Massive Spectroscopic Surveys & Fibre Positioner Robots

legacysurvey.org

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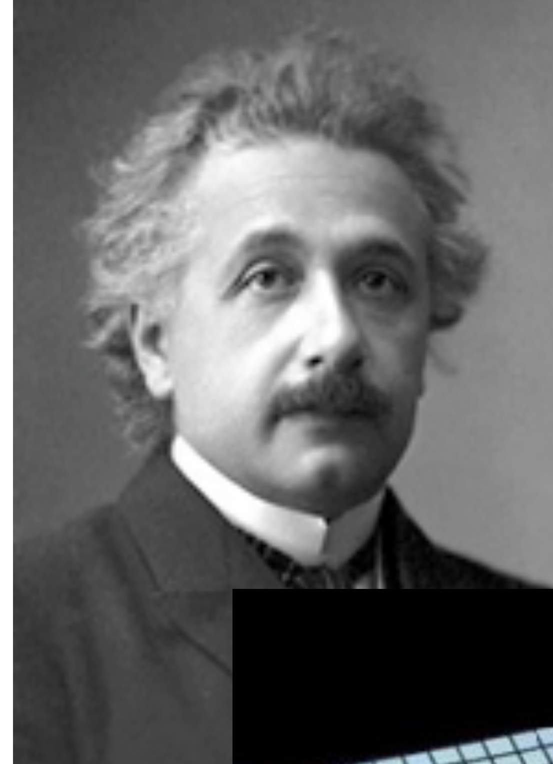
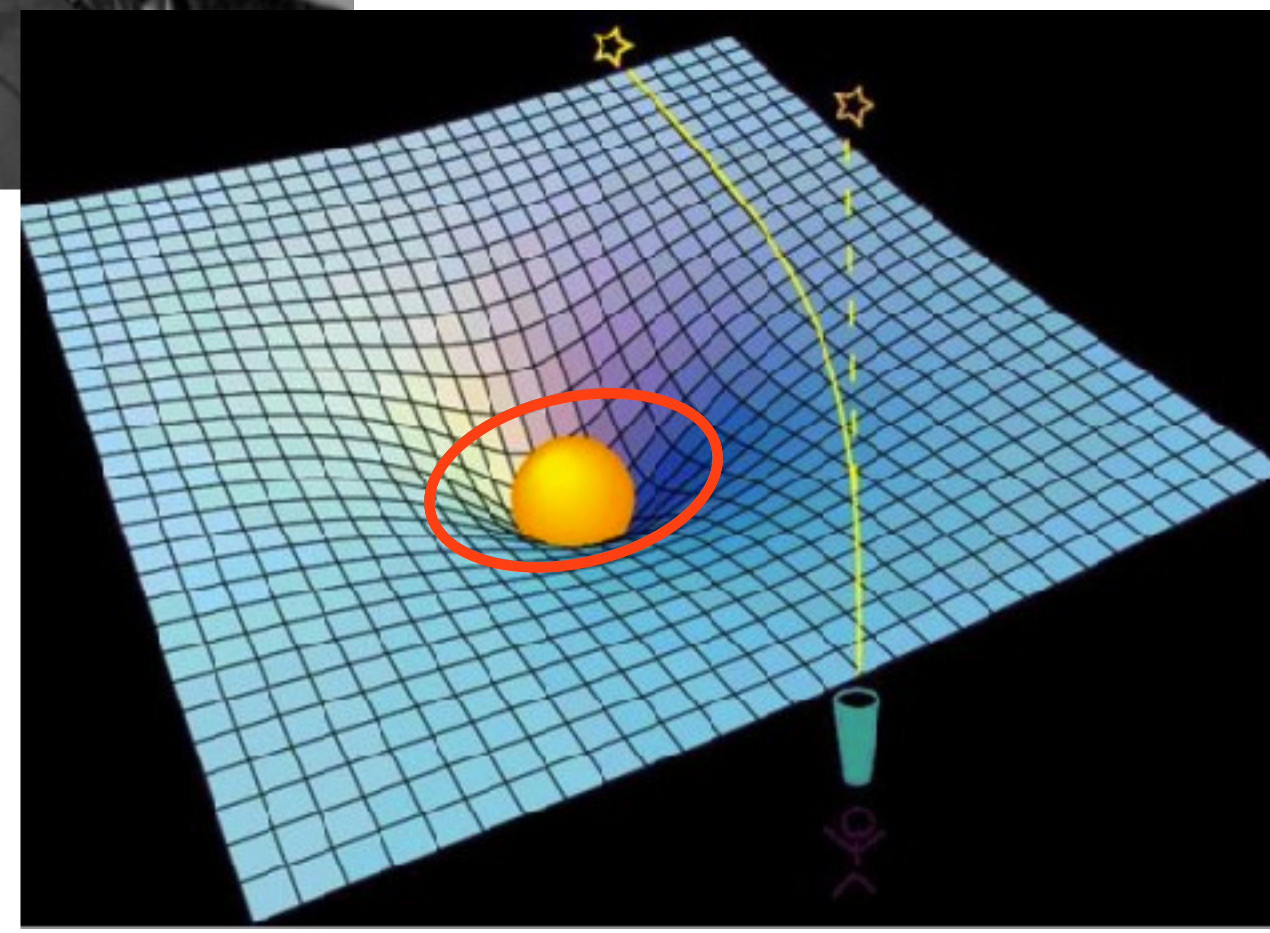
erc
European Research Council
KTI/CTI
DIE FÖRDERAGENTUR FÜR INNOVATION
L'AGENCE POUR LA PROMOTION DE L'INNOVATION
L'AGENZIA PER LA PROMOZIONE DELL'INNOVAZIONE
EPFL

Outline

- *Motivation*
- *Precision cosmology from galaxy redshift surveys: quest of dark energy and neutrino masses*
- *Ast**ro**bots: fiber positionning*
- *Outlook for massive redshift surveys*

<u>1916</u>:
General Relativity = Gravitation force by Einstein





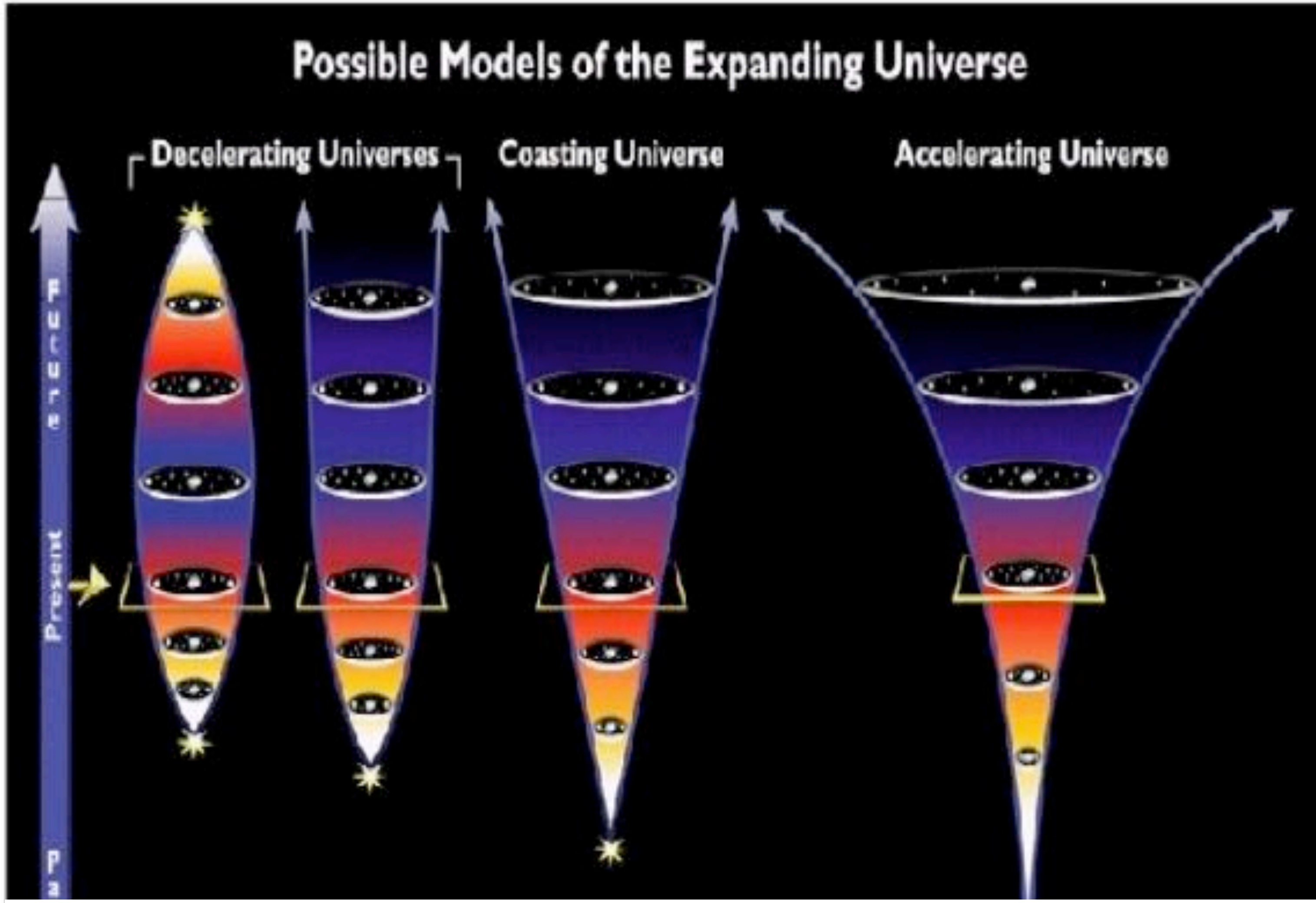
<u>Gravitation</u> = deformation of Space-Time by the existence of Matter.

G: gravitational constant.
c: speed of light
Λ: cosmological constant.

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Gravitation-Metric Mass/Energy

1924: Friedman-Lemaître Equations describe the evolution of the Universe depending on its content



Hubble constant (expansion)

Radiation photon/ neutrino

Matter

Curvature

Cosmological Constant (Dark Energy?)

$$\frac{H^2}{H_0^2} = \frac{\Omega_R}{(1+z)^4} + \frac{\Omega_M}{(1+z)^3} + \frac{\Omega_k}{(1+z)^2} + \Omega_\Lambda$$

redshift (time)

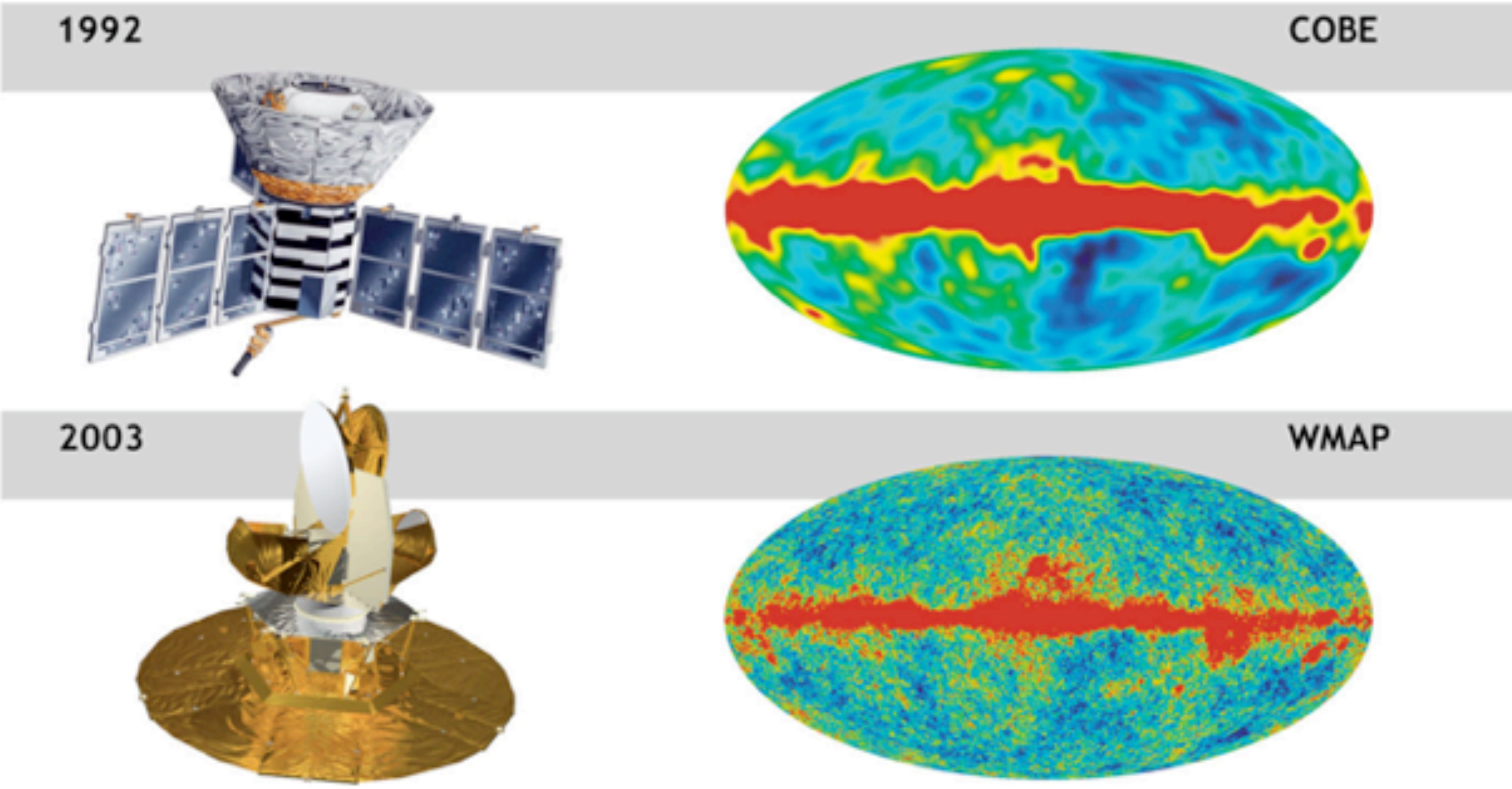
Edwin Hubble (1929):

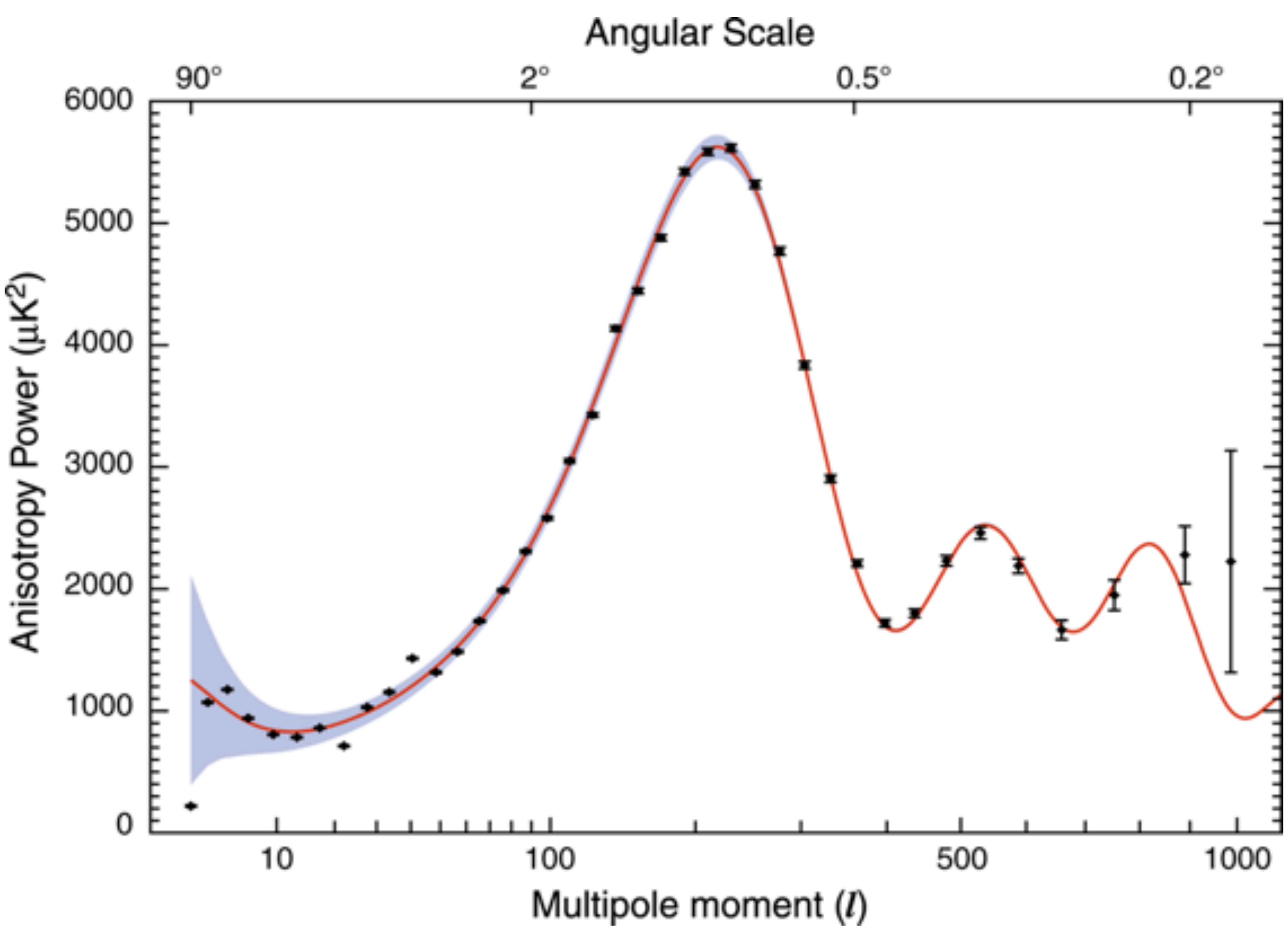
First clues on the expansion of the Universe

Penzias & Wilson (1965)

Confirmation of the expansion with detection of CMB

Woody Allen in Annie Hall (1977)



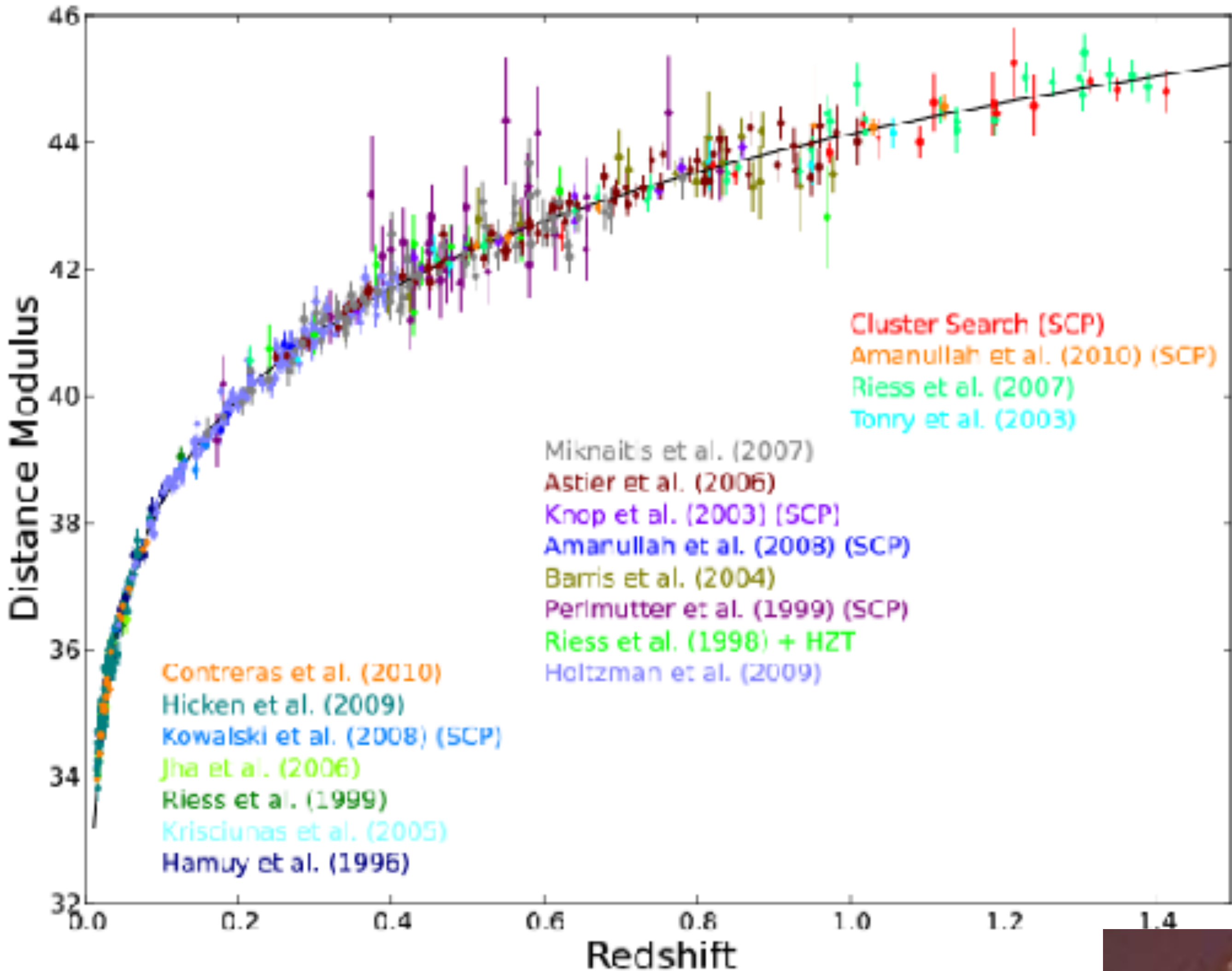


2003: <u>Precise measurement of the CMB</u>

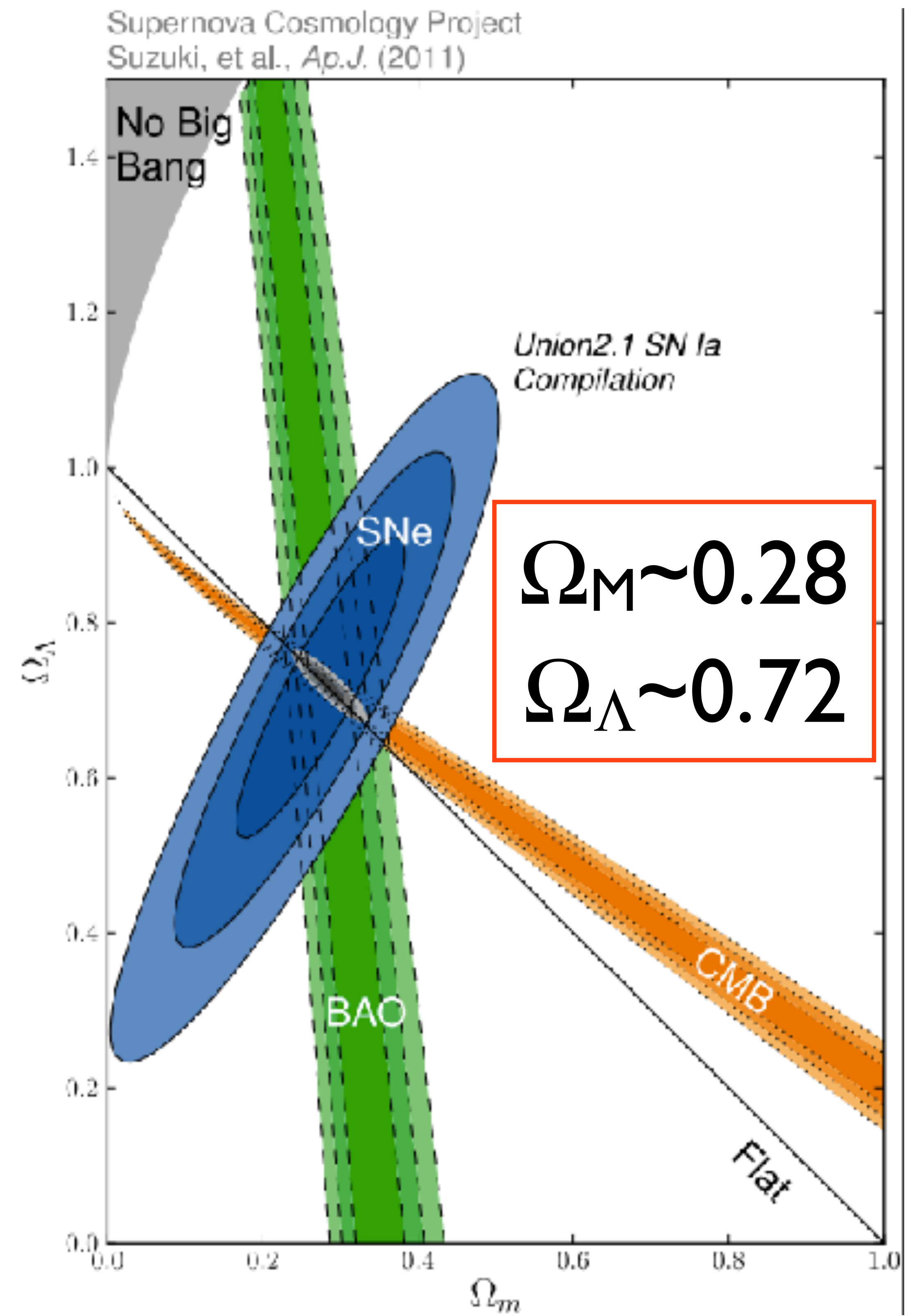
- Temperature fluctuations ($\Delta T \sim 10^{-5}$) are the seed of structure formation in the Universe.
- The size of the fluctuation is directly linked to the curvature of the Universe.
- **Our Universe is flat !**

<u>2006</u>: Nobel Prize

Precision Cosmology

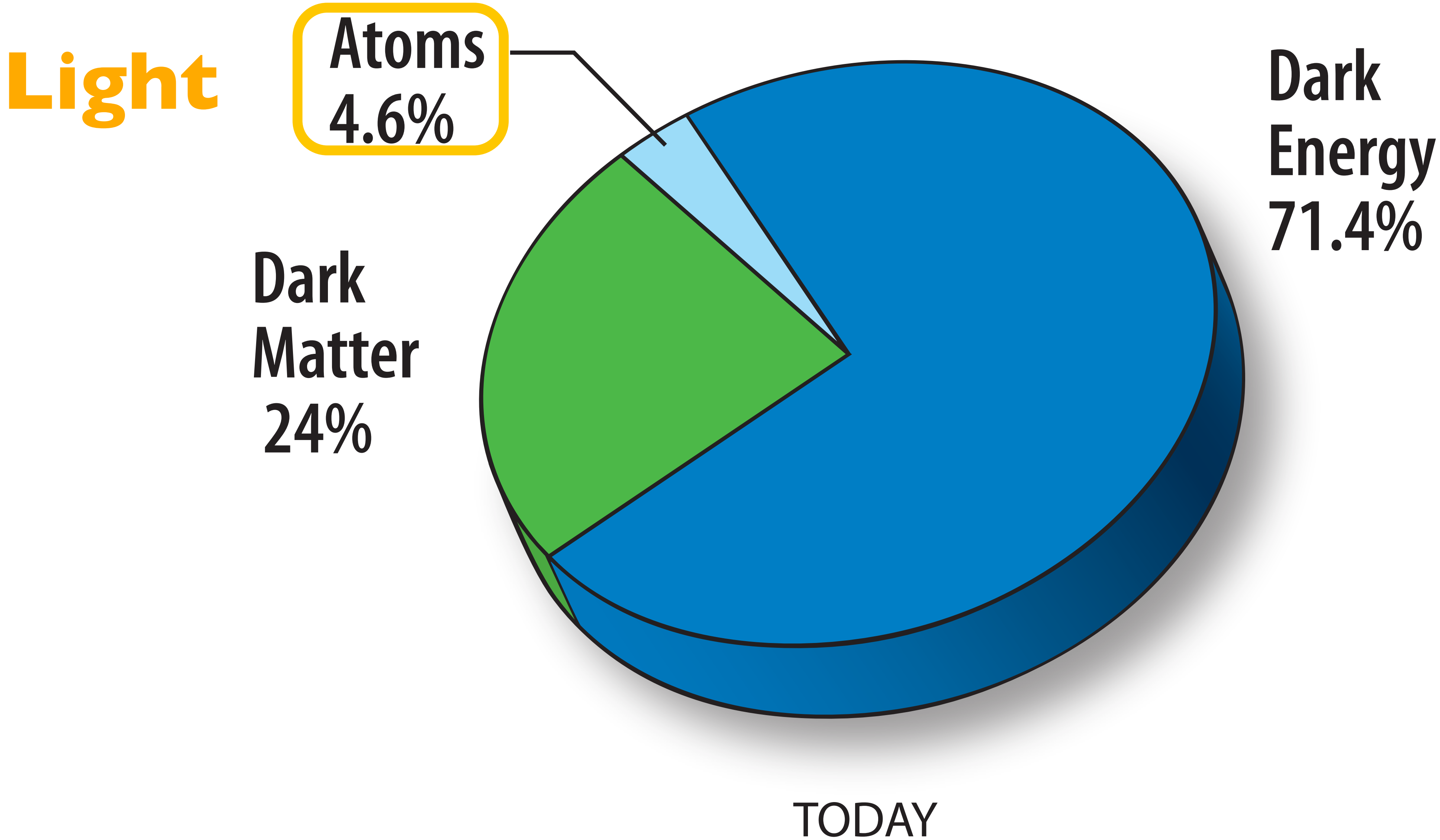


<u>2010</u>: ~600 SNIa
Confirmed the
Accelerated Expansion
<u>2011</u>: Nobel Prize



