DESI – Year 1

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On behalf of the DESI Collaboration

LHC Split Days, Hvar – Sept. 30, 2024

Dark Energy Spectroscopic Instrument

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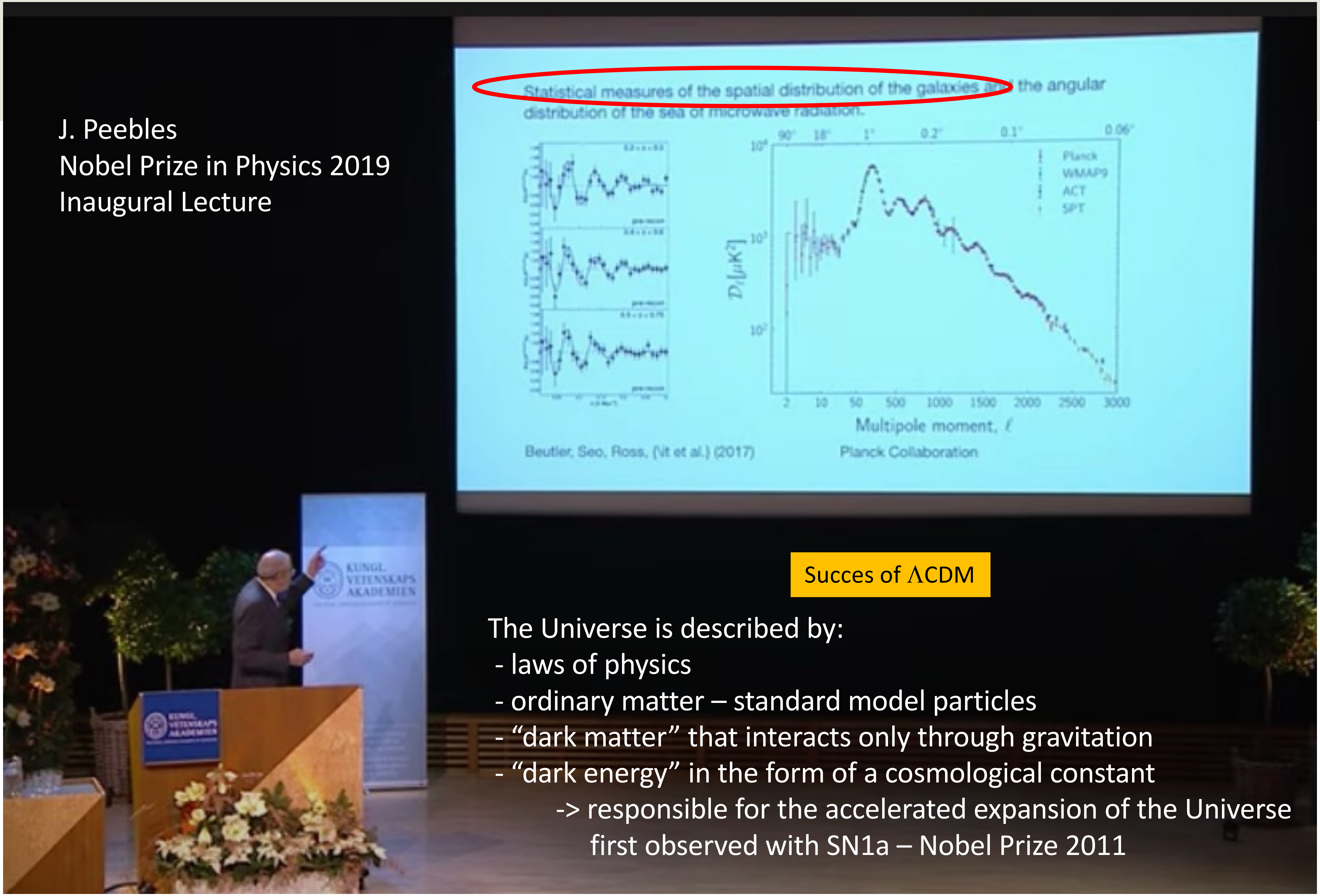
Outline

1. **Baryonic Acoustic Oscillations (BAO)**
2. **Overview of DESI**
3. **Status of DESI – Year 1**
4. **BAO with galaxies and quasars**

Baryonic Acoustic Oscillations

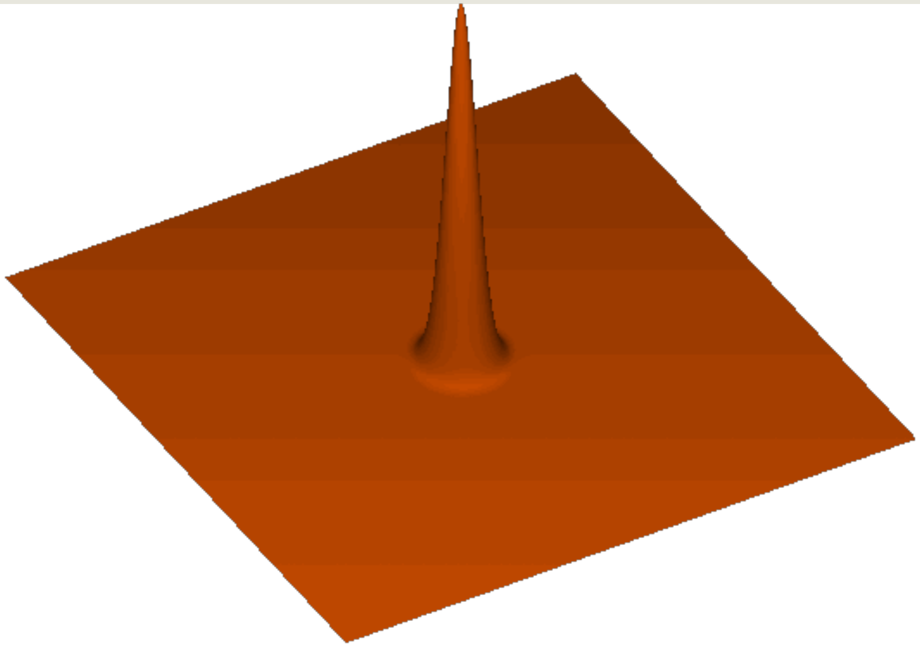
J. Peebles
Nobel Prize in Physics 2019
Inaugural Lecture



Succes of ΛCDM

The Universe is described by:
- laws of physics
- ordinary matter – standard model particles
- “dark matter” that interacts only through gravitation
- “dark energy” in the form of a cosmological constant
  -> responsible for the accelerated expansion of the Universe
  first observed with SN1a – Nobel Prize 2011

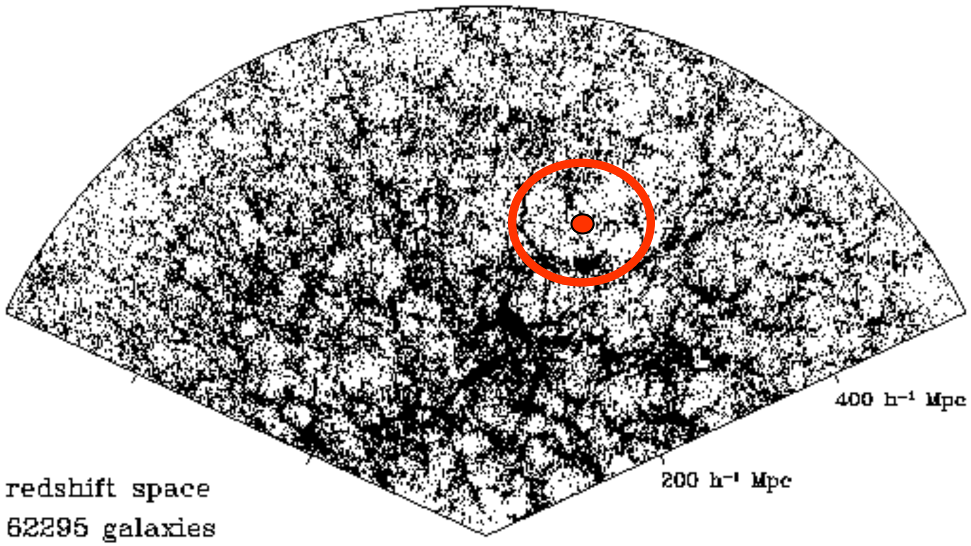
BAO, a probe for Dark Energy



Acoustic propagation of an over-density

- Sound waves propagates through relativistic plasma (baryons, electrons, photons).
- Baryon and photon perturbations travel together till recombination (z~1100) with a speed $\sim c/\sqrt{3}$ that depends on species densities
- Radius of the baryonic overdensity frozen at r_d ~150 cMpc (comoving).

BAO, a standard ruler



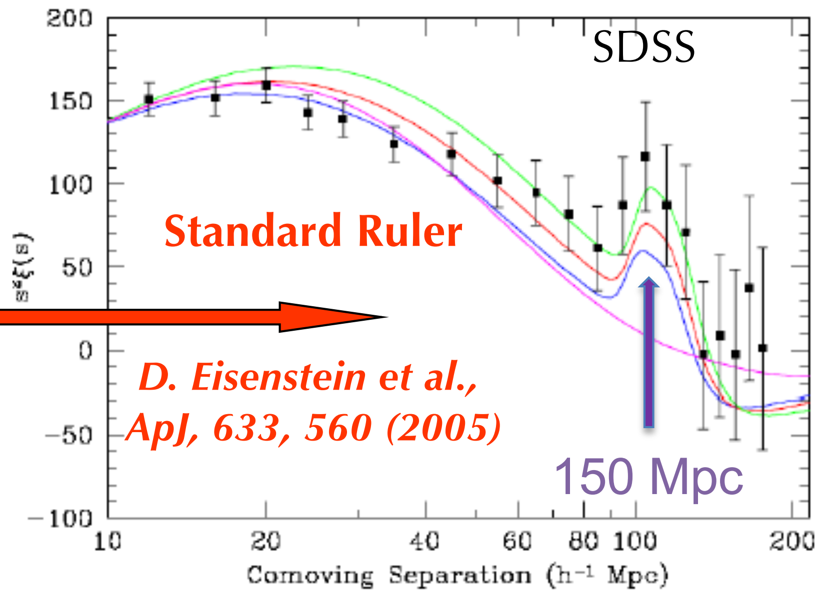
A special distance

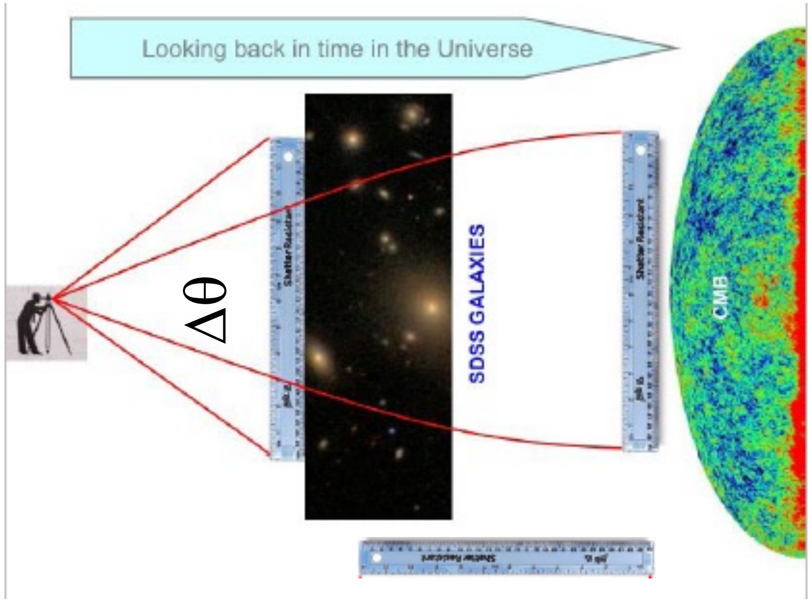
- Galaxies form in the overdense regions.
- Small excess of galaxies at r_d ~150 cMpc away from other galaxies.
- **Measure this BAO "standard ruler" over cosmic history**
  => Constrain the nature of Dark Energy

Observation of baryonic acoustic peak

First observation

- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at ~150 Mpc
- SDSS: ~50 000 LRGs, <z> ~ 0.35
  "Luminous Red Galaxies"





A 3D measurements

- Position of acoustic peak
- **Transverse direction:**

$\Delta\theta = r_d/(1+z)/D_A(z) = r_d/D_M(z)$

$\Rightarrow$ Sensitive to angular distance $D_A(z)$

- **Radial direction** (along the line of sight):

