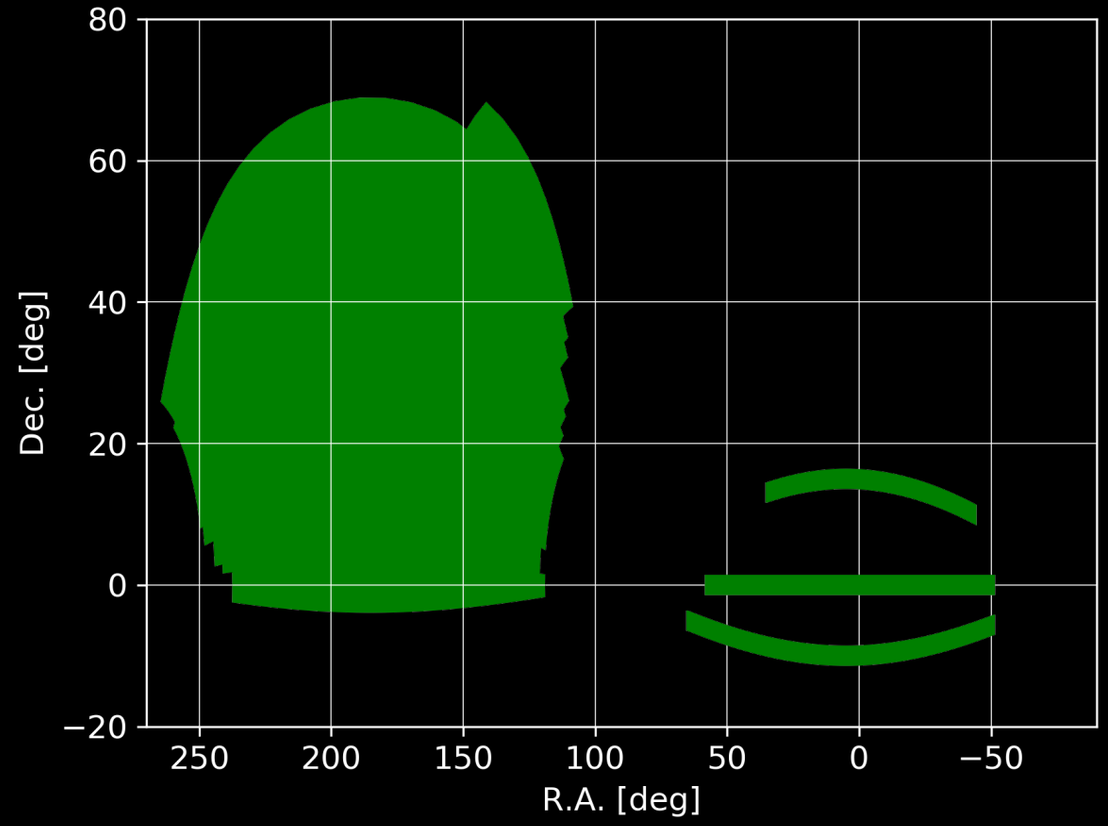


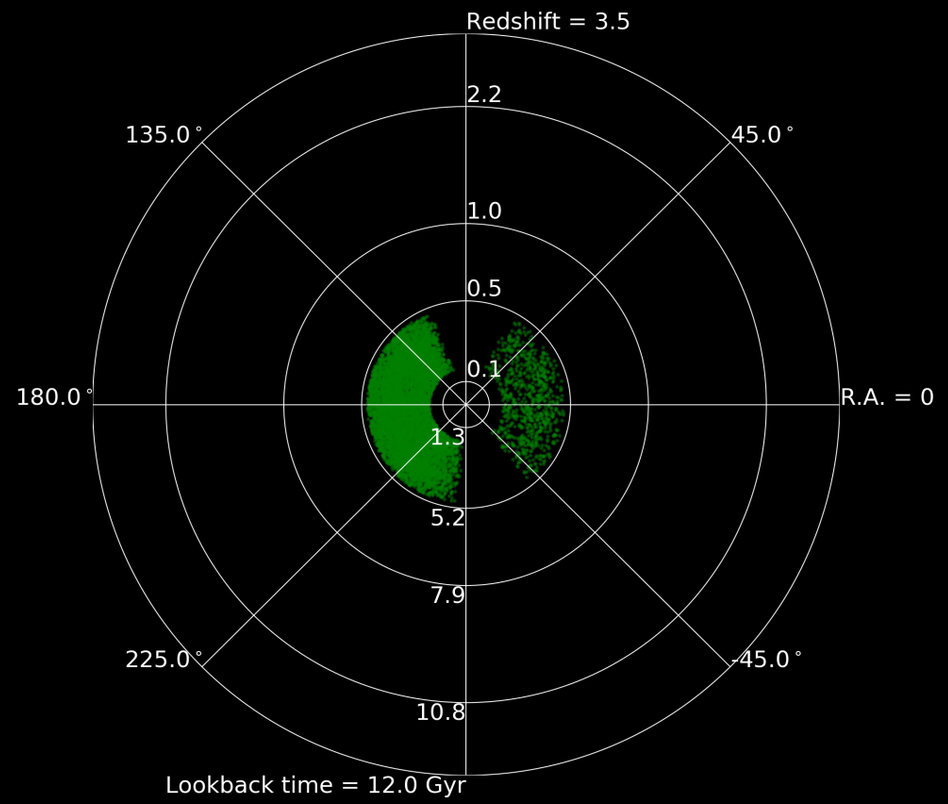
Credit: D. Kirkby

LSS surveys with the SDSS telescope

SDSS-LRG sample (2000-2008)

- 100k LRG at z ~ 0.35
- 2005: co-first BAO measurement with 45k LRG (5% precision), along with 2dFGS



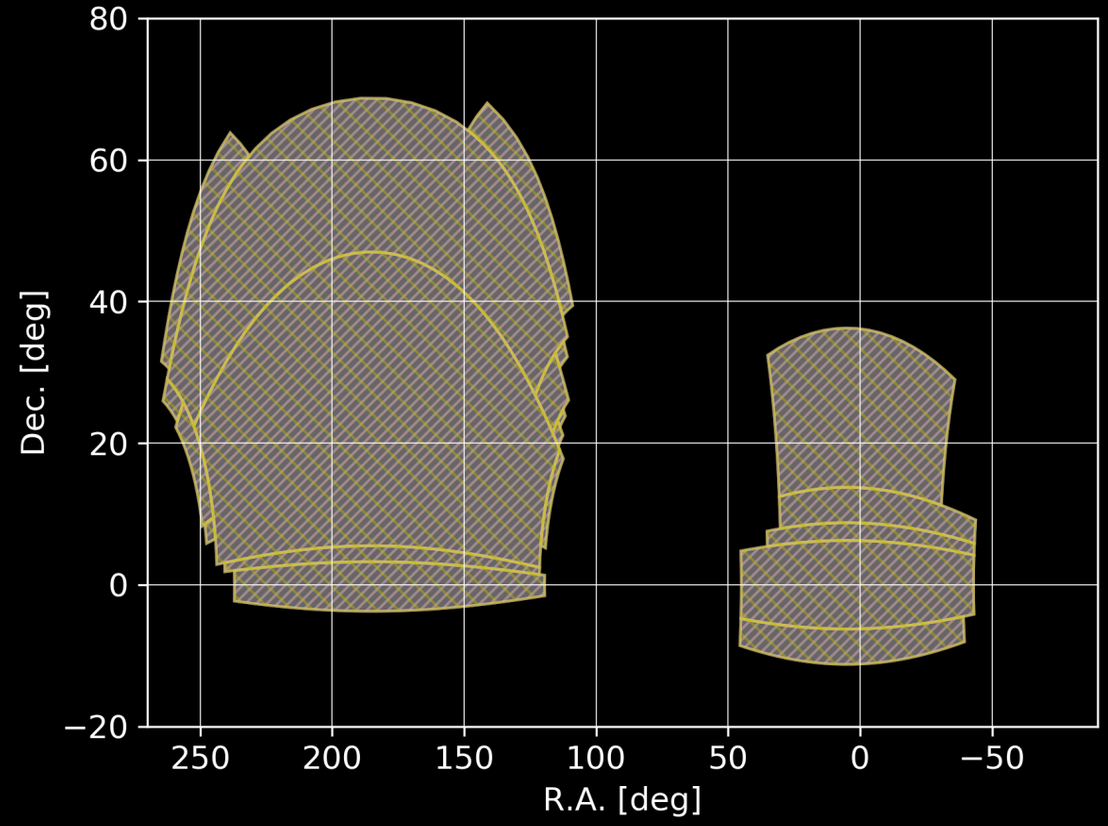


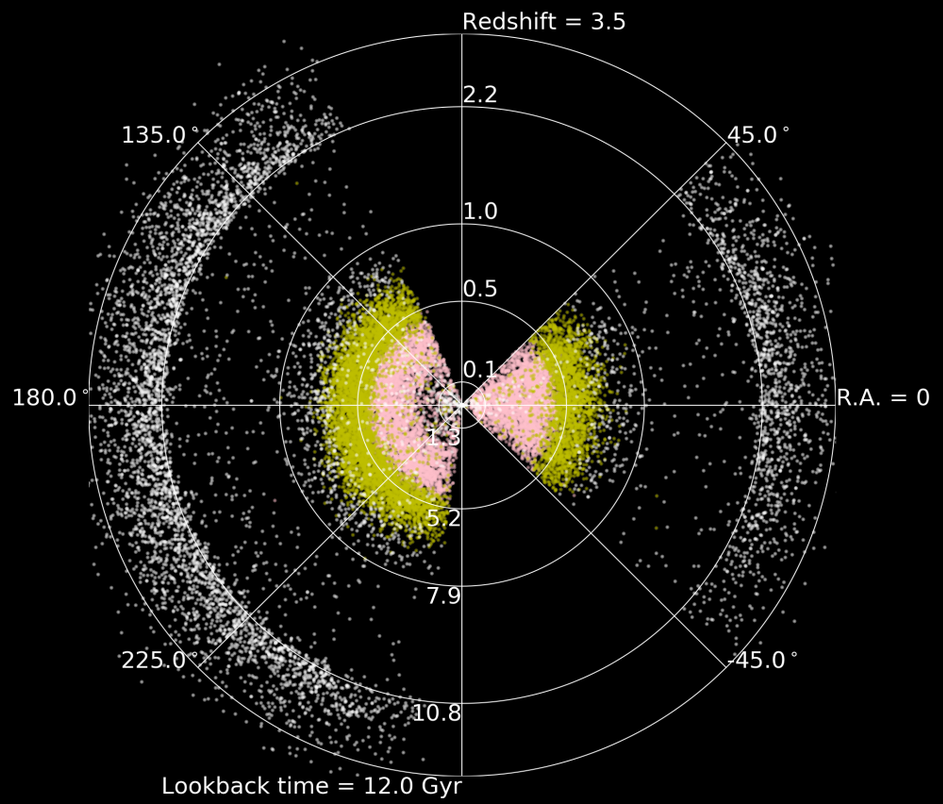
Credit: A. Raichoor

LSS surveys with the SDSS telescope

SDSS-BOSS sample (2008-2014)

- 1.5M spectra over 10k deg^2
- 2 tracers: 1.3M LRG at $0.2 < z < 0.75$ and 0.2M Lyα at $z \sim 2.3$
- BAO: 1-2% precision on distance measurement
- RSD: 8% precision on $f \cdot \sigma_8$ measurement



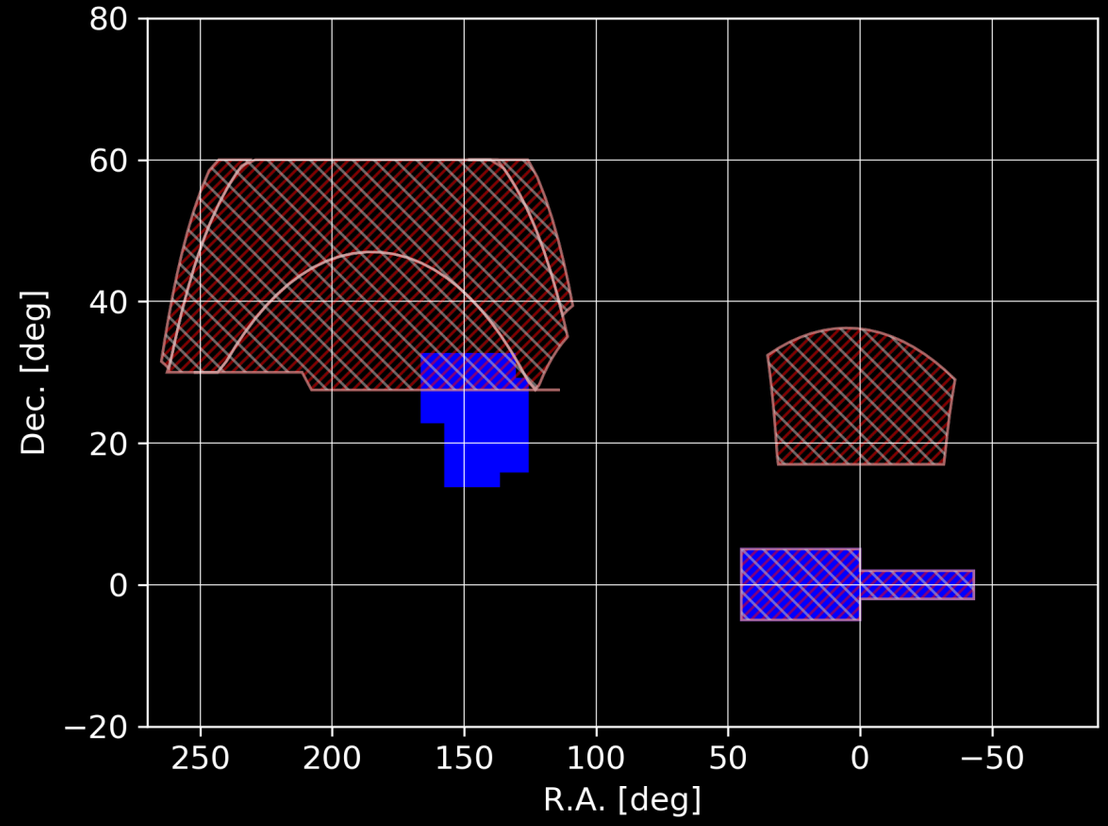


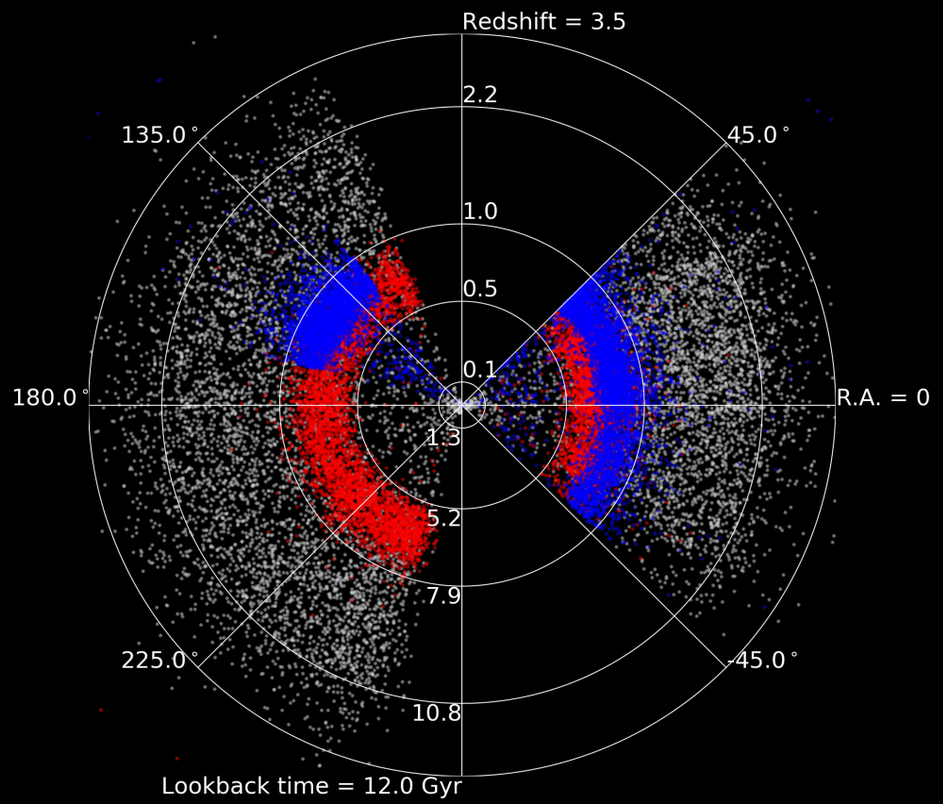
Credit: A. Raichoor

LSS surveys with the SDSS telescope

SDSS-eBOSS sample (2014-2019)