Ω_M~0.28
Ω_Λ~0.72

The Dark Side of the Universe

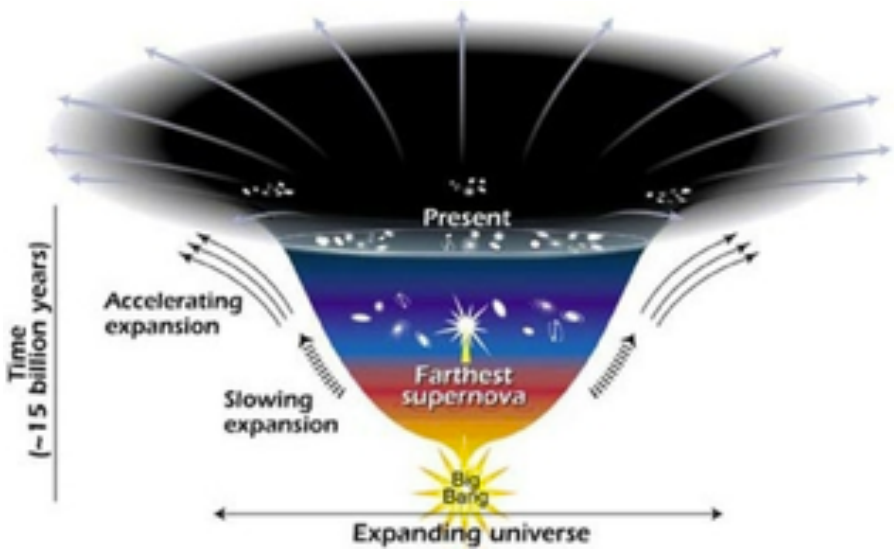


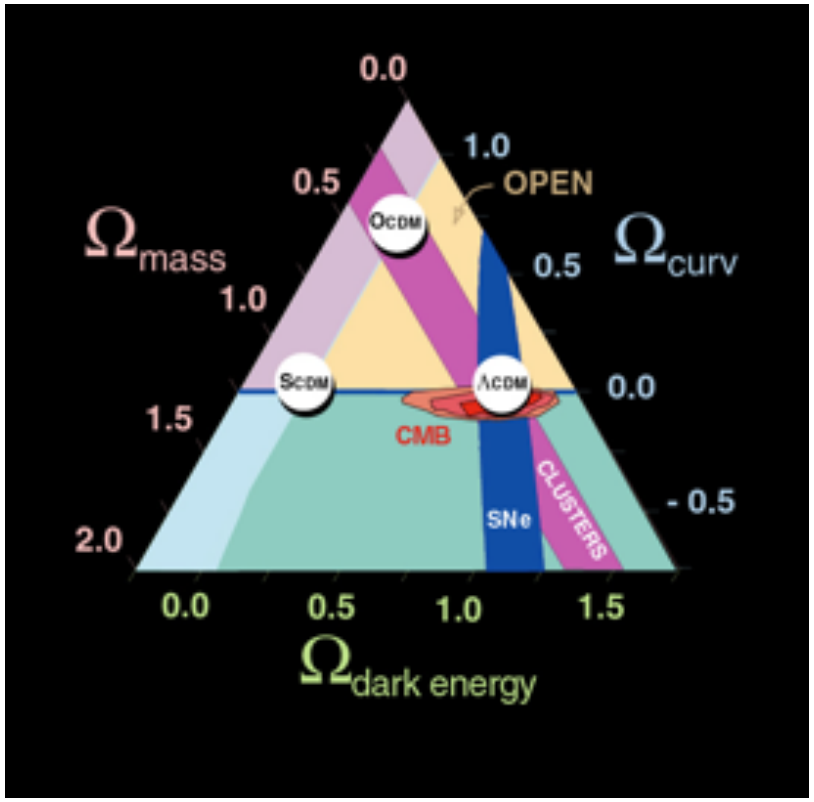
95% of the Mass-Energy content of the Universe is unknown!

24% of Dark Matter - *non identified particles*

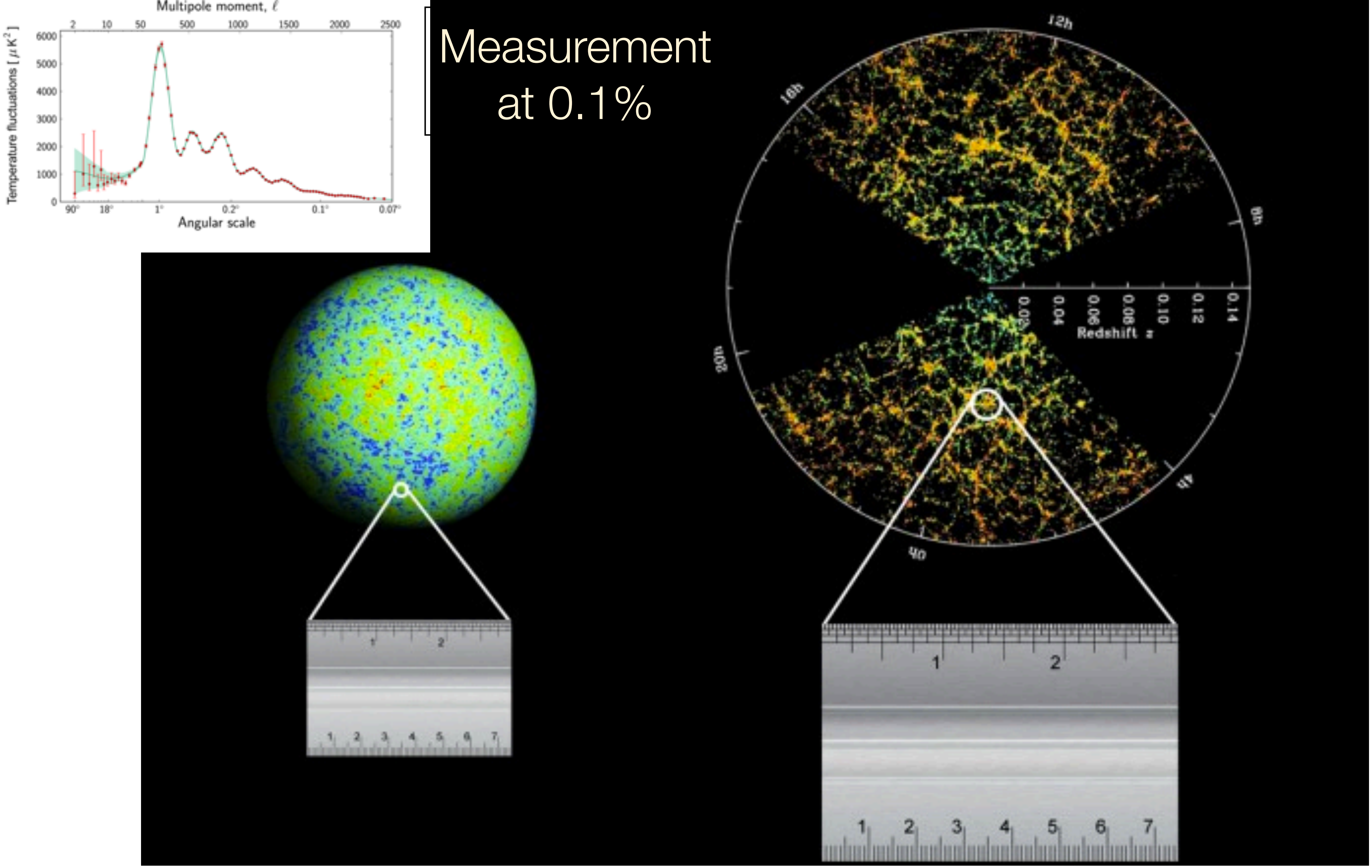
71% of Dark Energy - *non identified nature*

Understanding the accelerated expansion of the Universe





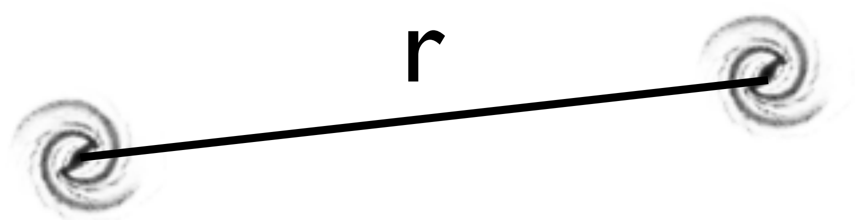
- **Origin of the accelerated expansion?** (many theories)
  - **Dark Energy** ? a new unknown component (probe its nature: eq. of state)
  - **Modified Gravity** ? correction of General Relativity on large scales
  - **Fractal Geometry/Scale Relativity??**
- **No good/simple/unique theory:** pragmatic approach need new observations => **precision cosmology:** requires measurement better than % level and not just at CMB redshift - ideally at any redshift ! => ***NEED DATA***

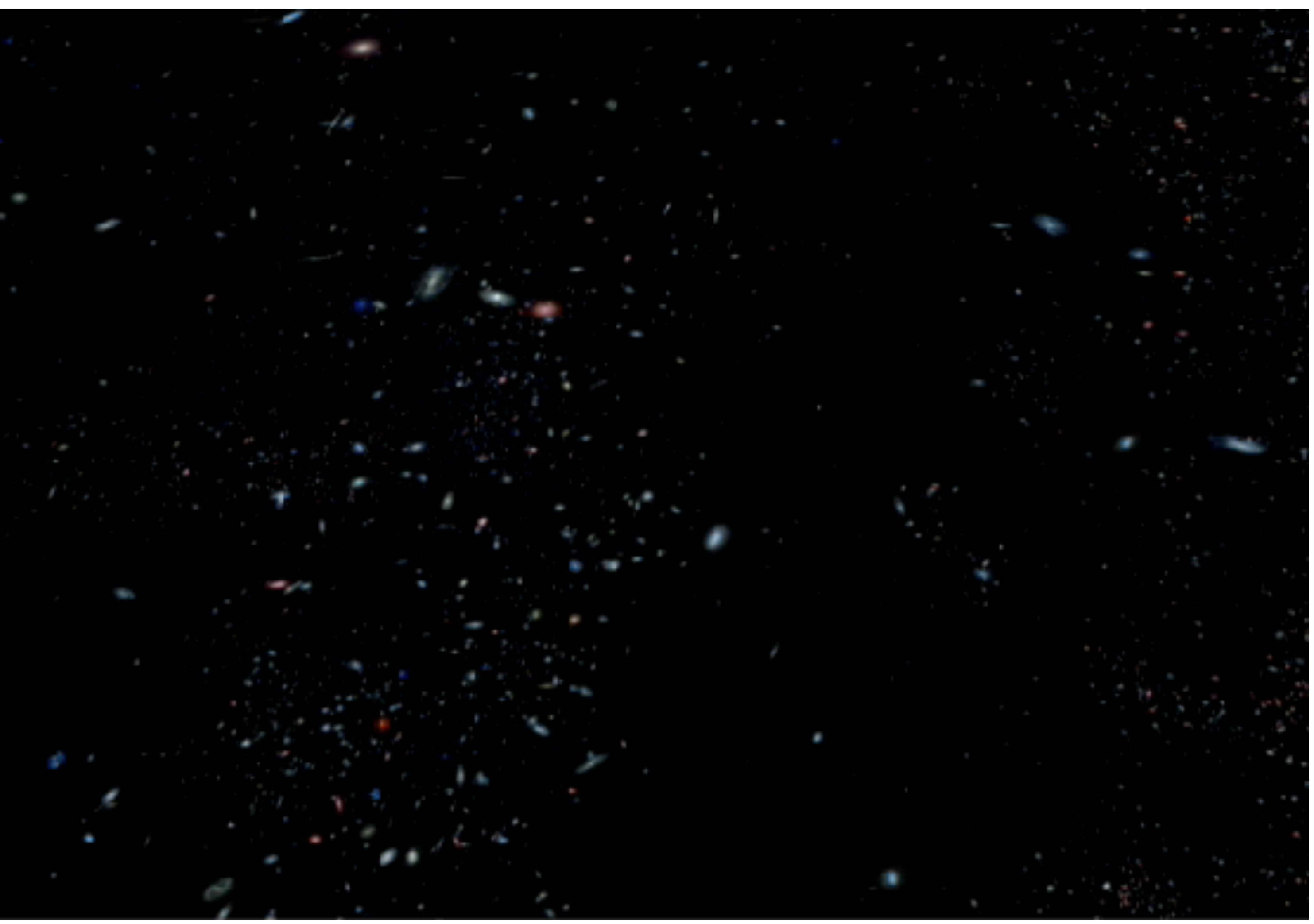


Mapping the Large Scale Structures and cosmological constraints

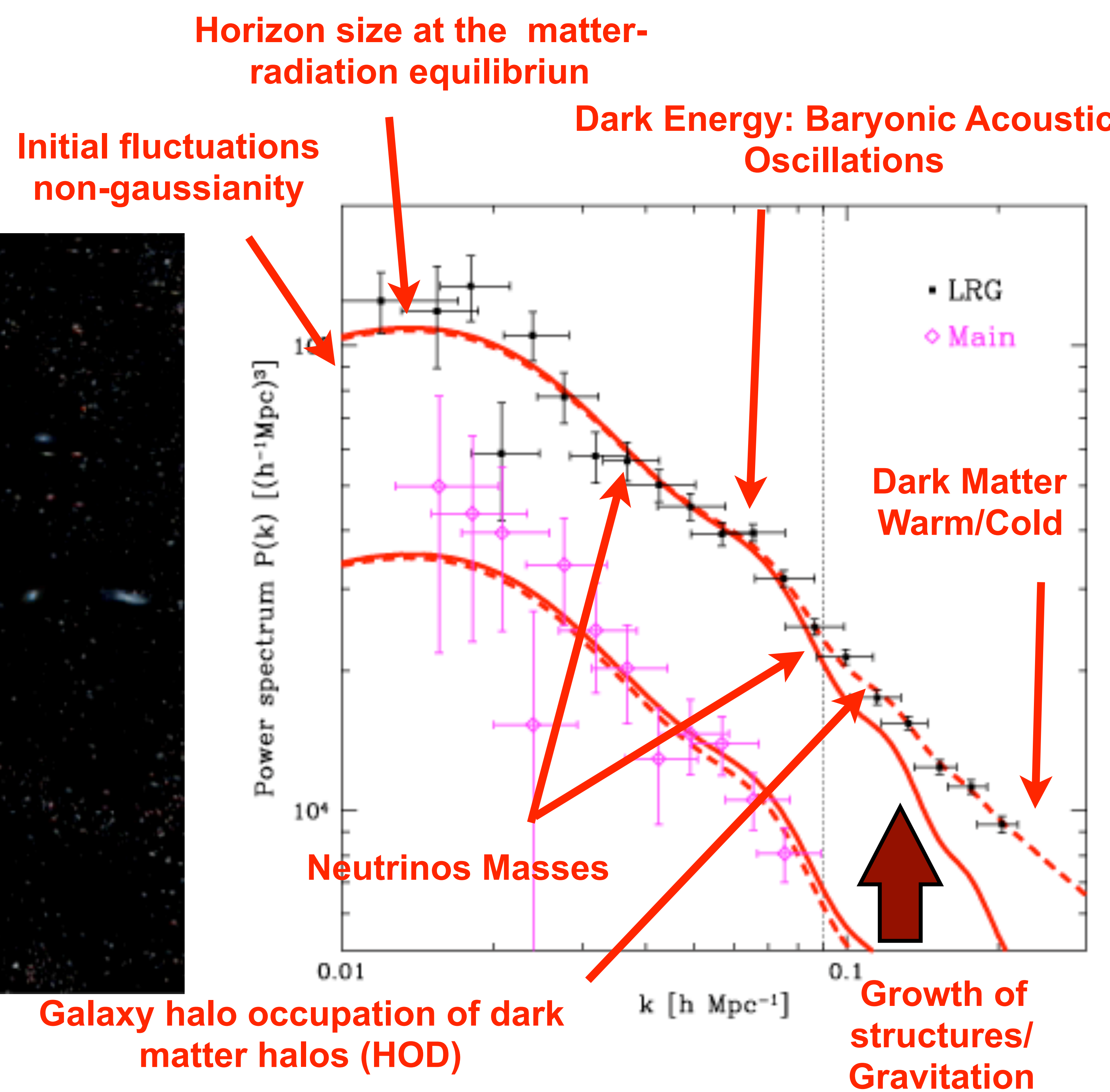
The acoustic fluctuations in the CMB is also seen in the distribution of galaxies. **The best technique to constrain the expansion of the Universe.**

Power Spectrum of Galaxy distribution

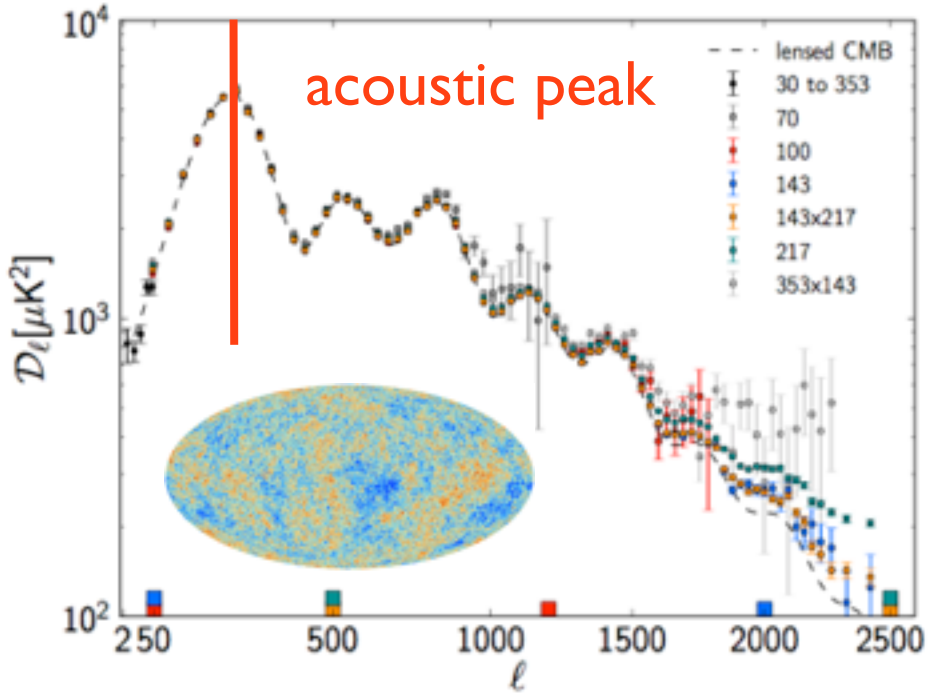




3D mapping of galaxies in the universe (SDSS I-II)

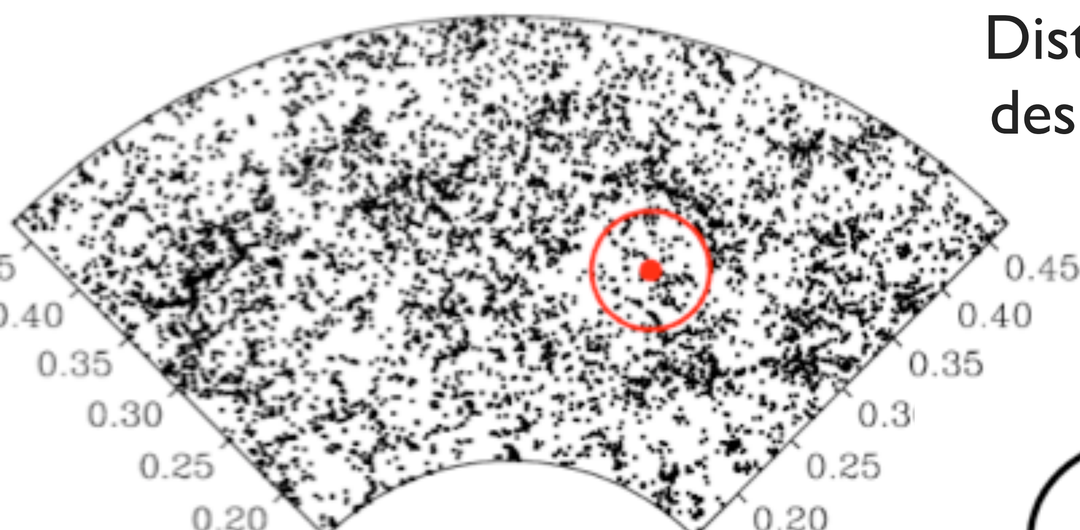


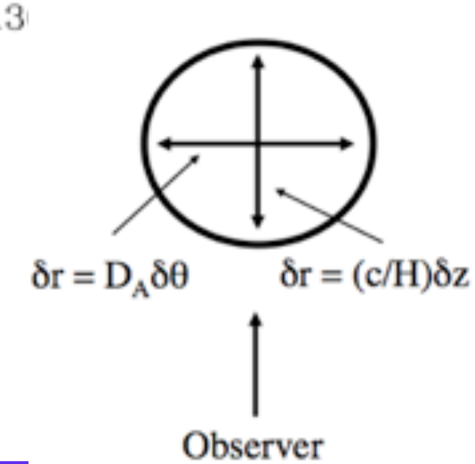
Baryonic Acoustic Oscillations (BAO)



Fond
Diffus
z~1100

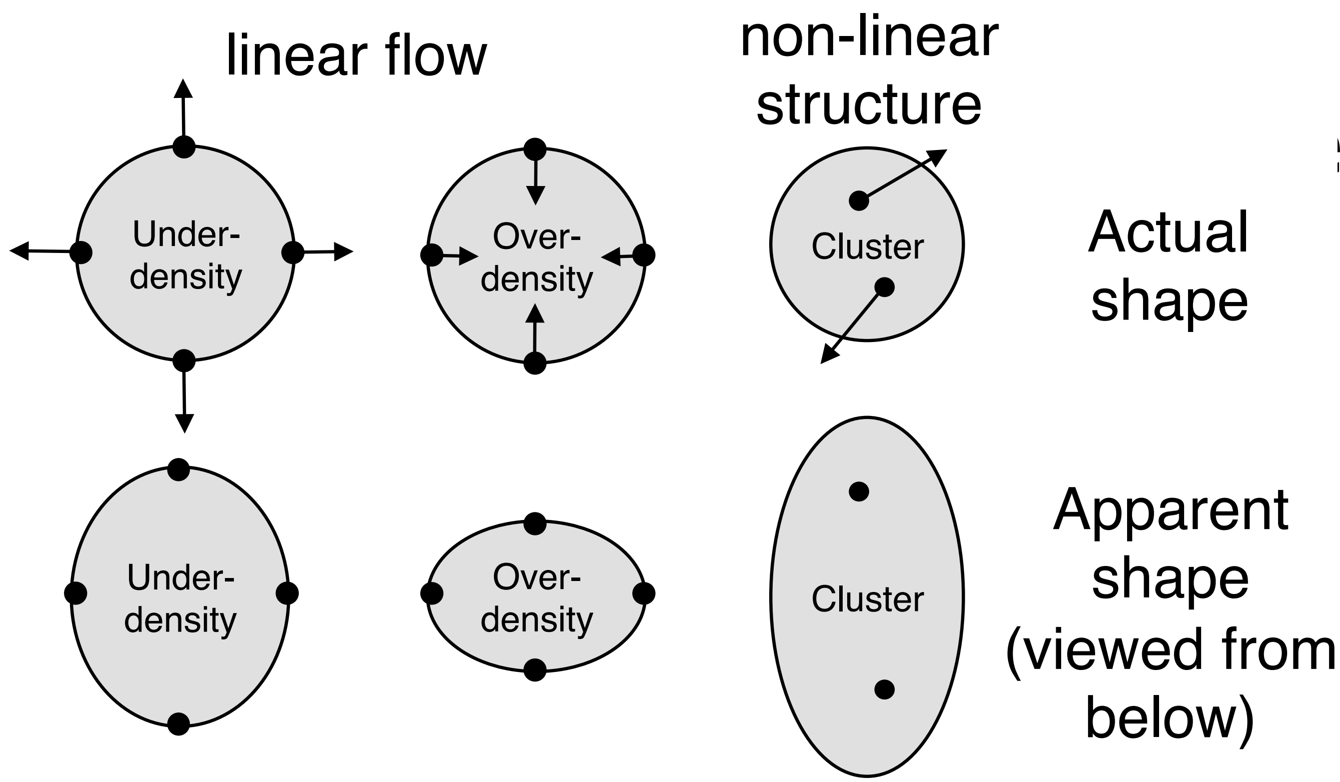
Distribution
des galaxies





- In the early universe: density fluctuations propagates like an acoustic wave.
- Measured in the CMB (z~1100)
- Spatial wavelength of ~140 Mpc (400 M.LY) at recombination
- Galaxy formation stronger in high-density region.
- **Measuring BAO scale in the distribution of galaxies give the relations H(z) and D_A(z) => expansion**

Redshift Space Distortion



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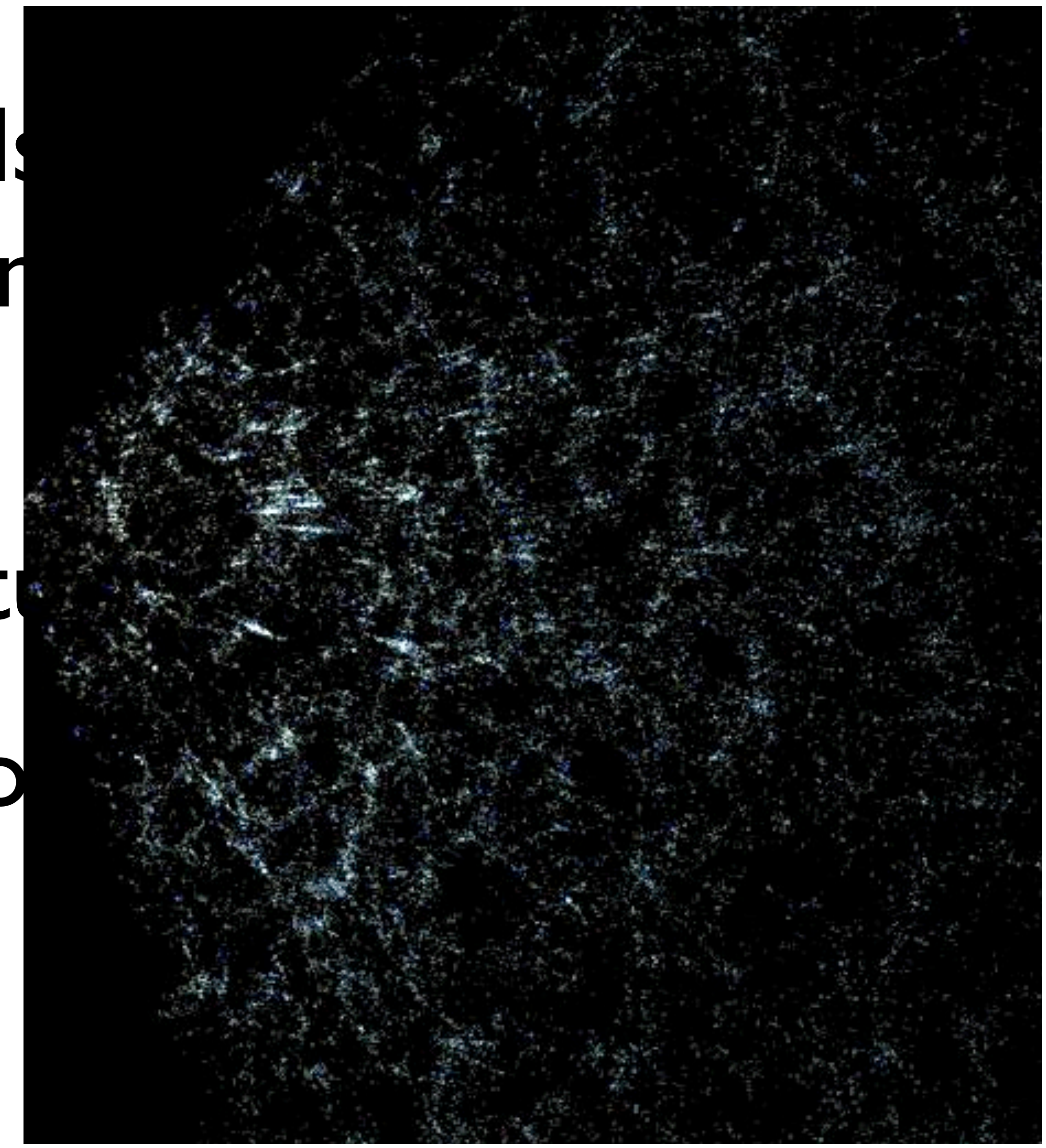