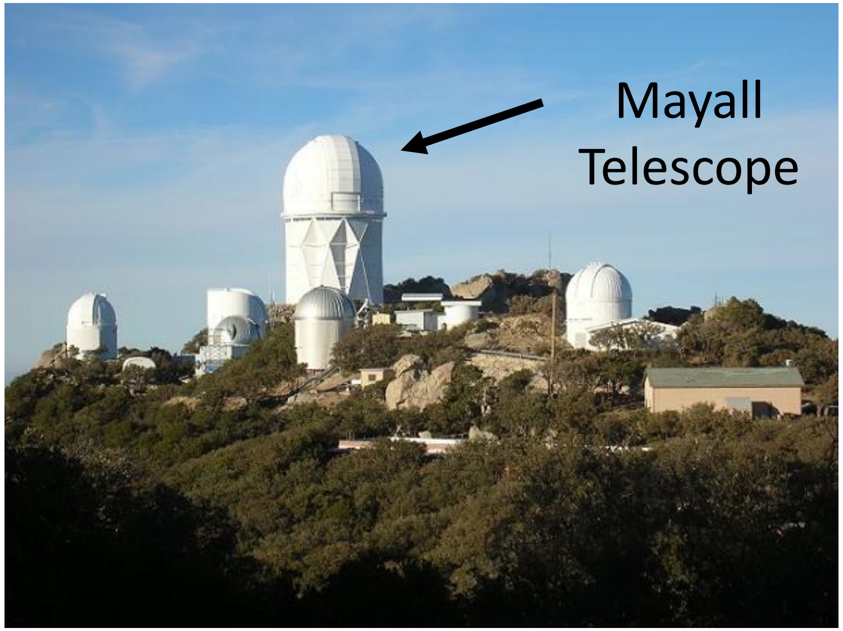
$\Delta z = r_s \cdot H(z)/c$

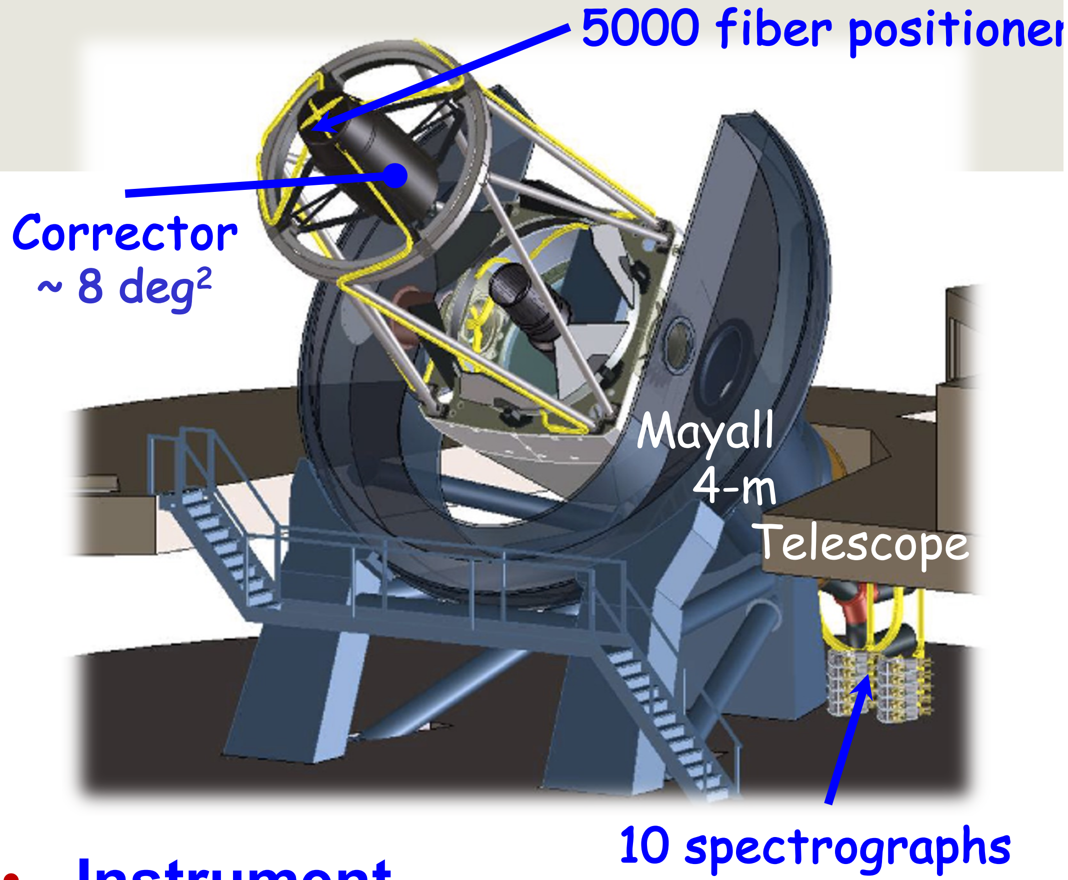
$\Rightarrow$ Sensitive to Hubble parameter H(z).

Overview of DESI

DESI Project

- **Scientific project**
  - 3D map for 0<z<4
  - Footprint ~ 14000 deg^2
  - International collaboration
  - 72 institutions (46 non-US)
  - ~900 members





- **Instrument**
  - 4-m telescope at Kitt Peak (Arizona)
  - Wide Field-of-View (~ 8 deg^2)
  - Multi-Object Spectrograph
    - Robotic positioner with **5000 fibers**
    - 10 spectrographs x 3 bands (blue, visible, red-NIR) →360-1020 nm

DESI tracers of the Matter

Five target classes

~40 million redshifts

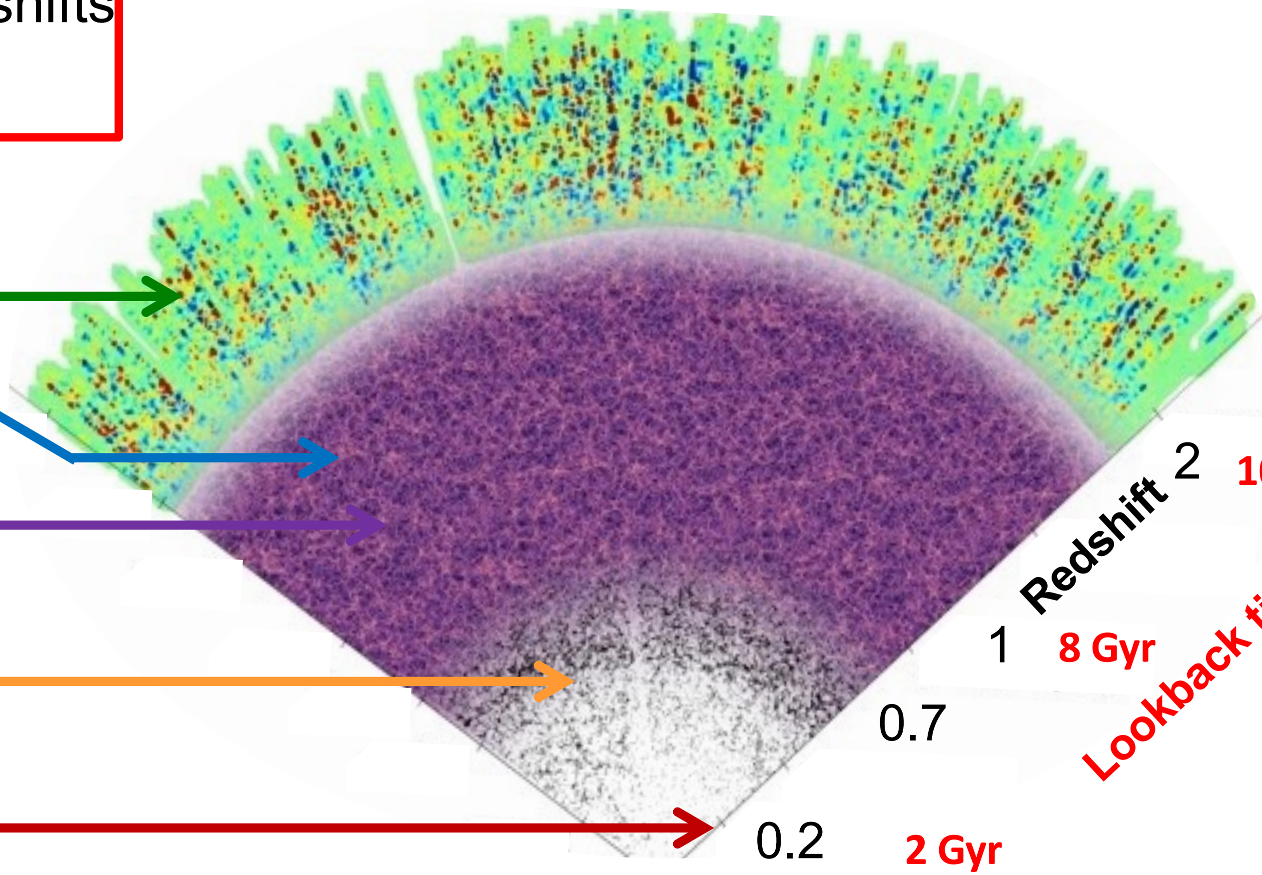
in 5 years

3 million QSOs
Ly-α z > 2.1
Tracers 0.9 < z < 2.1

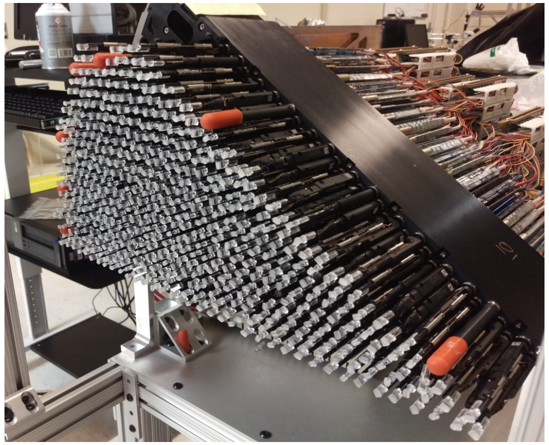
16 million ELGs
0.6 < z < 1.6

8 million LRGs
0.4 < z < 1.0

13.5 million
Brightest galaxies
0.0 < z < 0.4

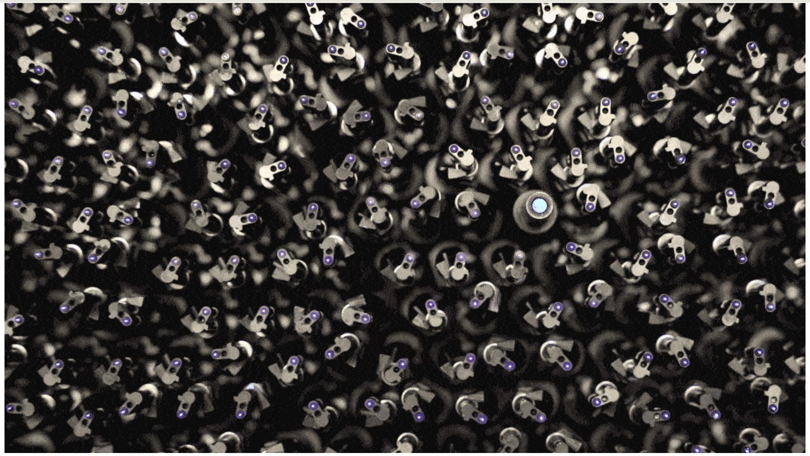


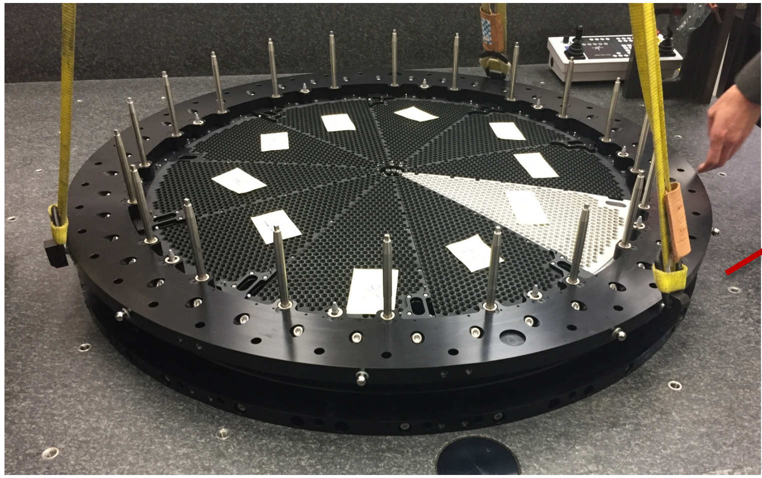
Focal Plane – 5000 robotic fiber positioners

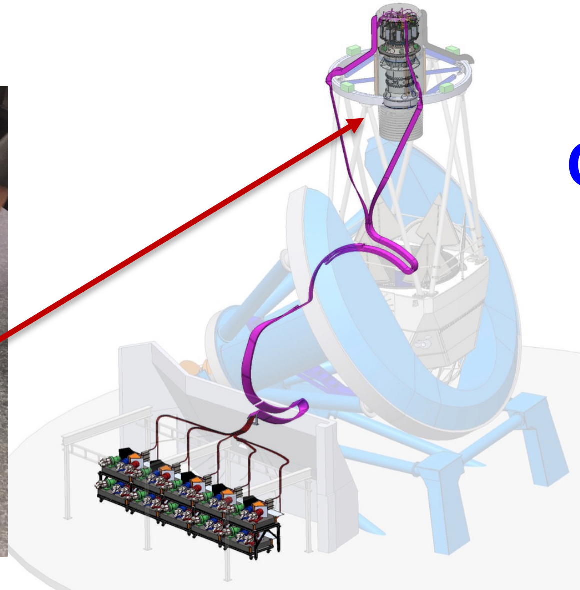


Configuration

- 10 petals in focal plane
- 500 fibers each (5000 total)
- 10.4 mm pitch
- 2 motors per positioner







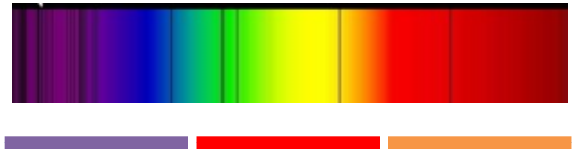
Challenge

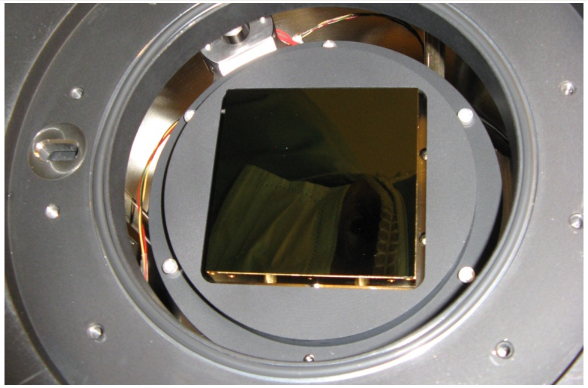
- Reposition the 5000 fibers in less than 2mns
- Position of each fiber better than 10 μm