- 1M spectra over 8k deg^2
- 3 tracers: LRG (0.6<z<1.0), ELG (0.6<z<1.1), QSO+Lyα (0.8<z<3.5)
- Results with **incomplete** sample (DR14)
  - BAO: BAO: 3-4% precision on distance measurement (LRG, QSO)
  - RSD: 18% precision on $f \cdot \sigma_8$ measurement (QSO)





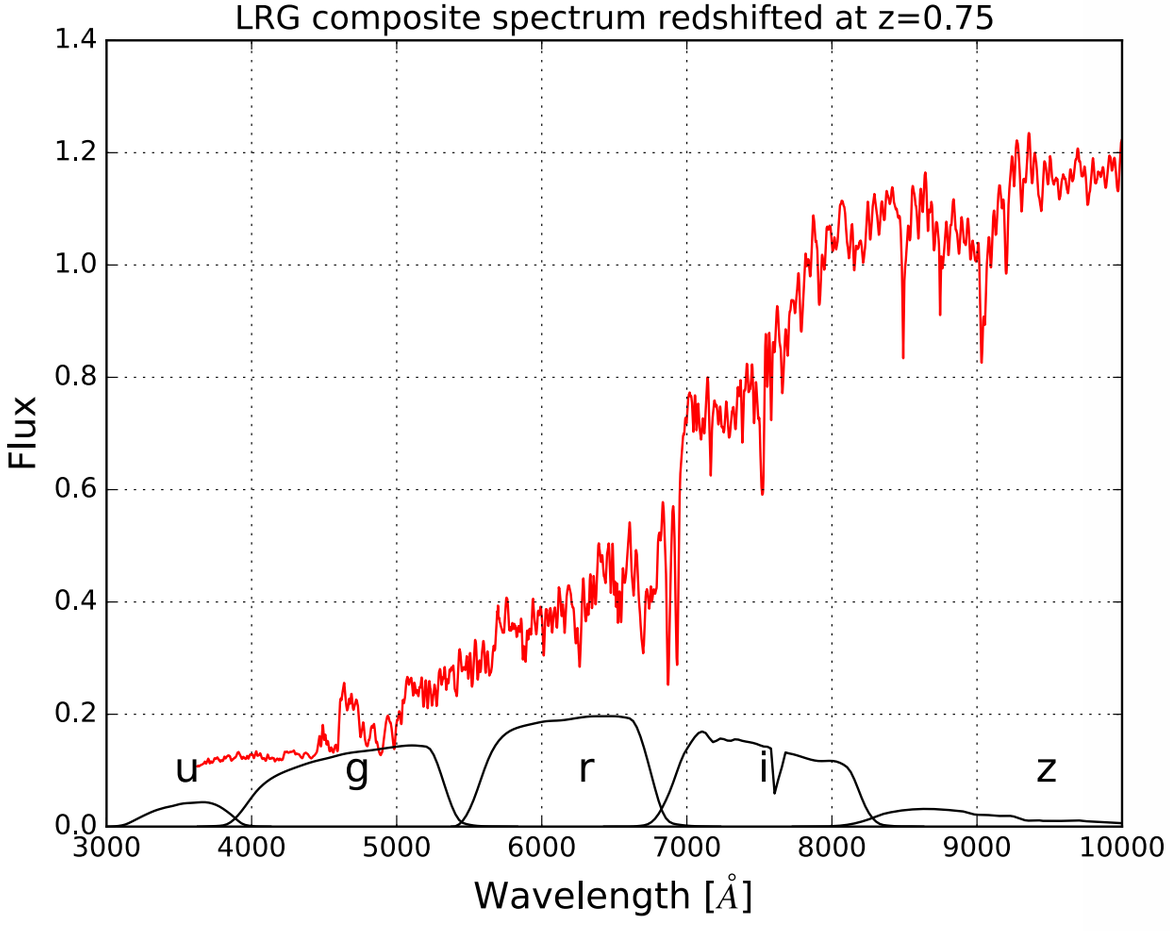
Credit: A. Raichoor

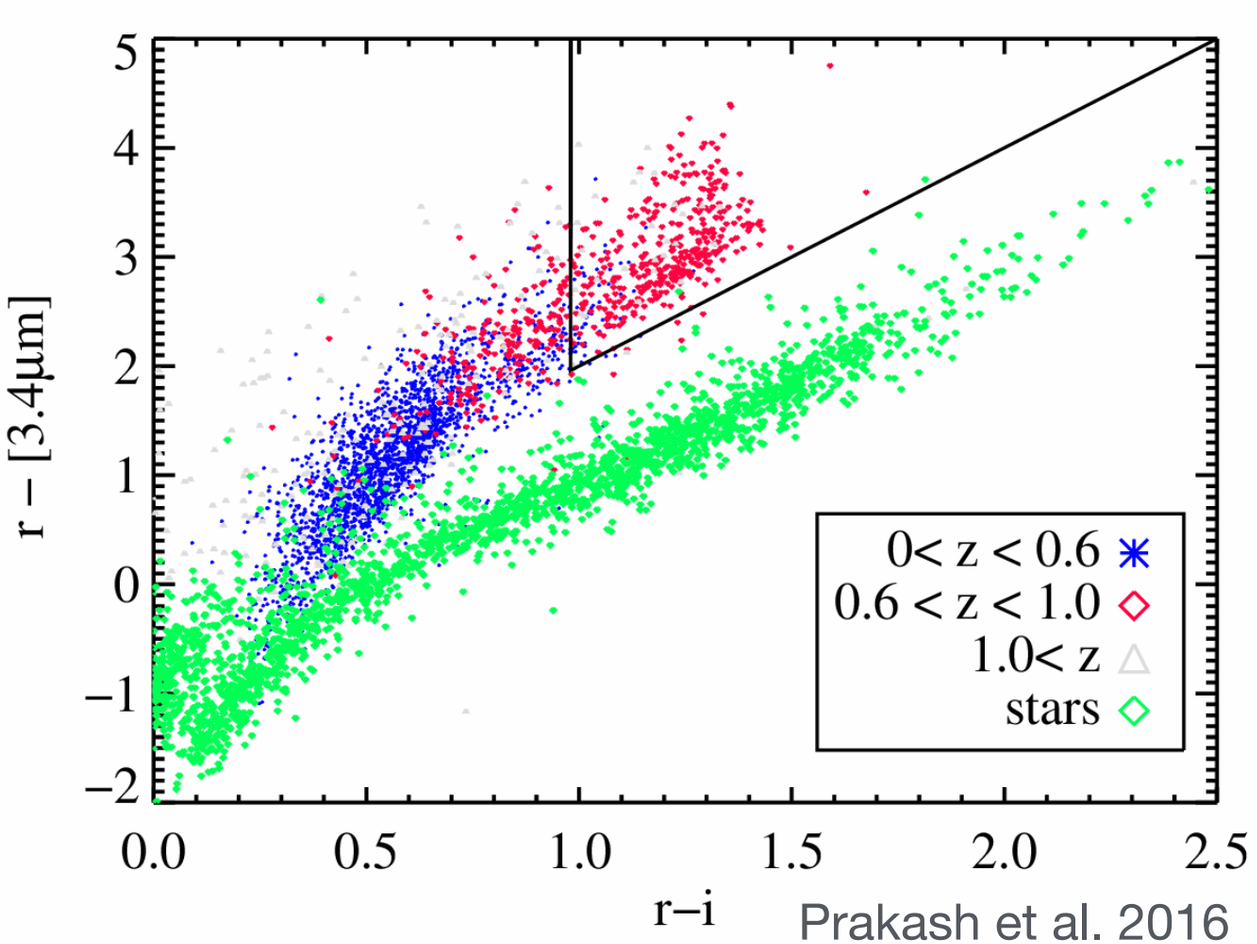
eBOSS Survey infrastructure

- Operations software (2013–2019) ➔ UW software developers
- Observations (2014–2019) ➔ APO observatory staff
- Imaging (2013-2014) ➔ WISE (Lang et al. 2016)
- Targets (2013-2015) ➔ Jeremy Tinker (NYU)
- Tiling (2013-2018) ➔ Hee-Jong Seo (Ohio)
- Mountain operations (2014-2017) ➔ Vivek Mariappan (Utah/ PennState)
- Calibrate 1D spectra (2013-2018) ➔ Julian Bautista (Utah/ Portsmouth), Stephen Bailey + Julien Guy (LBL)
- Redshift determination (2013-2019) ➔ Tim Hutchinson + Helion du Mas des Bourboux (Utah), Isabelle Paris (Marseille), Stephen Bailey (LBL), Brad Lyke (Wyoming)
- Clustering catalog (2015-2019) ➔ Rita Tojeiro (St. Andrews), Ashley Ross (Ohio State), Arnaud de Mattia (CEA)

eBOSS target selection: LRG

- Selection criteria
  - Avoid BOSS targets ➔ « dim » cut in i-mag
  - Balmer break (redshift selection) ➔ « red » cut in r–i and i–z
  - Avoid foreground stars ➔ « red » cut in r–infrared
- Target density: ~ 60 deg^{-2}

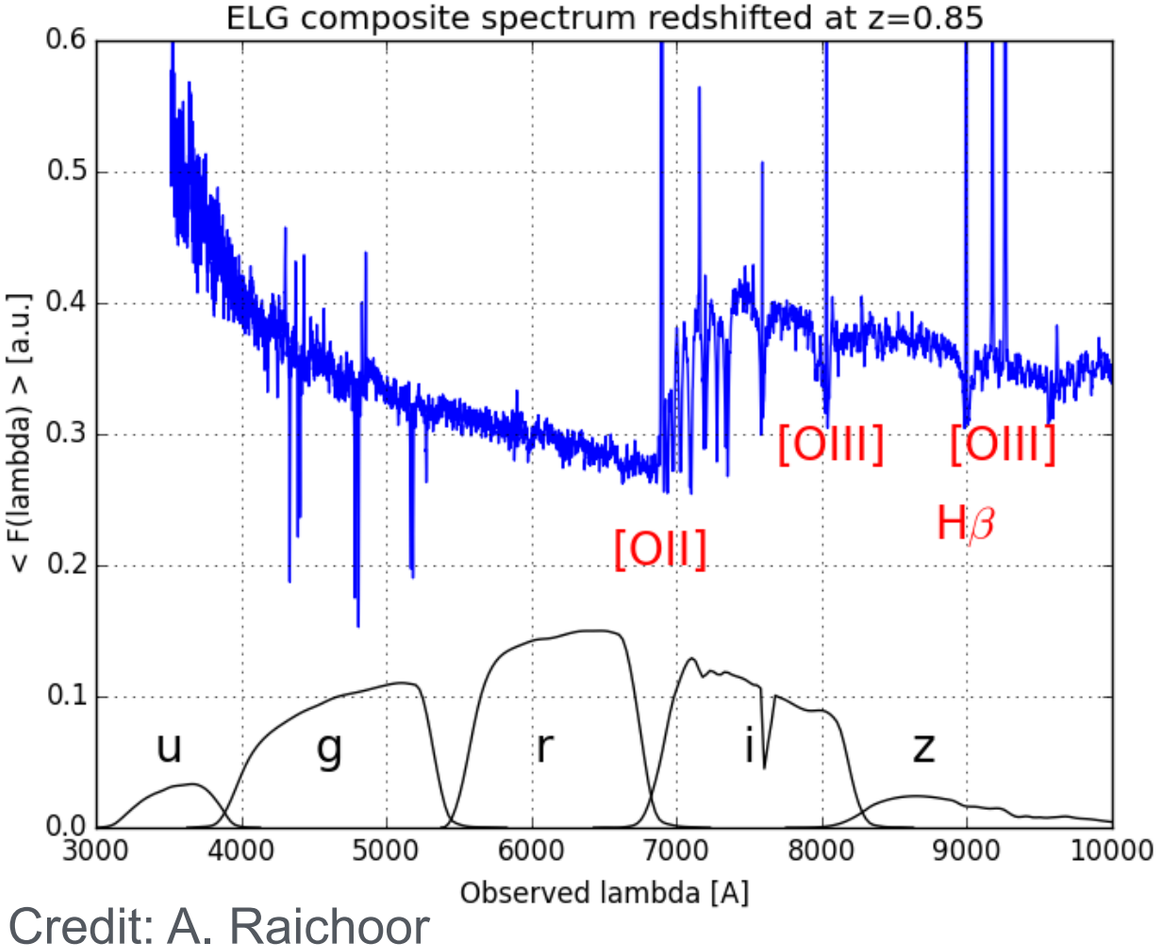




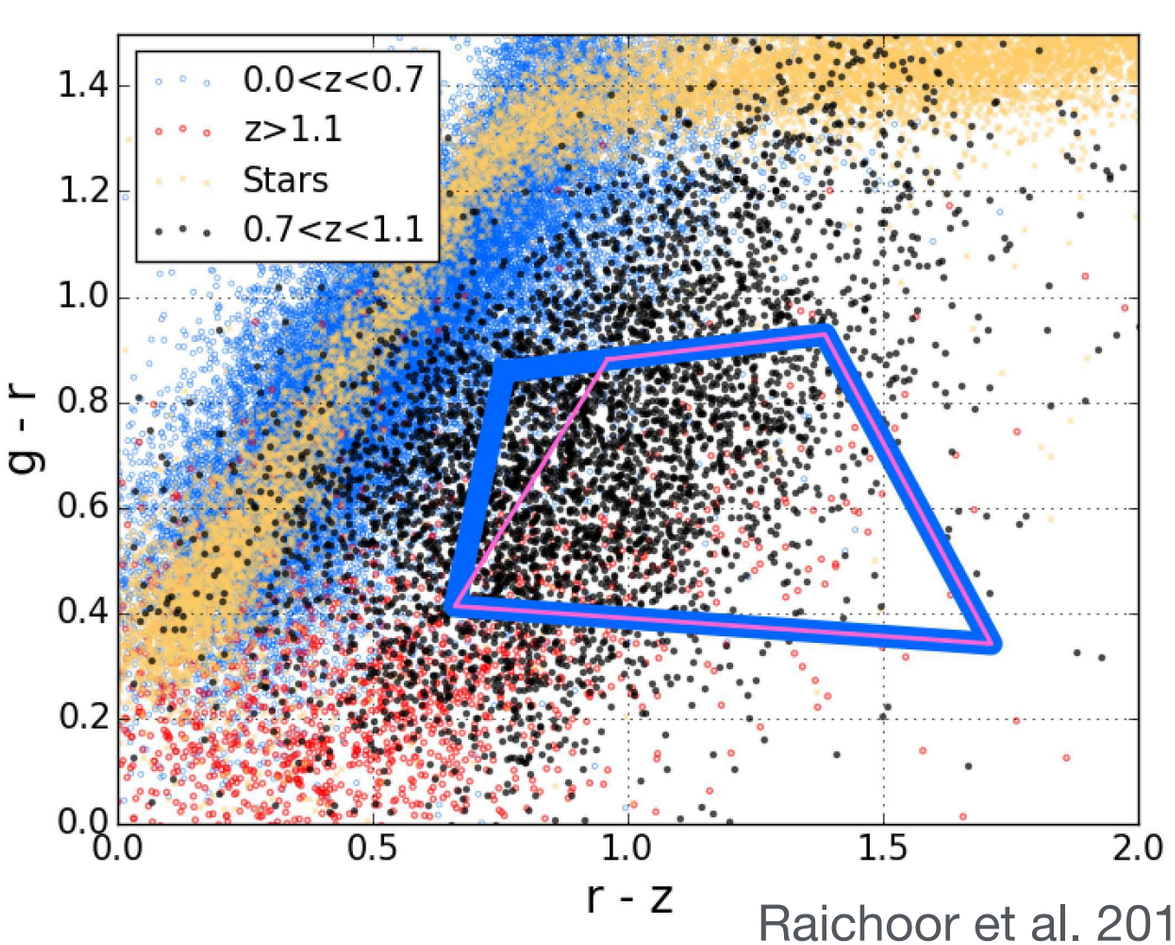
Prakash et al. 2016

eBOSS target selection: ELG

- Selection criteria
  - Star-forming ➔ « blue » cut in g–r
  - Balmer break ➔ « red » cut in r–z
  - $[O_{II}]$ flux correlates with g-mag ➔ « bright » cut in g-mag
- Target density: ~ 230 deg^{-2}