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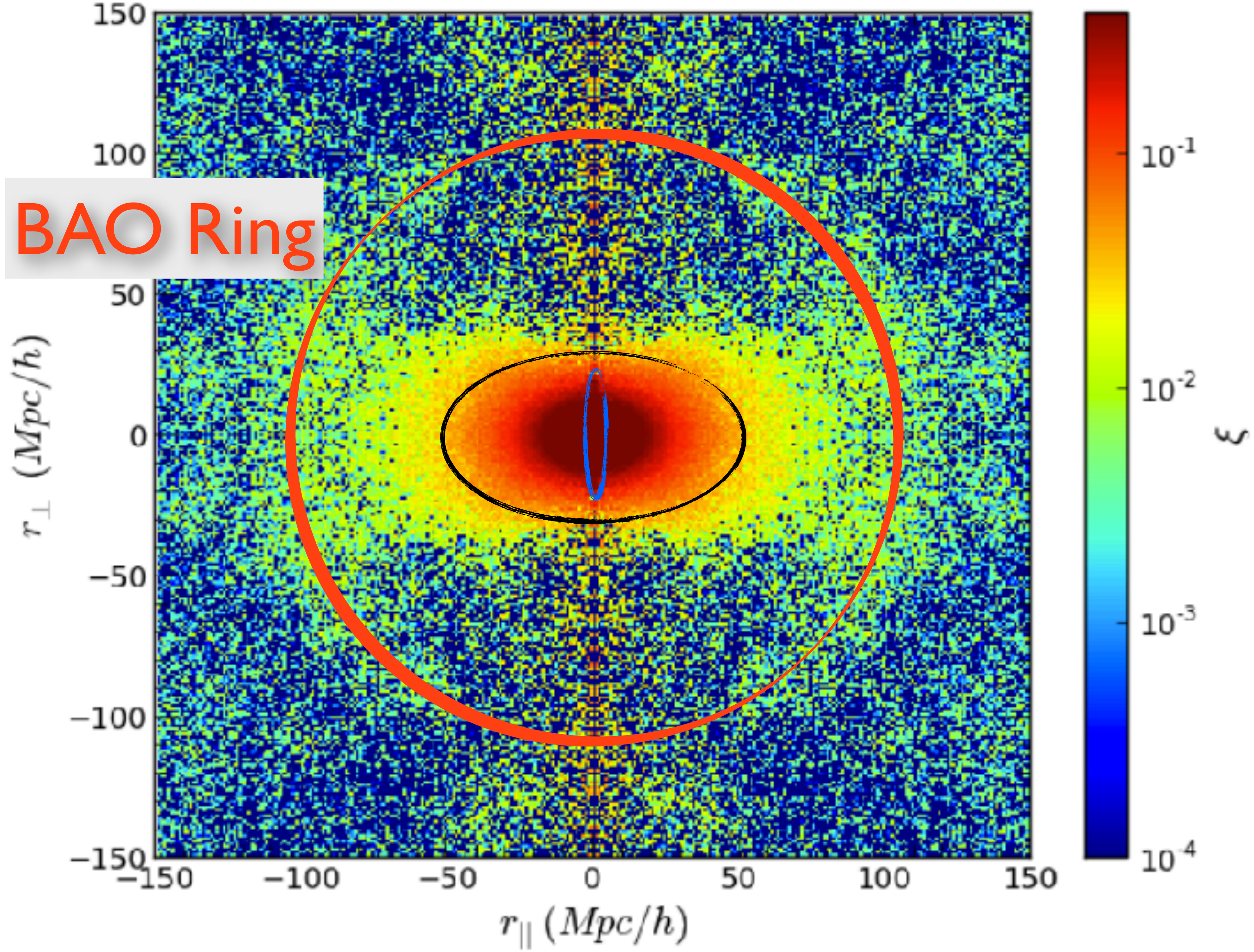
- Redshift is a combination of the expansion and intrinsic velocity.
- Galaxies are moving with the structures that grow.
- *The 2D correlation function depends on the growth factor (expansion+gravitation)*

vth rate

Redshift Space Distorsion



2D correlation fonction: parallel & perpendicular to the sky direction.

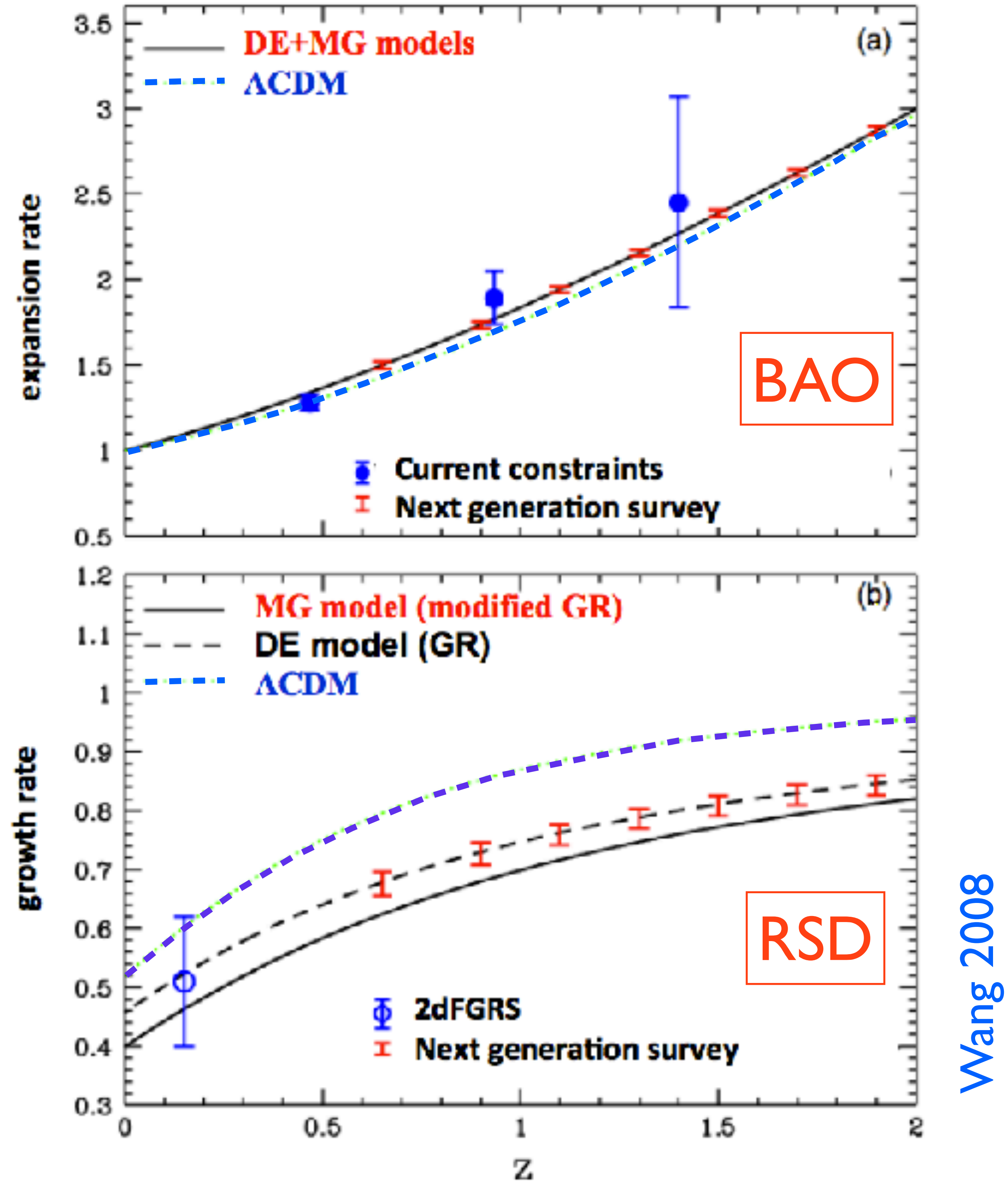
the size of the black ellipse is a measure of RSD at a given redshift.

RSD sensitive to growth of structure = gravitation model.

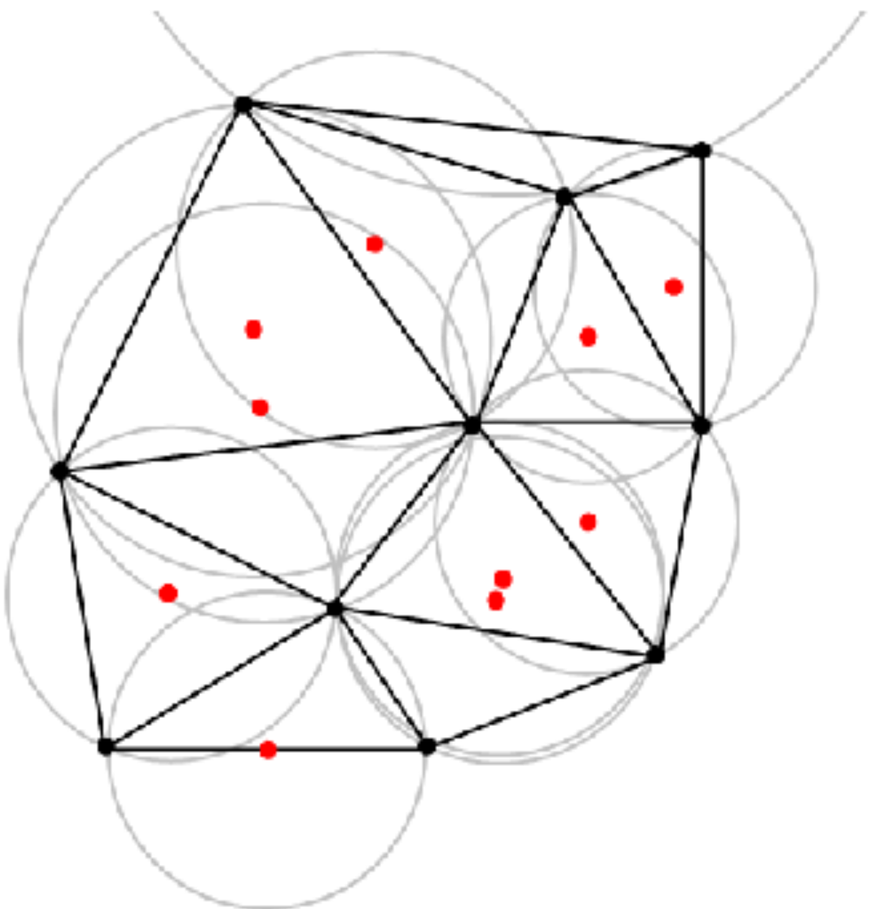
Complementarity: Expansion & Gravitation

Combining BAO and RSD is a precise method to constrain the accelerated expansion:

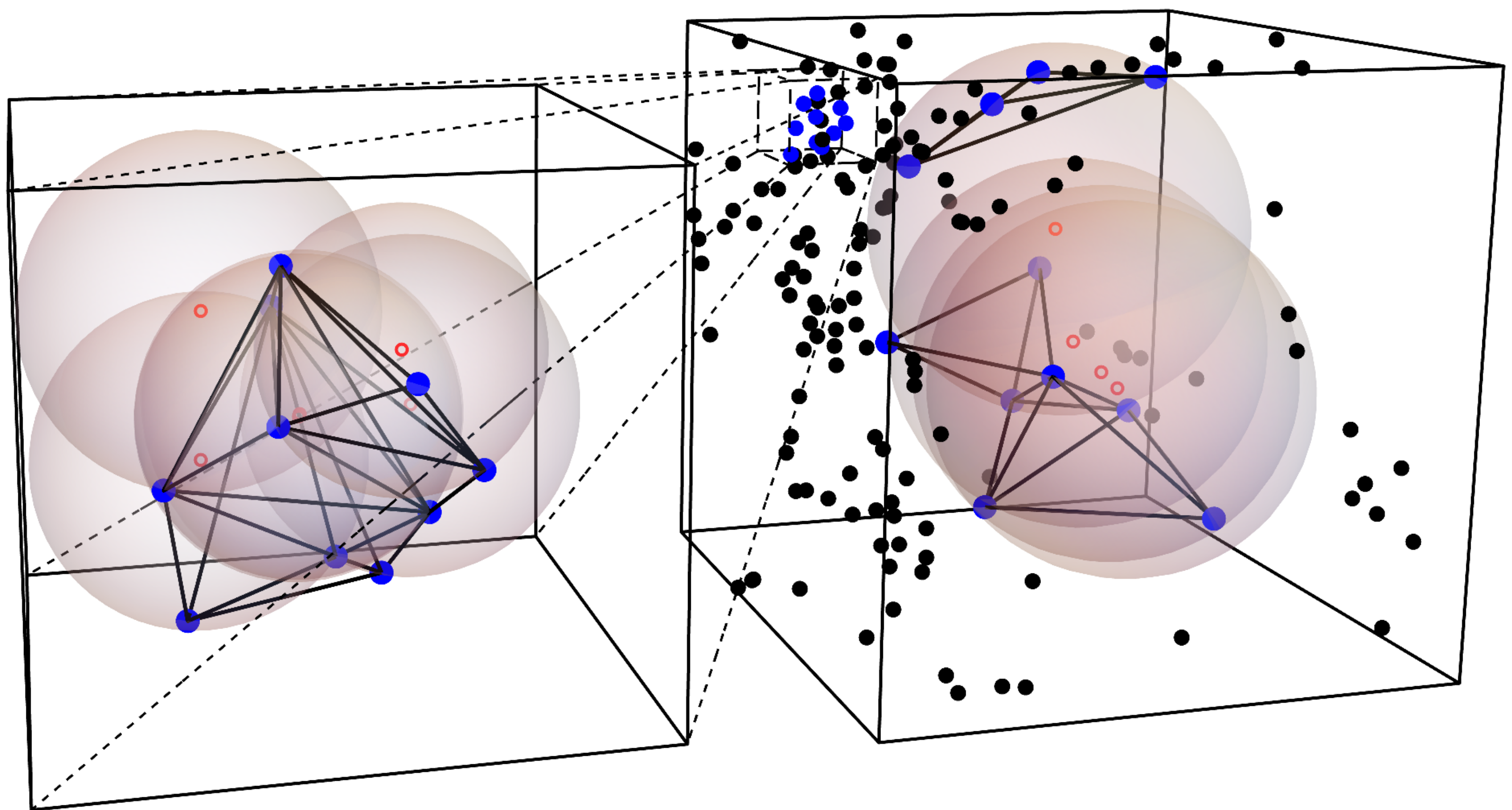
- Dark Energy
- Modified Gravity



Higher order statistics !



Delaunay Triangulation (DT)
Wikipedia



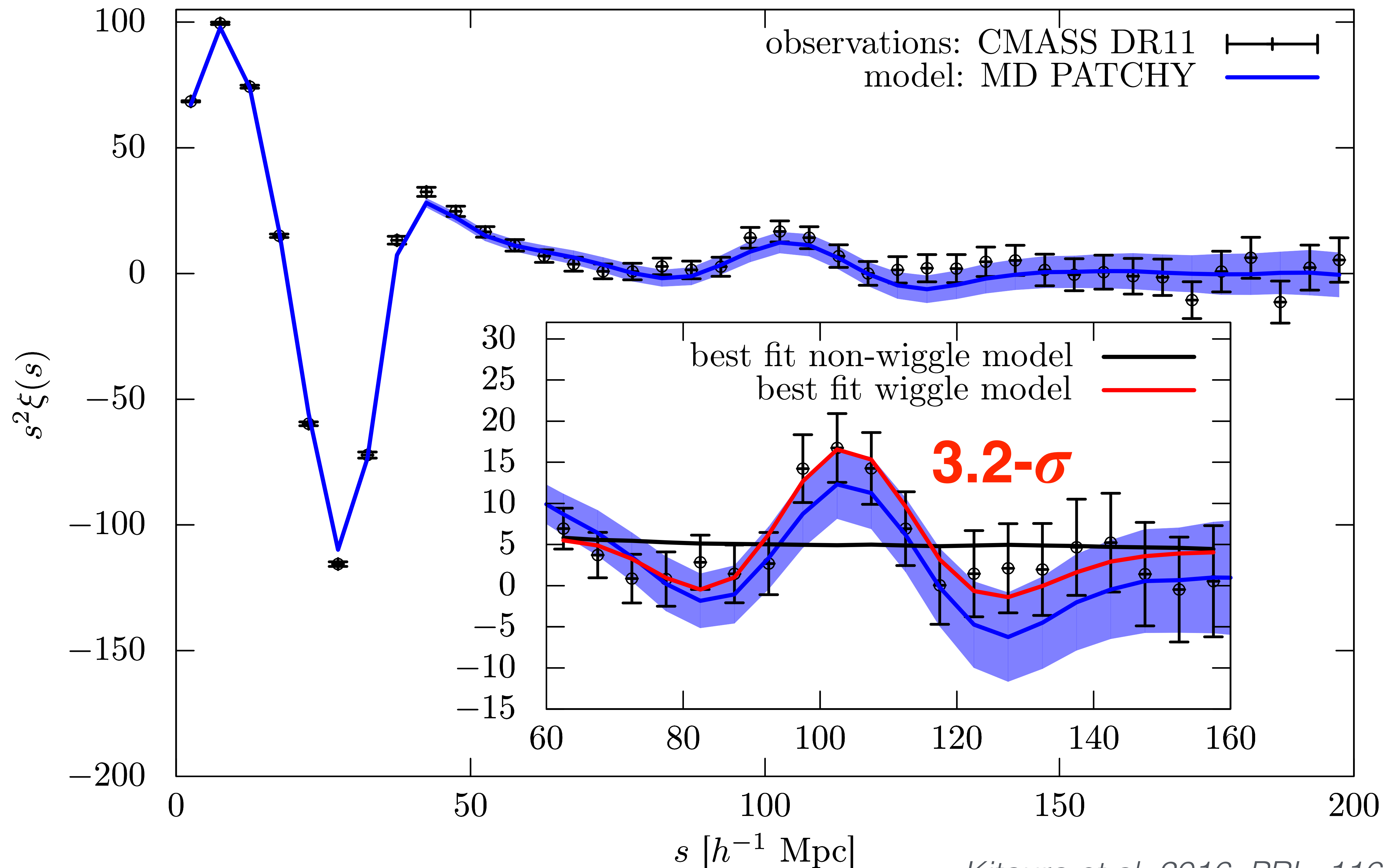
Zhao et al. 2016, MNRAS, 459, 2670

Dots: haloes
Open circles: centres of voids

cosmology independent
~10 minutes for 5.5 million haloes with a single CPU core

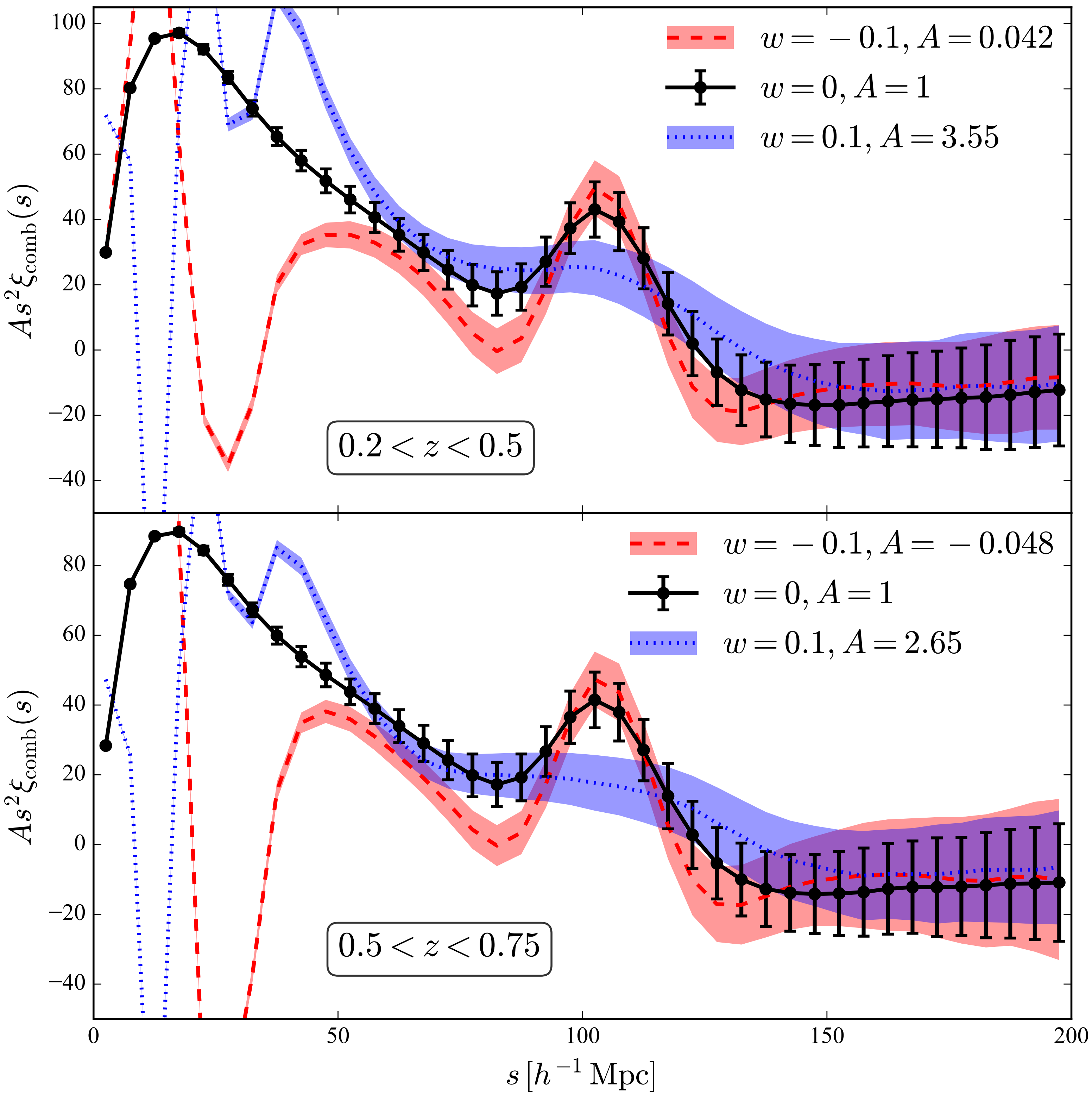
First void BAO detection

BOSS DR11 data



Kitaura et al. 2016, PRL, 116, 1301

2PCF: galaxy + void



Black:

Galaxy alone

Blue (almost no BAO):

Galaxy + positive weighted void

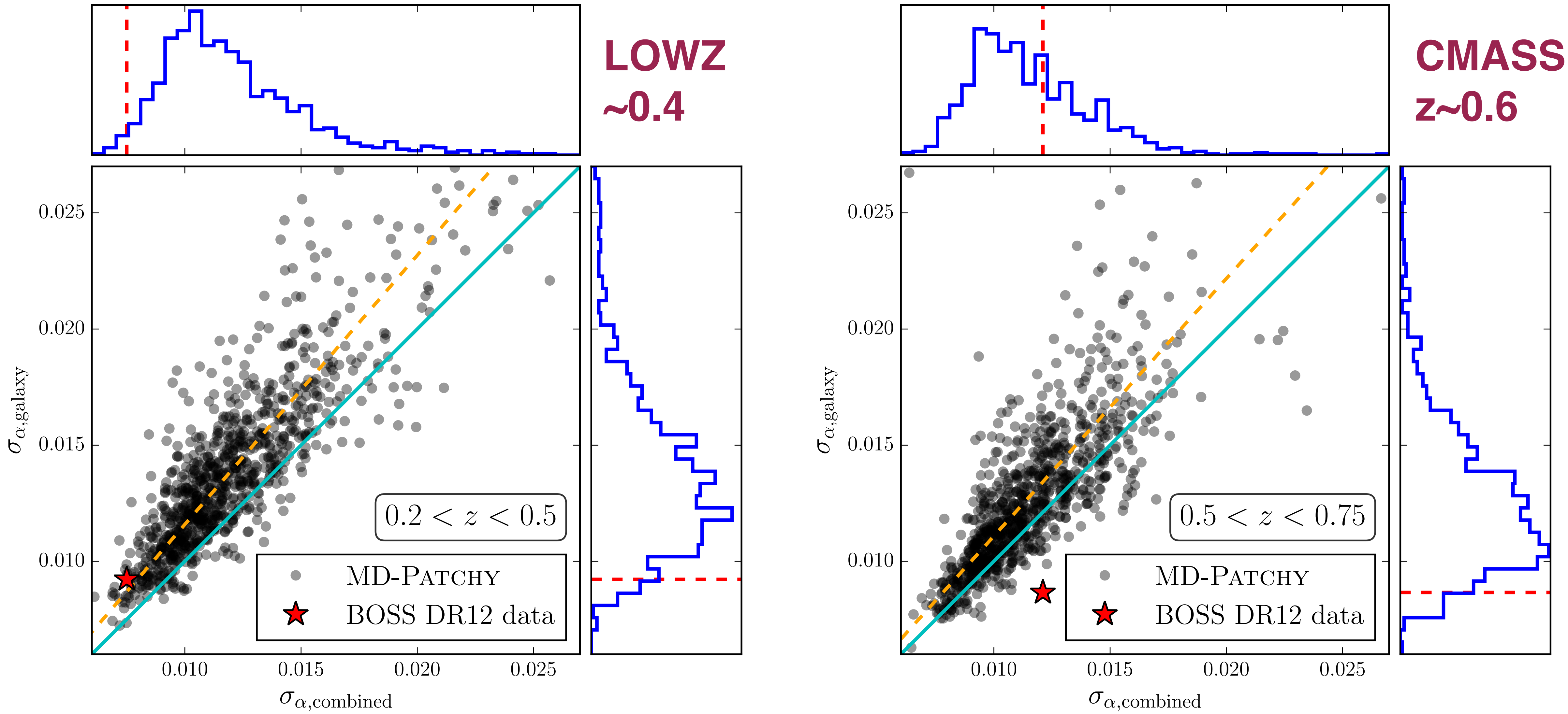
Red (stronger BAO than that of galaxy):

Galaxy + negative weighted void

The curves are rescaled such that the error on the BAO peak are the same.