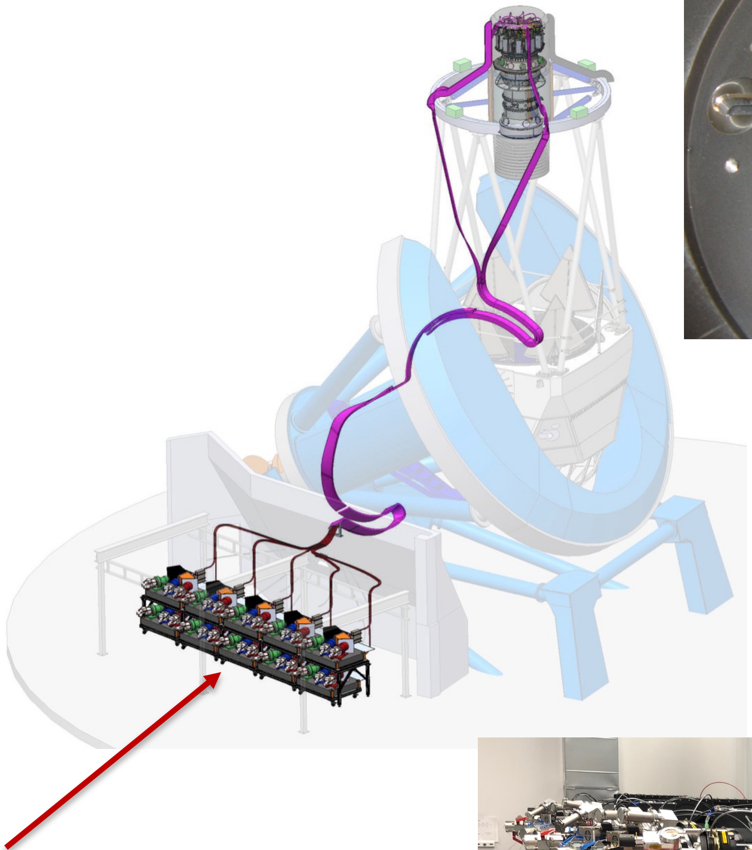
Ten spectrographs

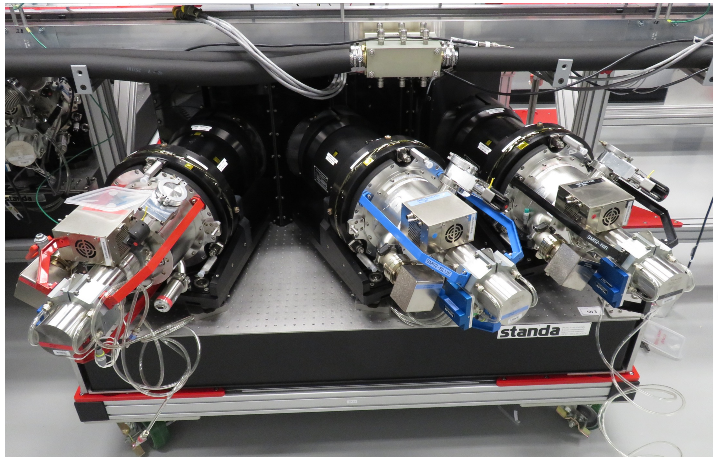
Ten 3-channel spectrographs

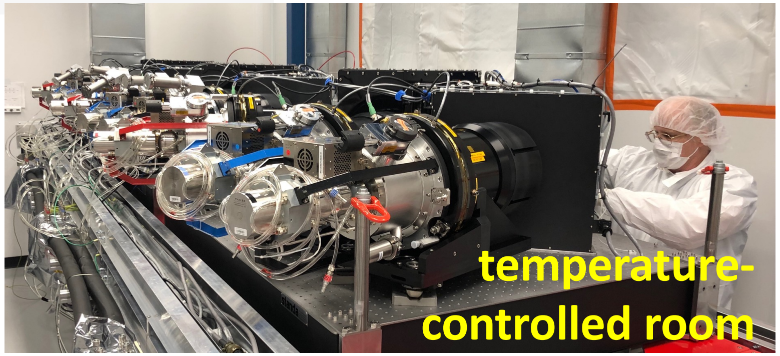
λ = 360 nm to 980 nm







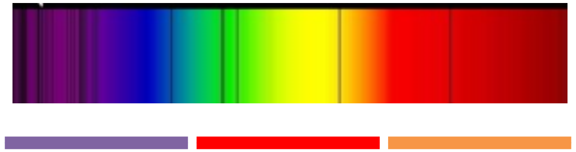




Ten spectrographs

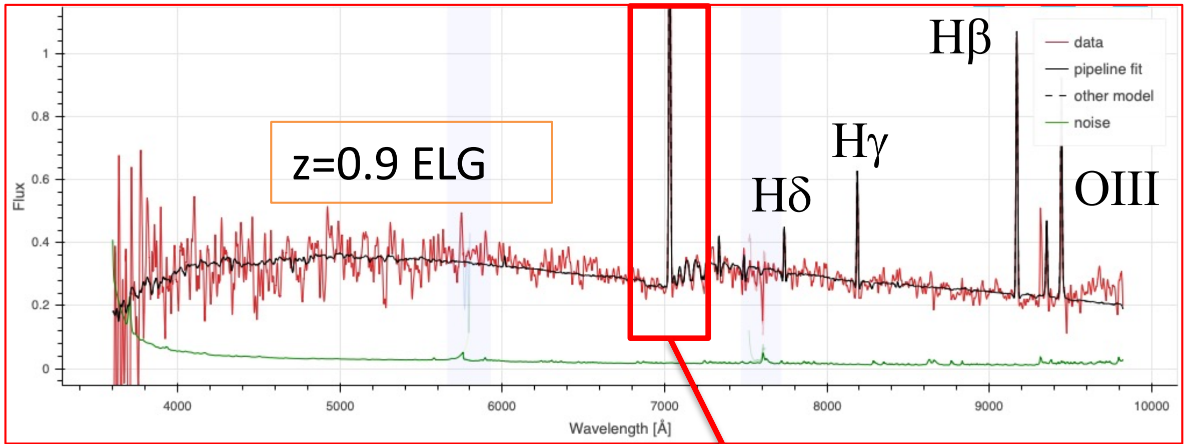
Ten 3-channel spectrographs

λ = 360 nm to 980 nm

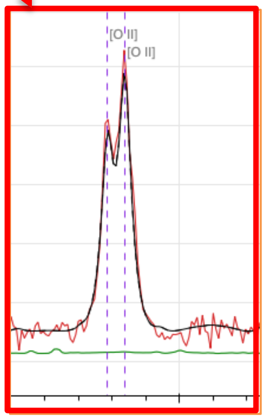


$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

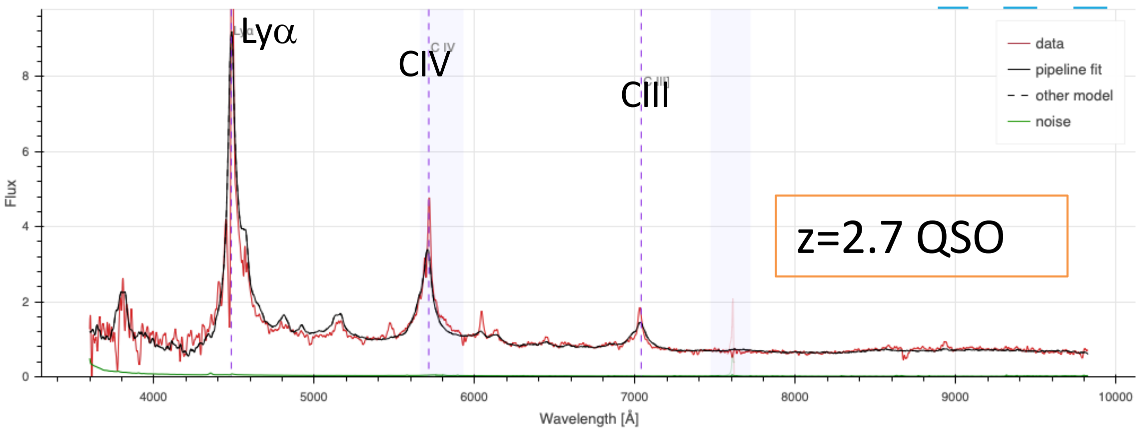
[OII] 373 nm
up to z = 1.6



[OII] doublet

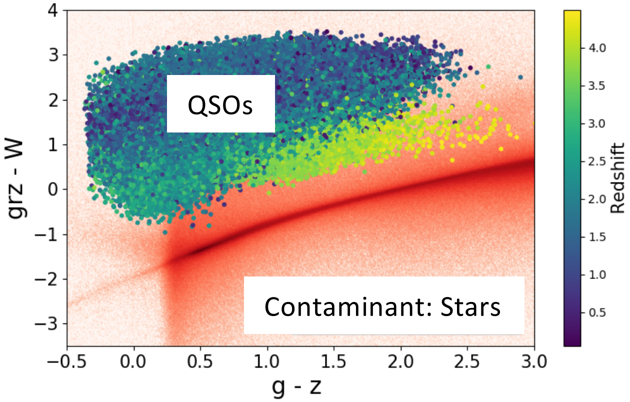


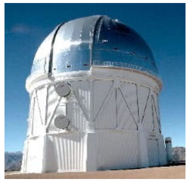
Ly-α 121.6 nm
down to z = 2.1



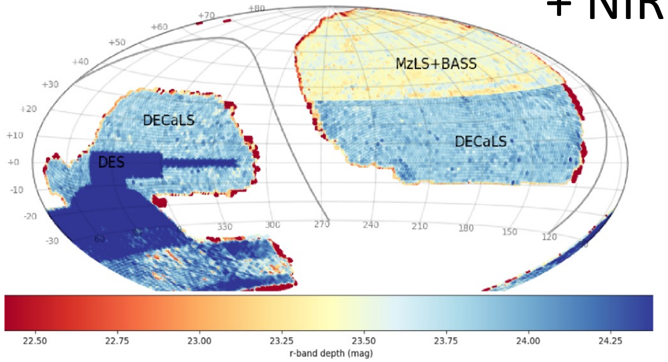
Rolling observations – Redshift factory

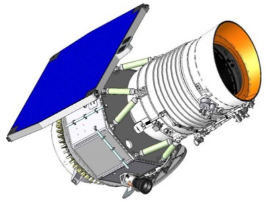
Target Selection





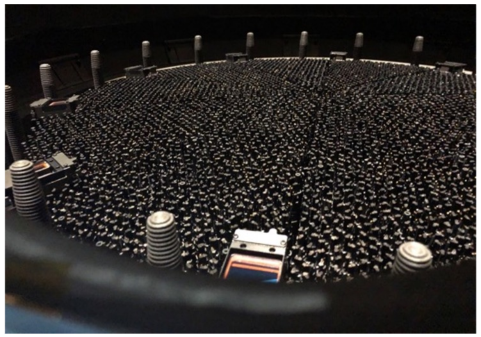
Imaging Surveys: optical grz bands
+ NIR with WISE