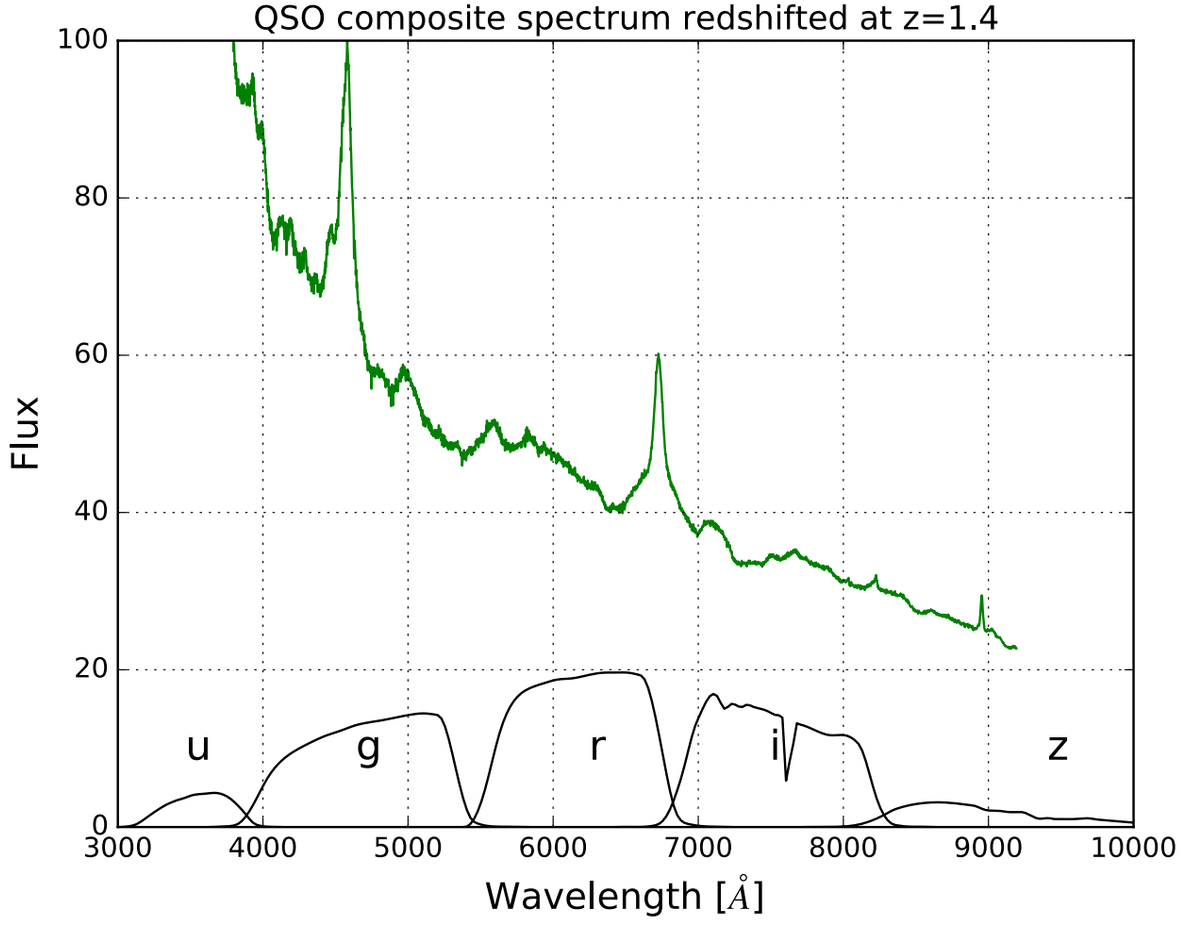
Credit: A. Raichoor

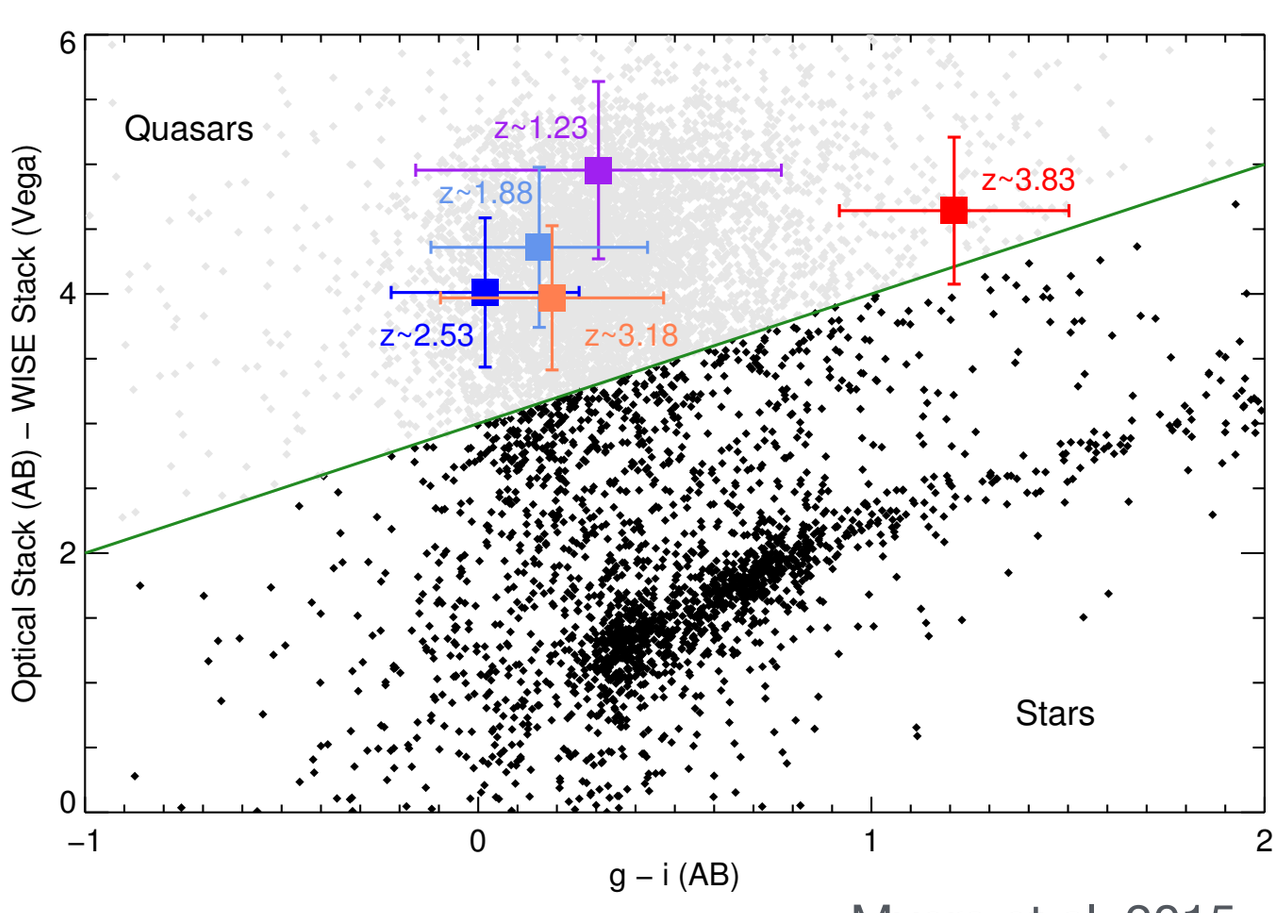


Raichoor et al. 2017

eBOSS target selection: QSO

- Selection criteria
  - Probabilistic selection ➔ `XDQSOz` algorithm (Bovy et al. 2012)
  - Remove contaminating stars ➔ « red » optical-infrared cut
- Target density: ~ 115 deg^{-2}