Zhao et al. 2019, in preparation

Joint BAO measurement with BOSS data

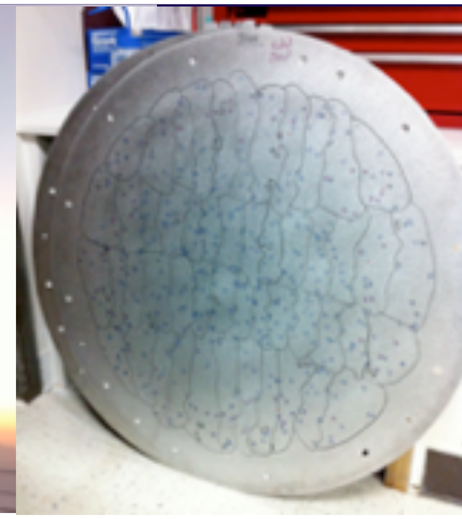


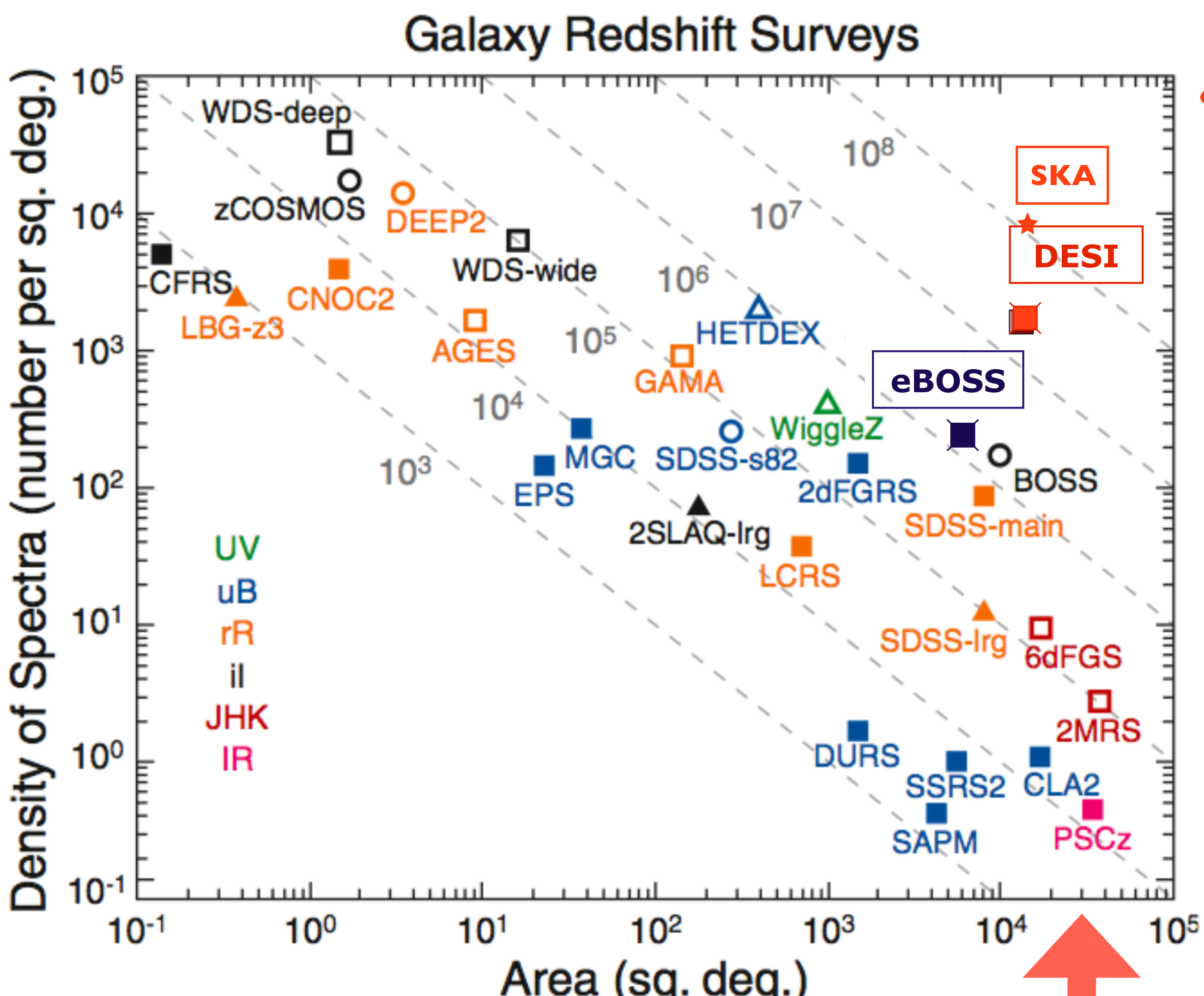
For the mocks, error reduced by an average of ~10%

~18% better BAO scale determination for the low-z BOSS DR12 data

Zhao et al. 2019, in preparation

3D mapping of galaxies

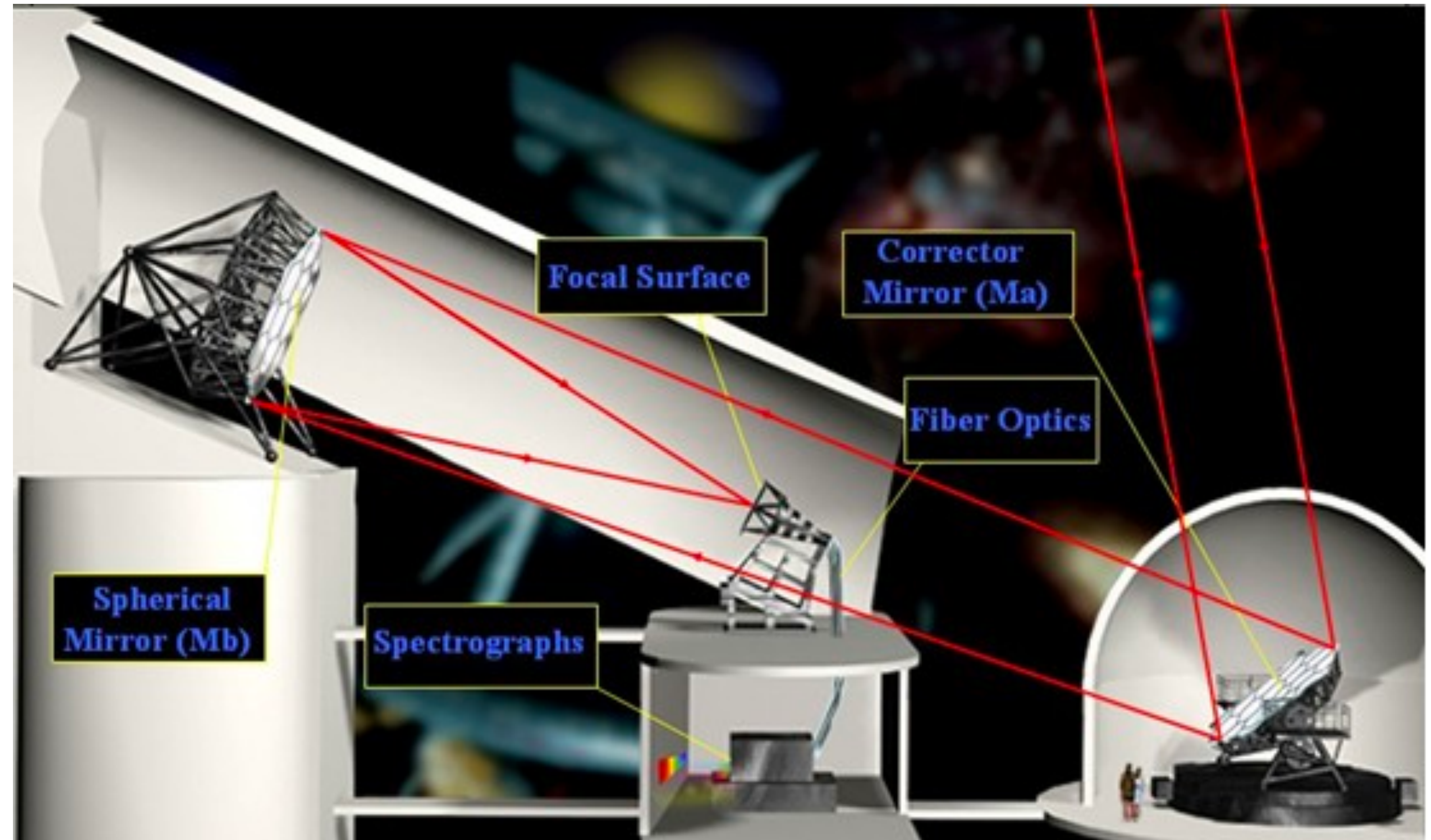


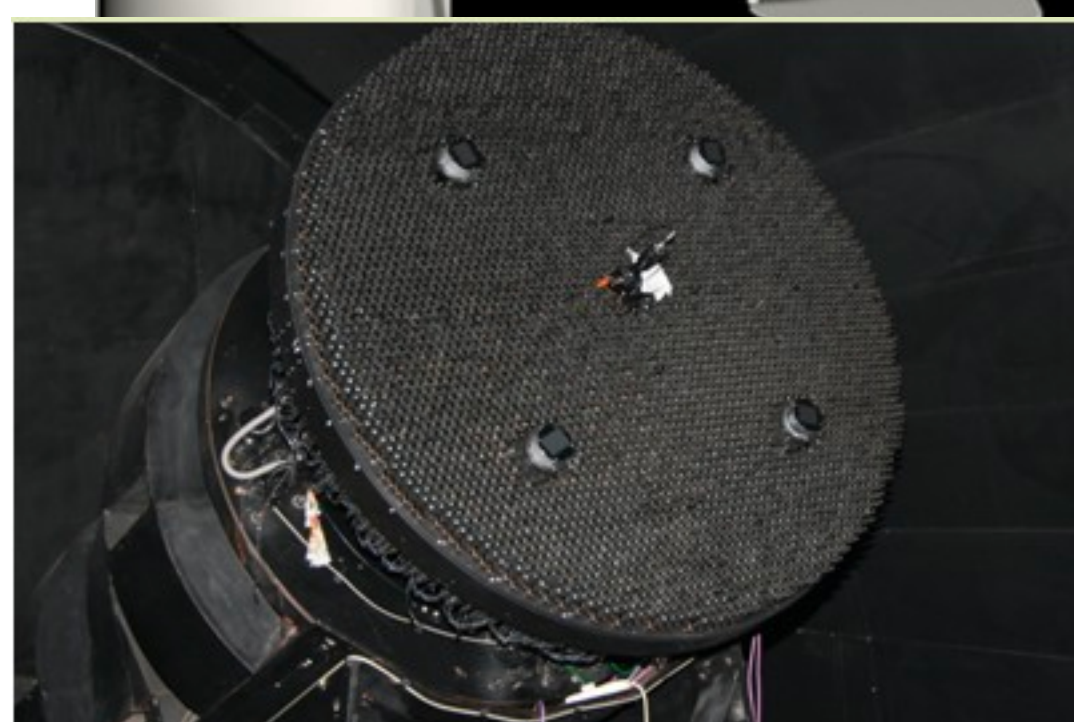


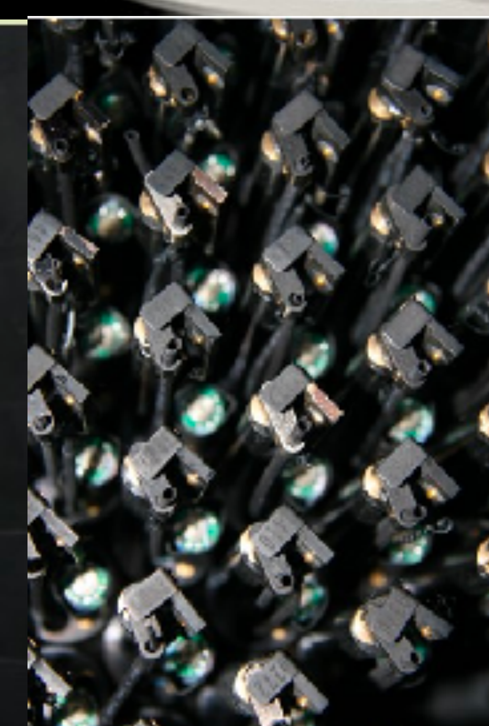
- **Hubble (1930):** Expansion of the Universe
- **CfA Redshift Survey (1985):** first large scale structures
- **2dF (~2000):** 1500 deg^2
- **SDSS-I-II (~2005):** 5700 deg^2
- **VVDS/DEEP2 (~2004):** Deep universe ~1 deg^2
- **LAMOST (~2008):** 8000 deg^2 - 6.3million
- **WiggleZ (2011)**: 800 deg^2 BAO
- **VIPERS (2012):** 25 deg^2 RSD
- **SDSS-III/BOSS (2009-2014)**: 10,000 deg^2 BAO/LSS - 1.5 million
- **e-BOSS** (2014-2019) - 1.1 million
- **PFS** (2020) ~3 million
- **DESI** (2020) ~35 million
- **EUCLID** (2022) ~50 million
- **4MOST** (2022) ~8 million
- **SPHEREx** (2023) ~50 million?
- **SKA-1** (2026) ~100+ million?
- **New Project** (2030?) 200+ million?

LAMOST

- Construction (2001-2008)
- ~4m aperture
- 5 deg FOV
- 4'000 fiber robots
- But poor seeing site limiting the interest for extragalactic science.
- The LEGAS was not implemented, but very productive MW survey.

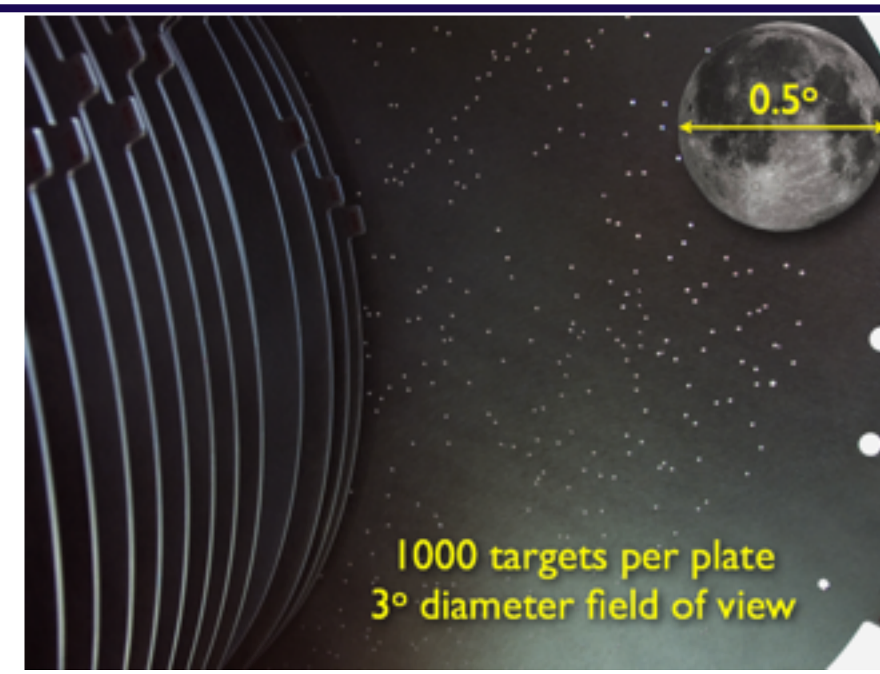


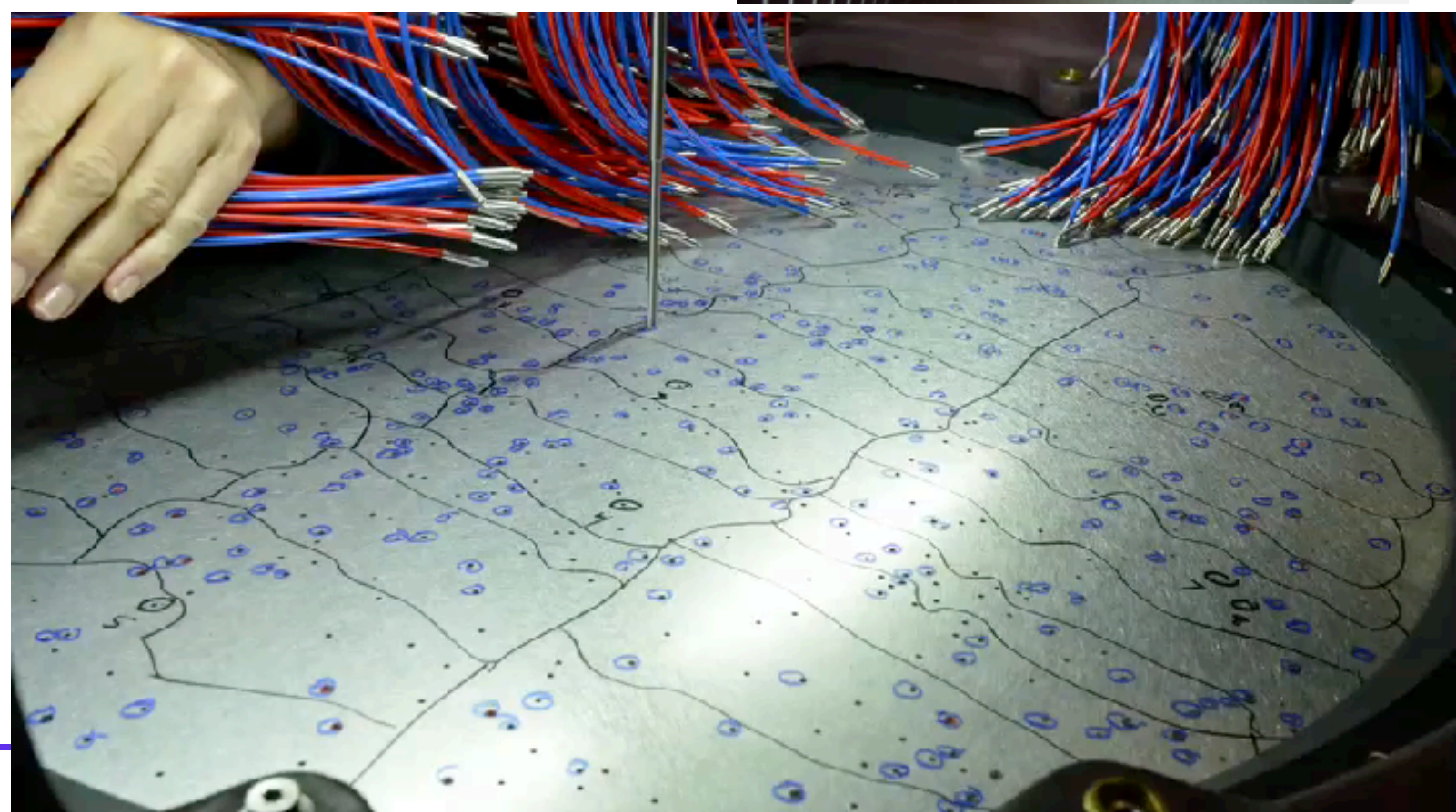




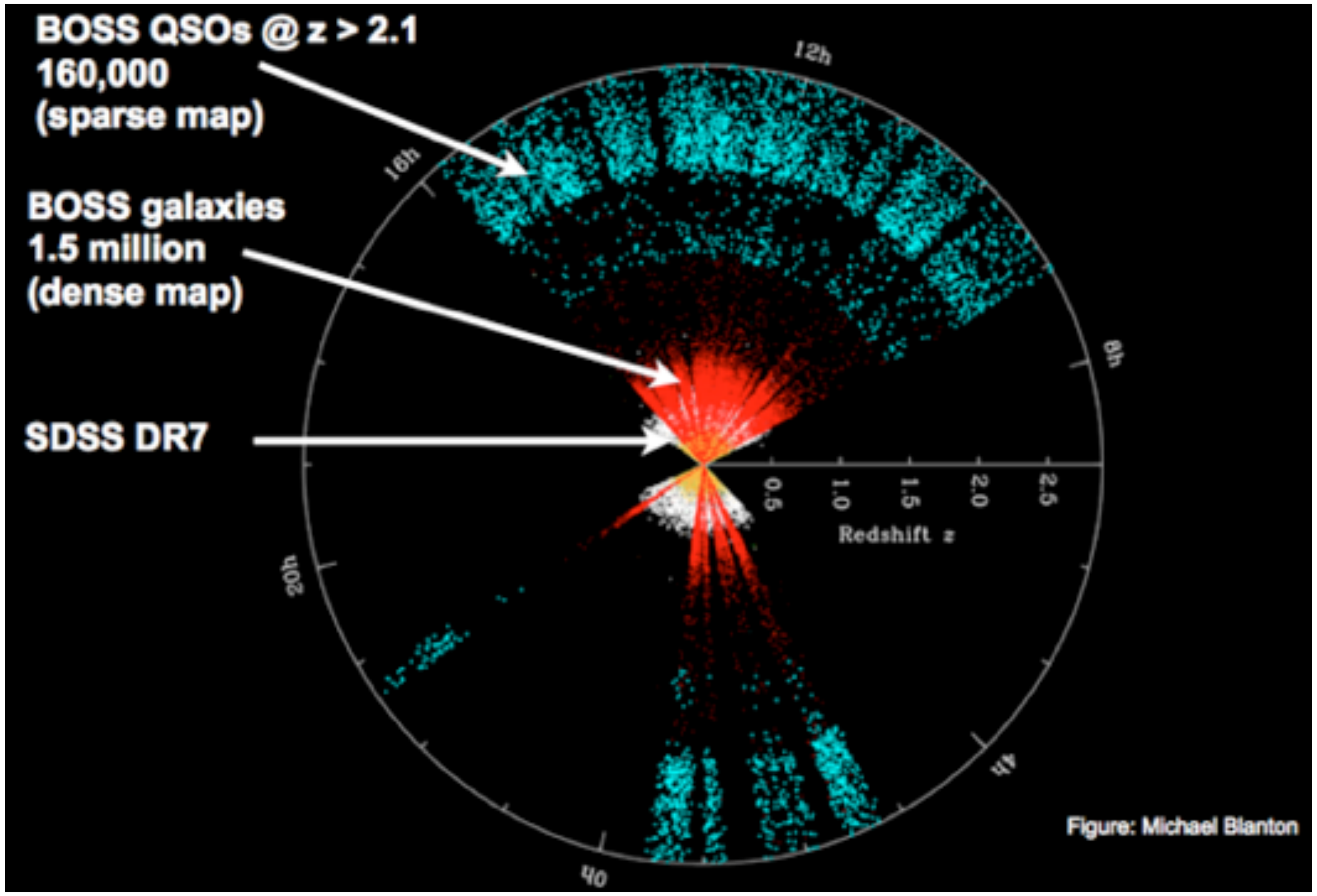
Sloan telescope & BOSS spectrograph

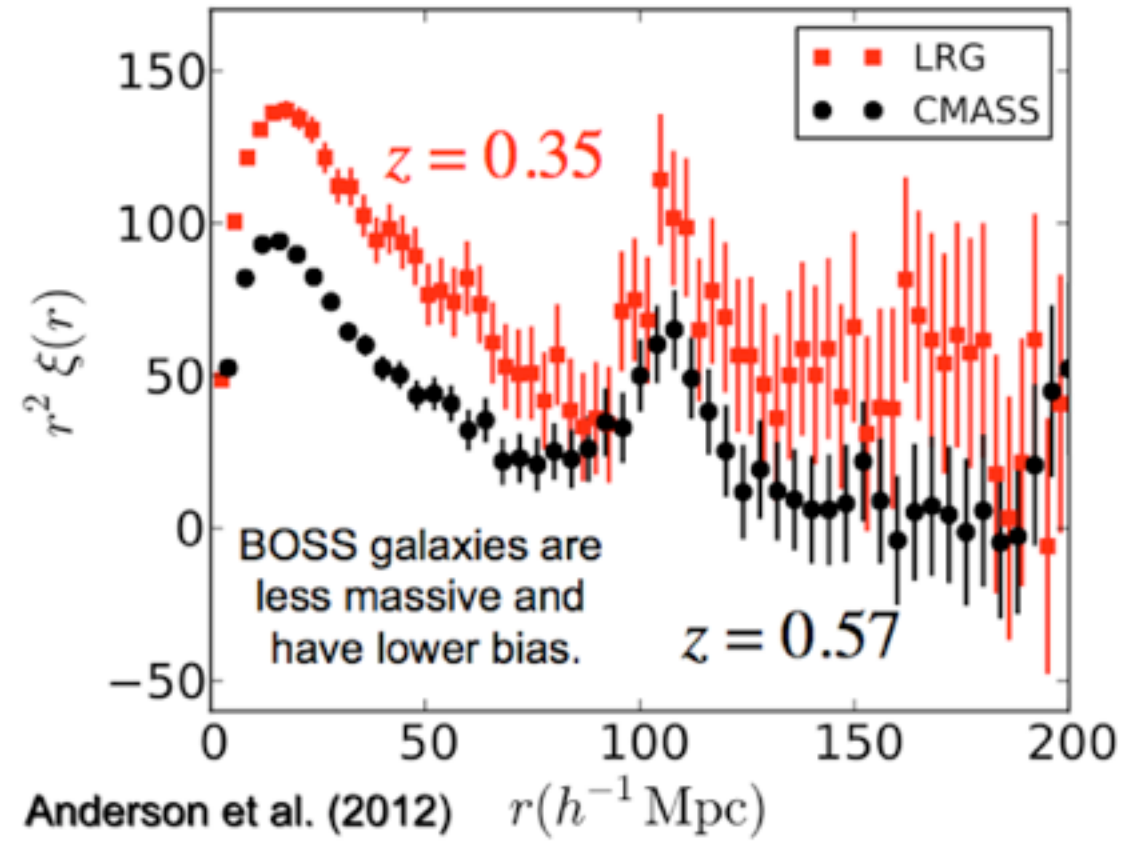
- Aluminum plate of 90 cm with 1000 holes,
- 45 min to insert 1000 fibers for ~1 hour observation
- up to 9 plates per night
- 1.5 millions redshift measurement in ~4 years

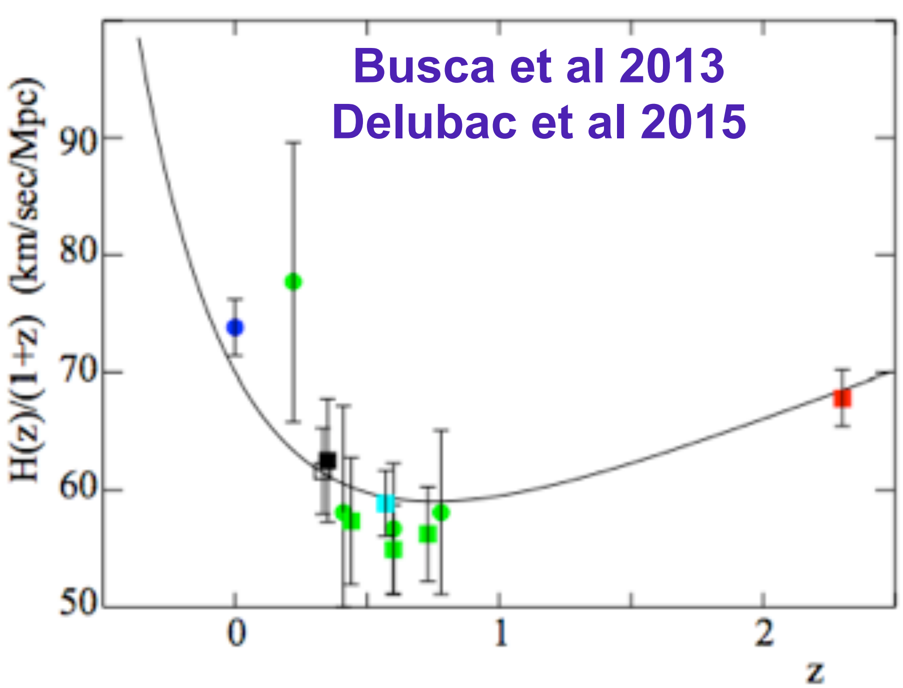


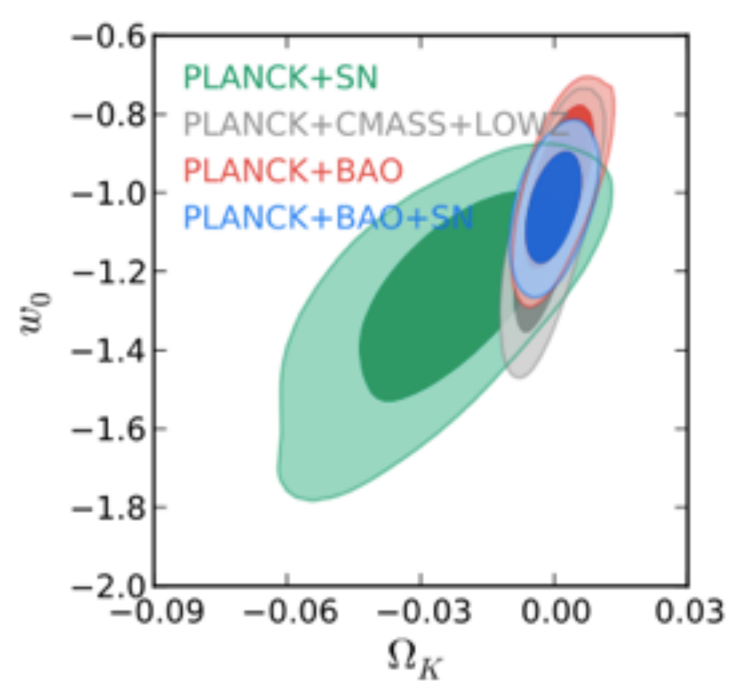


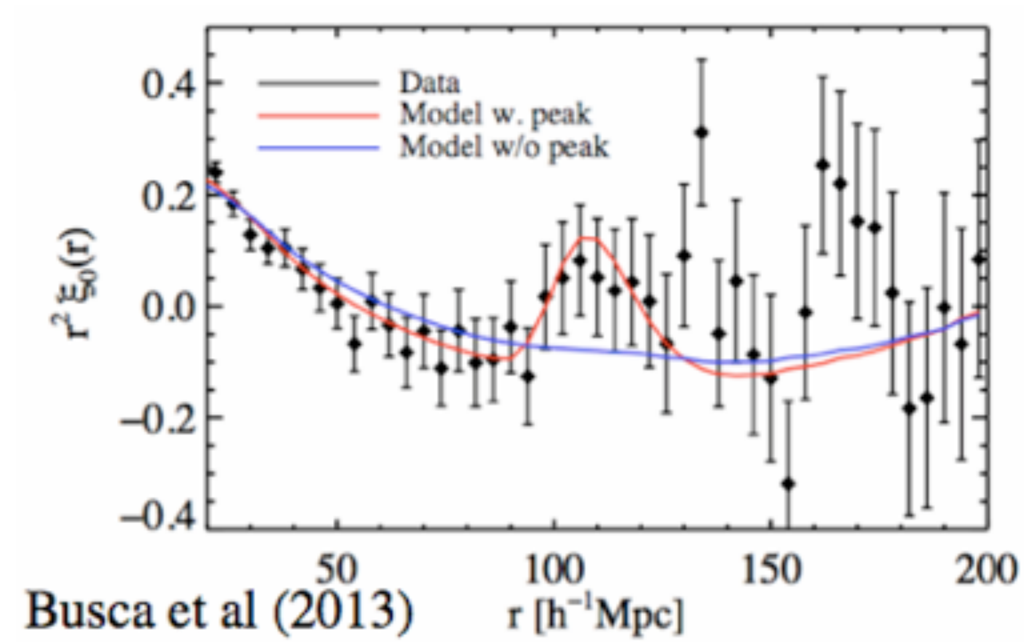
SDSS-III / BOSS (2009-2014)