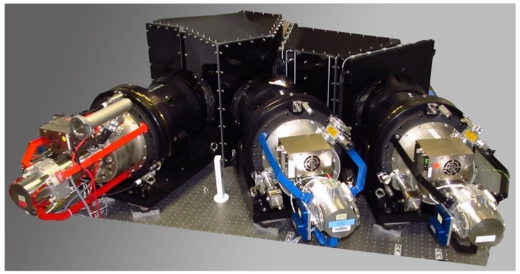


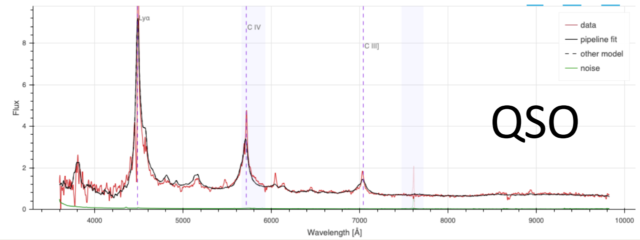
Observation…

…of 5000 objects
every ~20mins…



…and measure their redshift



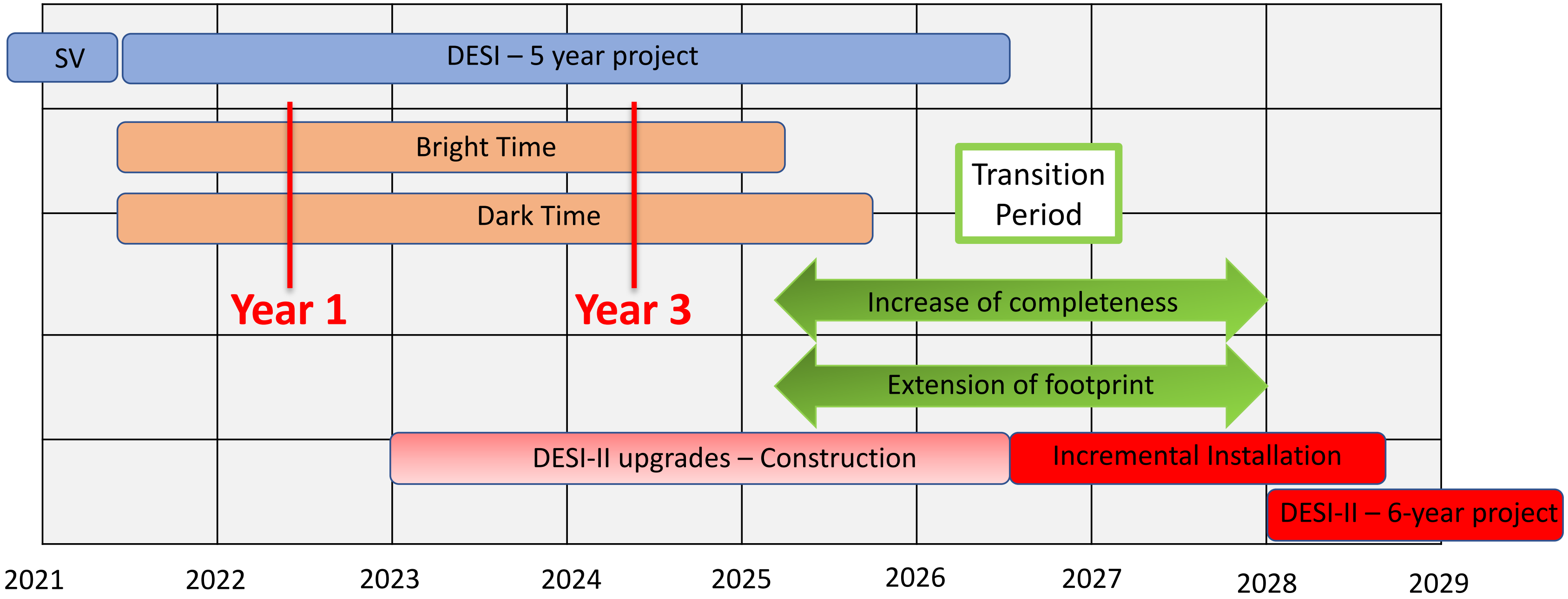


Status of DESI

-

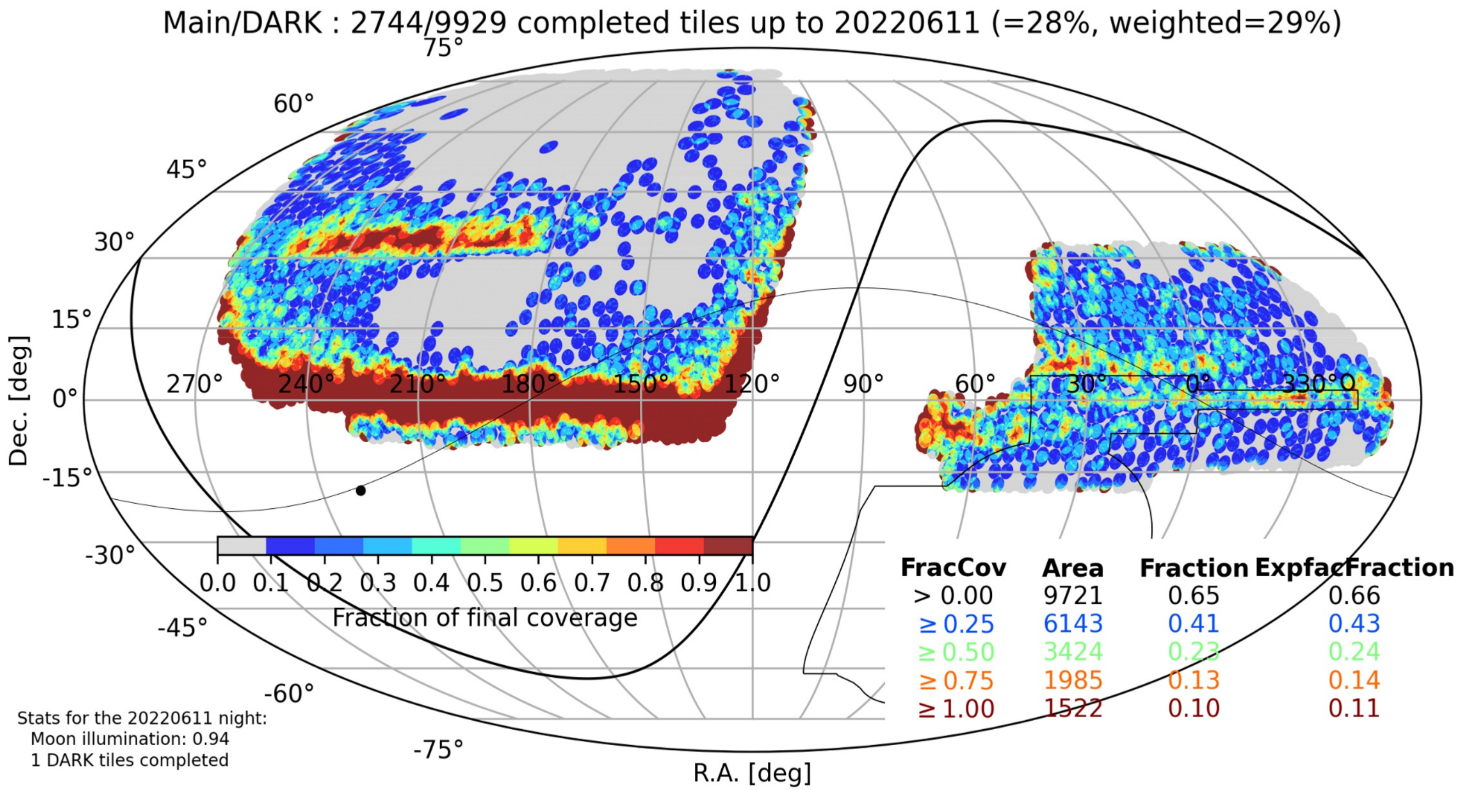
Year One (Y1)

DESI and DESI-II Timelines



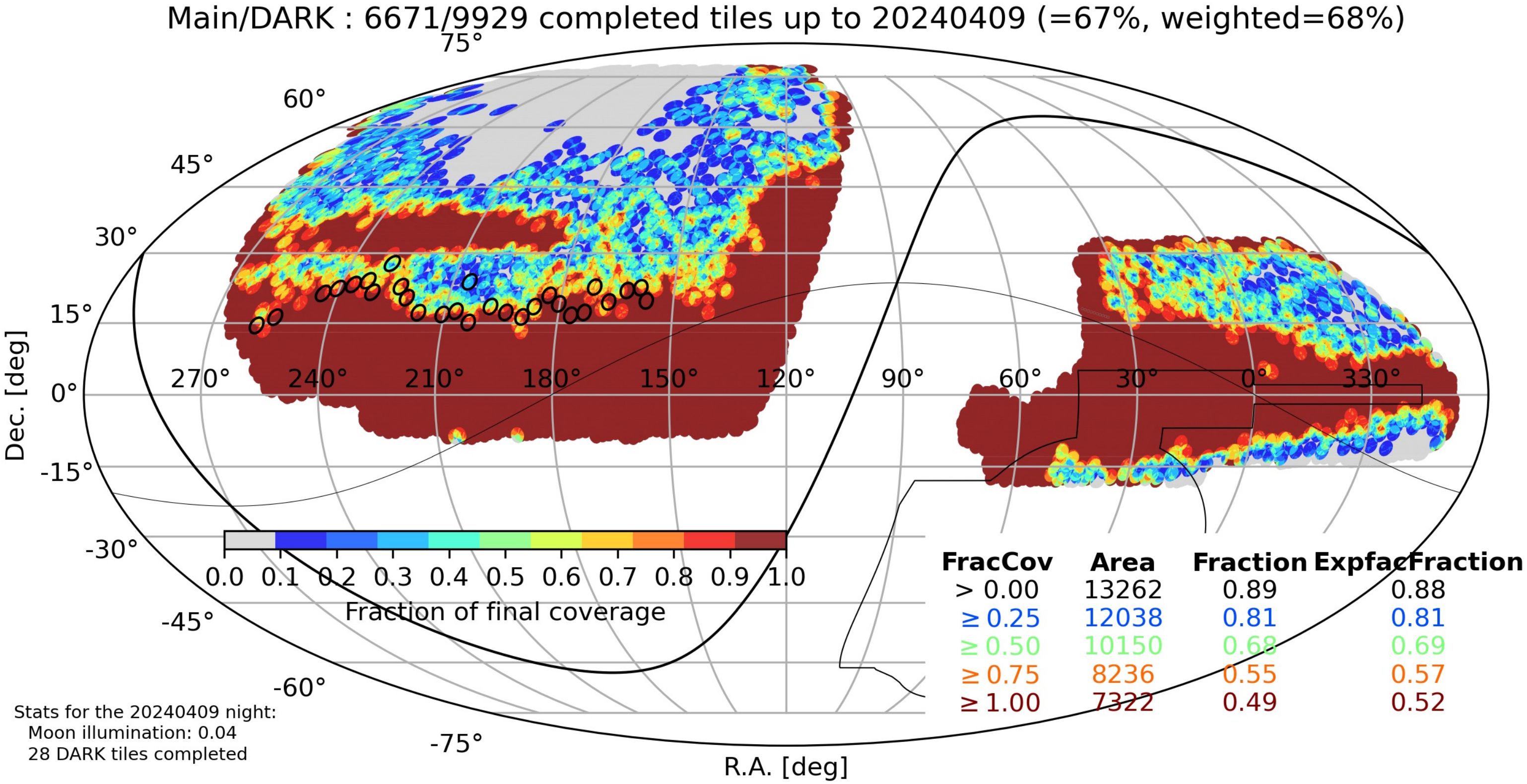
- **DESI-I** is ~4 months ahead of schedule, DESI should finish in 2025
  - Analysis of Year 1 Dataset
  - Year 3 Dataset completed in April 2024
- ~ 2-year transition period with extension of the footprint and the passes
- **DESI-II** starts in 2028-2029

DESI Y1 footprint



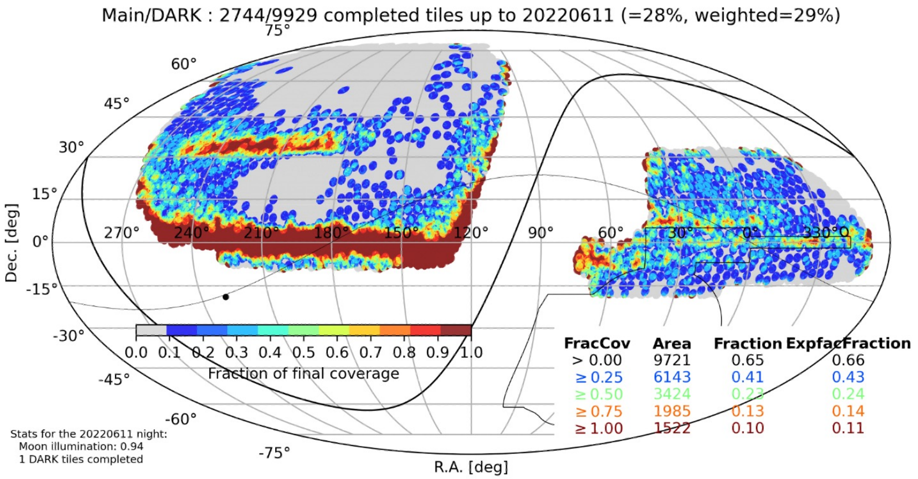
- Grey area: DESI footprint over 5 years, ~14000 deg^2
- On average 5 passes
- In Y1, only 1500 deg^2 with 5 passes

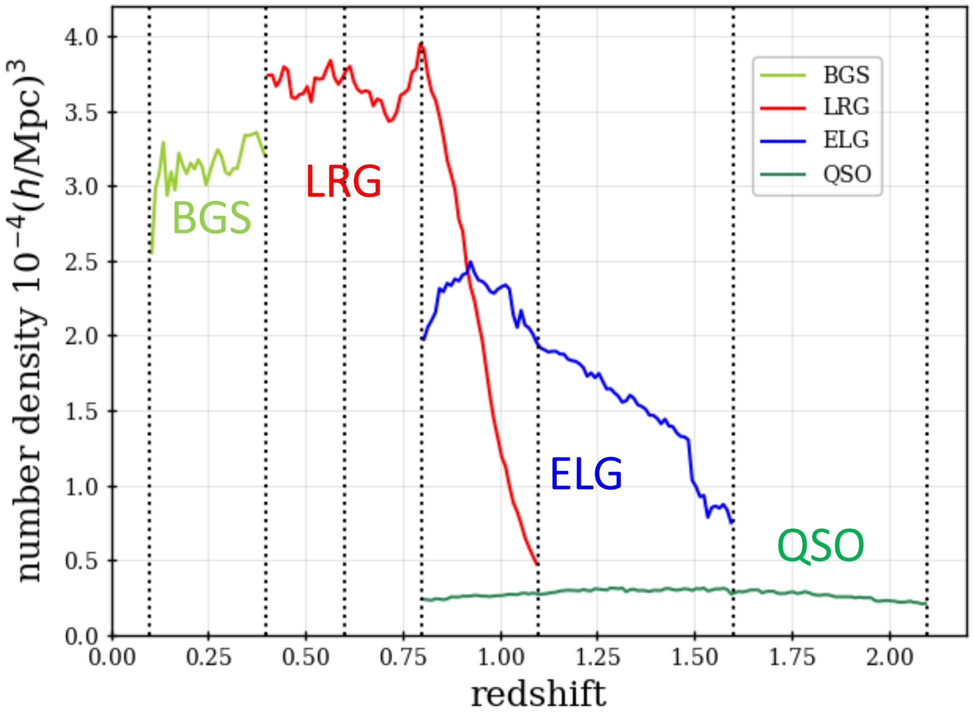
DESI Y3 footprint



- In April 2024, Y3 dataset is completed and frozen
- ~70% of the final dataset (much more ELGs)
- In Y3, already 7300 deg^2 with 5 passes

DESI Y1 dataset





– Already biggest ever BAO dataset (both in N_{tracer} and volume)
  - 5.7M discrete tracers (BG, LRG, ELG and QSO)
  - Effective cosmic volume V_{eff}= 18 Gpc^3

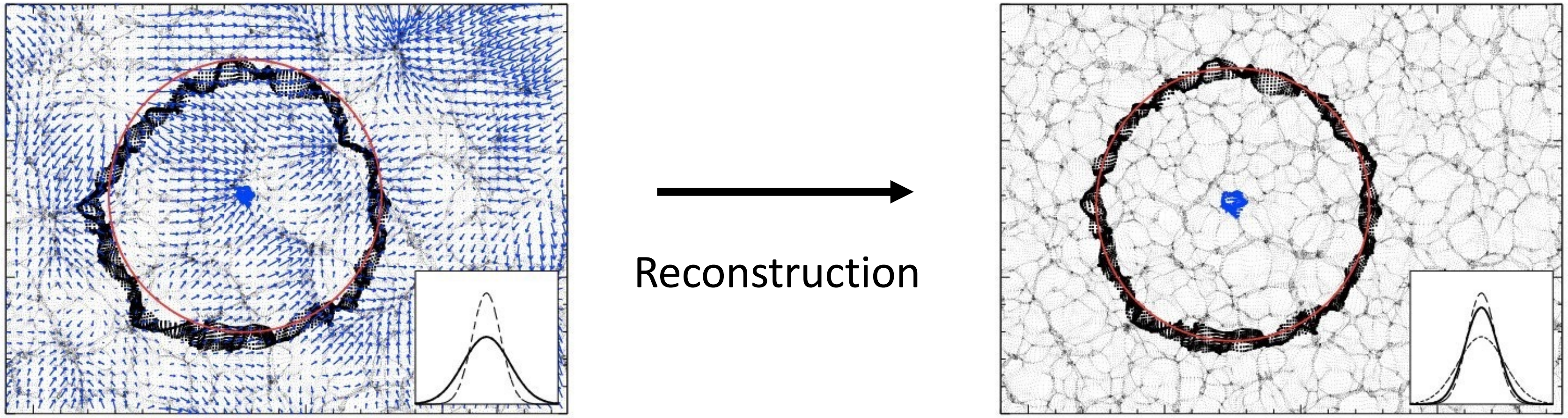
– **3 times bigger than SDSS (20 years of data)**