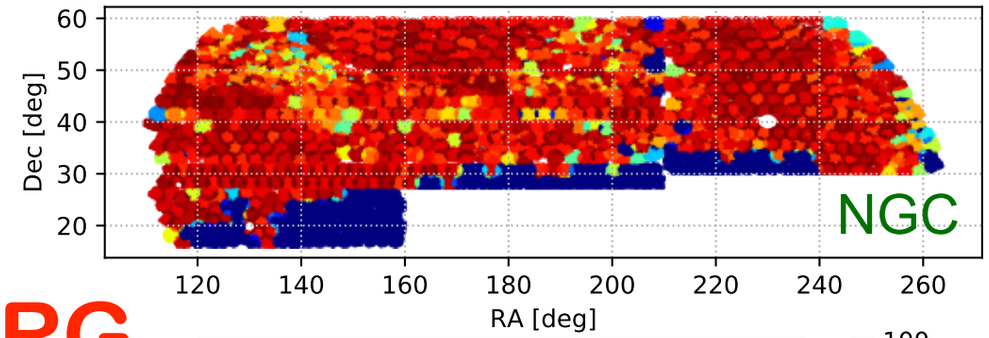


Myers et al. 2015

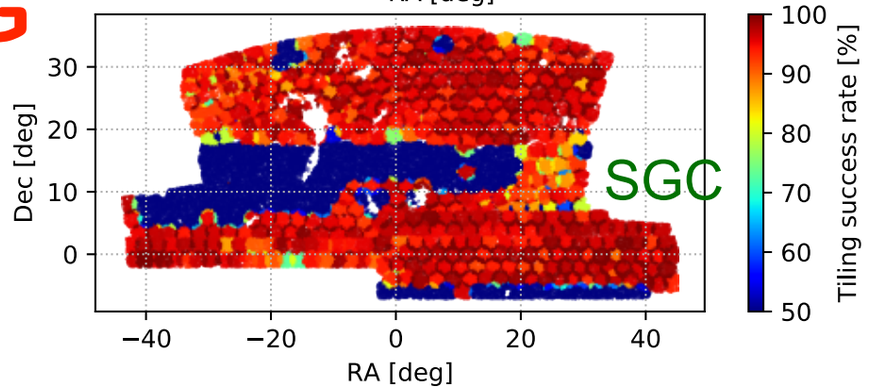
Tiling

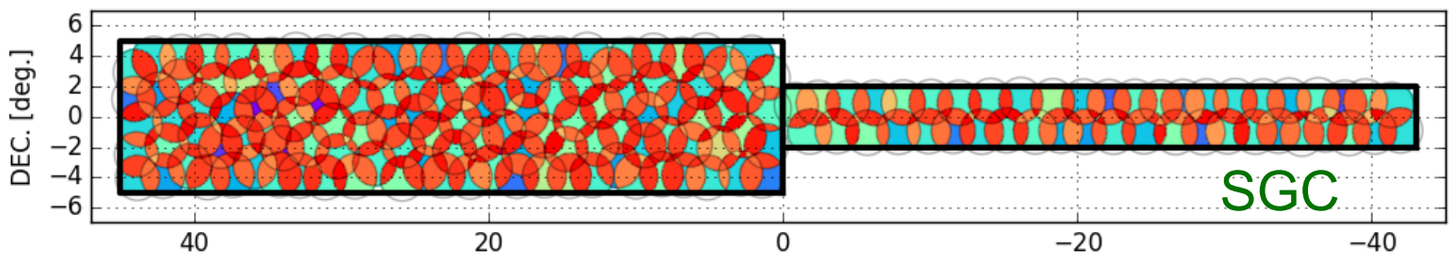
Distributing targets to plates

- 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



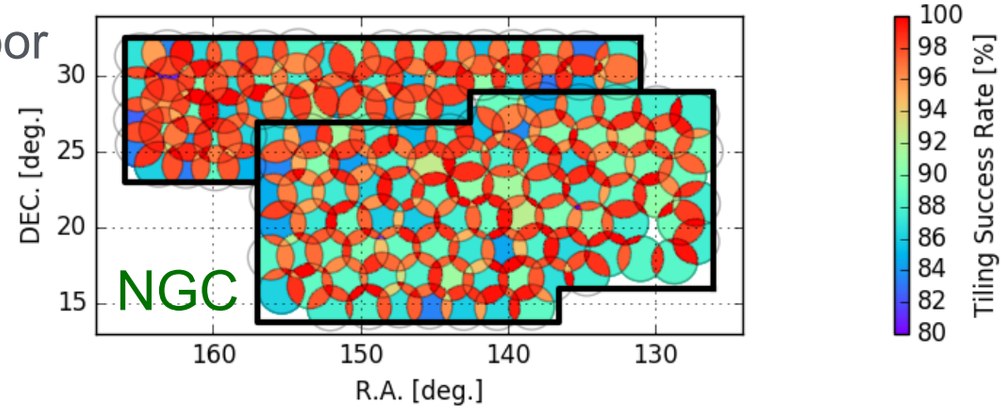
LRG

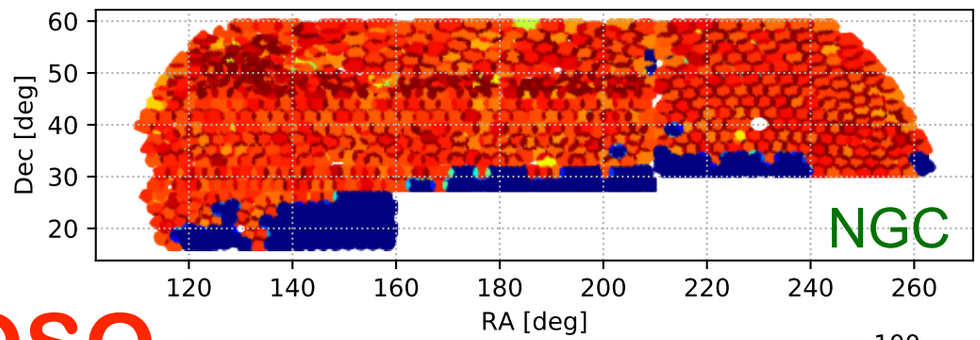




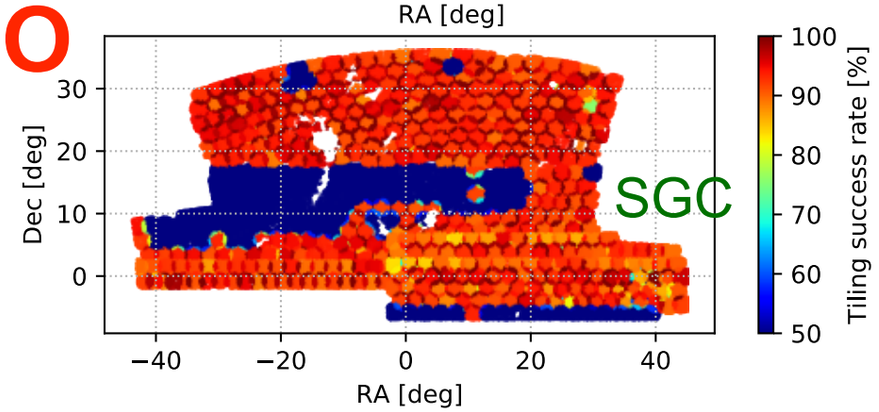
Credit: A. Raichoor

ELG



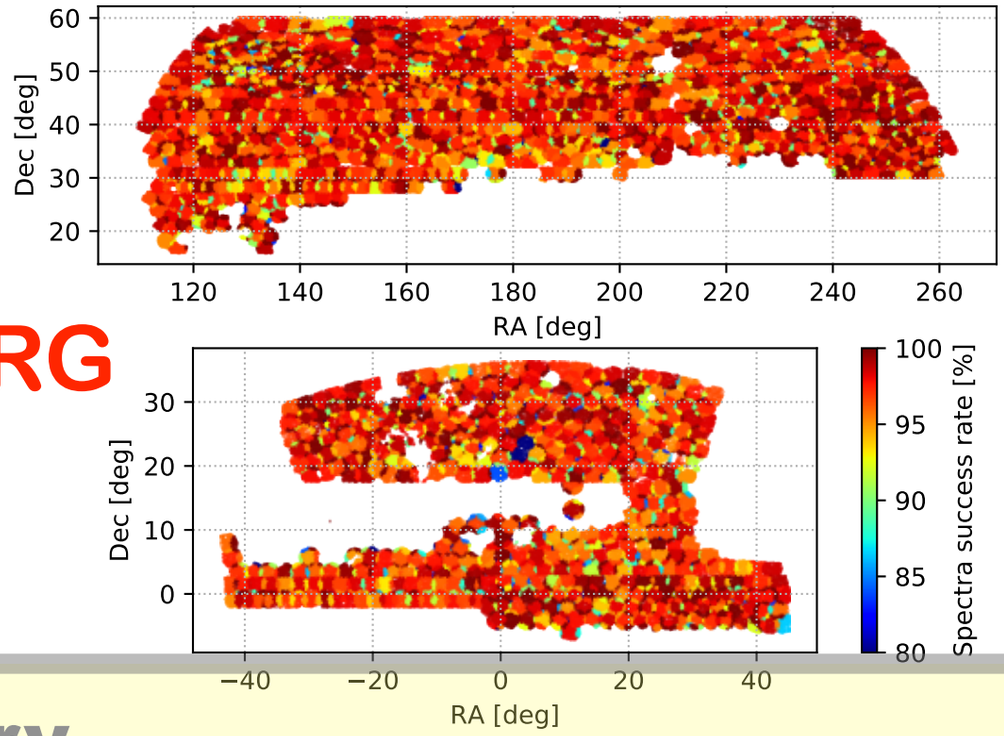


QSO

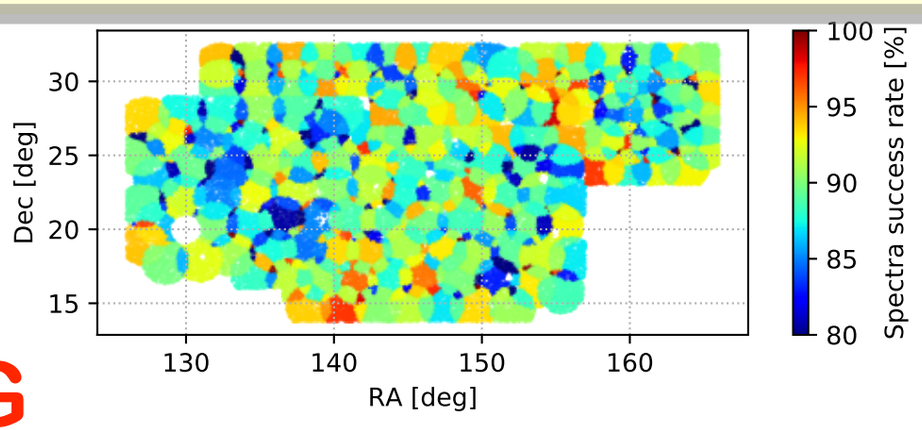


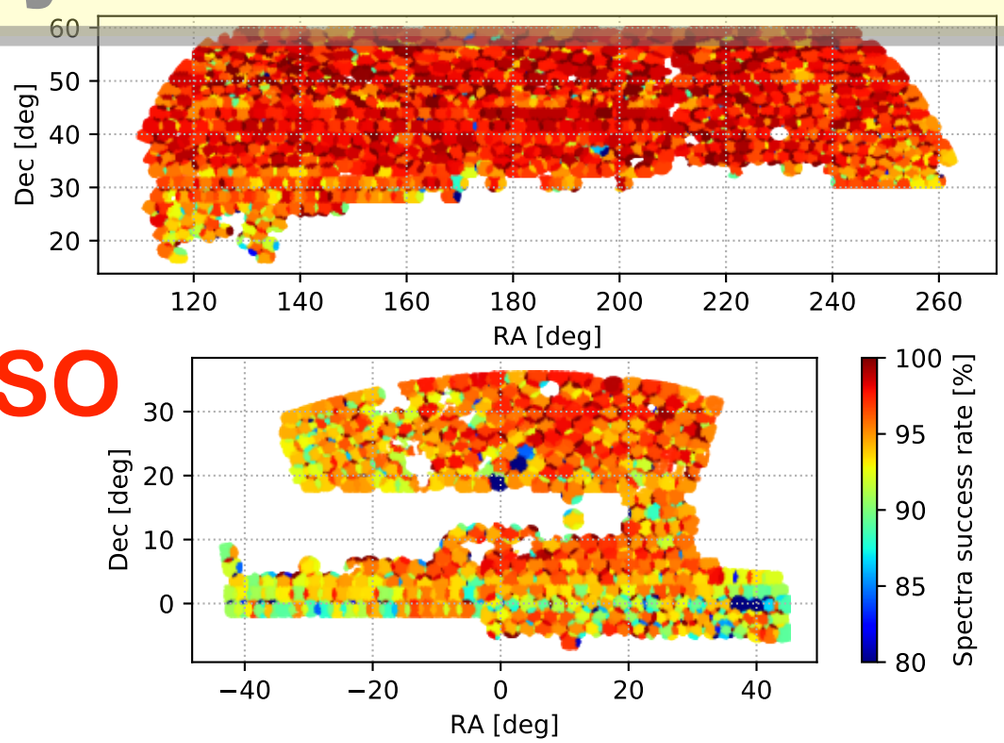
Redshift determination

- Sky subtraction: `idlspec2d`
  - http://www.sdss3.org/svn/repo/idlspec2d
- Redshift fitting: `redrock`
  - https://github.com/desihub/redrock



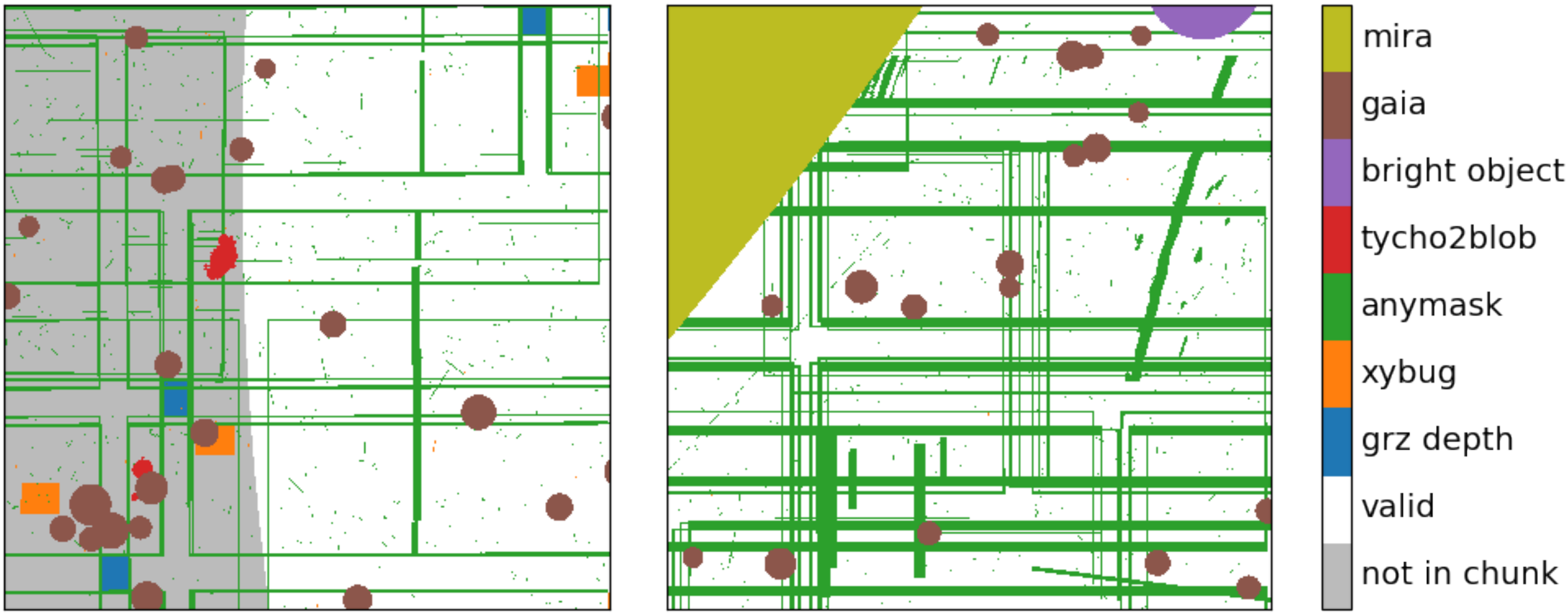
preliminary





LSS catalogue creation

Veto mask (ELG)