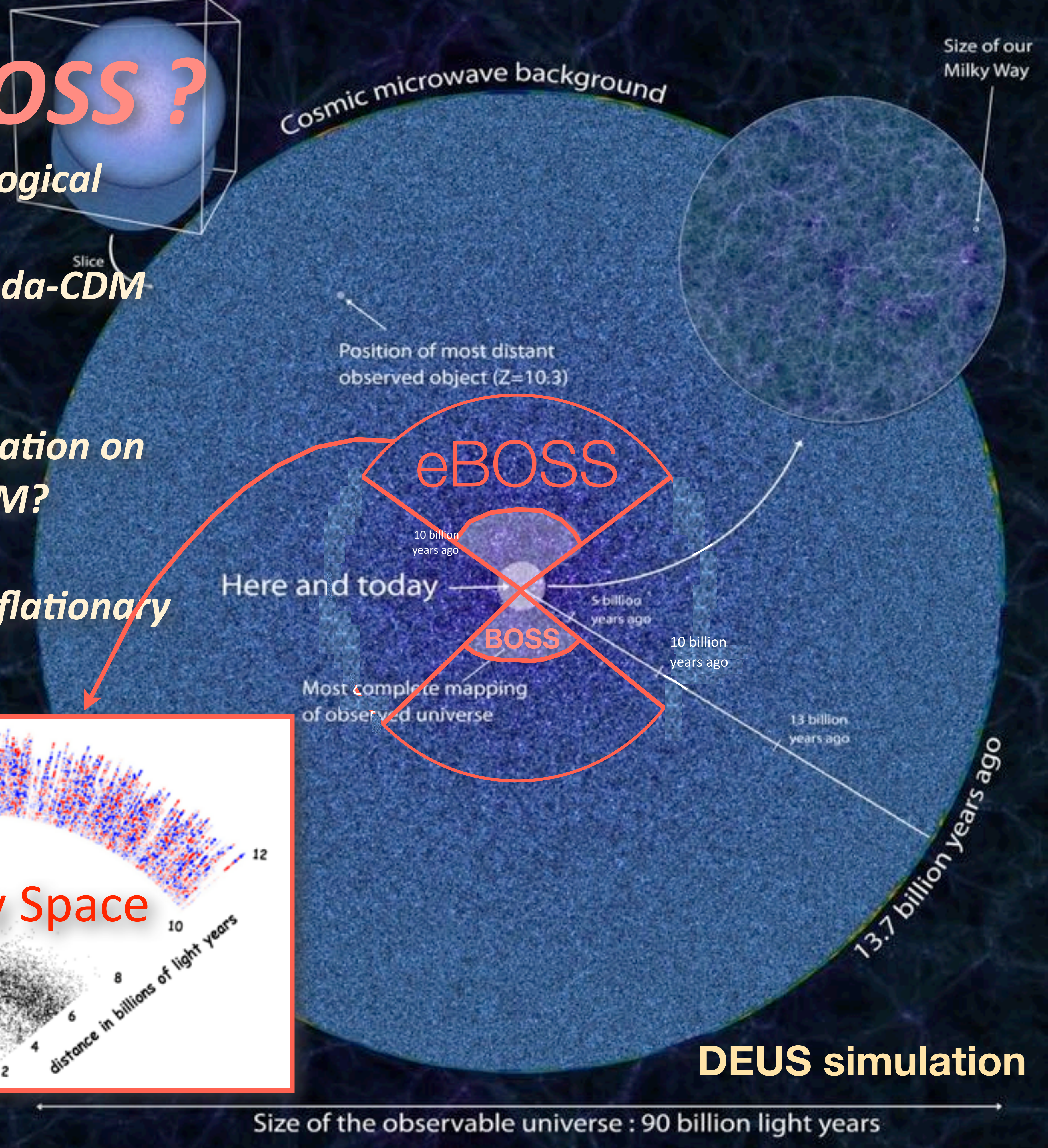


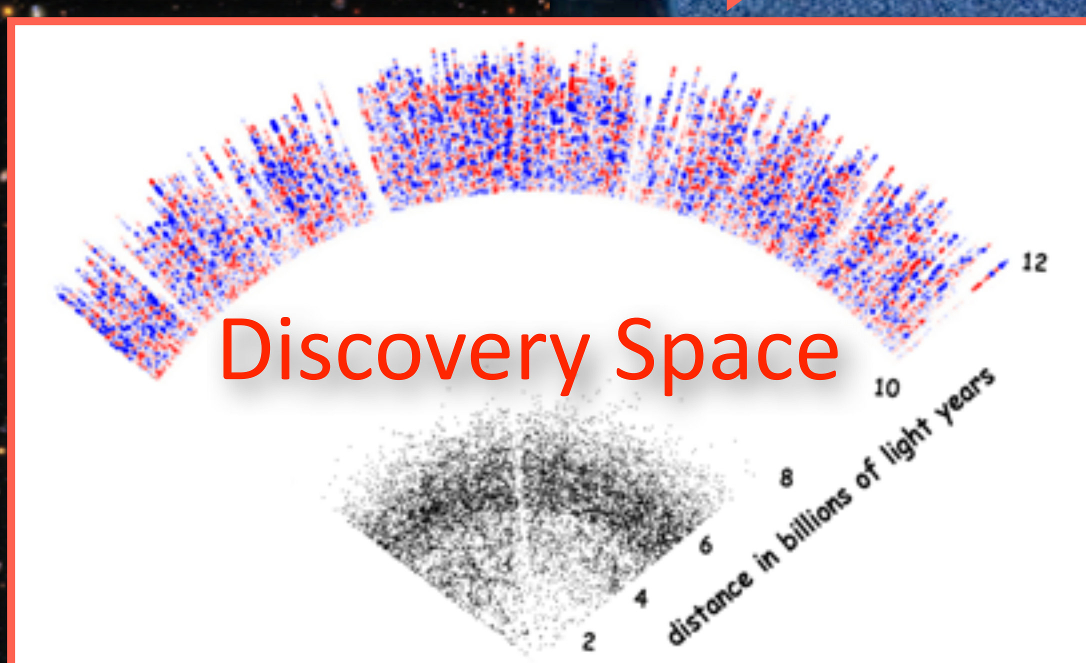


Goals of eBOSS ?

Understanding our Cosmological world model:

- *Are we leaving in a Lambda-CDM Universe?*
- *What is Dark Energy?*
- *Do we understand Gravitation on Large Scales? link with DM?*
- *Neutrino Masses?*
- *Non-Gaussianities and inflationary models?*