BAO with galaxies and quasars

Methodology for DESI Y1

- **Blind analysis** to mitigate observer/confirmation biases (catalog-level blinding)
- **Unified BAO pipeline** applied to all (discrete) tracers/redshifts consistently
- Common modeling of BAO used for all tracers
- Reconstruction method applied to all tracers
- Analytic covariance matrices (validated with mocks)
- Extensive tests of systematics, done before unblinding
- Results given for **6 redshift bins** over $0.1<z<2.1$

Density Field Reconstruction



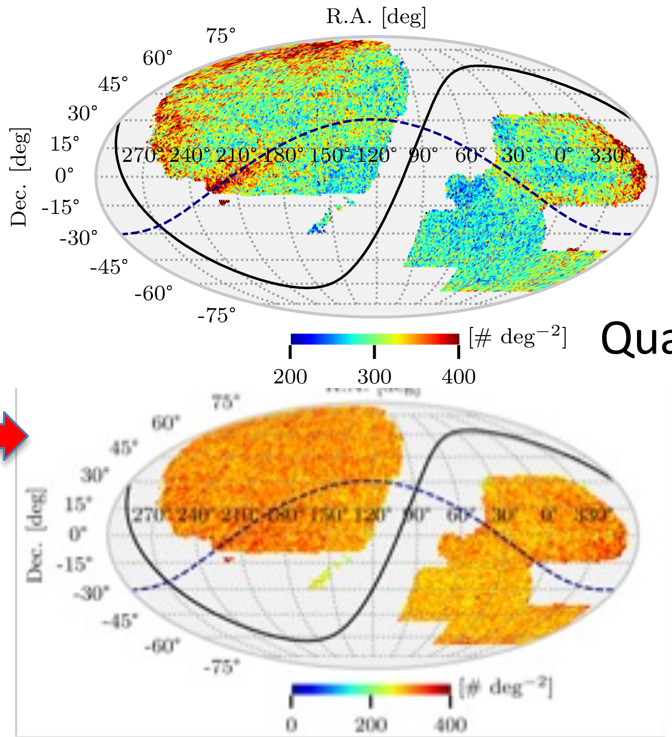
- BAO peak distorted by movements of tracers due to density field
- Estimation of the Zel'dovich (1st order) displacements from the observed field
- Reconstruction: correction of the displacements
- **Improve both precision and accuracy**

Systematics Error Budget

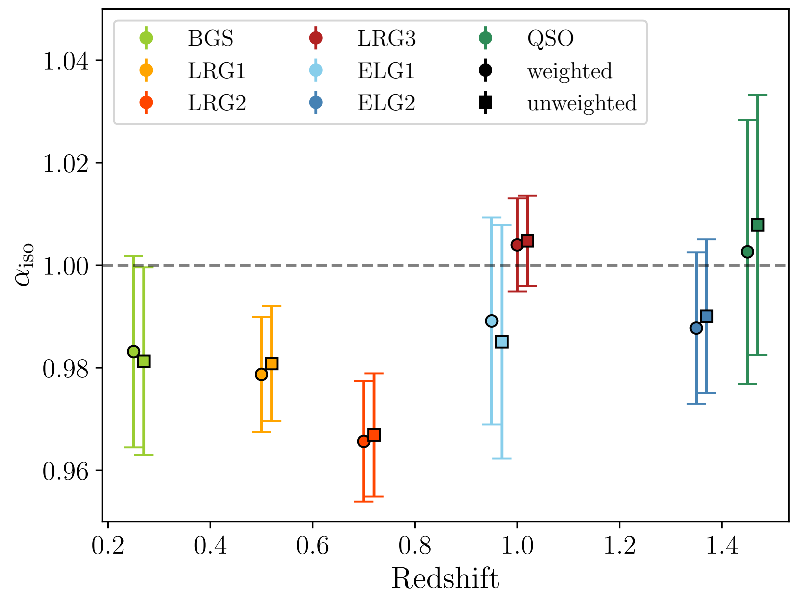
- Observational effects in data (**imaging**, fiber assignment,…)
- Reconstruction algorithm
- Covariance matrix construction

- Incomplete theory modelling
- Choice of fiducial cosmology
- Galaxy-halo (HOD) model uncertainties

Example of systematics: Imaging



Quasar target density



- Non-homogeneity in target selection due variations of imaging catalogs (depth, dust contaminants,…)
- Regression methods developed to correct those effect
- **BAO almost insensitive to imaging effects**

Systematics Error Budget

– Observational effects in data (imaging, fiber assignment,…)
– Reconstruction algorithm
– Covariance matrix construction

No effect on BAO

– Incomplete theory modelling
– Choice of fiducial cosmology
– Galaxy-halo (HOD) model

Systematics Error Budget

– Observational effects in data (imaging, fiber assignment,…)
– Reconstruction algorithm
– Covariance matrix construction

Negligible effect on BAO

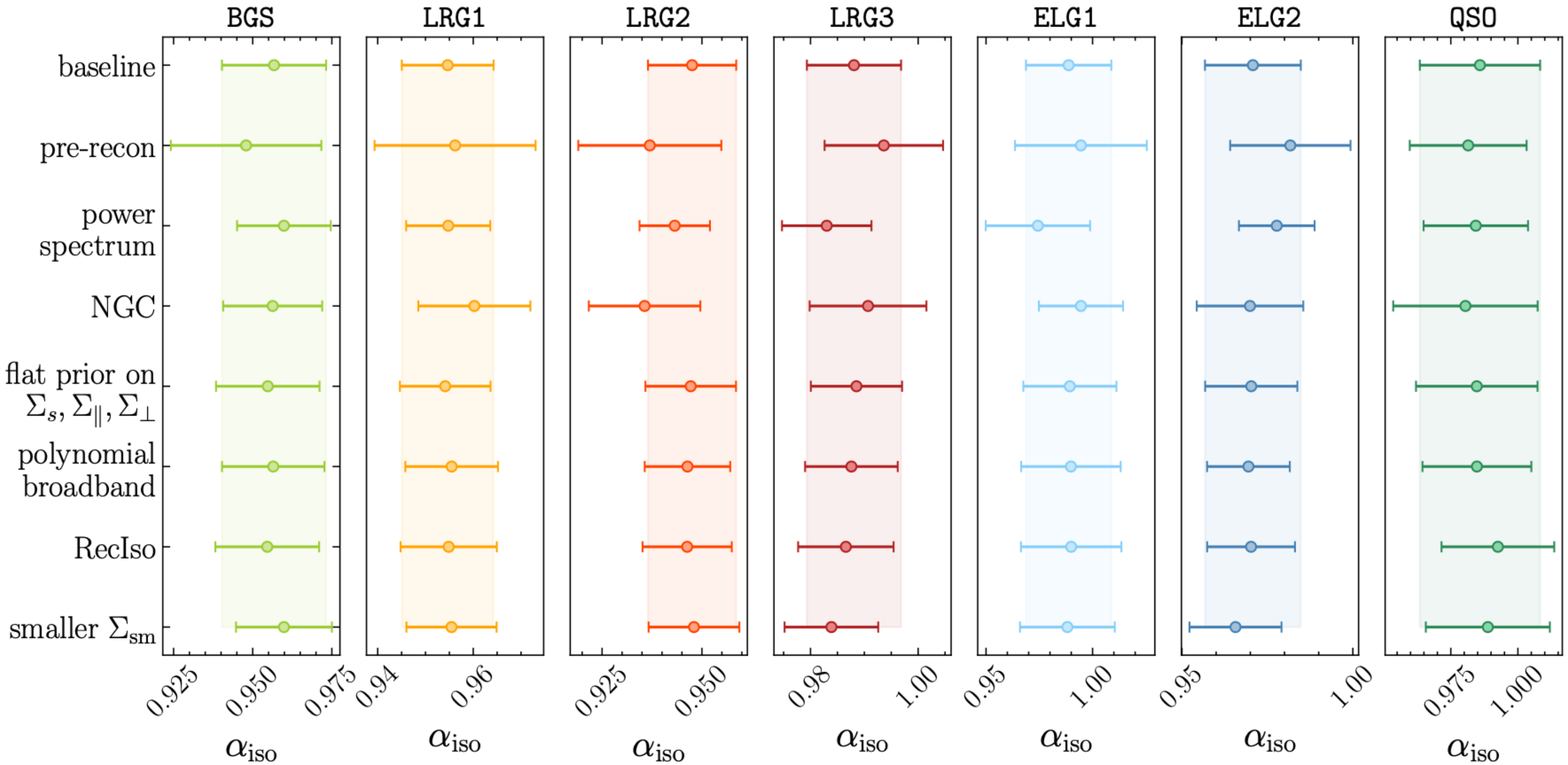
– Incomplete theory modelling $\boldsymbol{\sigma_{theo}} = 0.1\%$
– Choice of fiducial cosmology $\boldsymbol{\sigma_{fid}} = 0.1\%$
– Galaxy-halo (HOD) model $\boldsymbol{\sigma_{HOD}} = 0.2\%$

$\sigma_{sys} = 0.25\%$

All systematics much smaller than statistical errors

$$\boldsymbol{\sigma_{total} = 1.05\sigma_{stat.}}$$

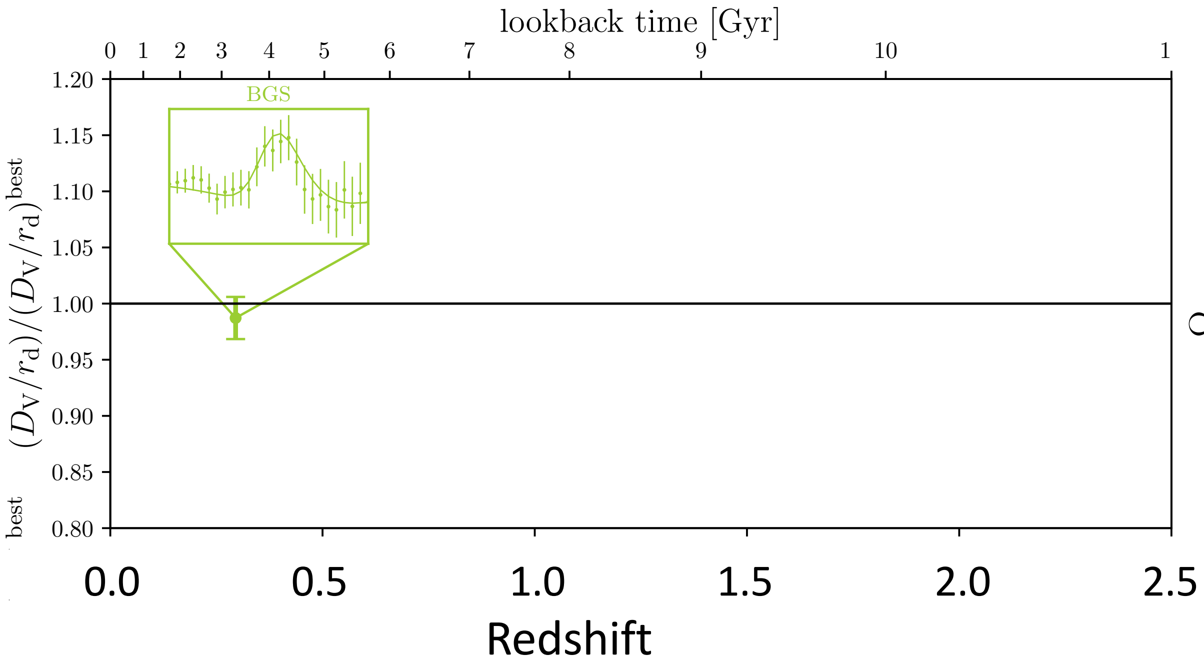
Stability of the results

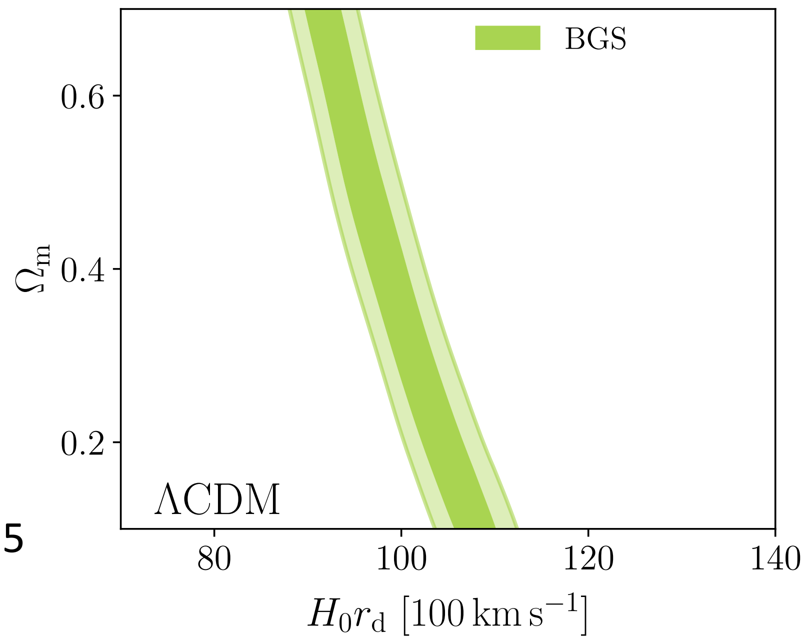


- Comparison with the baseline analysis for different configurations (with/without reconstruction, power-spectrum, without SGC, priors damping parameters, broadband modeling and reconstructions)
- **Robust results**