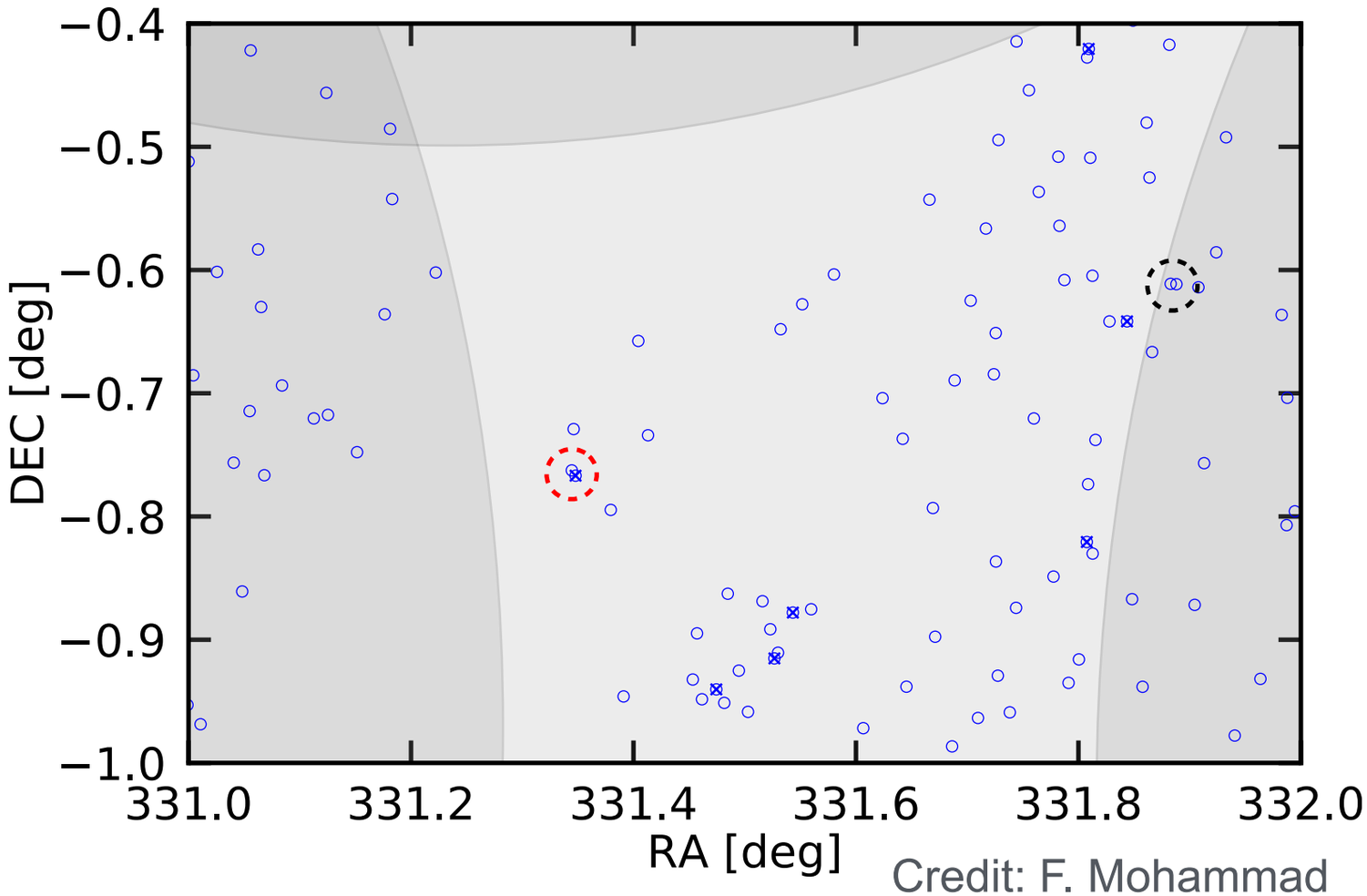


3600 pixel (~0.25 deg) per side for each brick

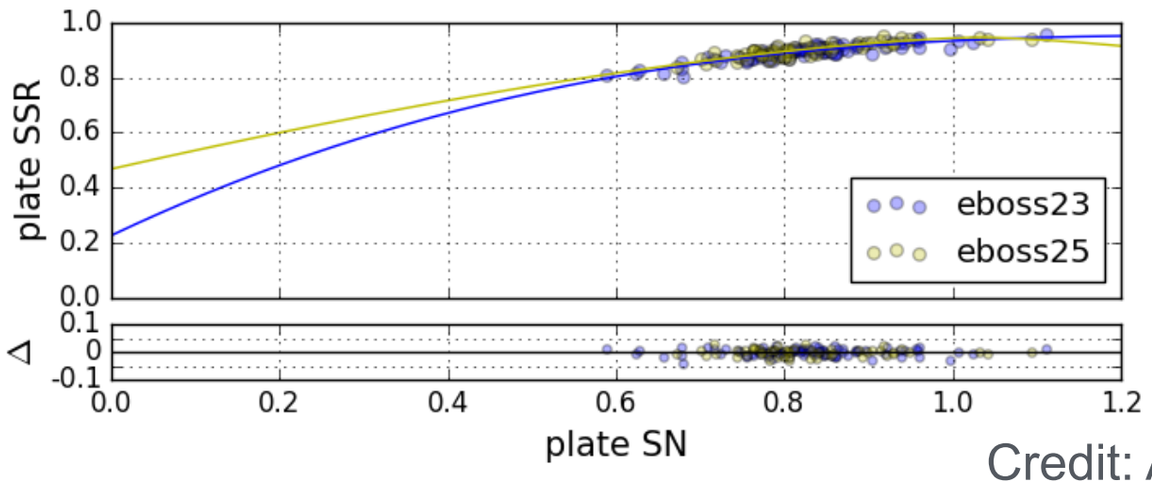
LSS catalogue creation

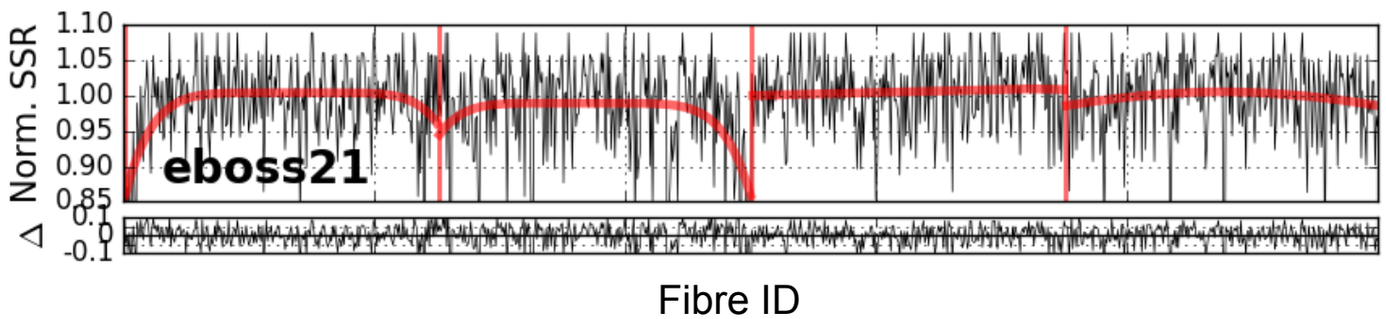
Systematics and corrections (1)

- Fibre collision
  - Physical size of fibre (62″)
- Redshift failure
  - Good spectra are more difficult to be obtained near the edges of CCDs of the spectrograph
  - The spectroscopic success rate is related to observational conditions (signal-to-noise ratio of spectra)



Credit: F. Mohammad



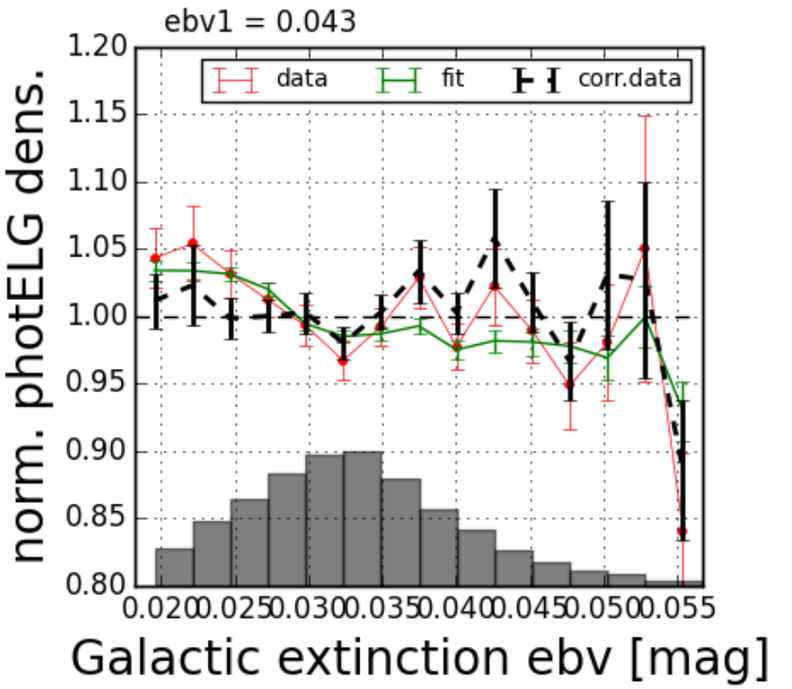


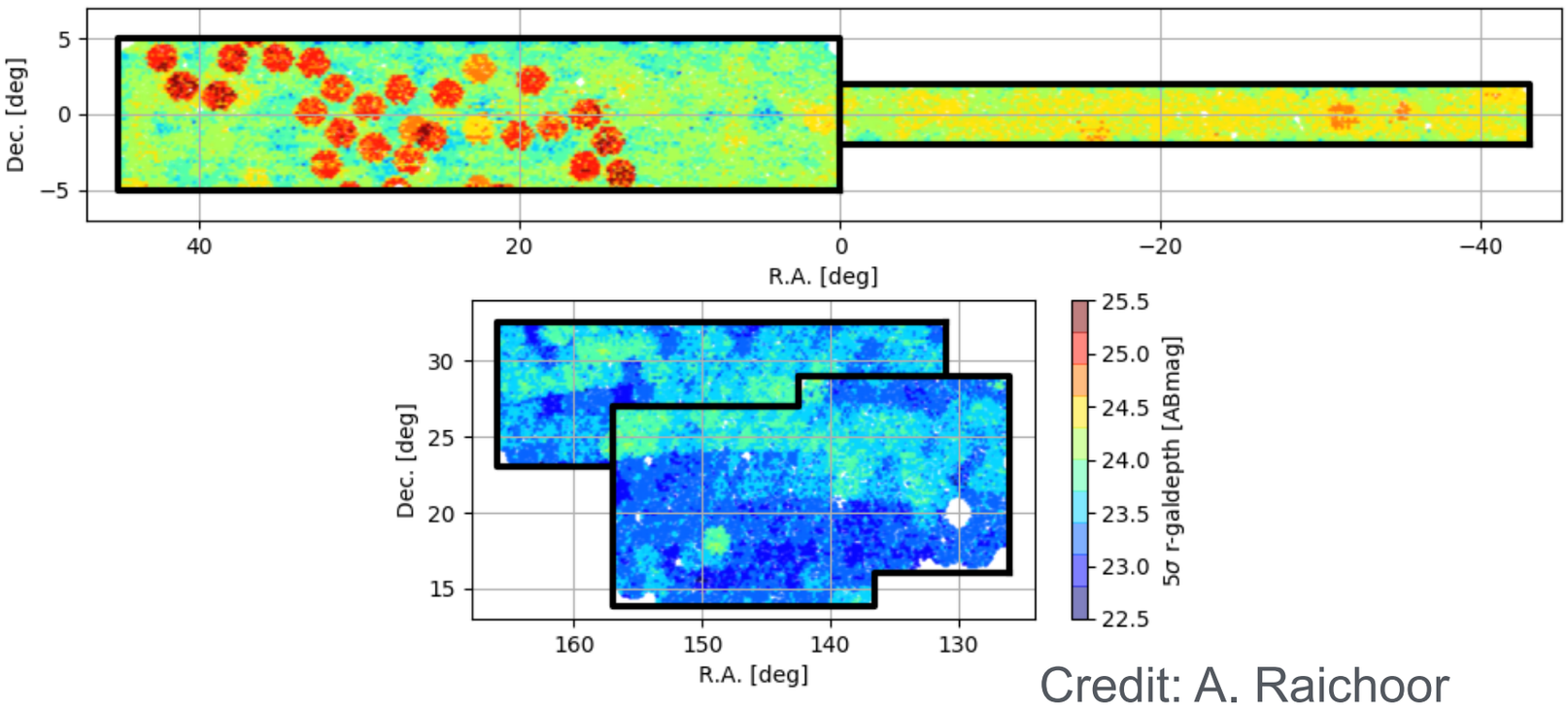
Credit: A. Raichoor

LSS catalogue creation

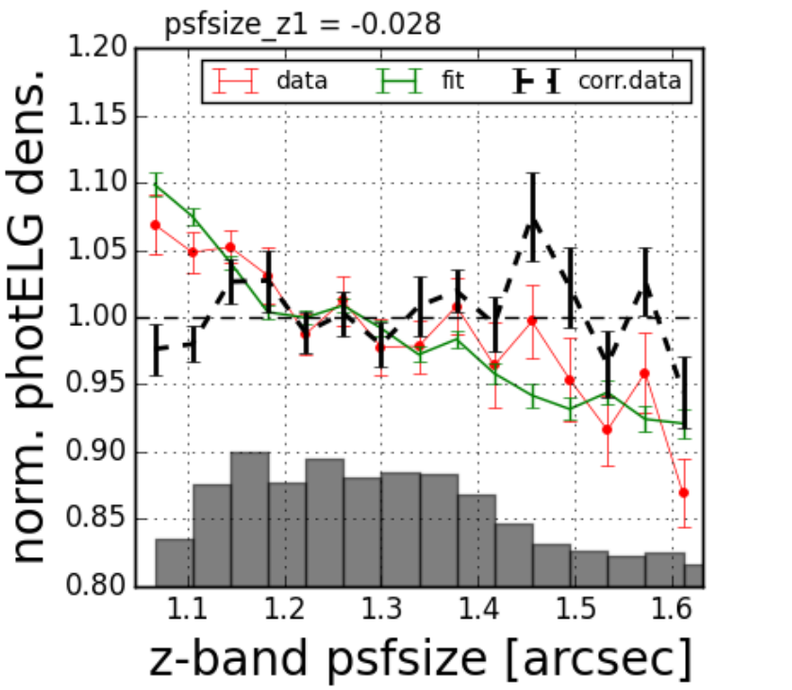
Systematics and corrections (2)

- Angular photometric systematics (linear regression)
  - Galaxy extinction
  - Stellar density
  - Depth and seeing
  - Others
- Depth-dependent redshift density (ELG only)
  - significant imaging depth inhomogeneities