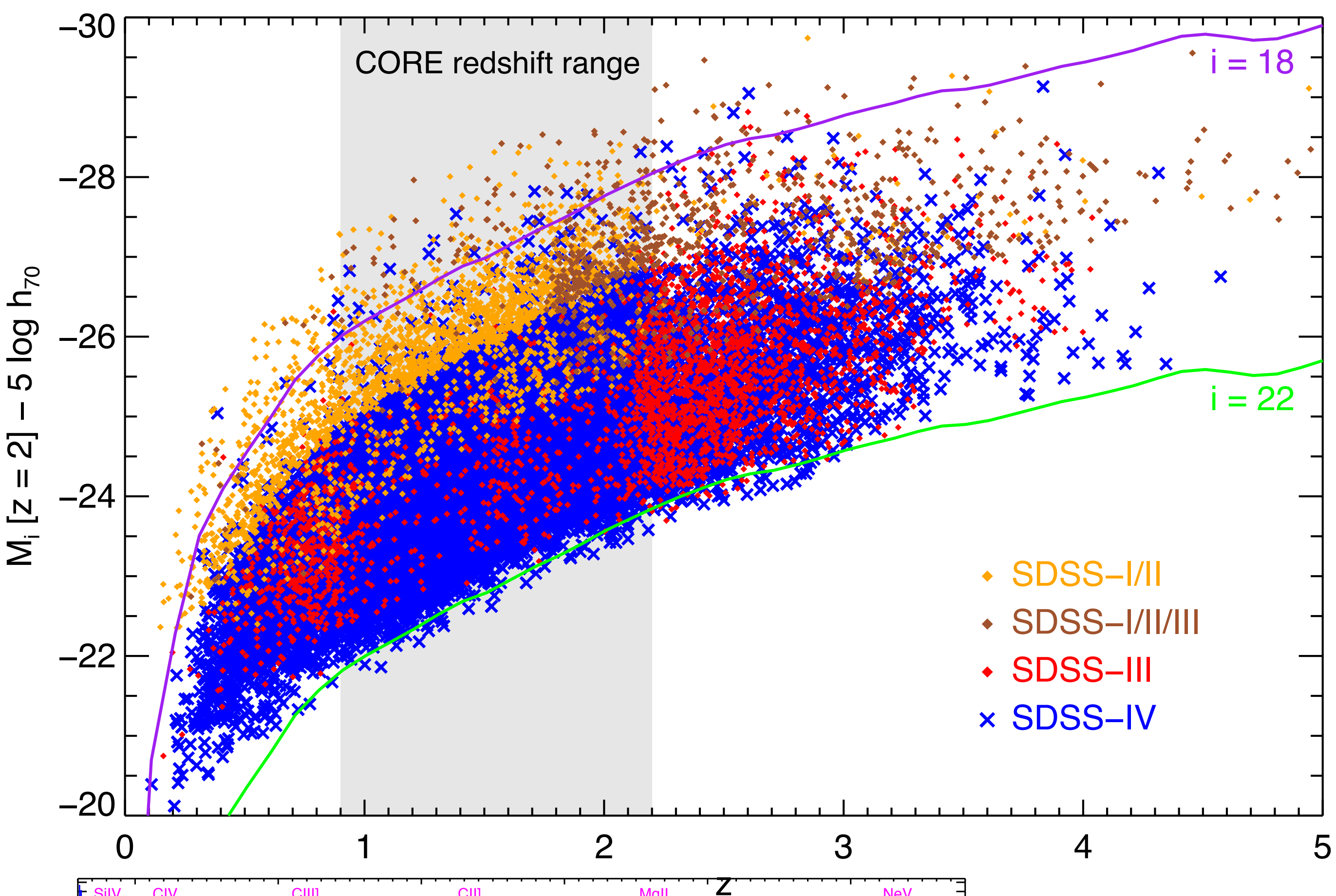




eBOSS

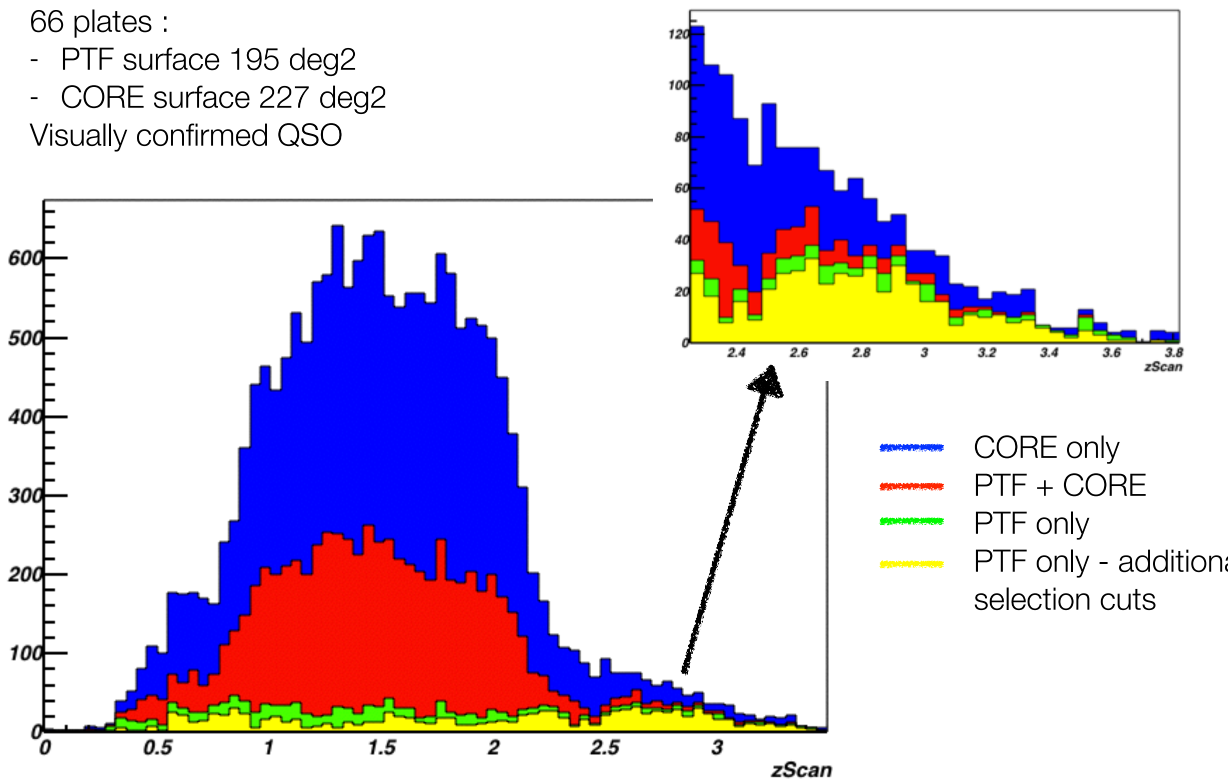
eBOSS QSOs

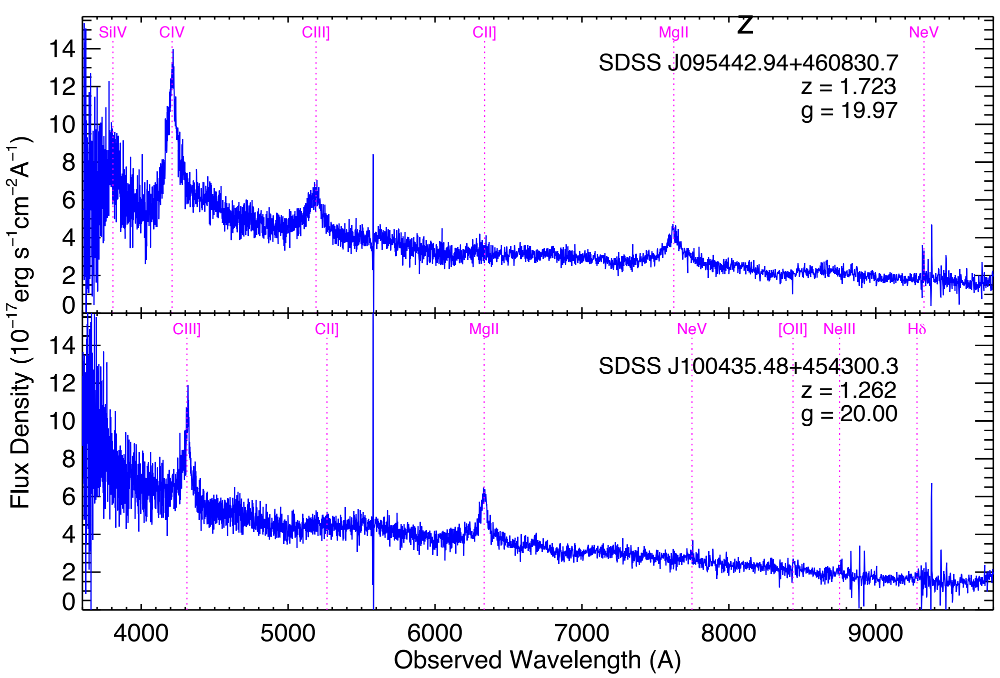
Huge QSO Science Legacy



66 plates :
- PTF surface 195 deg2
- CORE surface 227 deg2

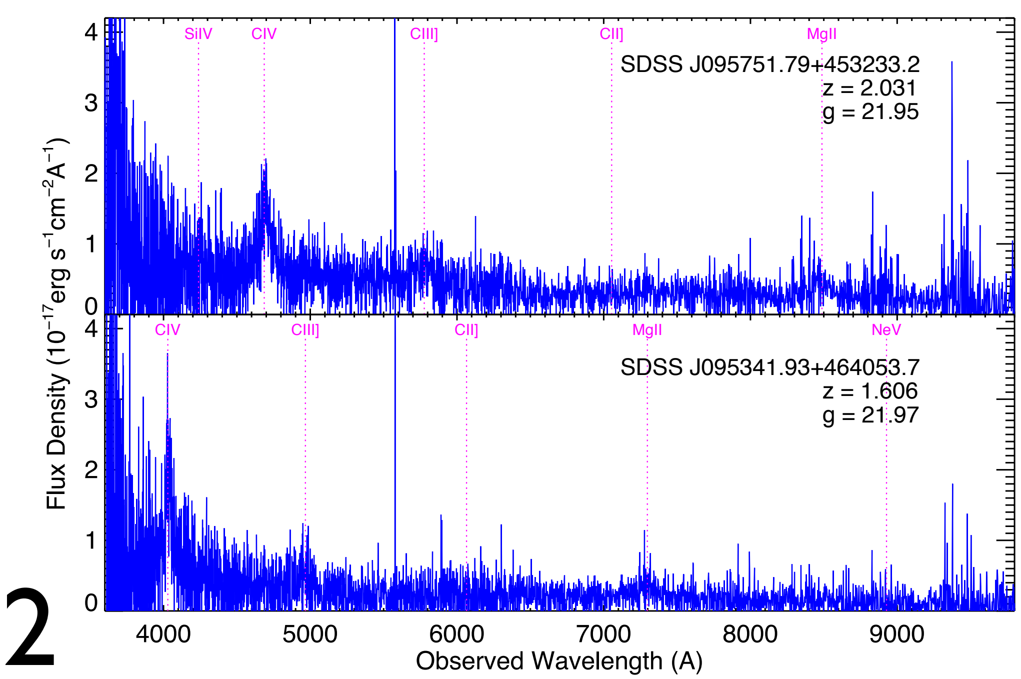
Visually confirmed QSO





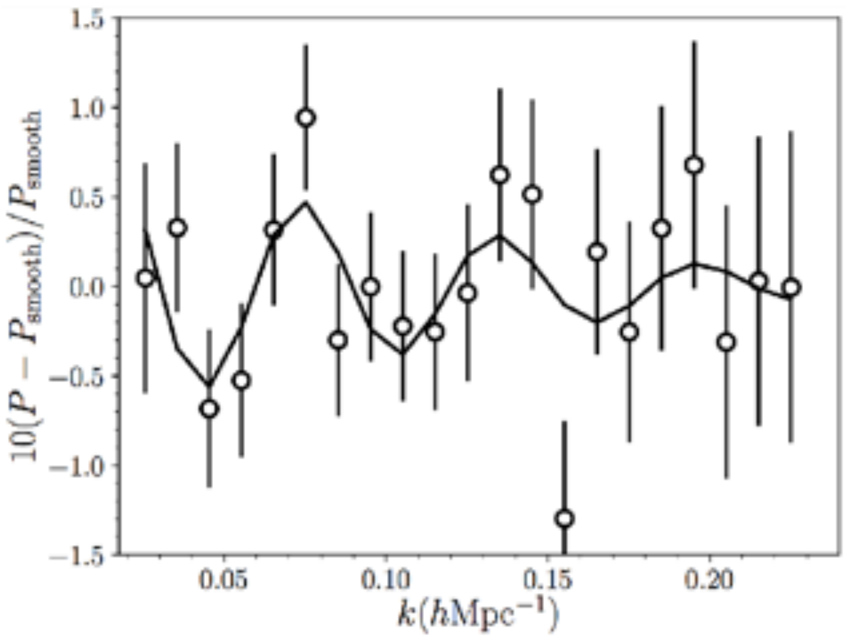
g~20

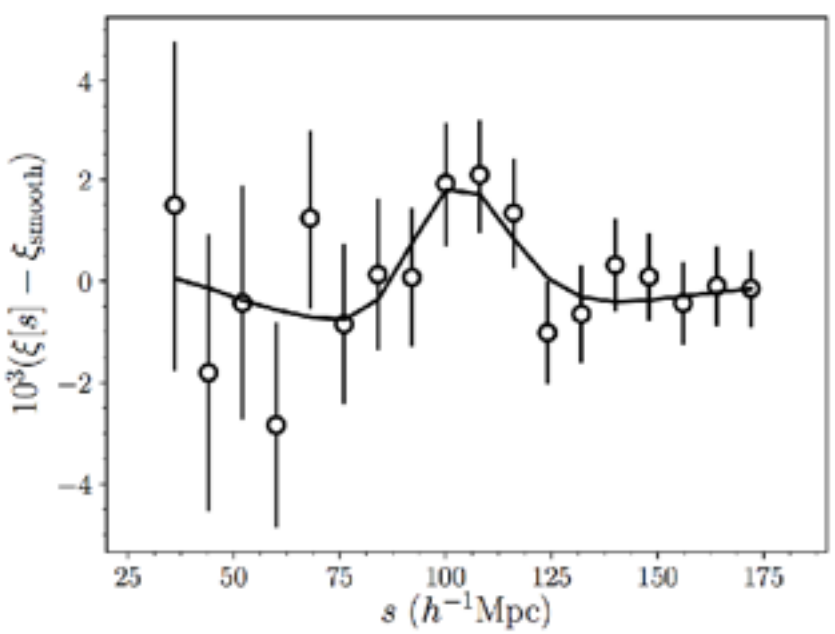
g~22

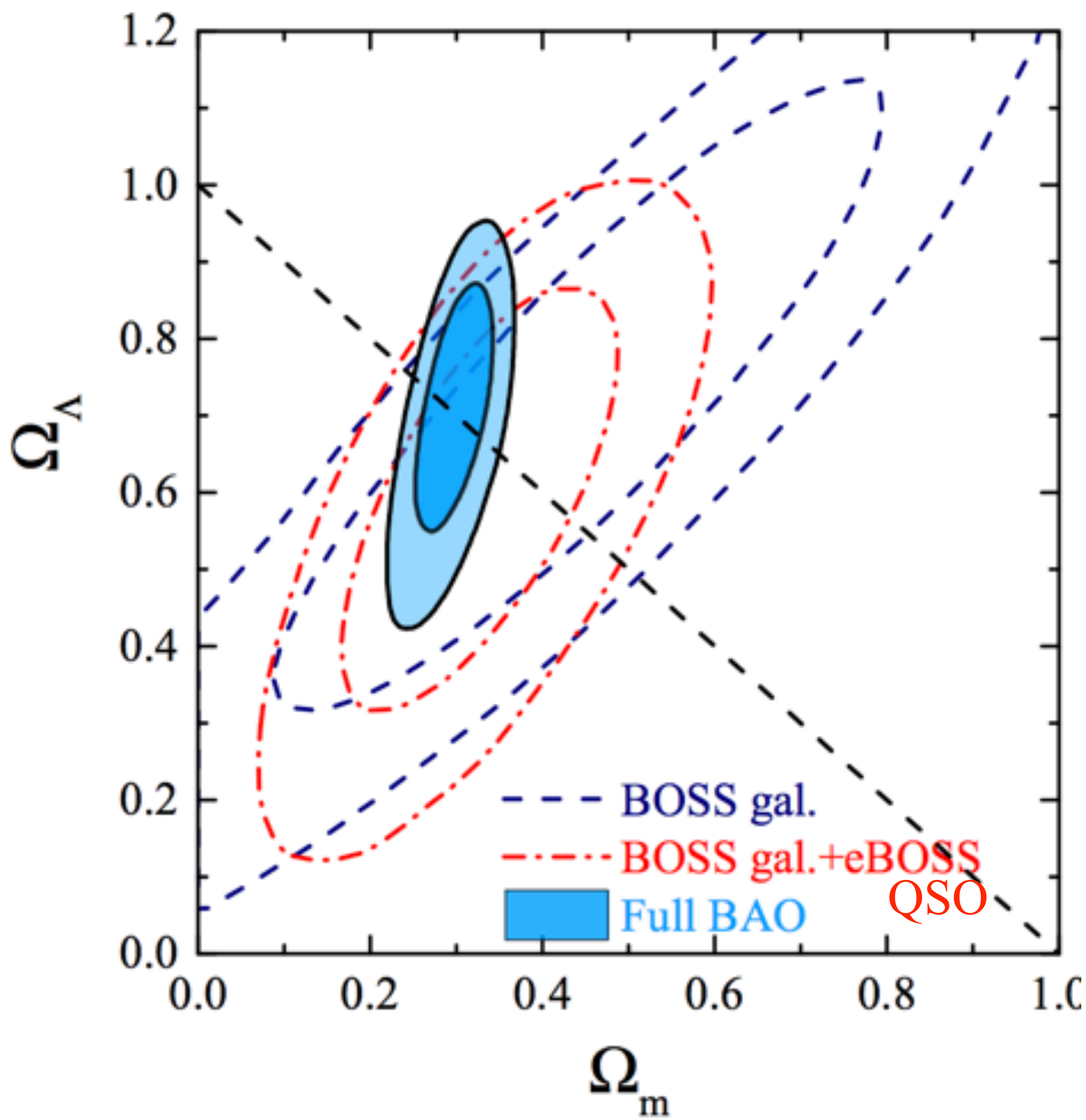


SDSS-IV/eBOSS - 2017 results

BAO detection with 200k Quasars over ~2100 deg²
at z~1.5 - 2.8 sigma detection

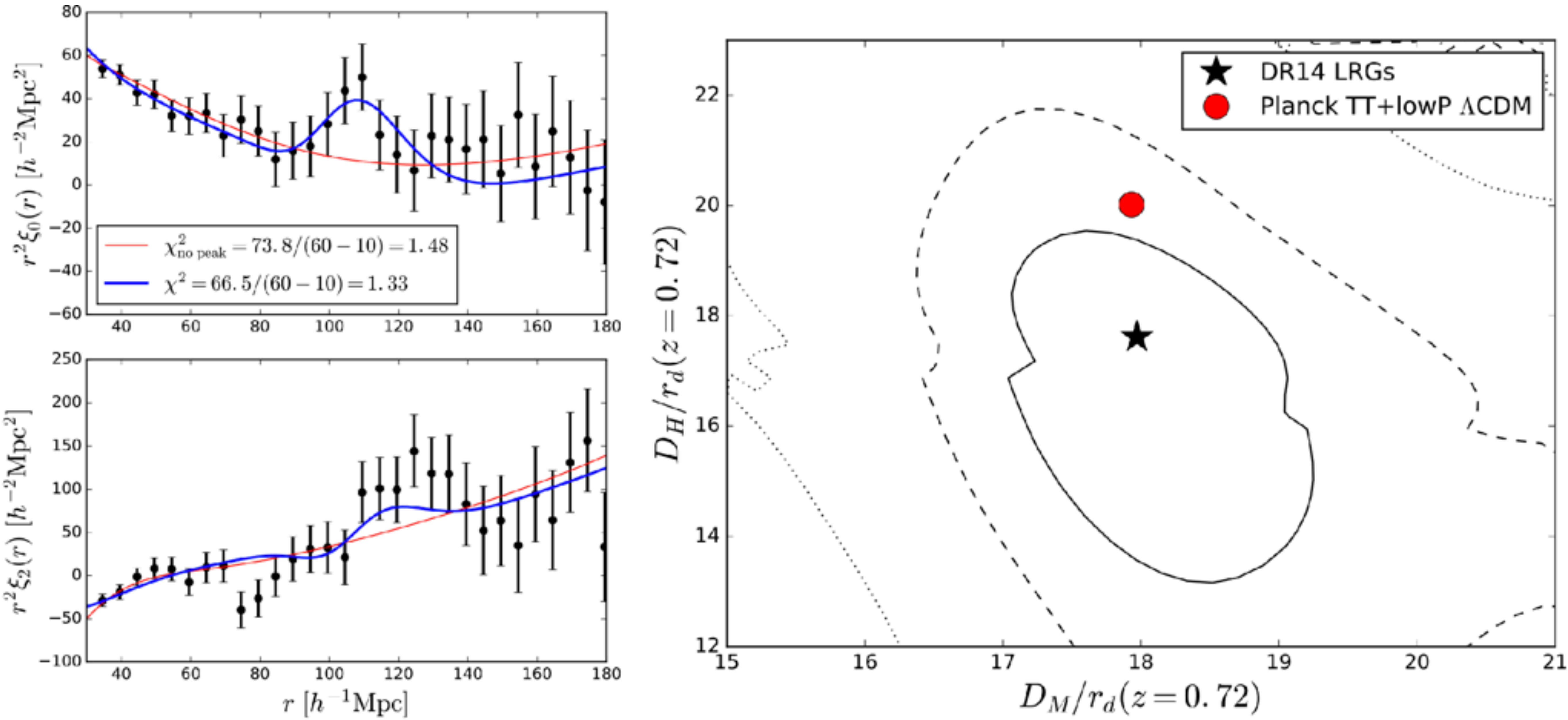




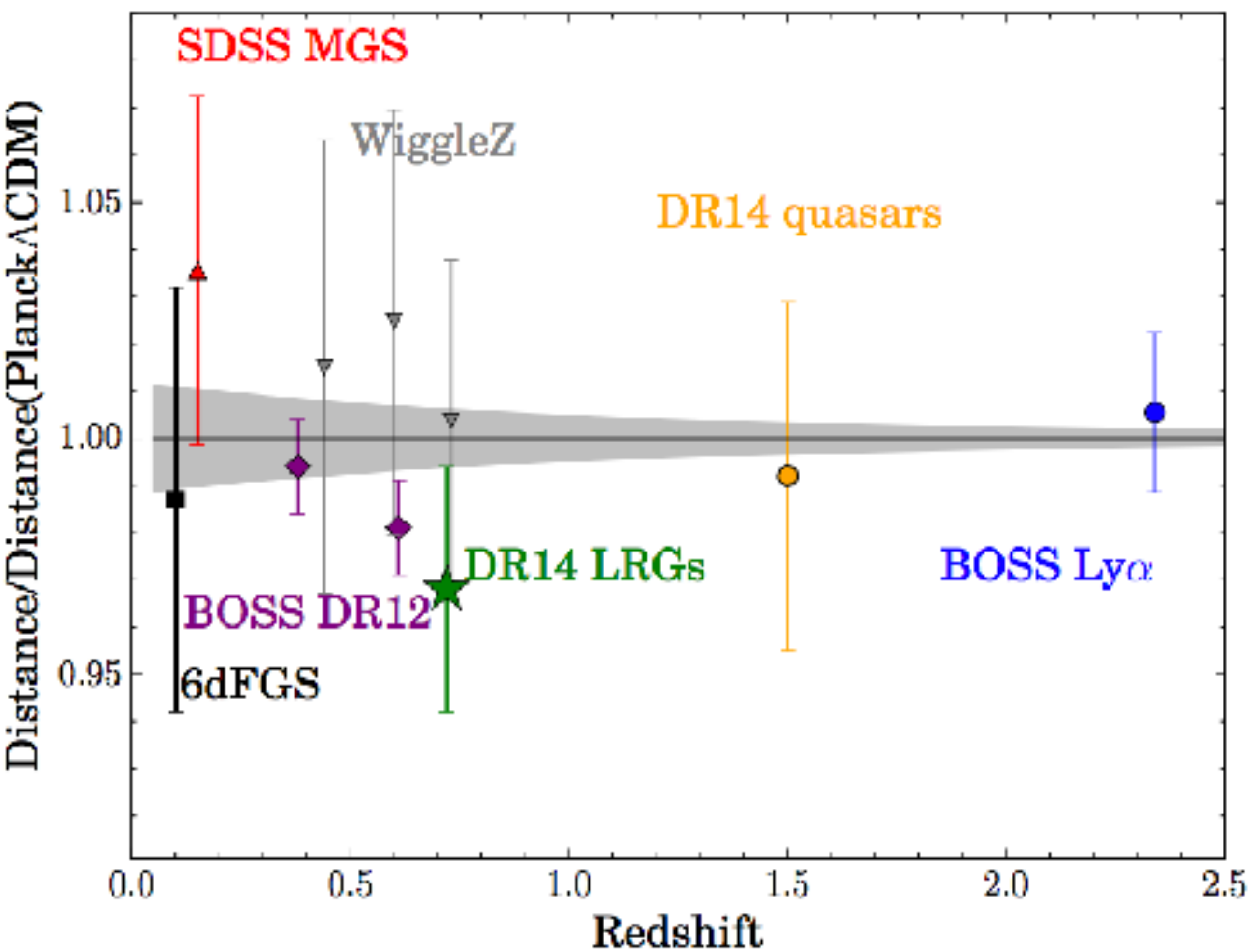


SDSS-IV/eBOSS - 2018 results

BAO detection with BOSS/CMASS+eBOSS/LRG
z~0.72 - 2.8 sigma detection



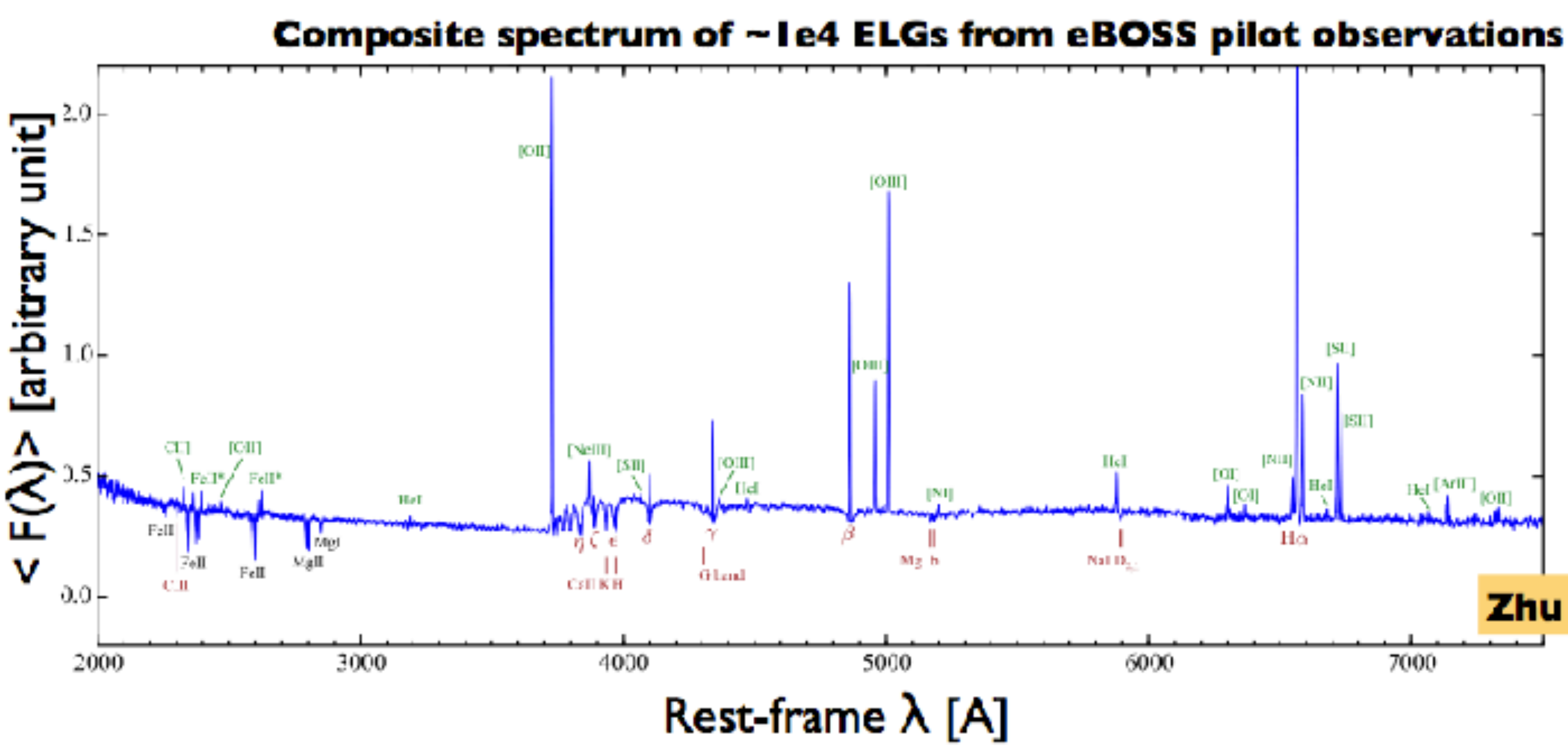
SDSS-IV/eBOSS - 2018+ results

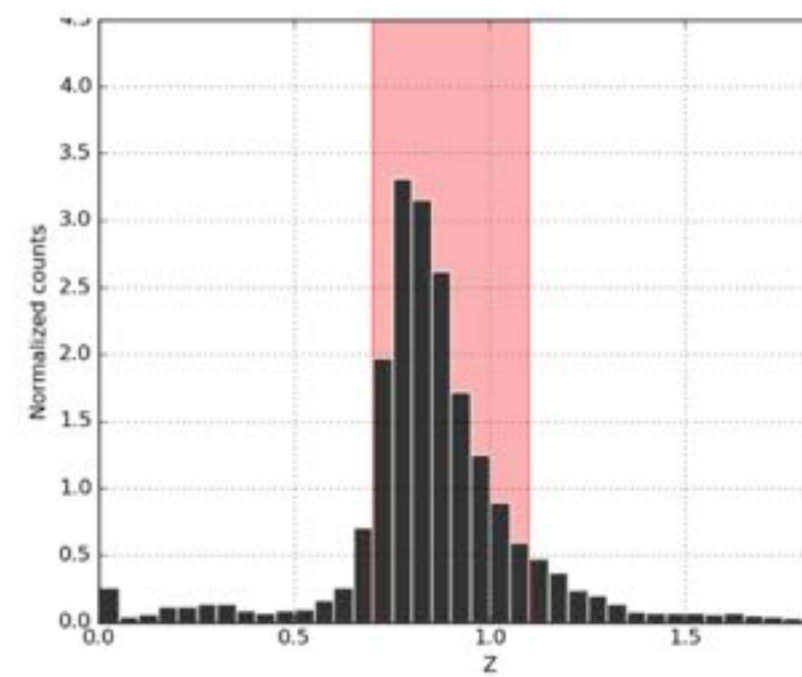


- Sloan-DR14: July 2017; DR16: end 2019
- **BAO peak:**
  - 170'000 **quasars at z~1.5** over 1800 deg^2 - 3.5% BAO uncertainty
  - 125'000 **LRGs+CMASS at z>0.6** over 1800 deg^2 we measure a ~2.6% BAO uncertainty on D_V
- **ELG obs. finished 2018:** 189,000 ELGs with reliable z, 0.7<z<1.1) over >1000 deg^2 - mean redshift: z~0.85

eBOSS ELG survey

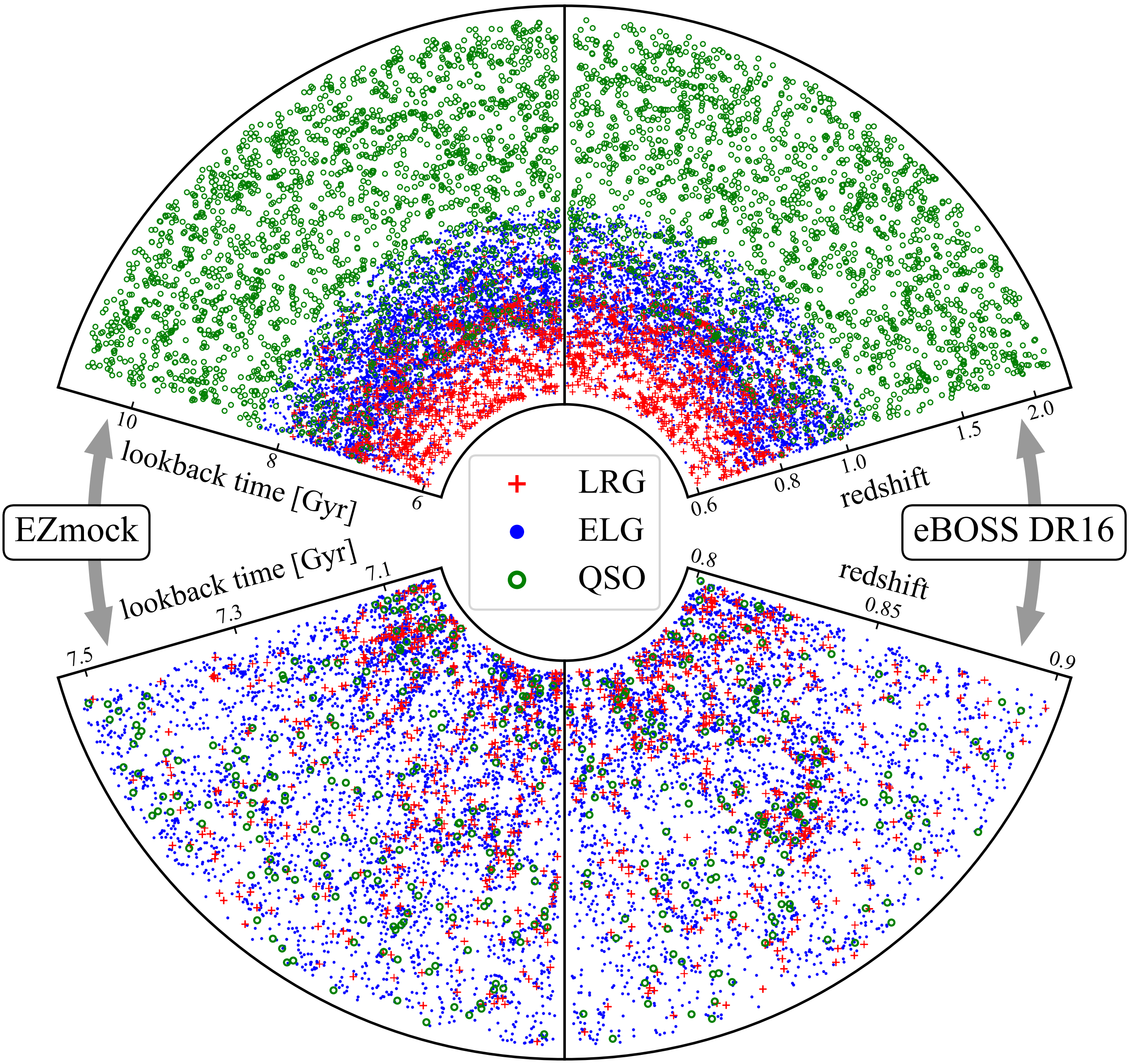
- 255,000 targets based on DECaLS *grz* color box => 189,000 ELGs for BAO (reliable z, 0.7<z<1.1) over >1000 deg^2 - mean redshift: z~0.85
- efficiency = N[ELGs for BAO] / N[observed] ≧ 74%
- eBOSS ELG survey completed 2018 => **thorough analysis, results to be published beginning 2010**

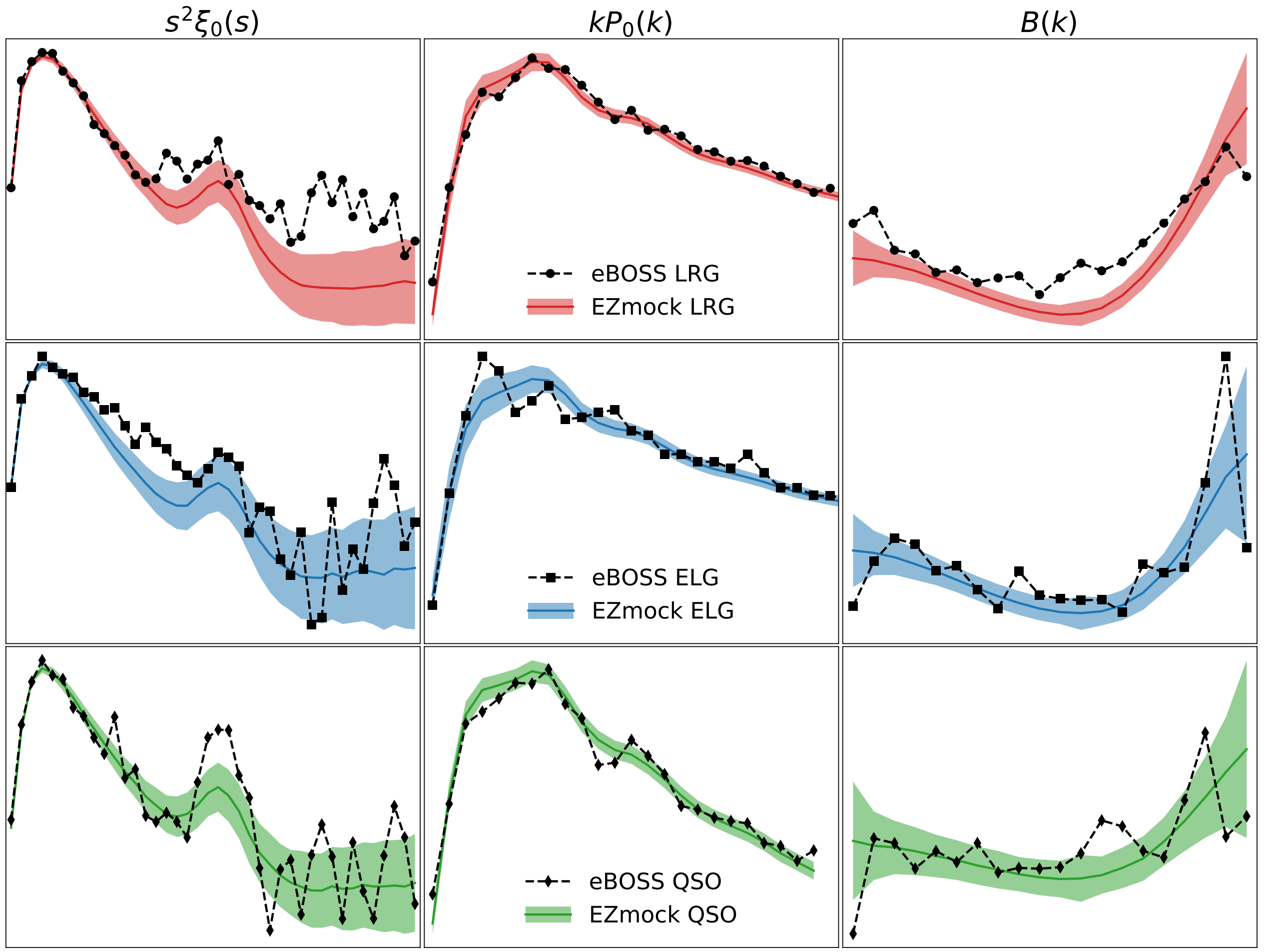




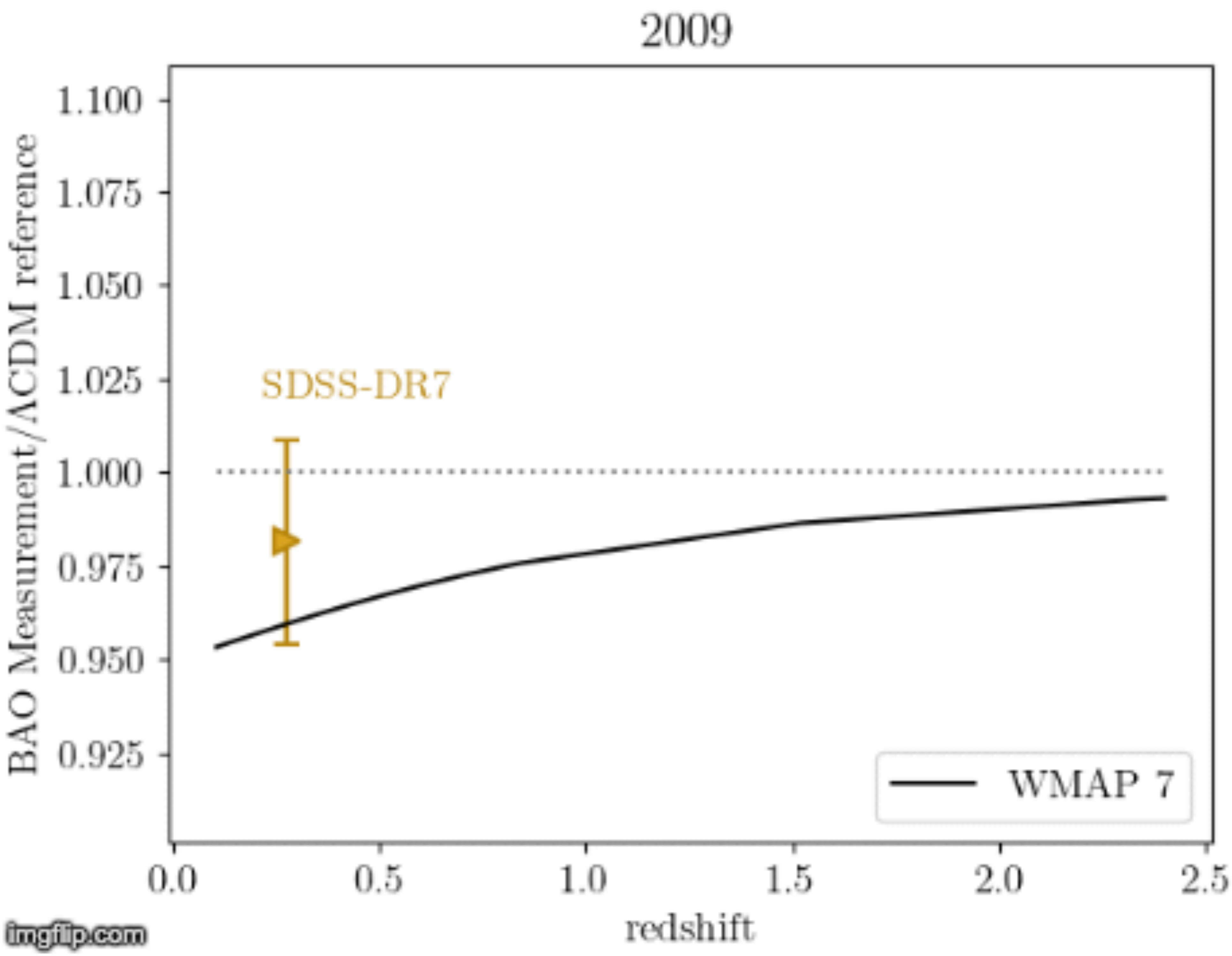
Zhu et al. 2015

eBOSS results vs. Simulations





BAO progress over last 10 years



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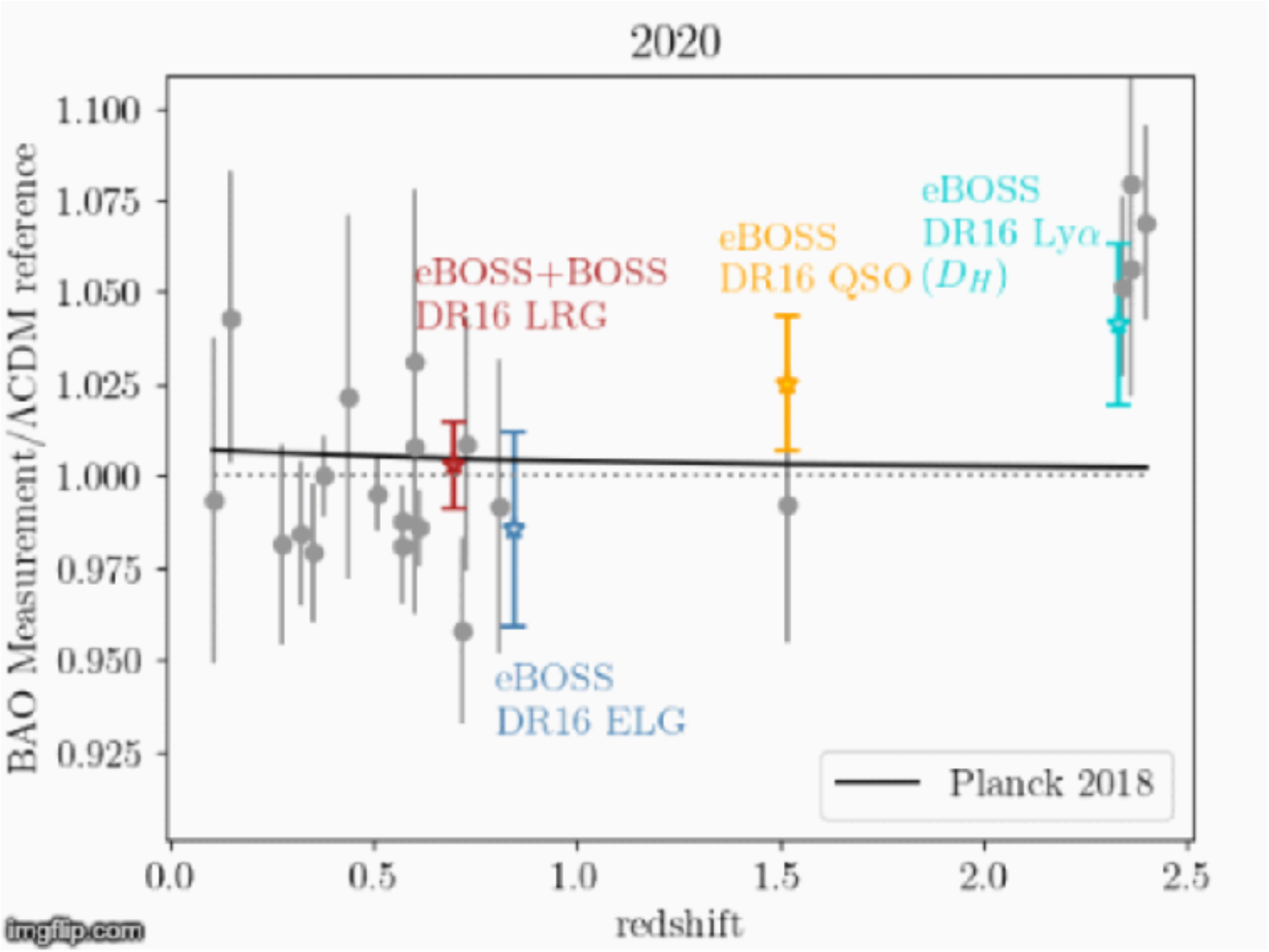
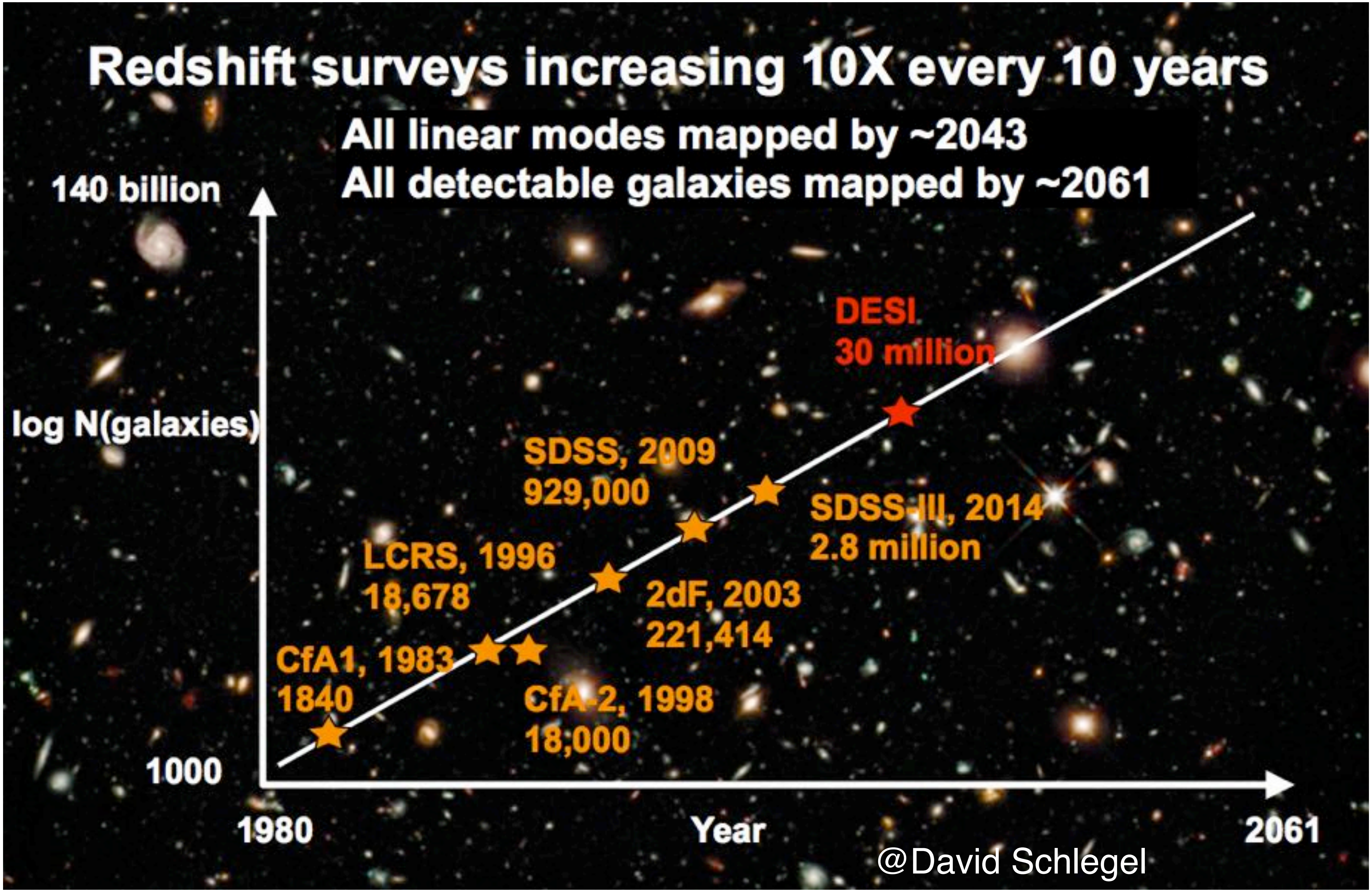