DESI Year 1: BGS

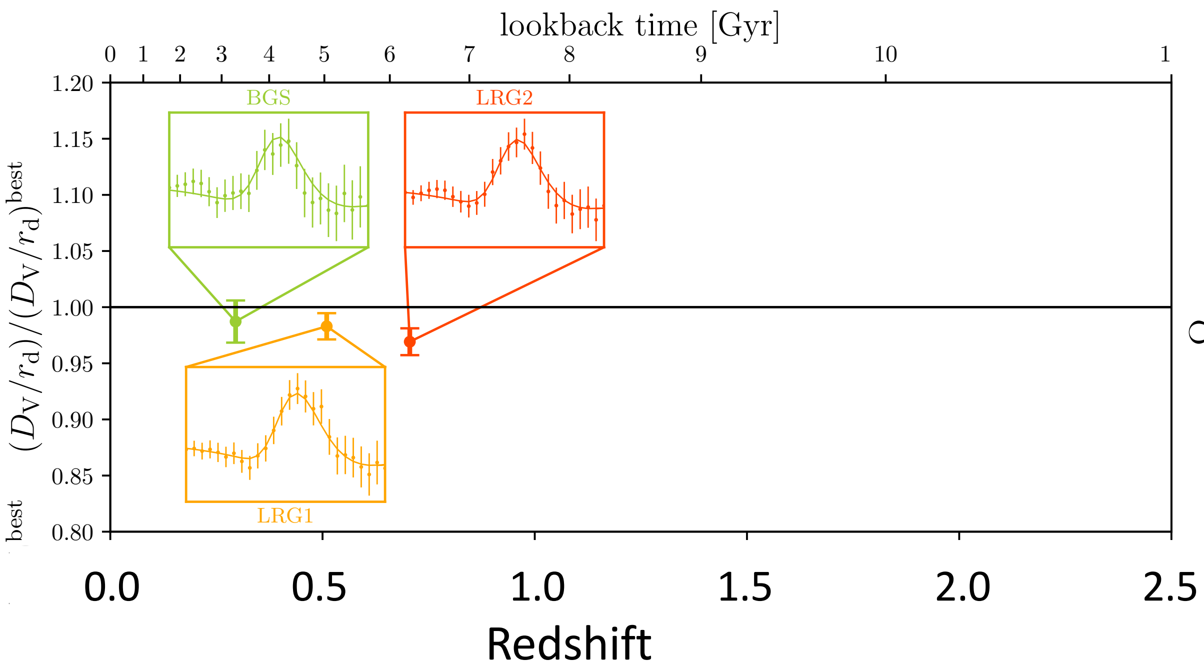
$$\alpha_\perp = \frac{D_M}{r_d}\frac{r_d^{fid}}{D_M^{fid}} \qquad \alpha_{||} = \frac{H^{fid} r_d^{fid}}{H r_d} \qquad \alpha_{iso} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$$

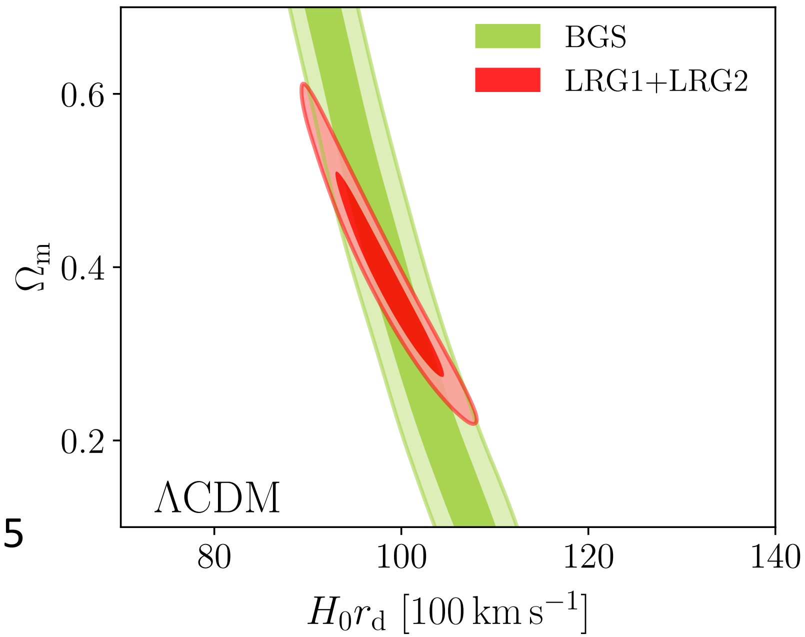




- Friedman equation for a flat Universe $H(z) \equiv H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}$
- Limitation due the cosmic variance (small part of the visible Universe)

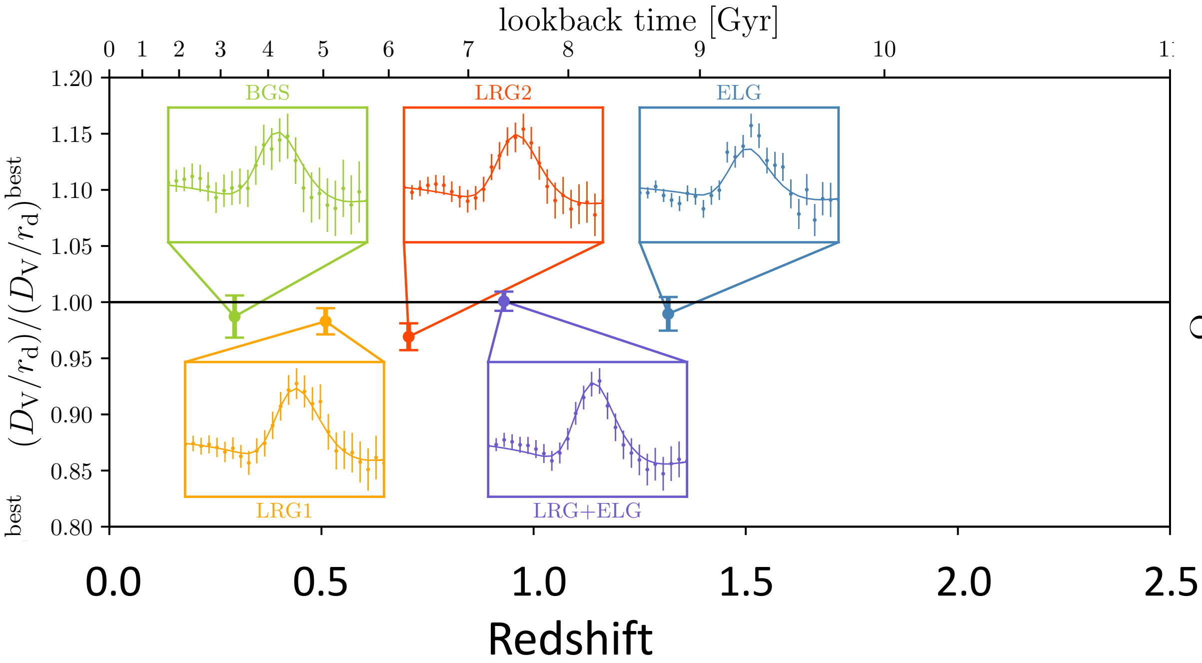
DESI Year 1: BGS + LRG

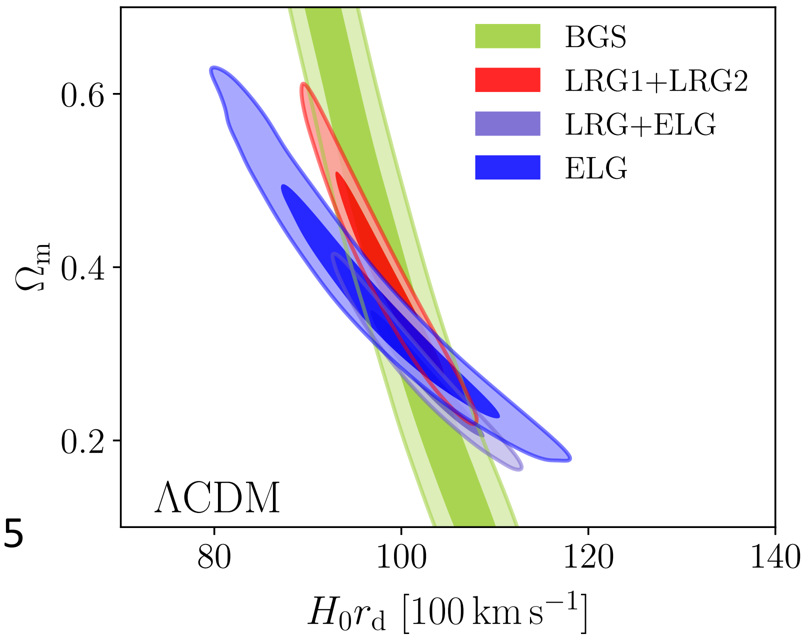




– LRG: Main tracer in SDSS, precise measurement

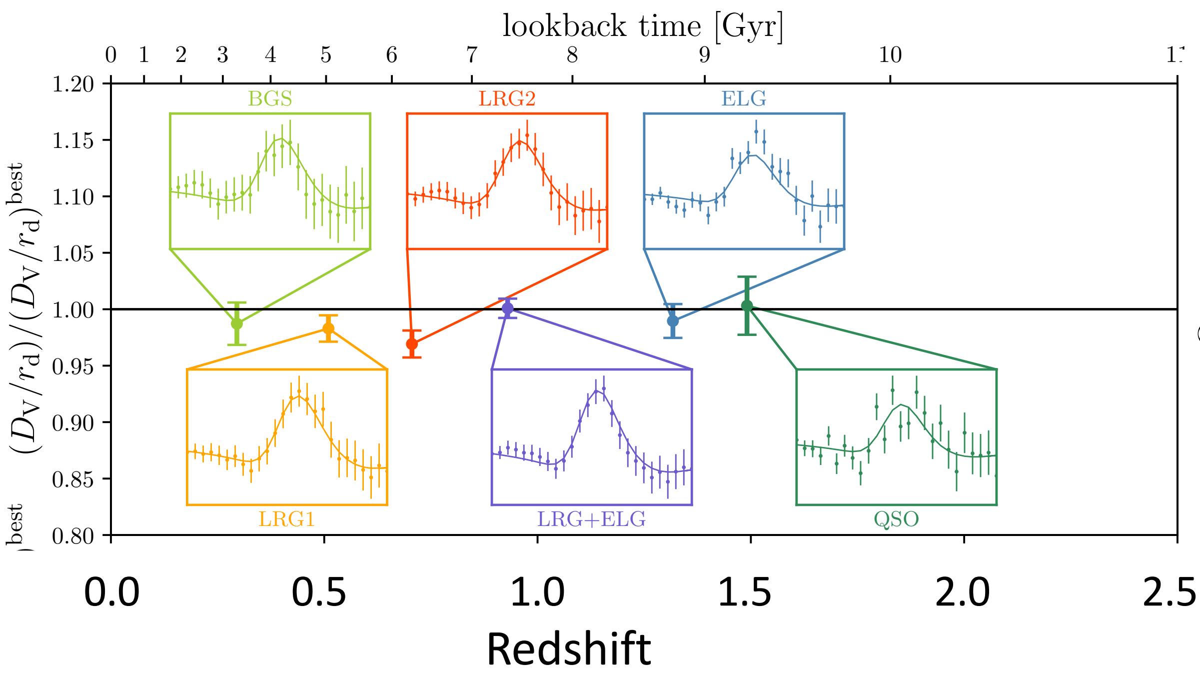
DESI Year 1: BGS + LRG + ELG

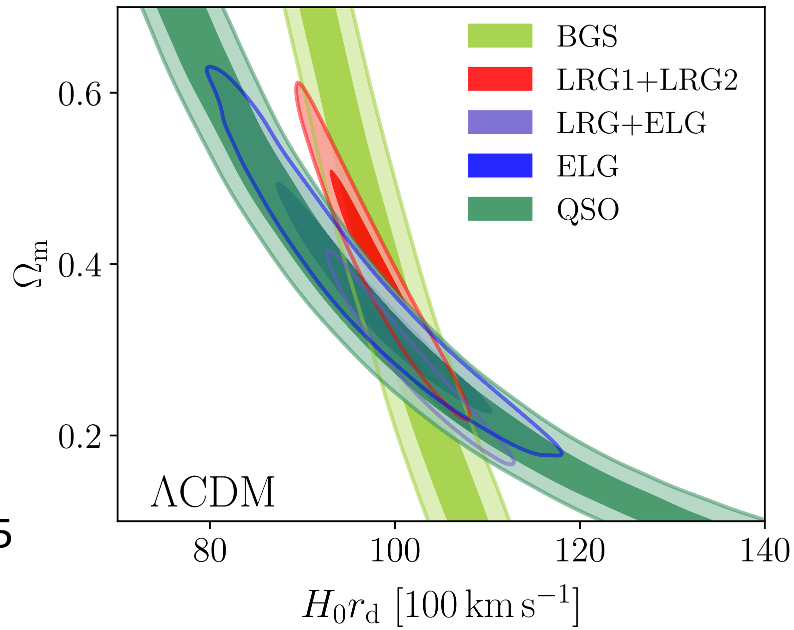




– ELG: Main tracer in DESI, precise measurement, but only a small fraction was observed in DESI Y1