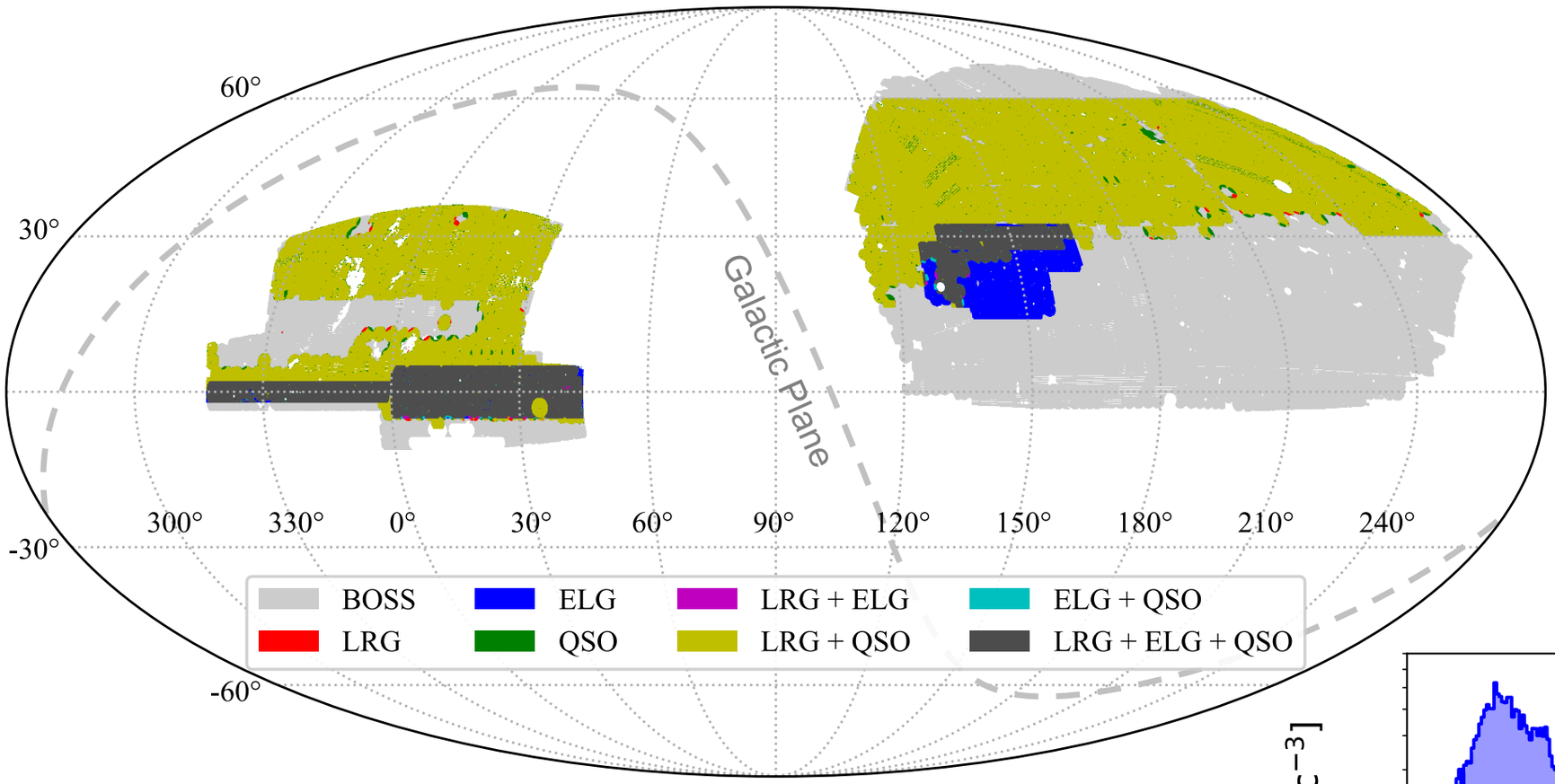


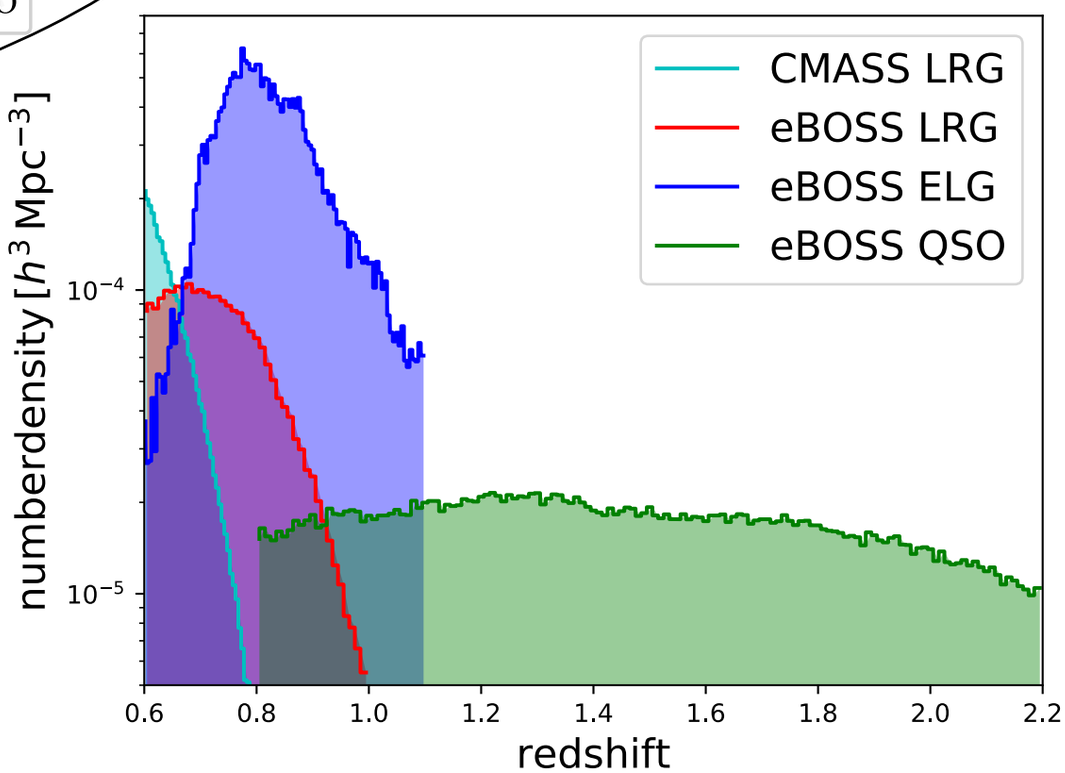
Credit: A. Raichoor



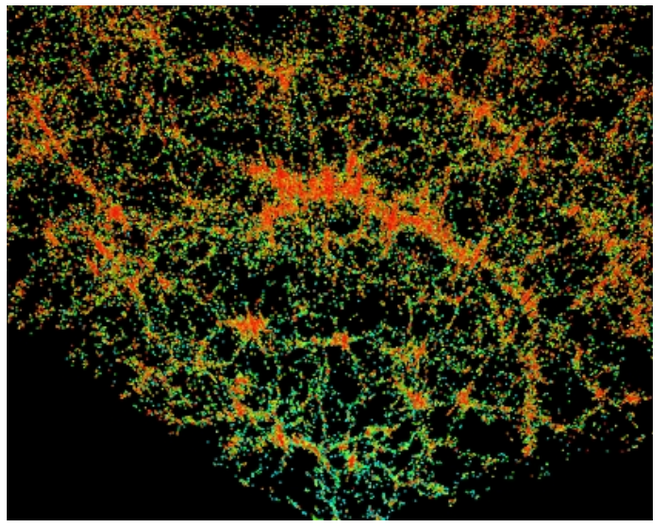
eBOSS LSS catalogues

Distribution

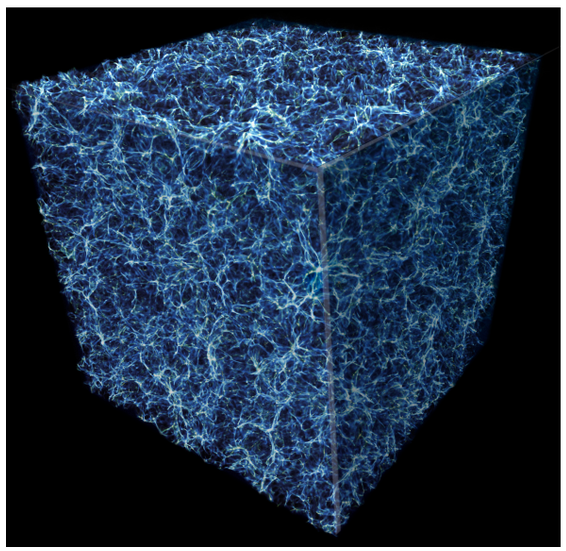




Cosmic variance



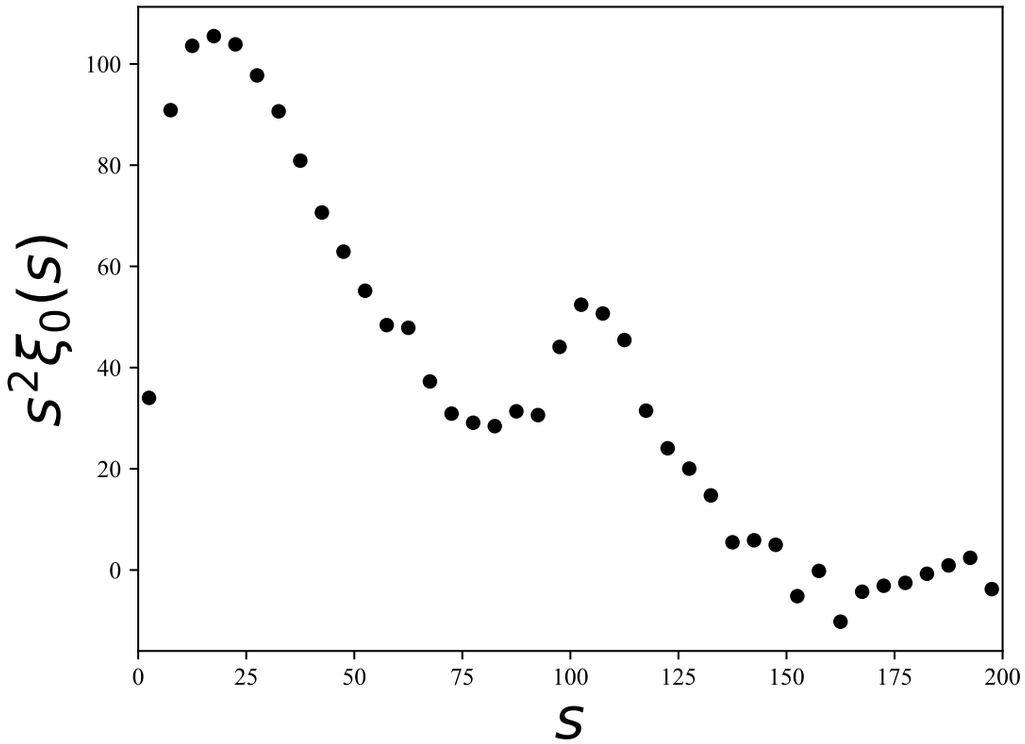
Observed data

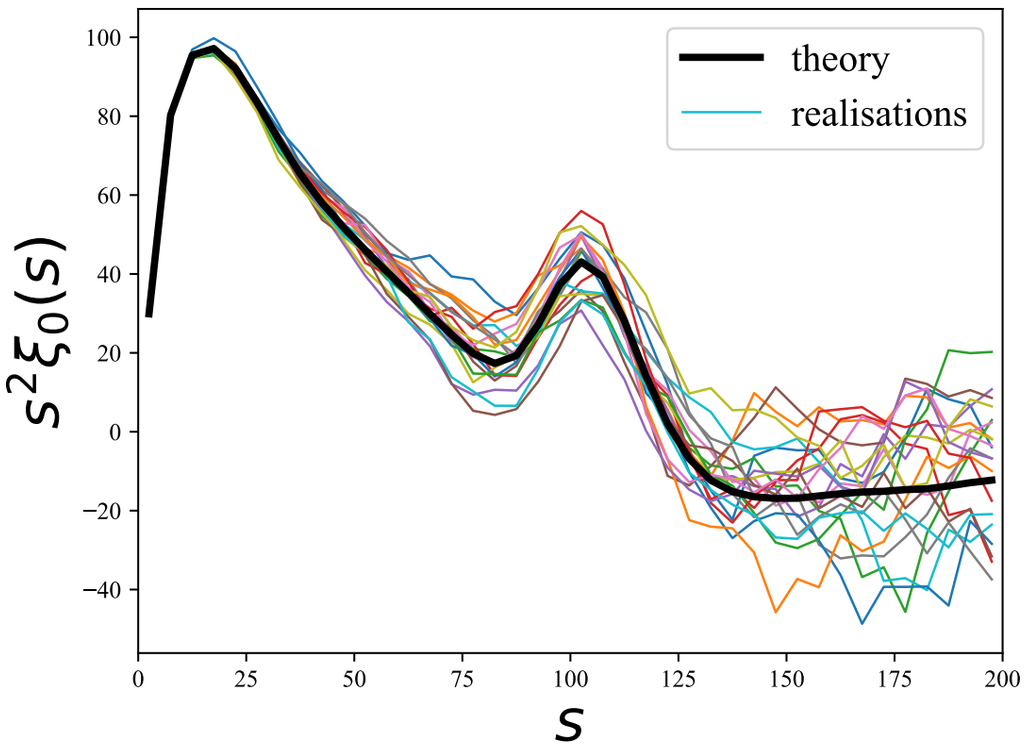


N-body simulation

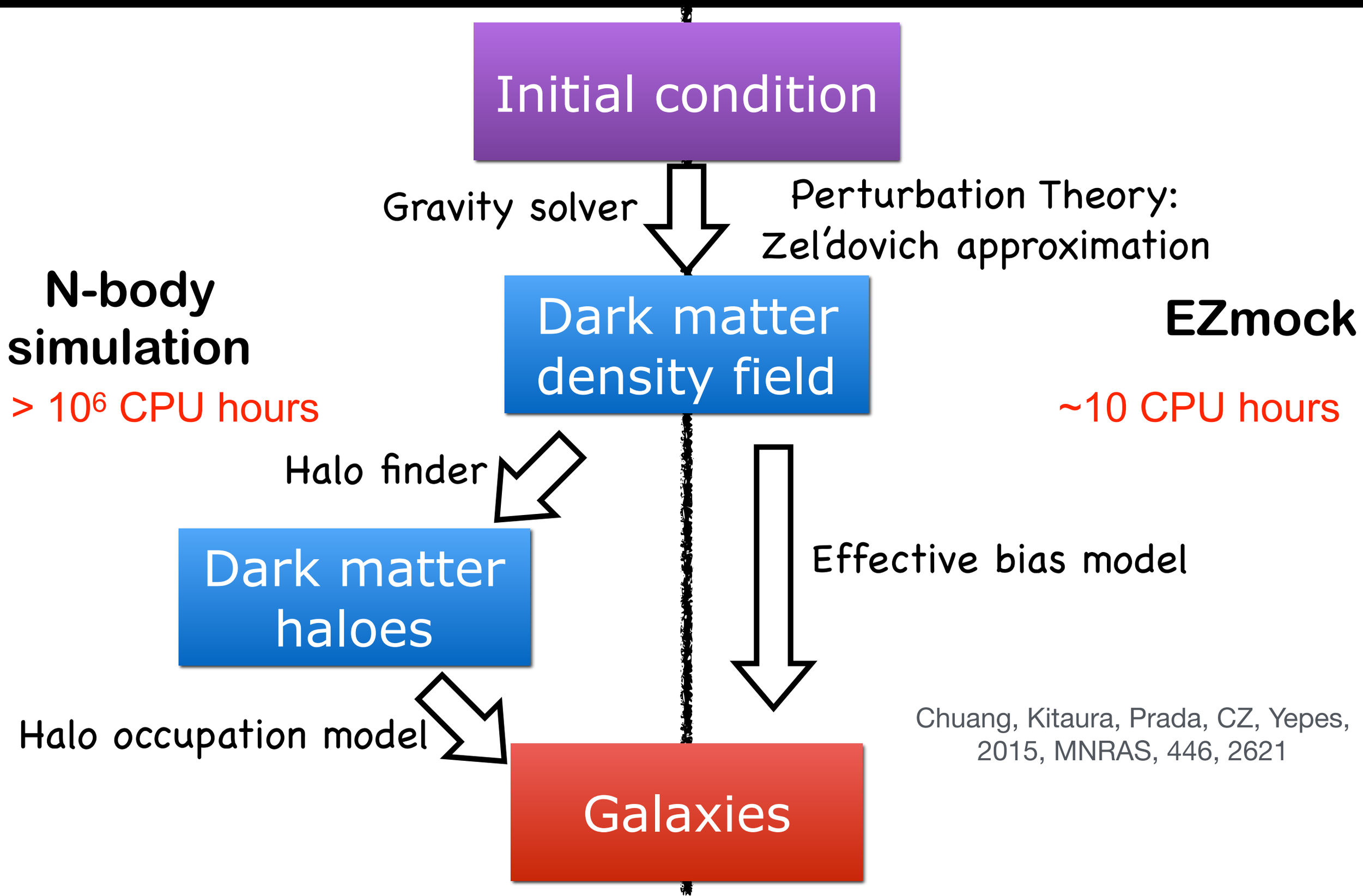
Same cosmology

different white noises





Fast mock: EZmock



N-body simulation

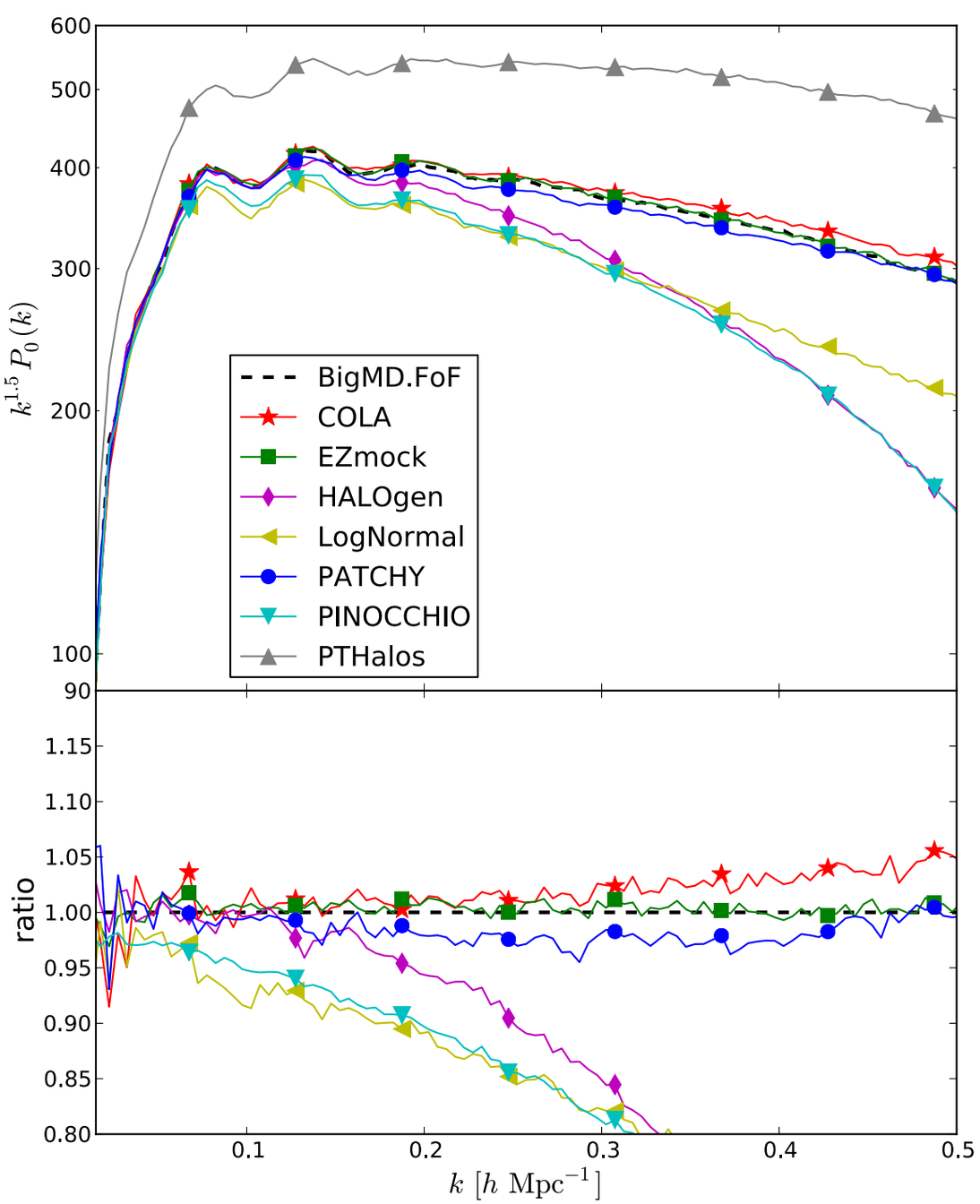
> 10^6 CPU hours

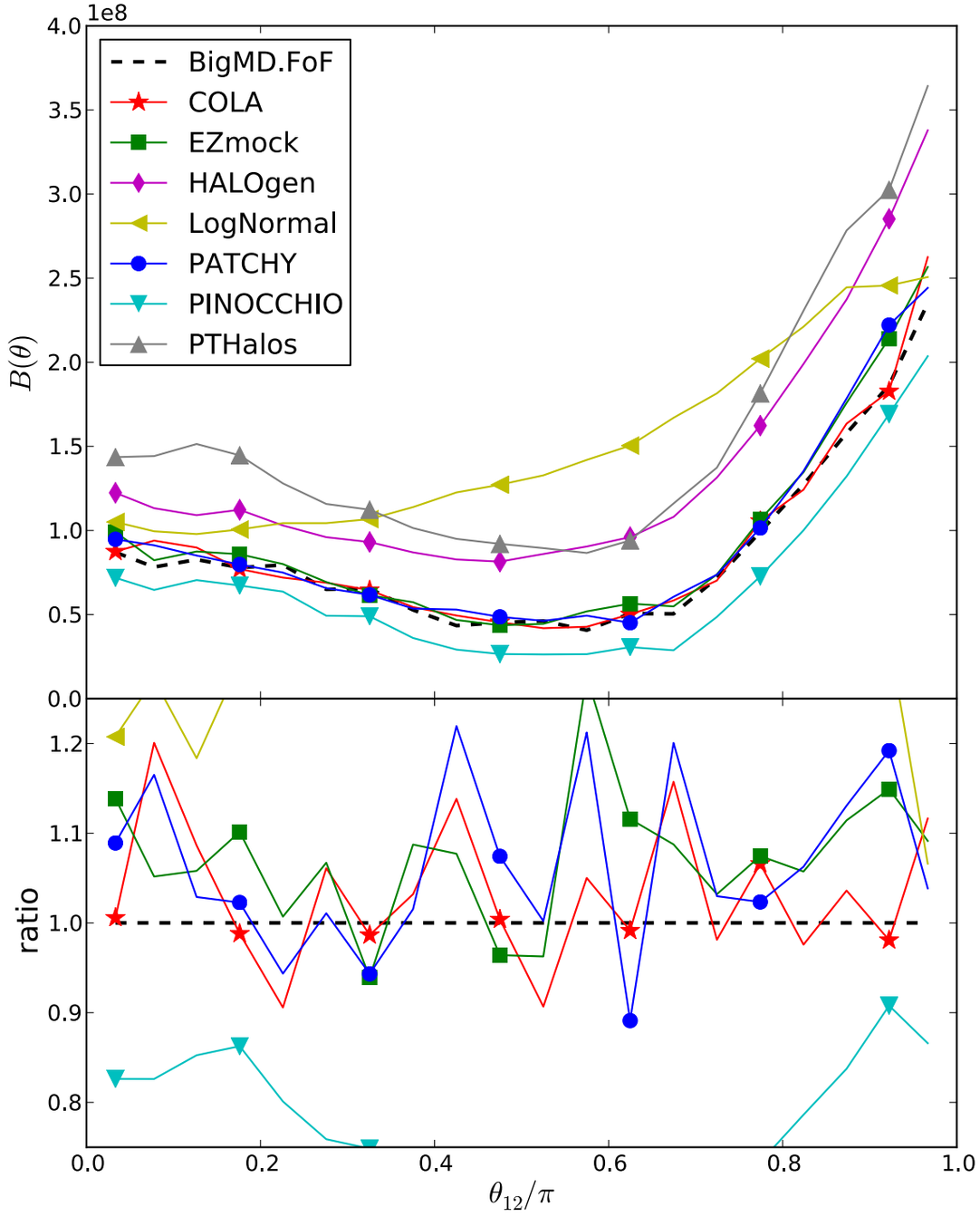
EZmock

~10 CPU hours

Chuang, Kitaura, Prada, CZ, Yepes, 2015, MNRAS, 446, 2621

Comparison of mocks





COLA, EZmock, PATCHY: percentage accuracy of 2-point statistics for k up to 0.3 h Mpc^{-1}