FUTURE Massive Spectroscopic Surveys



Numerous projects of 3D mapping of the Universe:

- eBOSS (2014-2020): continuation of BOSS
- DESI (2020-23): 4m telescope, 5000 fibers
- ESO/4MOST (2022-27): 4m telescope, 2400 fibers
- Euclid (2022-26): space mission
- SPHEREx (2023-24): space mission
- SKA (2027++): radio telescope
- New Redshift machine? (~2027++)

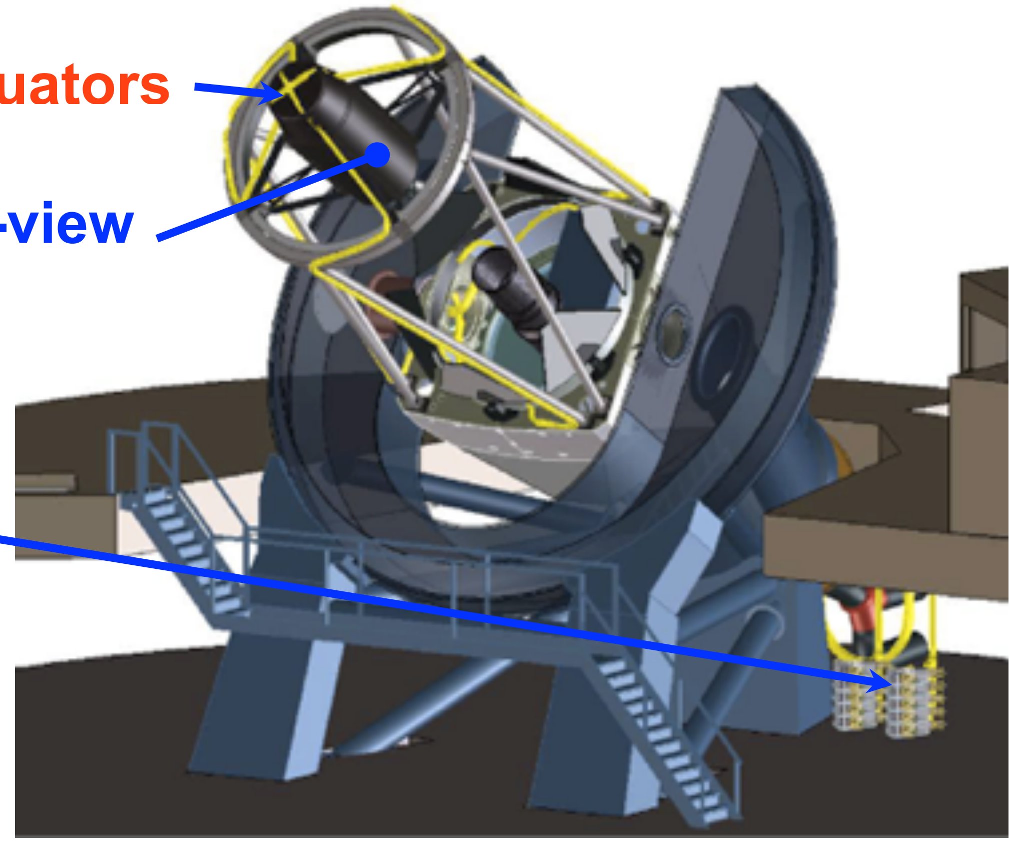
Dark Energy Spectroscopic Instrument

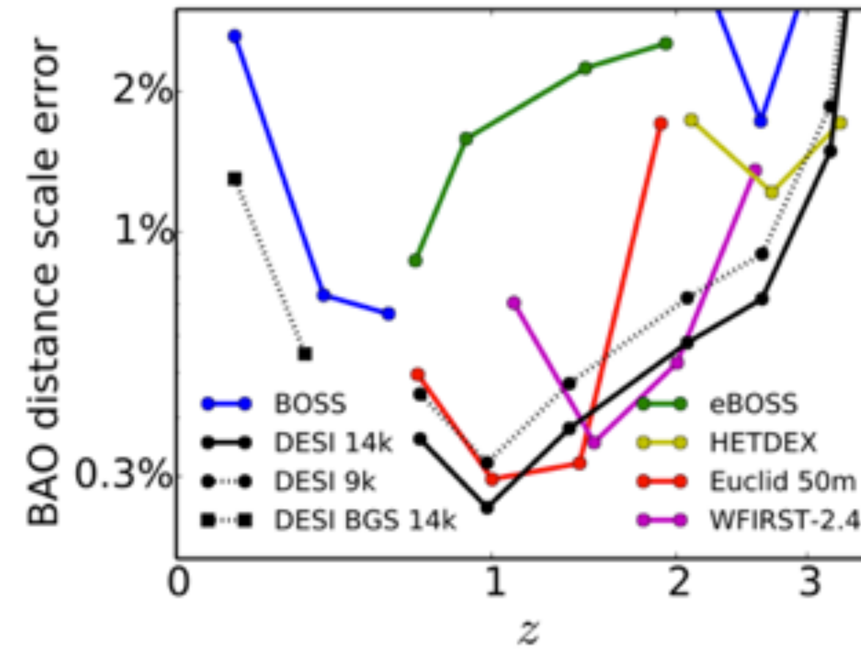
(2019-2024)

5000 fiber actuators

New 3° field-of-view corrector

10 New spectrographs





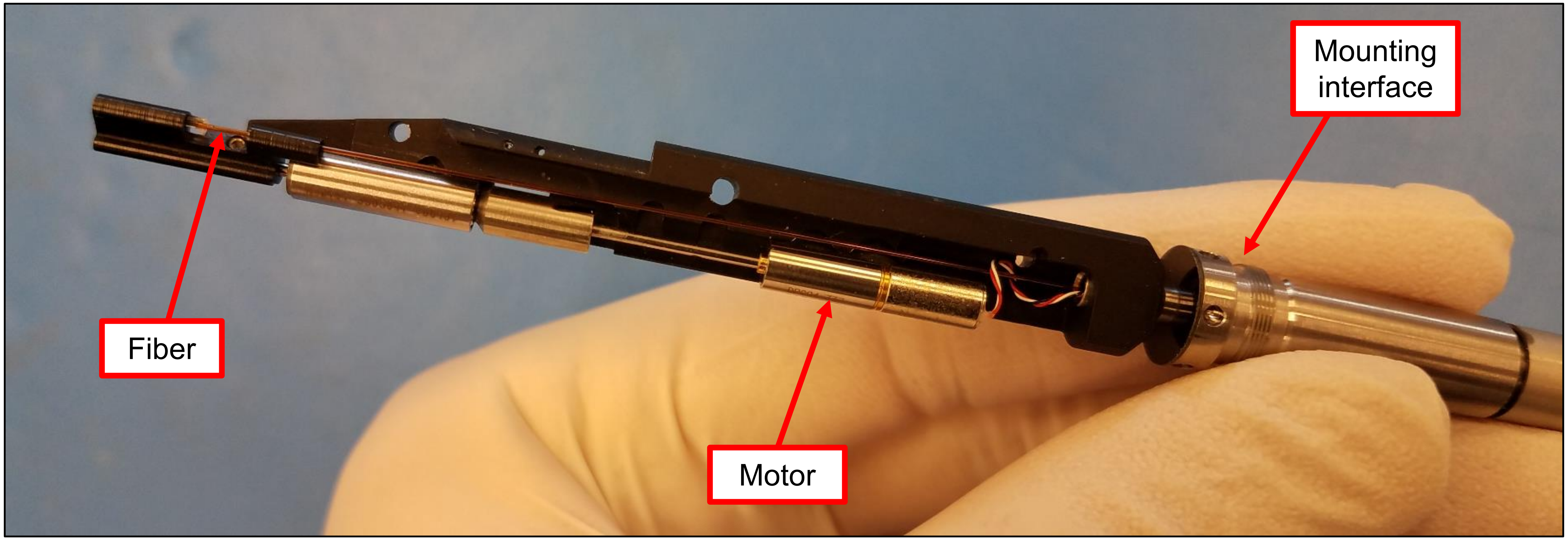
Contribution to the observational strategy and to the robotic system

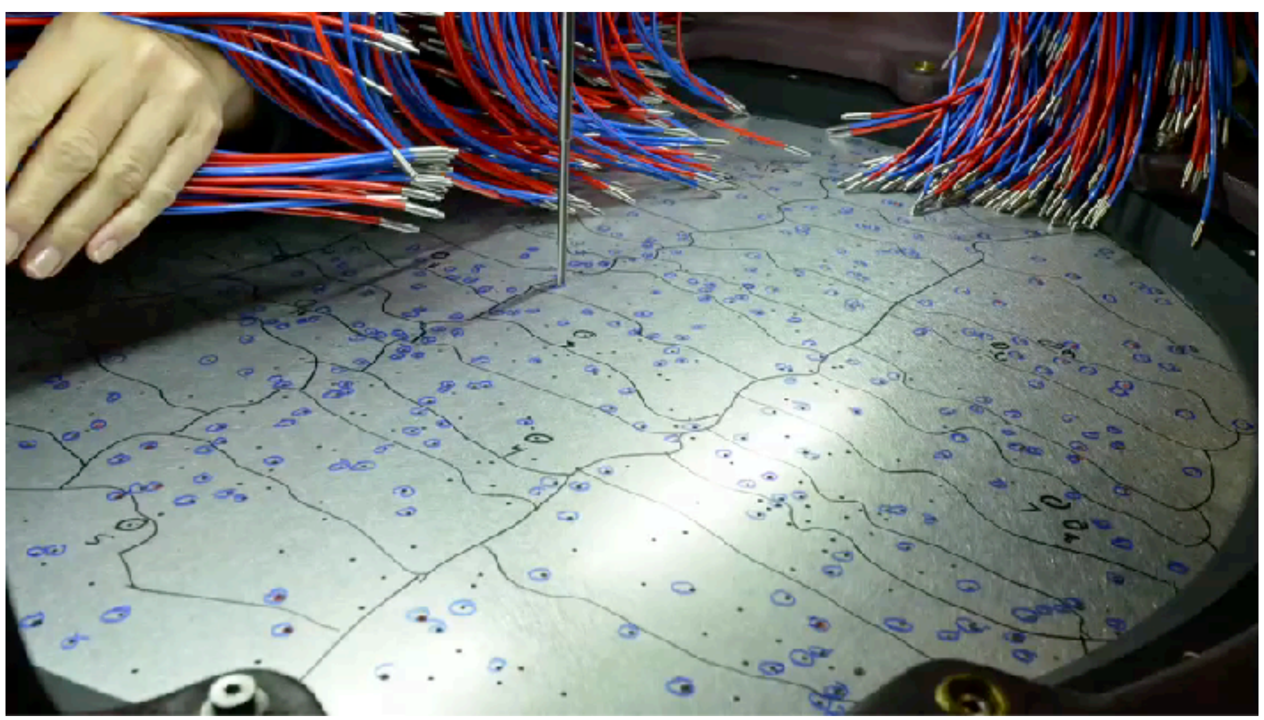
35 Millions redshifts

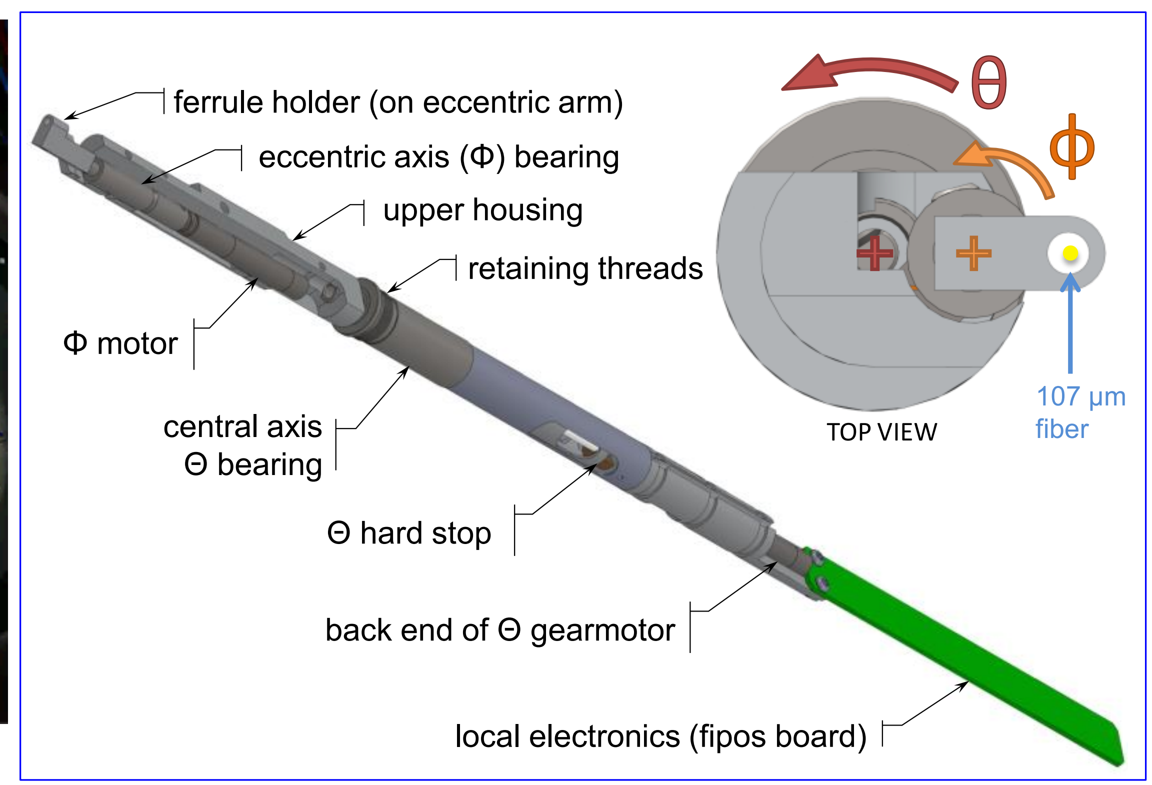
most of them from ELGs

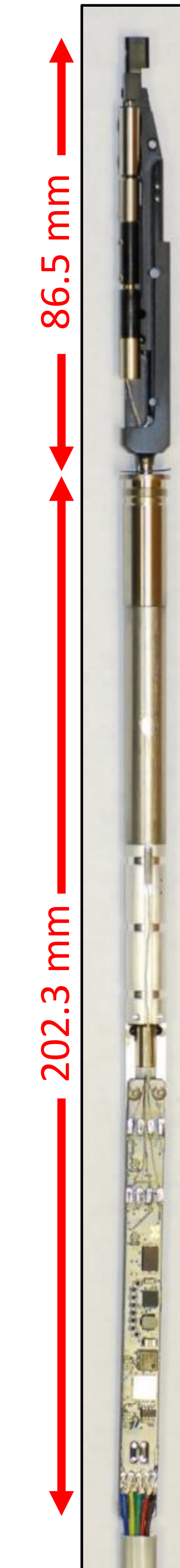
- BAO better than 1%
- Gravitation
- Neutrino masses
- Inflation model

DESI Fiber Positioners

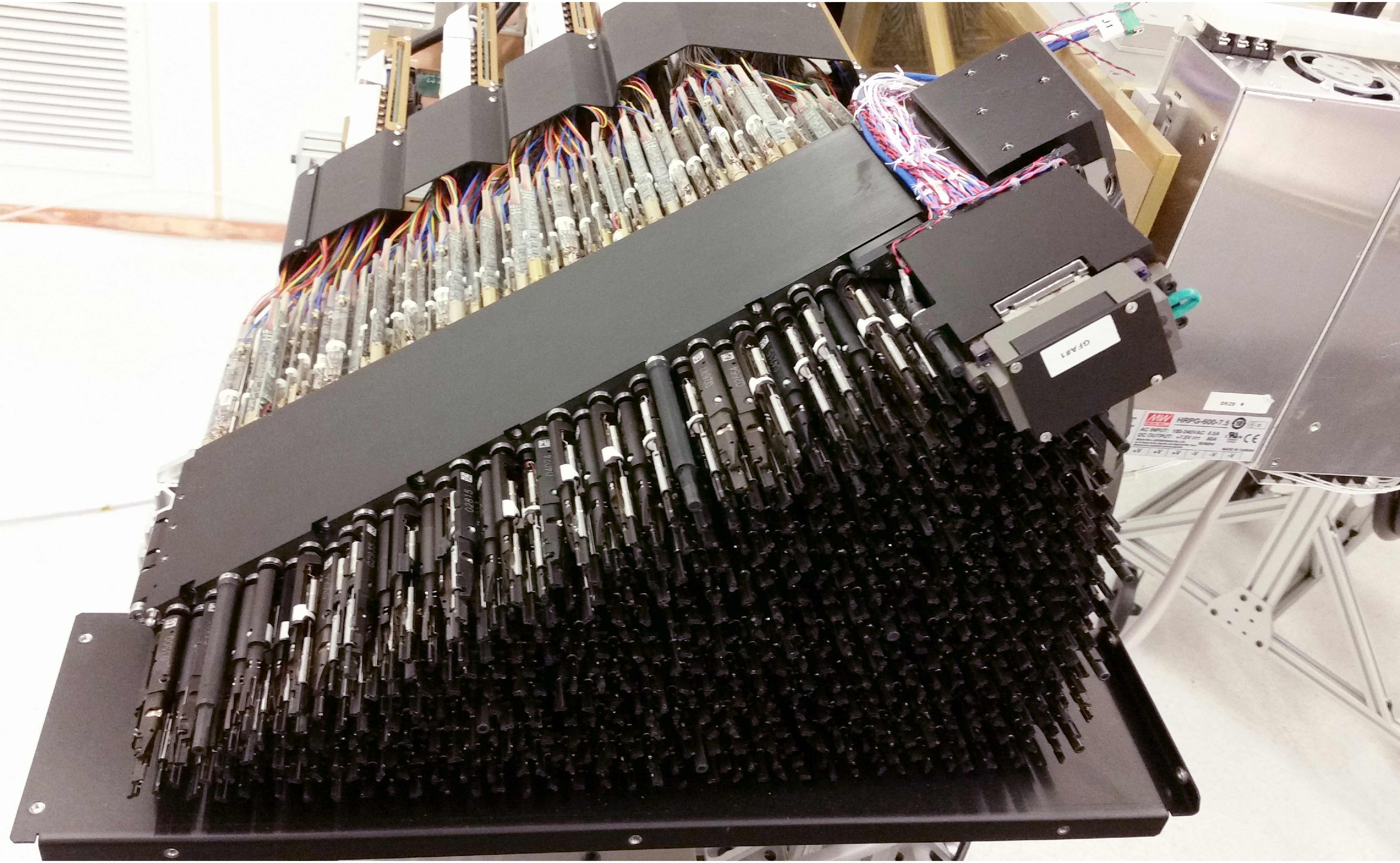




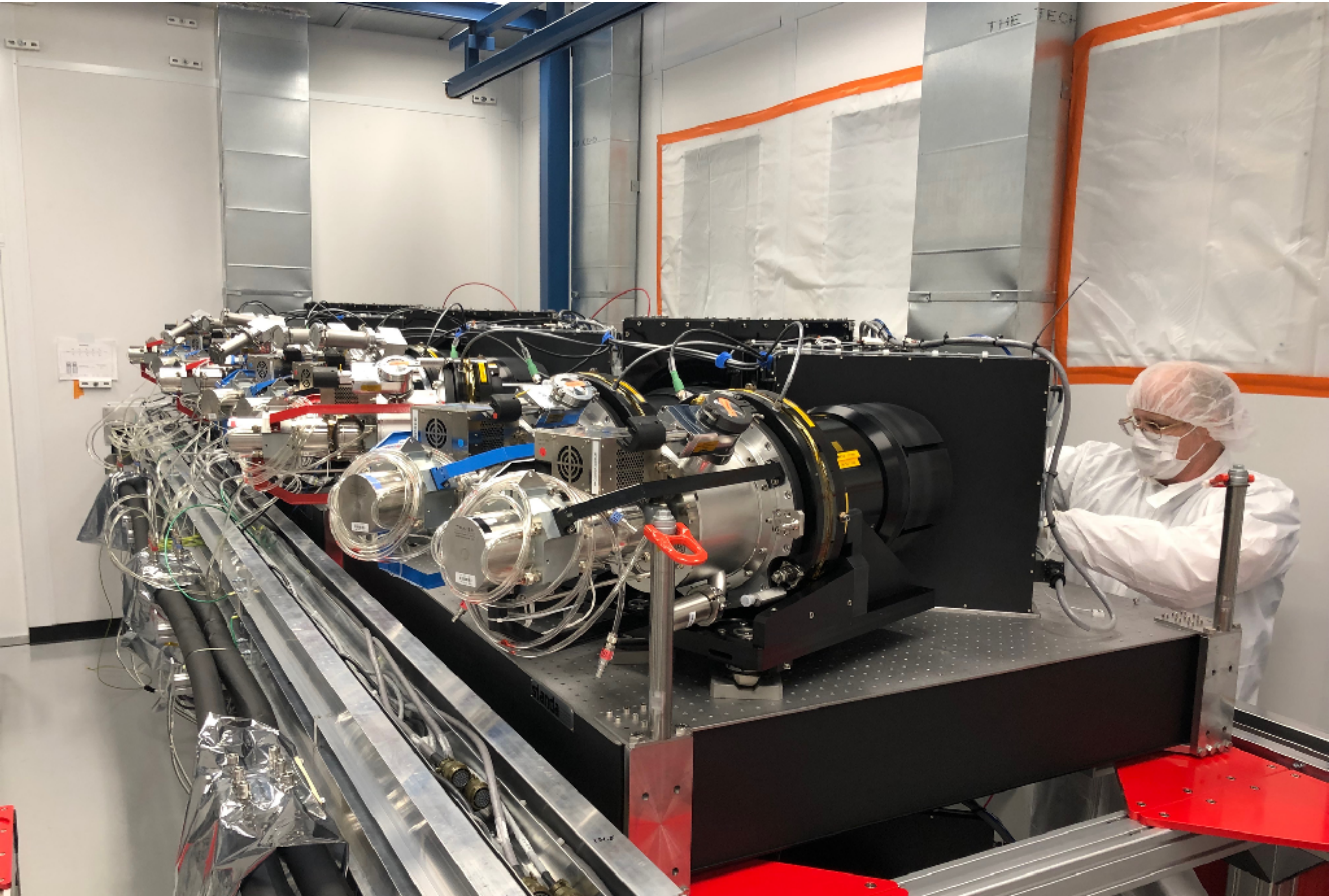


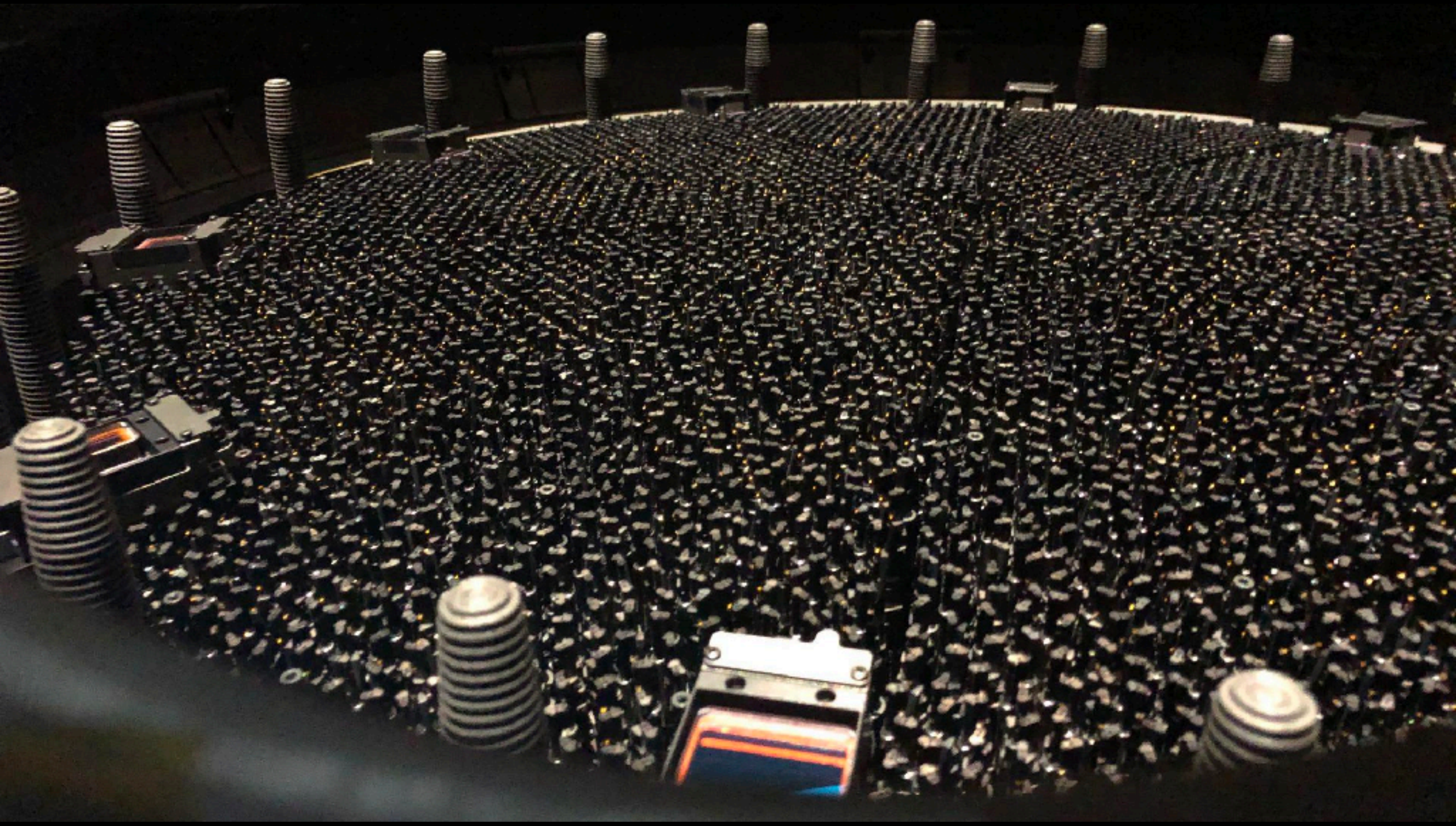


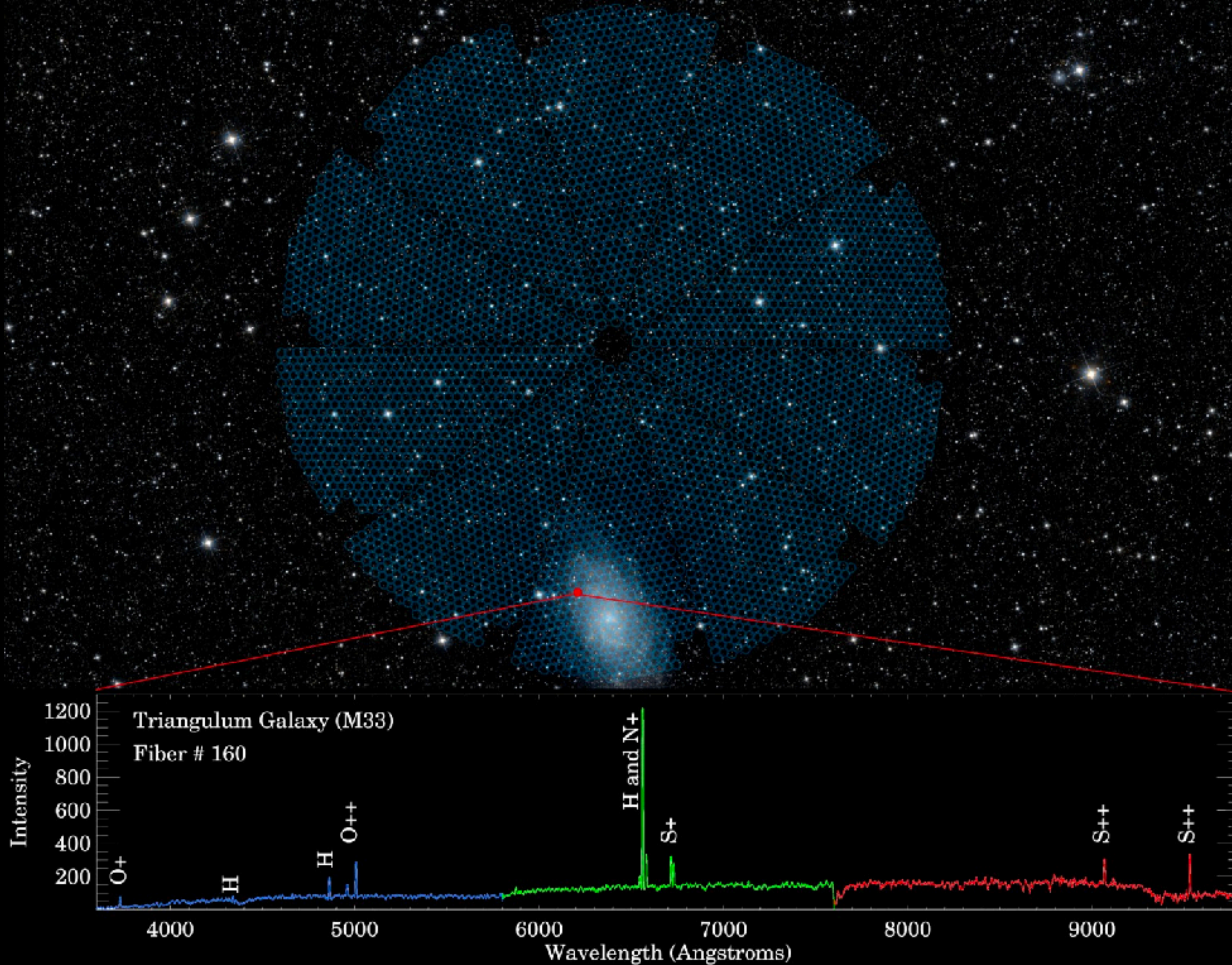
500 (out of 5000) fibre-positioner robots