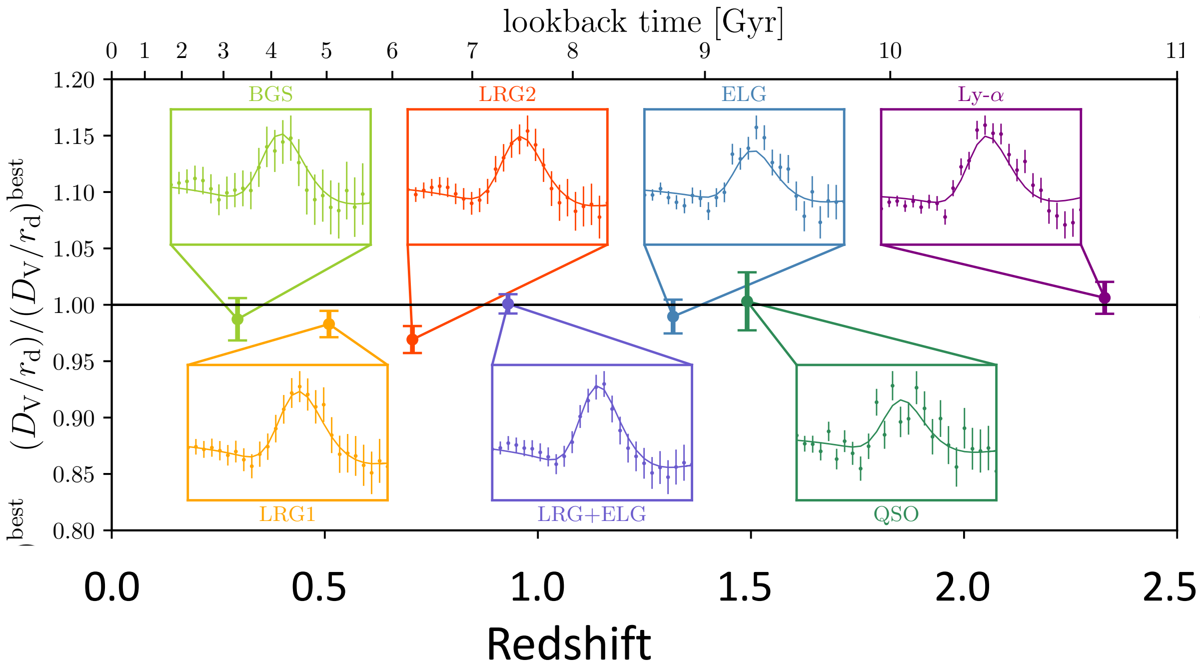
DESI Year 1: BGS + LRG + ELG + QSO

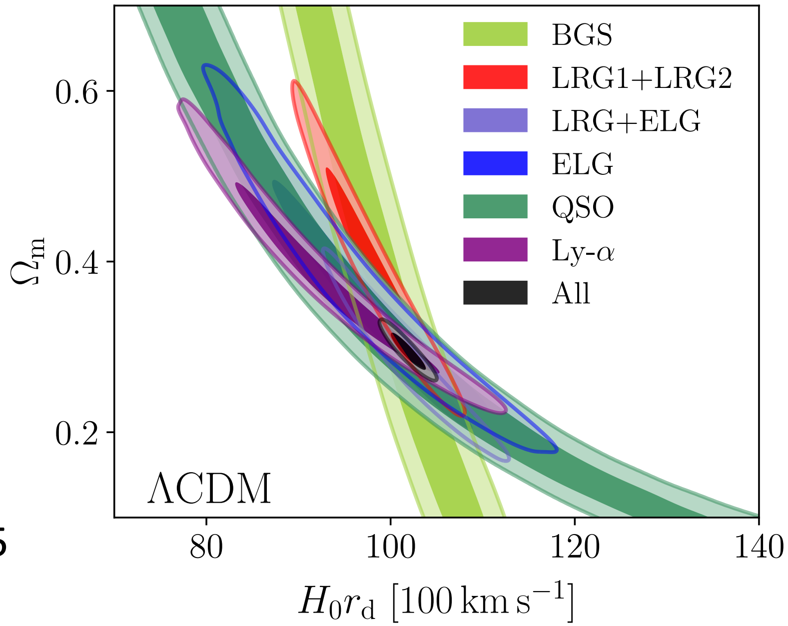




– QSO: huge volume but small density (shot noise limitation)

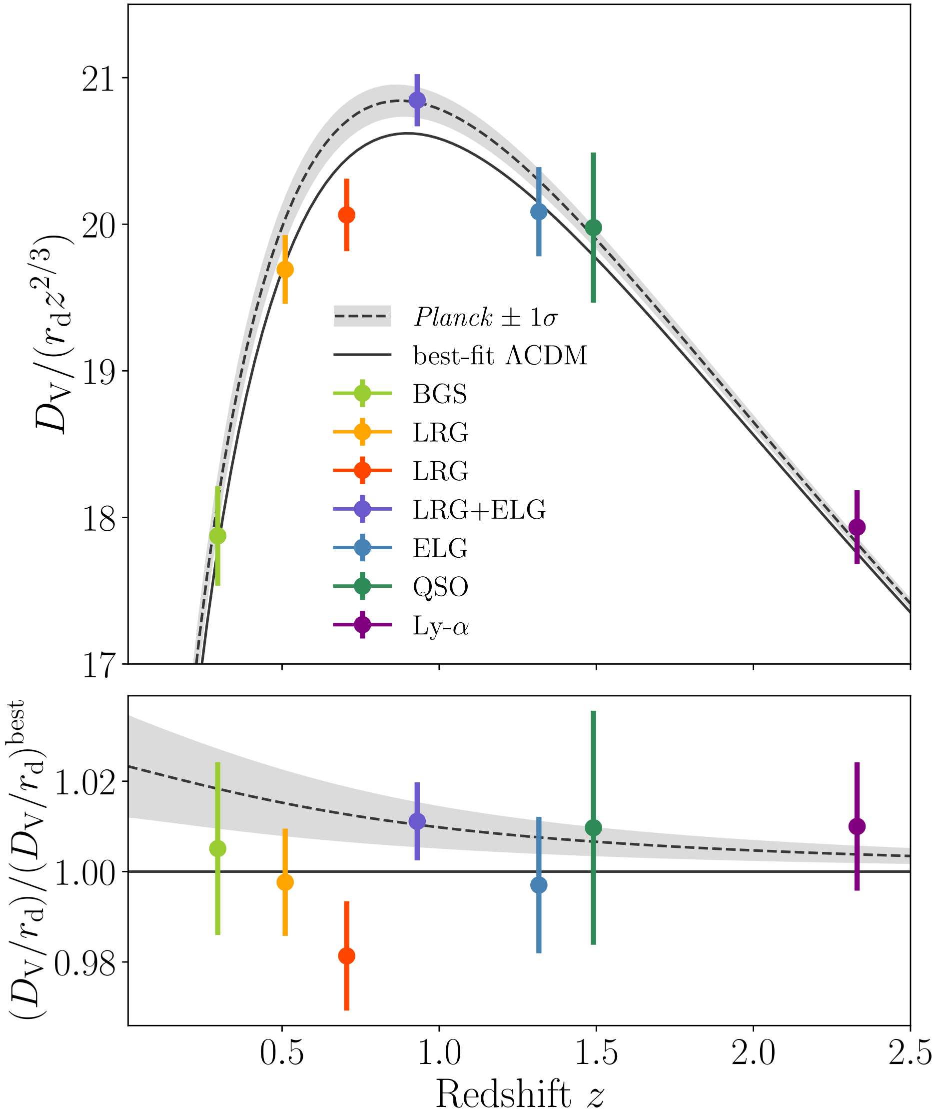
DESI Year 1: BGS + LRG + ELG + QSO + Ly-α





- Different dependence as a function of redshift (Ω_m,r_d)
- Break the degeneracy without knowing r_d

DESI Year 1 - Hubble diagram



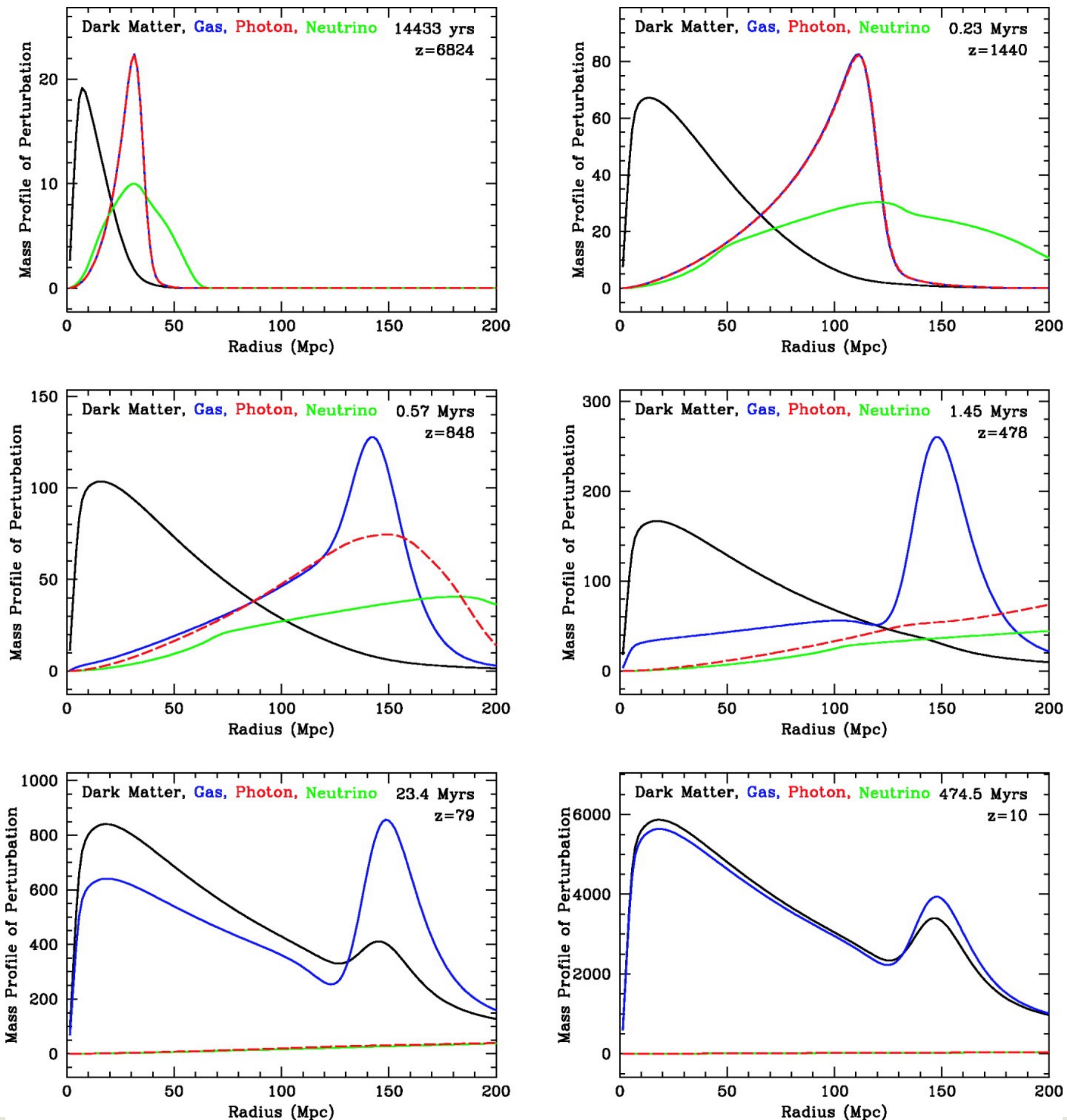
- ~6 million discrete tracers
- $0.1 < z < 2.1$
- 3 times bigger than SDSS
- Measurement with Ly-α forest of QSOs at higher redshift

- Total precision on BAO: 0.52%
- Consistent with ΛCDM
- Agreement with Planck: 1.9σ
- BAO ~very low systematics
- Cosmological constraints