Chuang, CZ, et al., 2015, MNRAS, 446, 2621

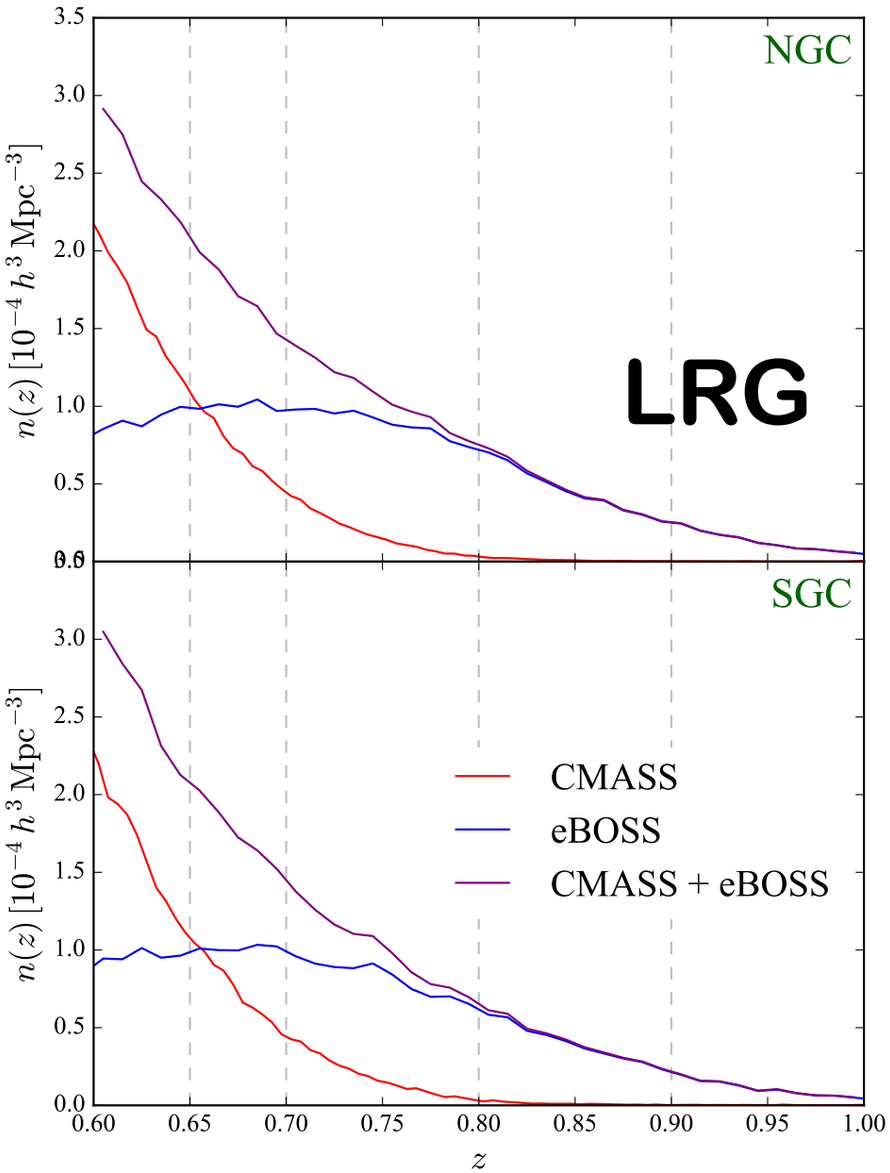
Mock production pipeline

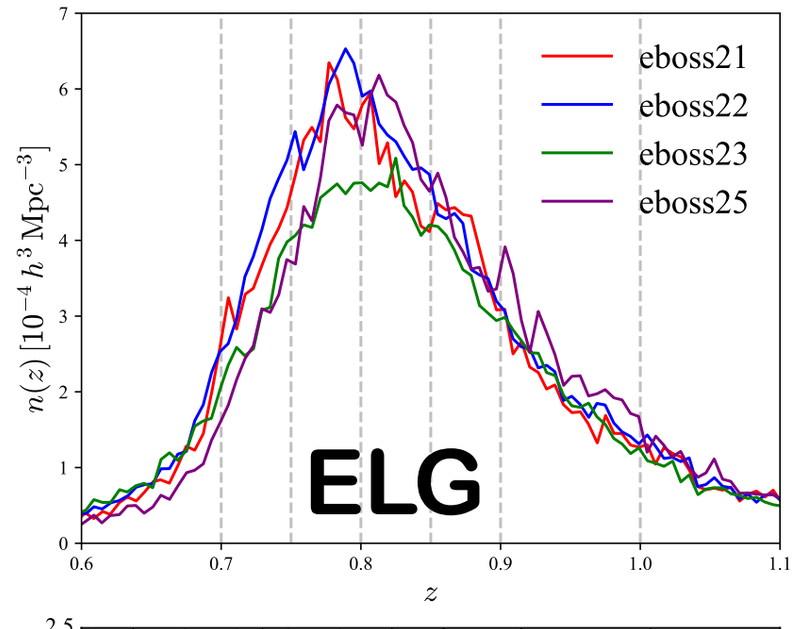
- Define box size & snapshots based on data
- Generate EZmock boxes at different redshift snapshots
- Construct lightcone mocks with redshift shells*
  - Redshift space distortions
  - Footprint trimming
  - Radial selection
- Apply veto masks
- Fit clustering measurements to data
- Massive production (1000 mocks)

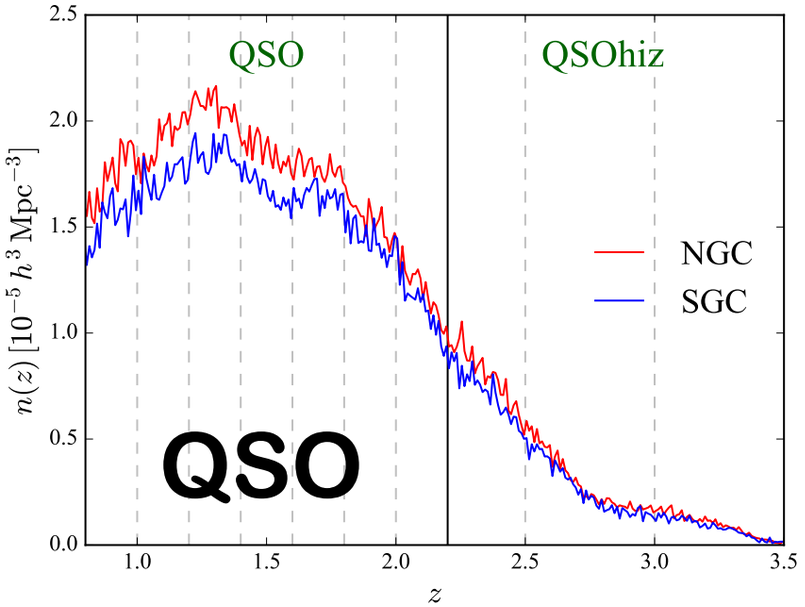
* https://github.com/mockFactory/make_survey

Redshift snapshots

- BOSS-CMASS LRG
  - 4 snapshots
  - 3.5 × 10–5 h3 Mpc–3
- eBOSS LRG
  - 5 snapshots
  - 3.5 × 10–4 h3 Mpc–3
- eBOSS ELG
  - 7 snapshots
  - 6.4 × 10–4 h3 Mpc–3
- eBOSS QSO
  - 7 snapshots
  - 2.4 × 10–5 h3 Mpc–3