⇒Next talk by Dragan Huterer

Additional Slides

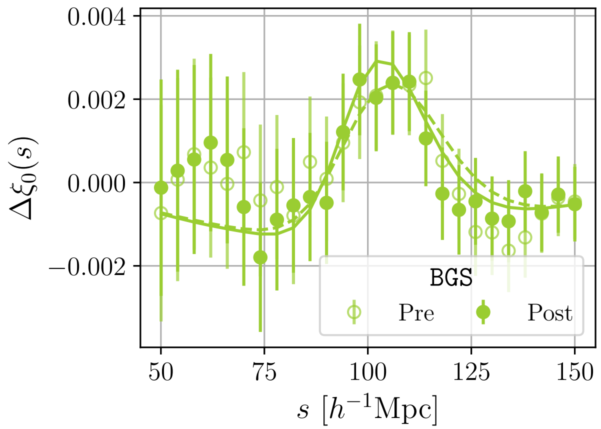
Evolution of density perturbations



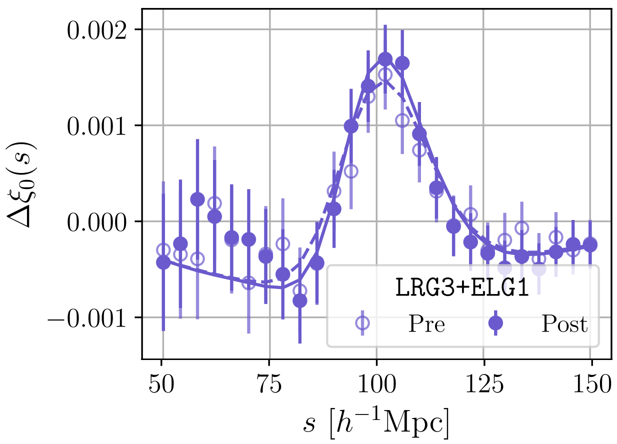
From Eisentein 2007

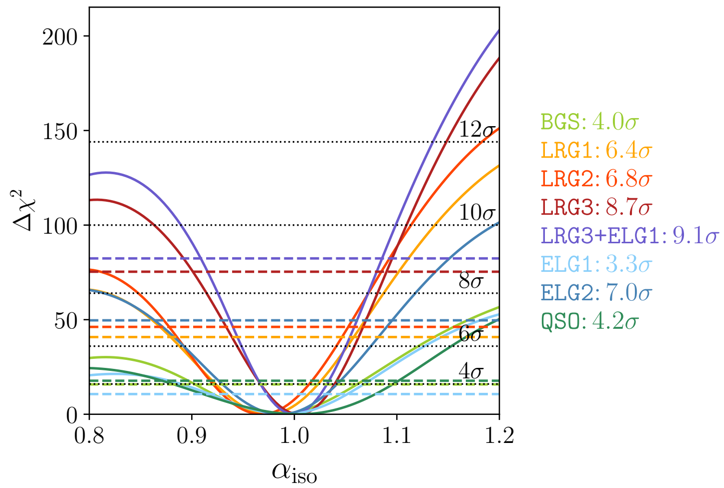
Results: a few examples

BGS z=0.30



LRG3+ELG1 z=0.93



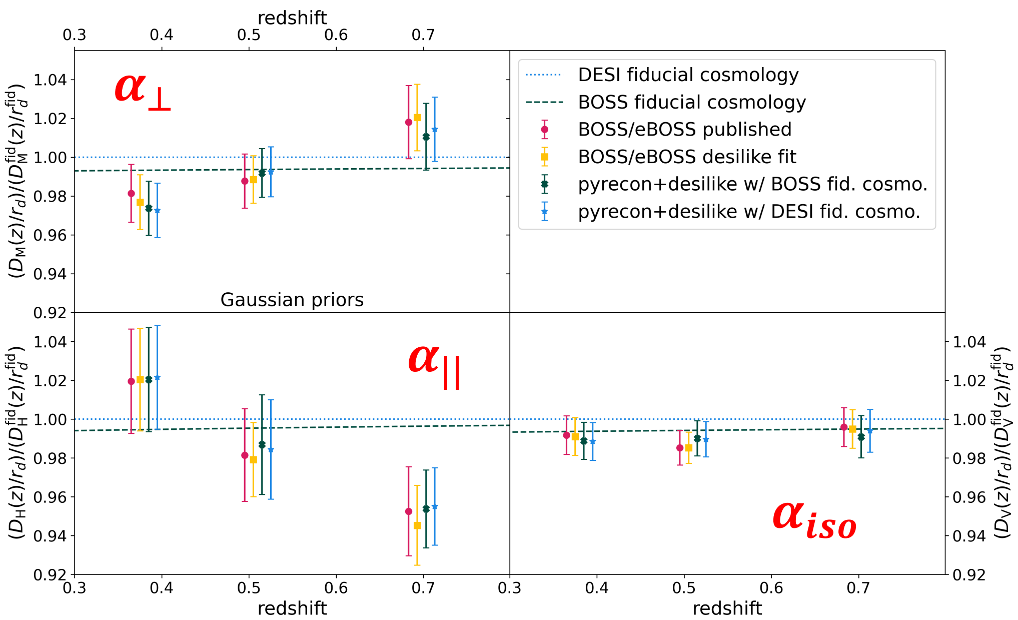


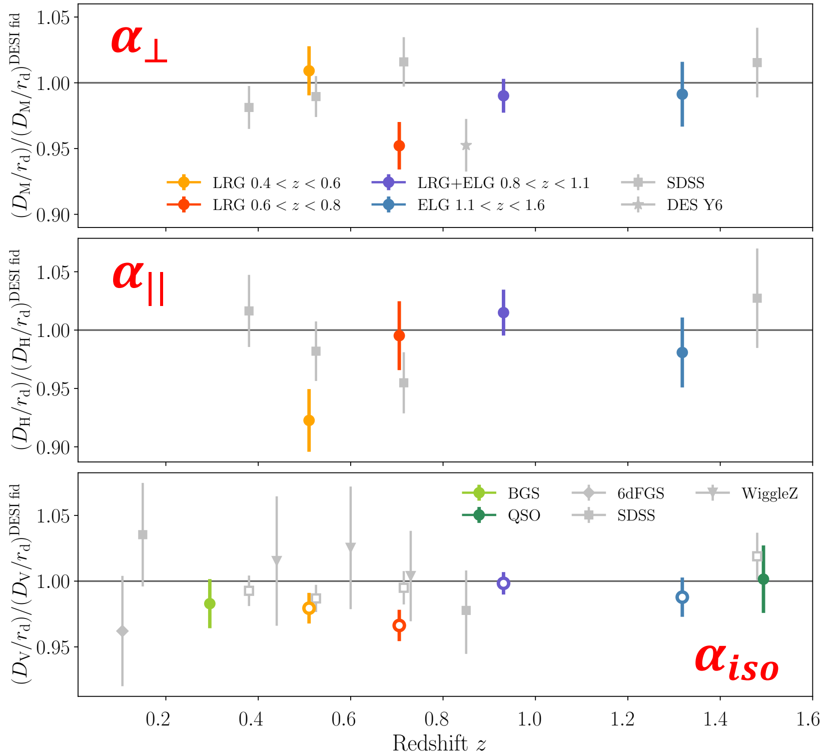
Significance: 4.0σ
Precision: 1.85%

Significance: 9.1σ
Precision: 0.81%

- **Dilation compared to a fiducial cosmology**
  - Perpendicular or parallel to the line of sight, $\alpha_\perp$ and $\alpha_{||}$
  - Combined through $\alpha_{\rm iso} = \left(\alpha_\perp^2 \alpha_{||}\right)^{1/3}$
- 6 bins in redshifts covering the redshift range, 0.1<z<2.1
- Bin with lowest significance 4.0

Comparison DESI/SDSS

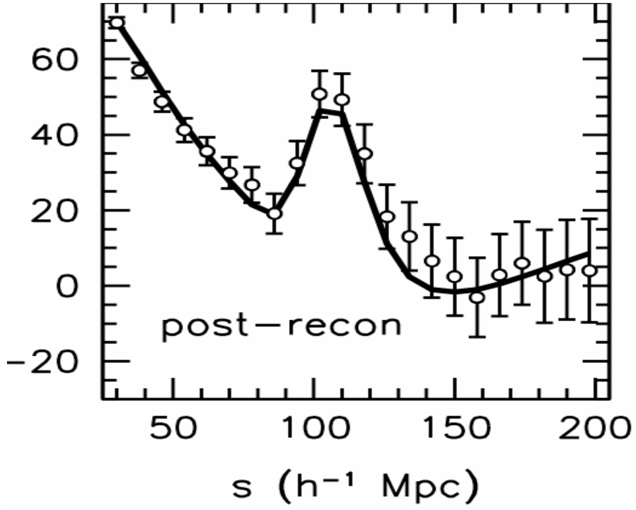


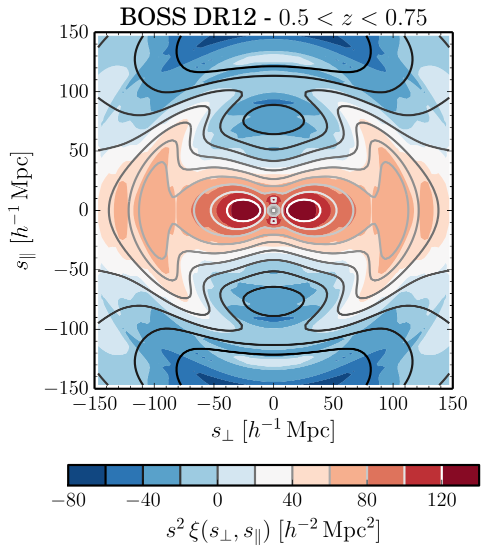


- 2.5σ to 3.0σ discrepancy depending on the correlations between the two samples
- Same redshift for the overlap catalog
- SDSS measurements identical when we use DESI pipeline

Main science at DESI

- **Baryonic Acoustic Oscillations (BAO)**
  - σ(BAO) ~0.2 % for 0.0<z<1.1
  - σ(BAO) ~0.3% for 1.1<z<1.9
  - σ(BAO) ~0.5% for 1.9<z<3.5
  - SDSS(BOSS+eBOSS) few % measurements
- **Redshift Space Distorsion (RSD)**
  - Multiple few % measurements over wide redshift range (z<2)
  - ~10x better compared to SDSS
- **Neutrino masses**
  - $\sigma(\Sigma m_\nu)$ ~20 meV
  - Current limit : Σm_ν <~100 meV, @ 95 CL
- **Non-Gaussianity (f_{NL})**
  - $\sigma(f_{NL})$~4 with k dependence of bias
  - As precise as Planck with a different technique

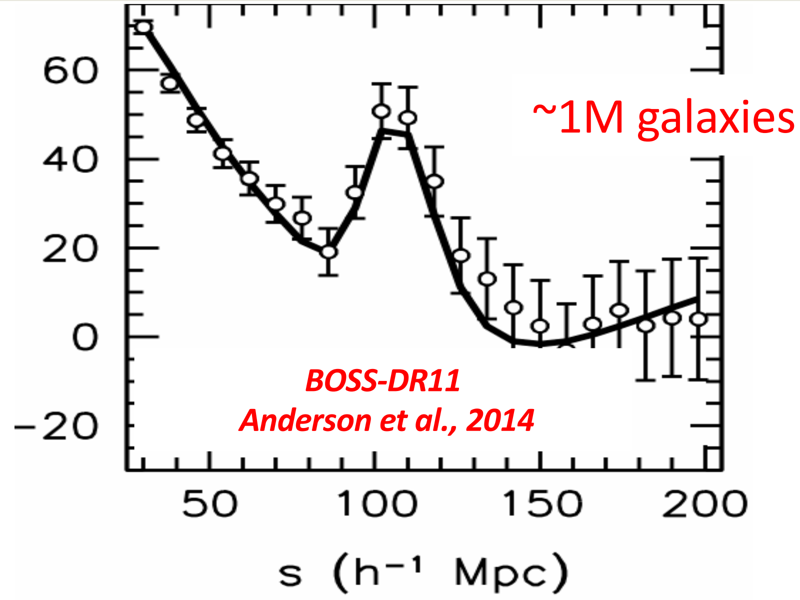


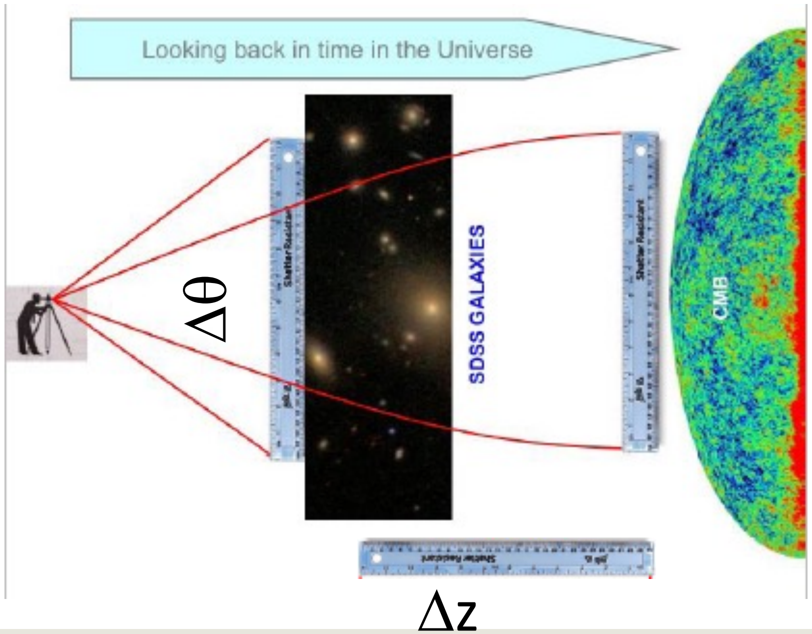


Baryonic Acoustic Oscillations (BAO)

- **BAO distance**
  - Non-uniform distribution of galaxies, they form in overdense shells about 100 $Mpc.h^{-1}$ in radius.
  - Excess in the correlation function at ~100 $Mpc.h^{-1}$

    ⇒ Standard Ruler



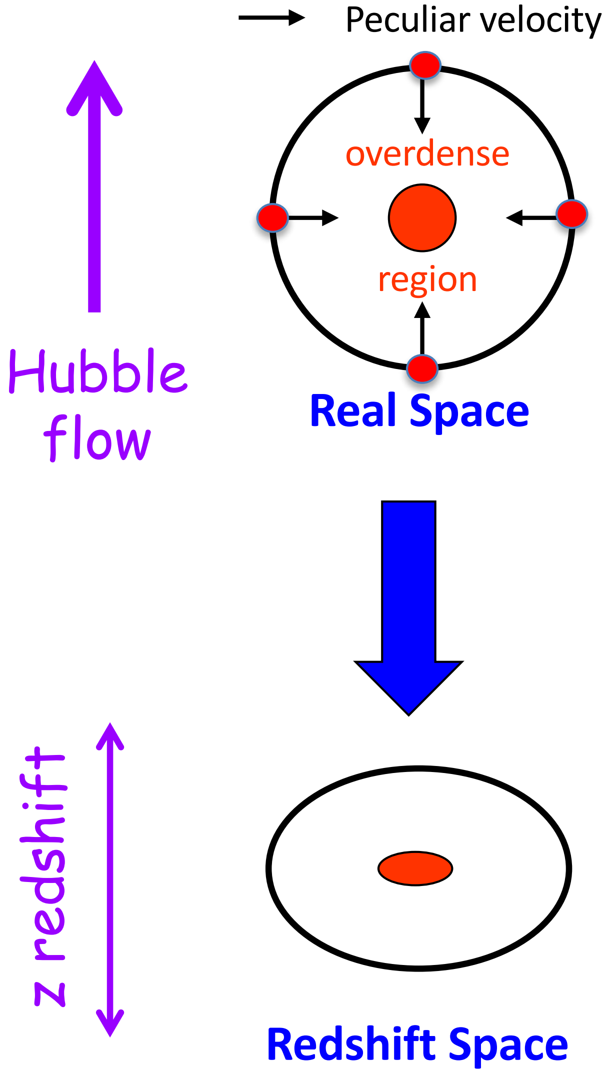


- **3D measurement**
  - Position of acoustic peak
  - **Transverse direction:**

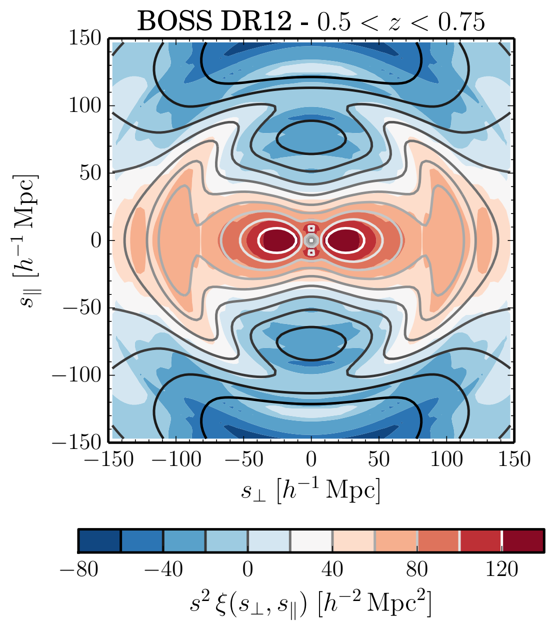
    ⇒Sensitive to angular distance $D_A(z)$
  - **Radial direction** (along the line of sight):

    ⇒ Sensitive to Hubble parameter H(z)

Redshift Space Distorsion (RSD)



- **RSD origins**
  - Acceleration toward overdense regions
  - Flattening in radial direction from real space to redshift space (over tens Mpc)
  - Allow us to measure action of gravity (10-40 Mpc) at cosmological distance (Gpc)



BOSS Collaboration
Alam et al. (2016)