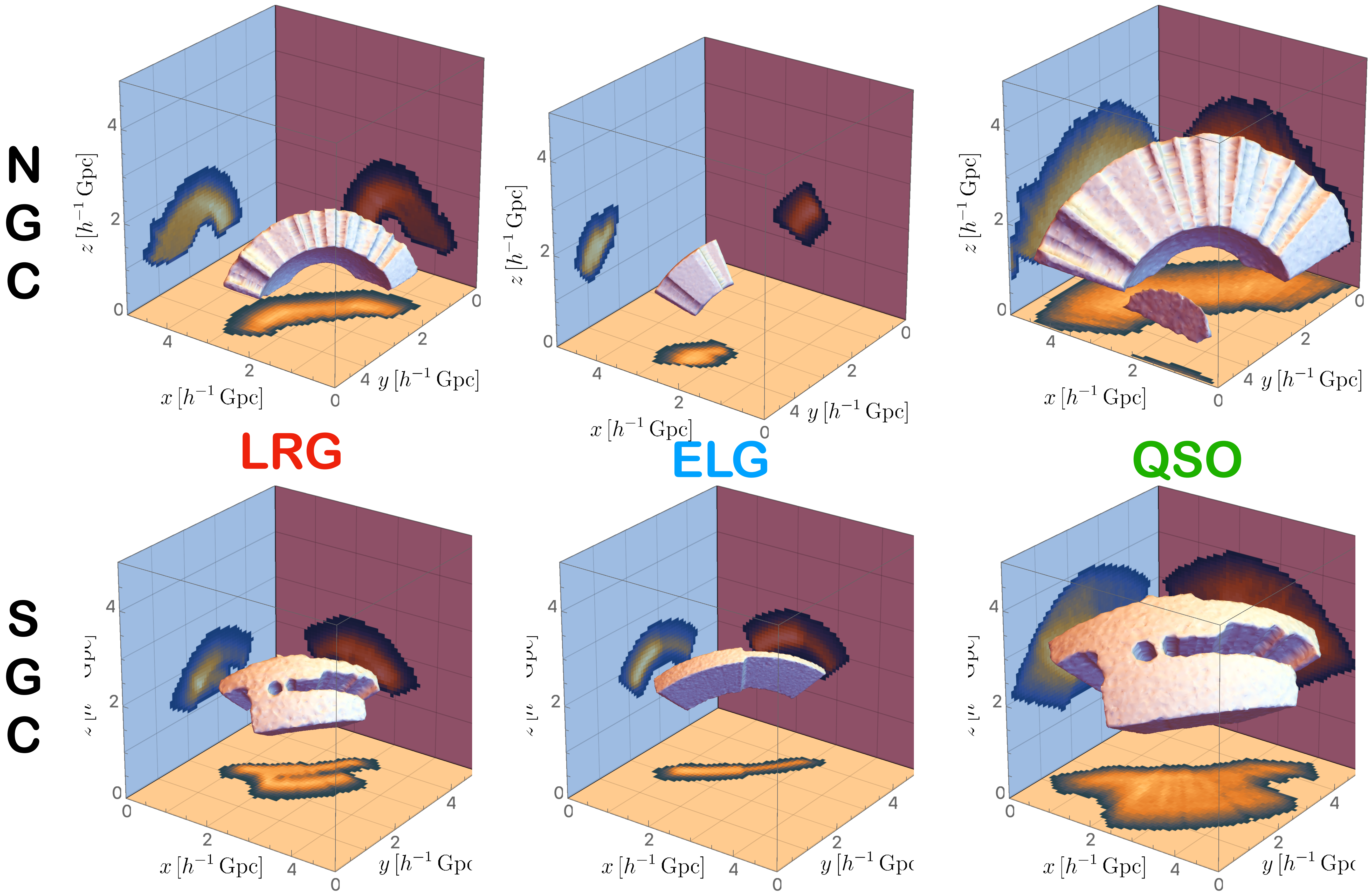




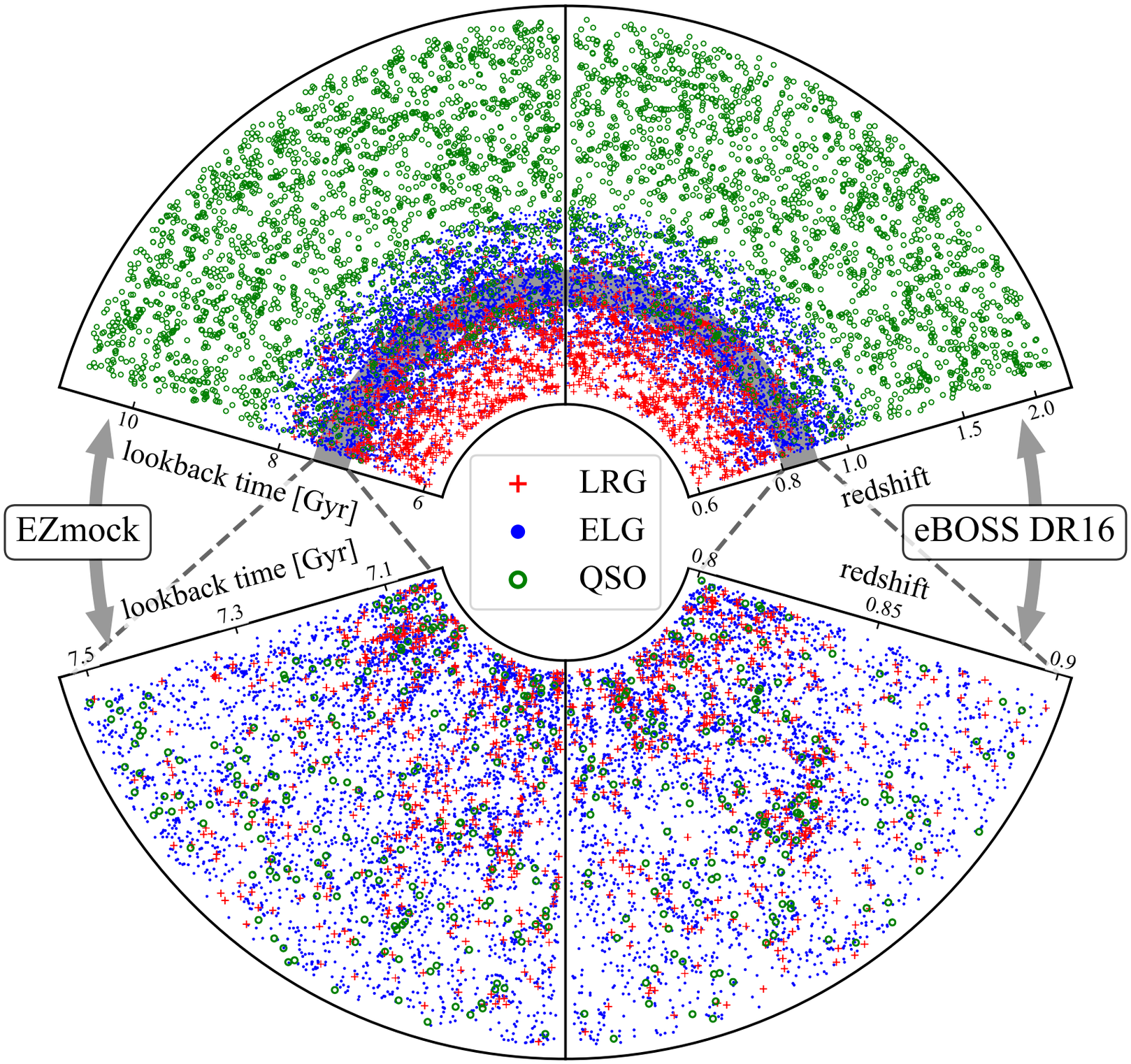


46000 boxes (L = 5 h-1 Gpc) in total
for 1000 NGC+SGC realisations

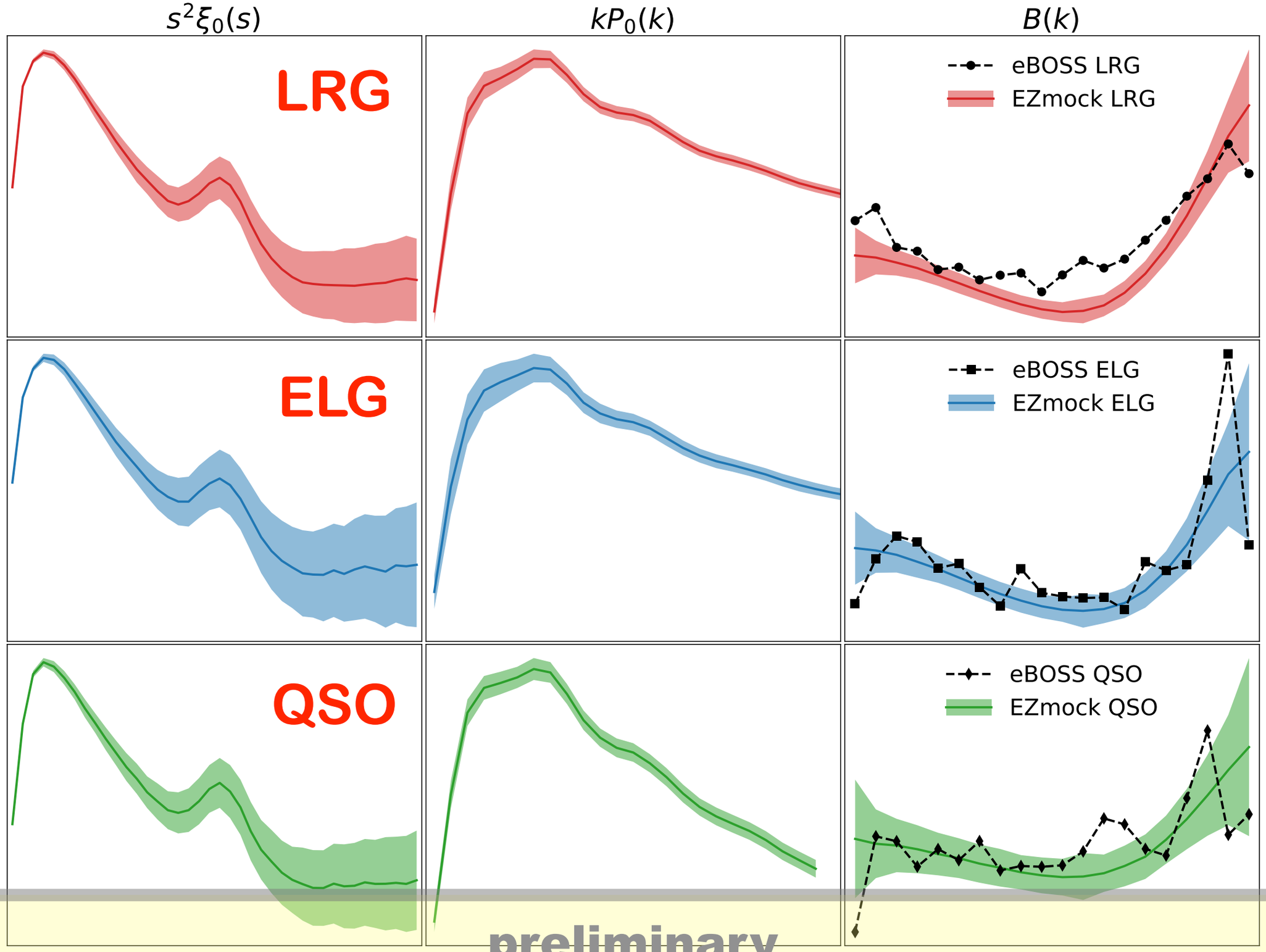
Survey geometry cut



Tracer distribution

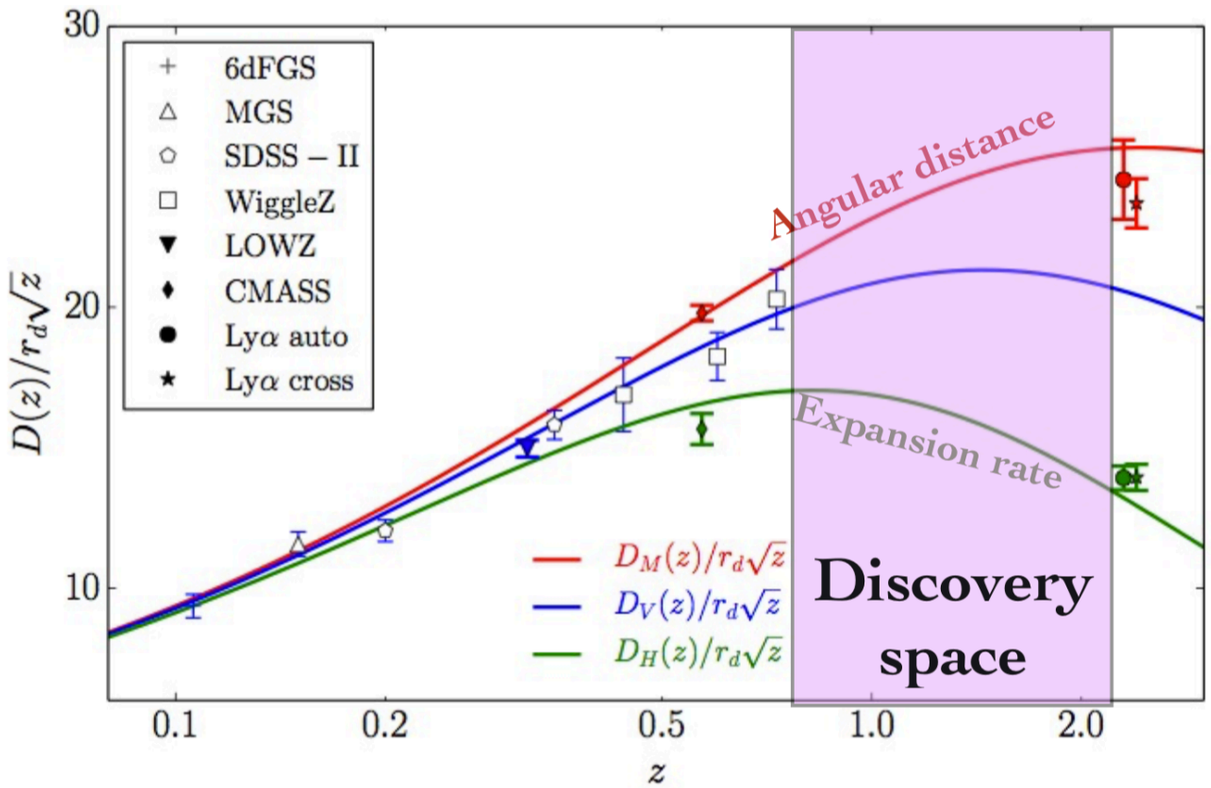


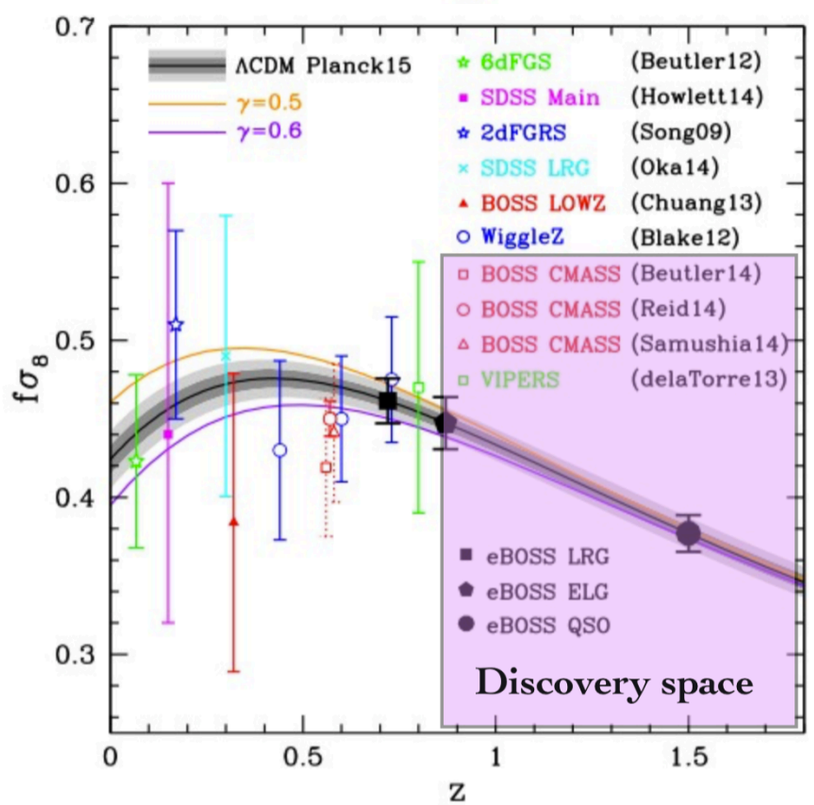
Clustering measurements



Results

- LRG
  - BAO precision: ~2%
  - RSD f·σ8 precision: ~10%
- ELG
  - BAO precision: ~3%
  - RSD f·σ8 precision: ~20%
- QSO
  - BAO precision: ~2%
  - RSD f·σ8 precision: ~10%





Final cosmology analysis

eBOSS + SDSS legacy

- Assess progress in cosmological model in the past decade
  - 7 BAO and 6 RSD measurements from SDSS legacy
  - New Pantheon SN Ia sample compared to SNLS
  - Planck compared to WMAP
- Explore impact of BOSS/eBOSS expansion history measurements on dark energy models
- Inverse distance ladder to estimate H_0
  - Likely mild change
- Neutrino masses
  - Tighter constraints expected, dominated by CMB lensing and BAO
- Model independent measurements of curvature
- Implications of growth measurements
  - Growth-only cosmology constraints
  - Modified gravity
  - Comparison to weak lensing constraints on $\Omega_m - \sigma_8$

Summary

- BOSS/eBOSS: a decade of leadership in cosmological spectroscopic surveys comes to an end
  - Data taken completed in Mar. 2019
- Special session and press release
  - 5—9 January 2020, AAS meeting in Honolulu
  - Data release, final results, cosmological constraints
- LSS catalogues under revision
  - Various systematical effects considered
- 1000 realisations of EZmocks for each type of tracer
- Enable many additional works on inflation, fnl, cross correlations, and galaxy/quasar astrophysics
- Final BOSS/eBOSS sample provides measurements over unparalleled range of cosmic history ($0.2 < z < 3.5$)