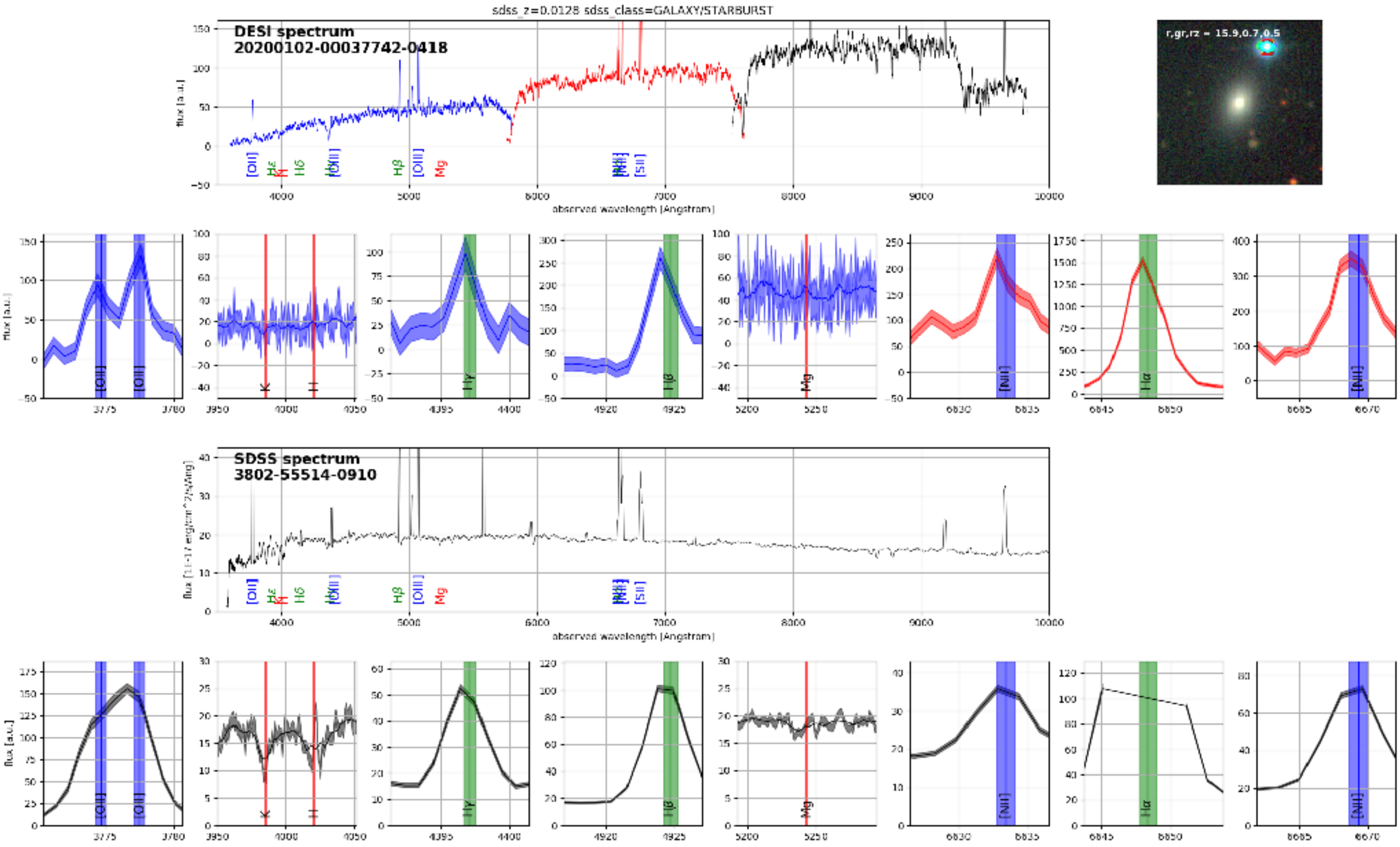
6 (out of 10) 3-arm spectrograph



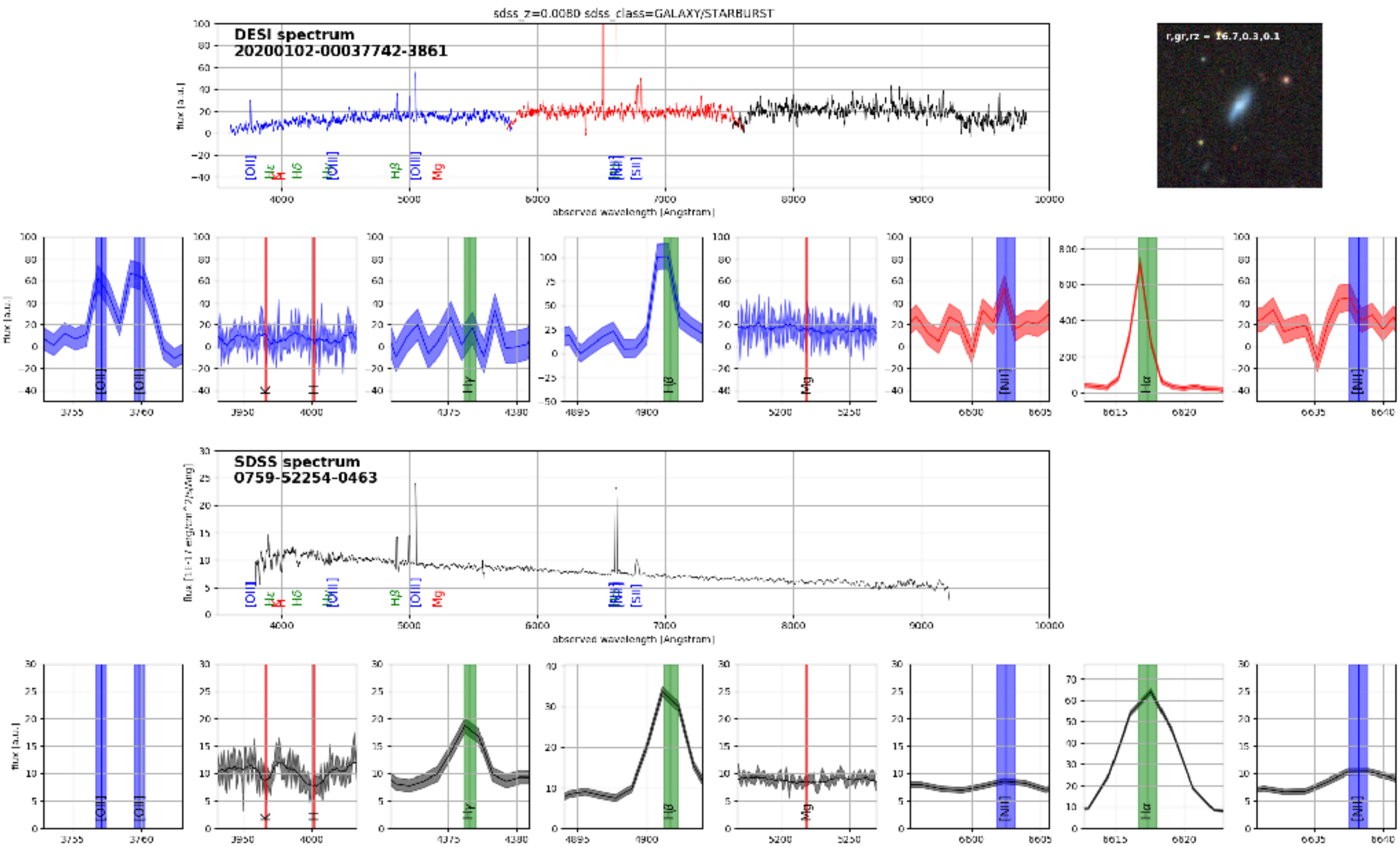



Triangulum Galaxy (M33)
Fiber # 160
Intensity
1200
1000
800
600
400
200
O+
H
H
O++
H and N+
S+
S++
S++
4000
5000
6000
7000
8000
9000
Wavelength (Angstroms)

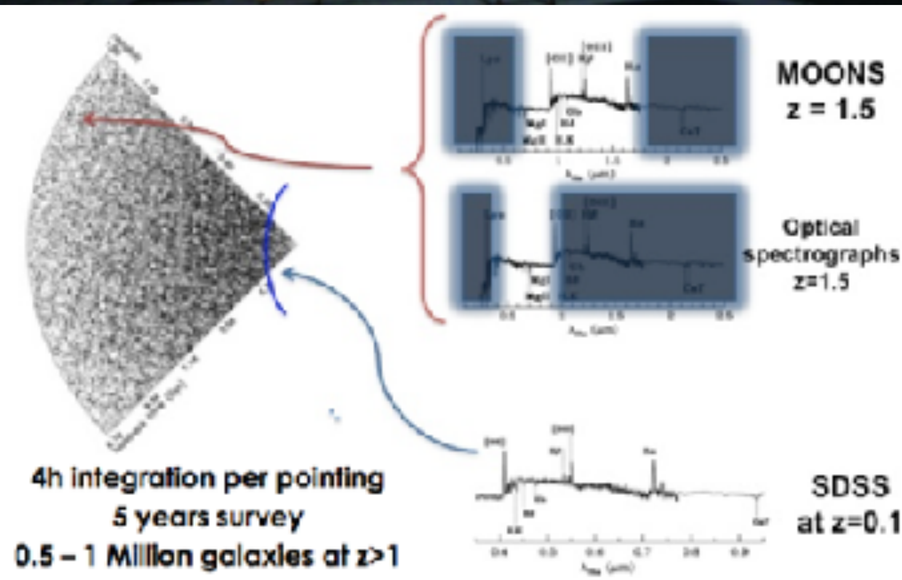
DESI vs. SDSS spectra

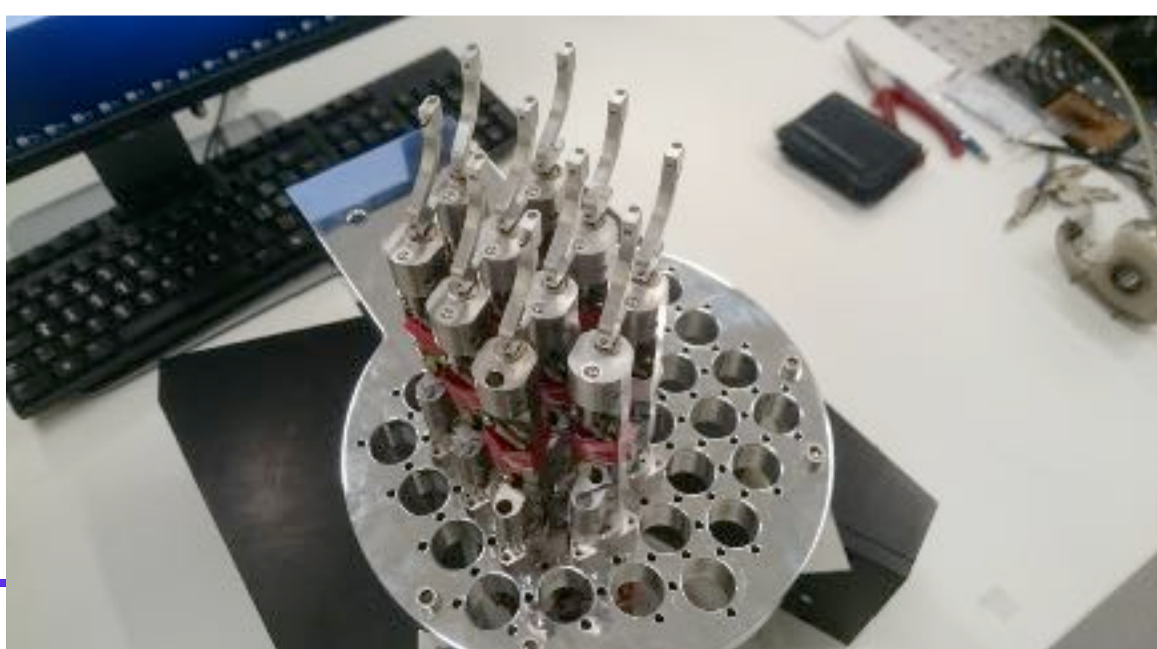


DESI vs. SDSS spectra



VLT-MOONS (2021-2026)

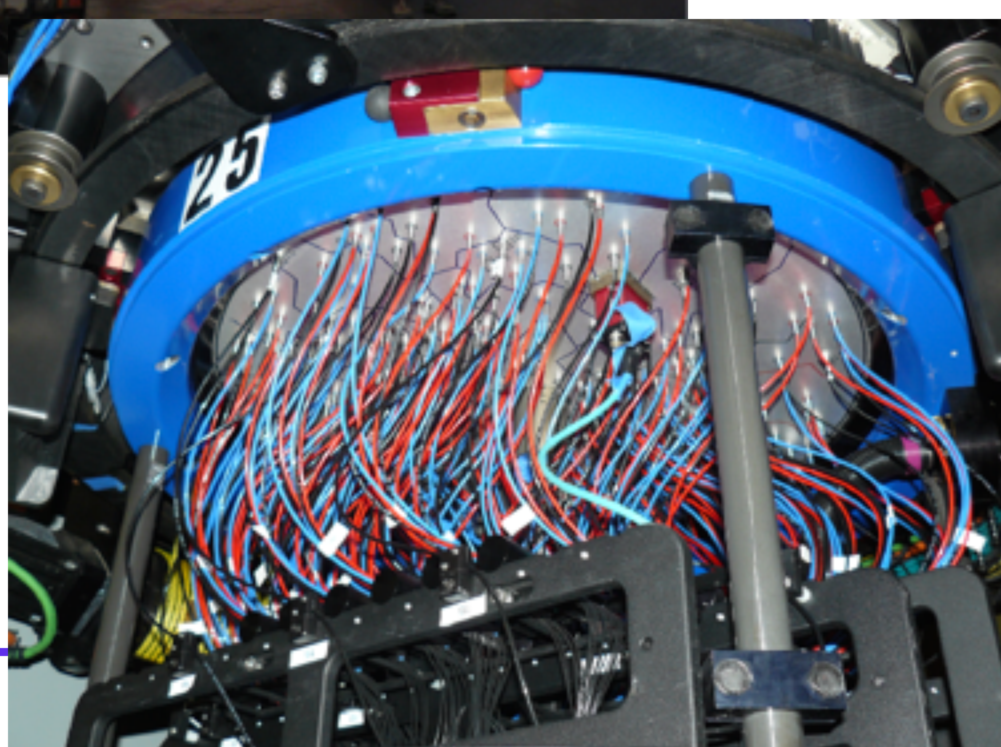


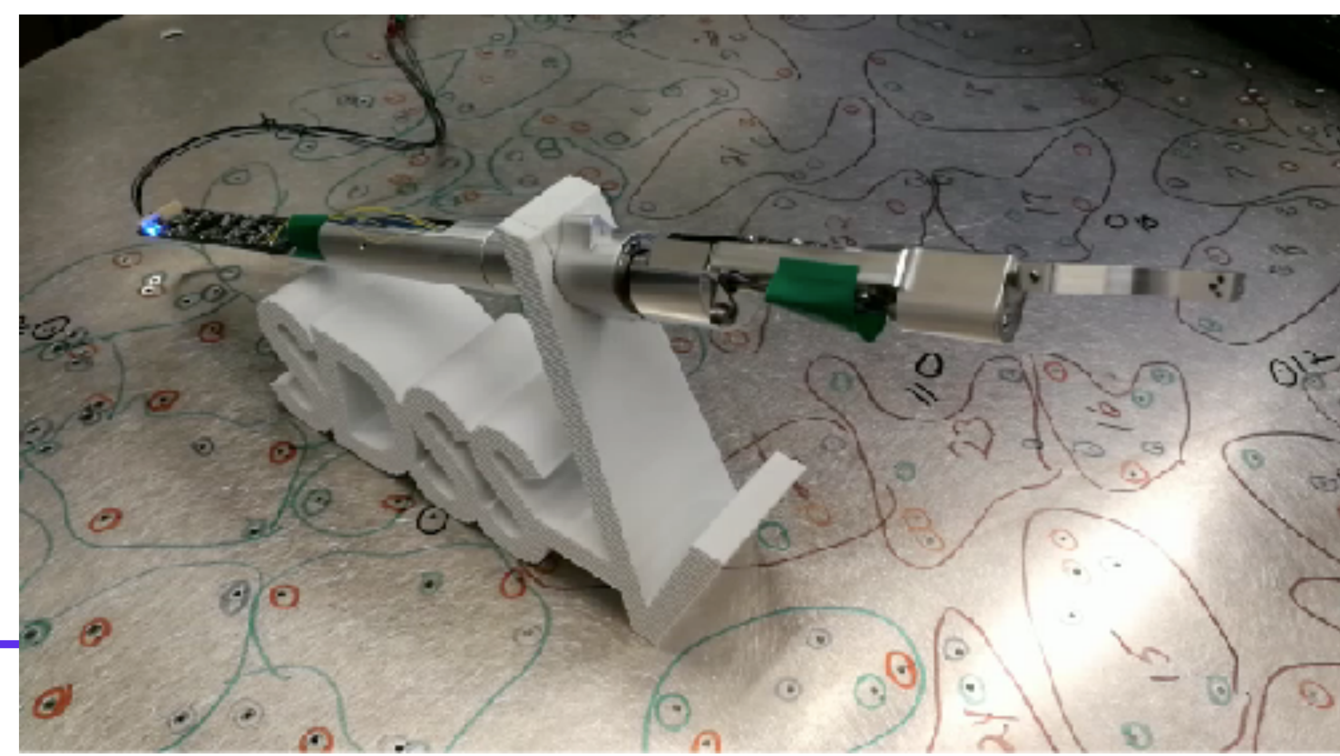


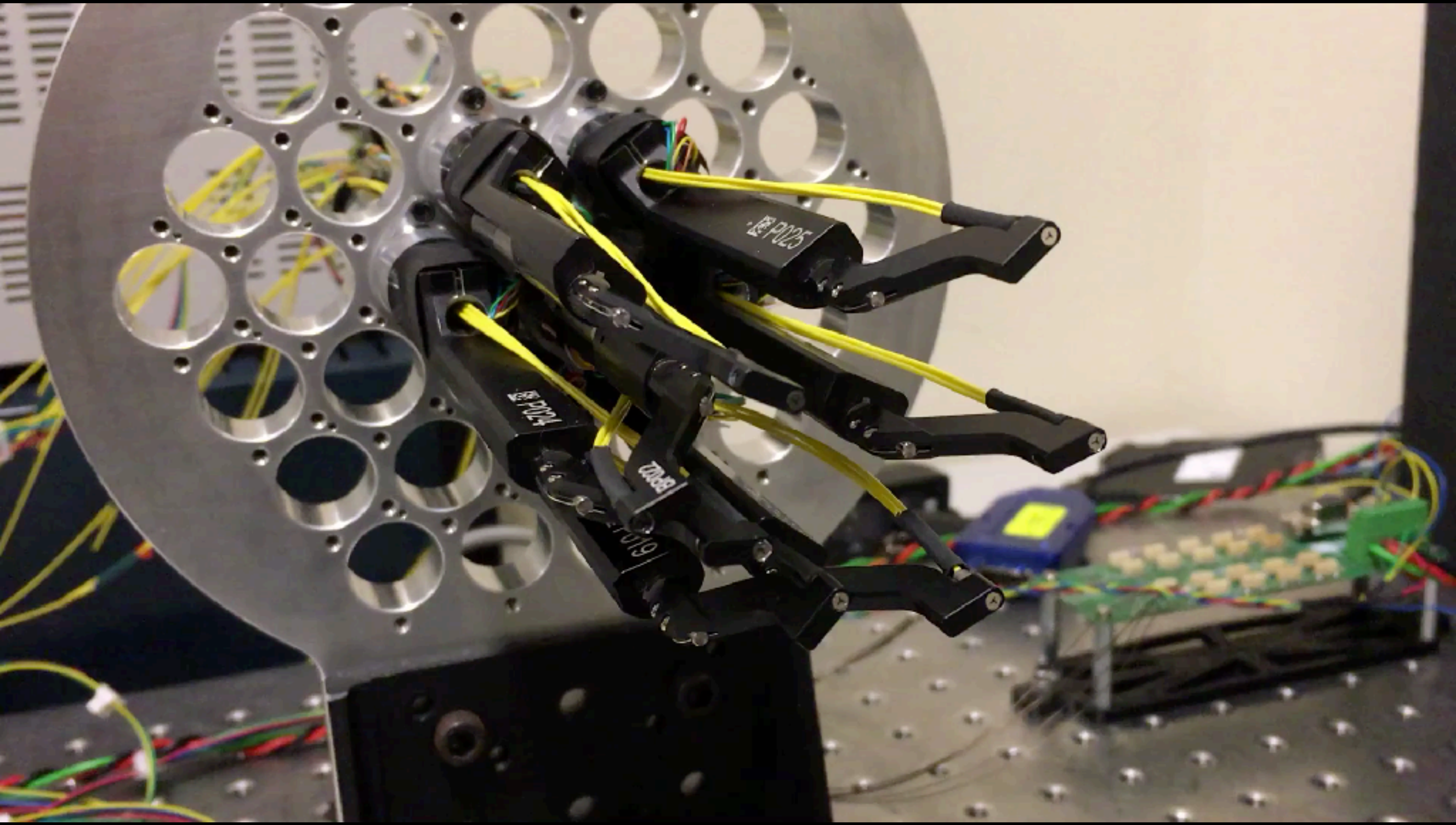
- Approved project by ESO in 2014: IR spectrograph for the 8m VLT (1000 fibers) first light end 2021.
- **Science**: formation & evolution of galaxies
- ~1 million of galaxies to be observed between 1<z<7.
- U. Edinburgh lead of the project
- EPFL helped on the fiber positionner system (with U. of Edinburgh) and collision free navigation.

SDSS-V massive spectroscopy

- Project SDSS-V started Sept. 2017
- 2 telescopes (New-Mexico+Chili), 1000 robots
- Quick tech project to be on sky Fall 2020.
- EPFL responsible of the robotic fiber positioning system
- **Science**: Multi-epoch spectroscopy+AGN+Cluster Galaxies+ Transients

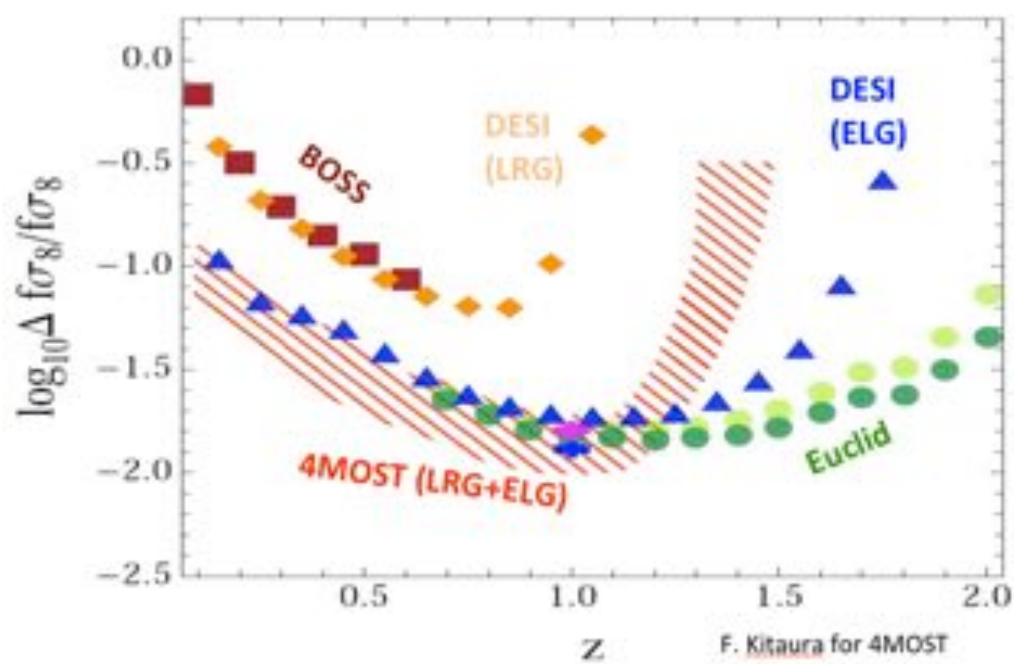


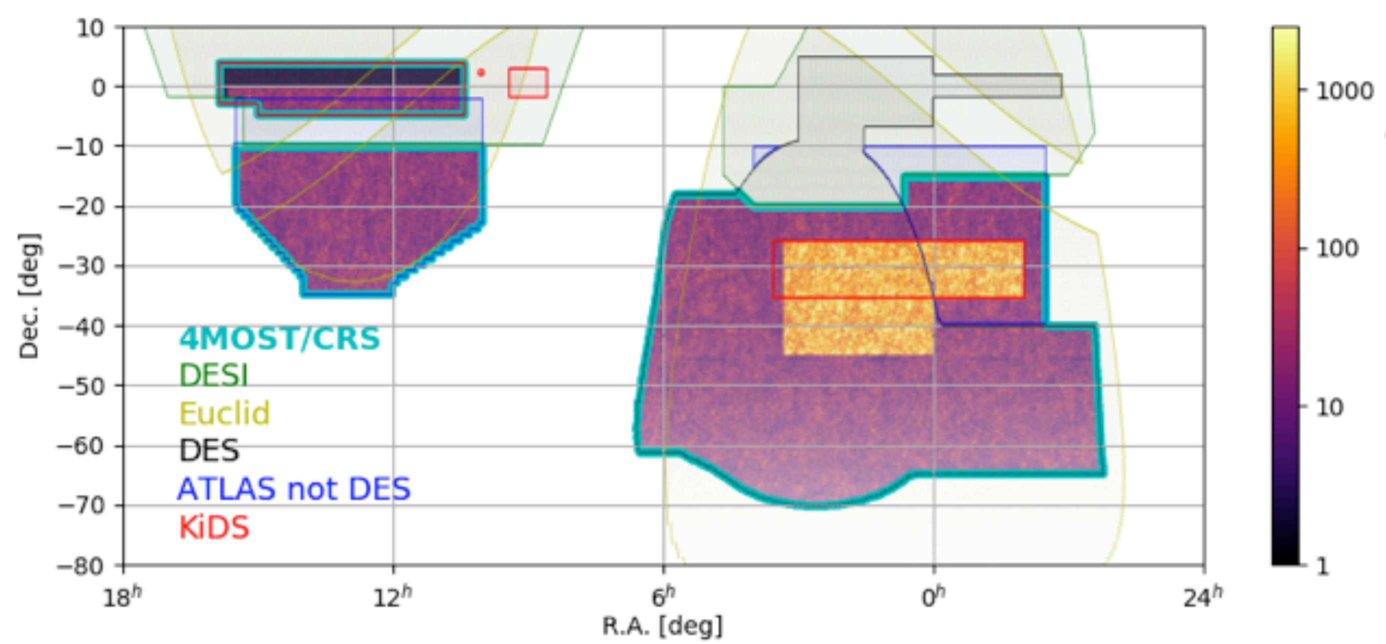



P025
P024

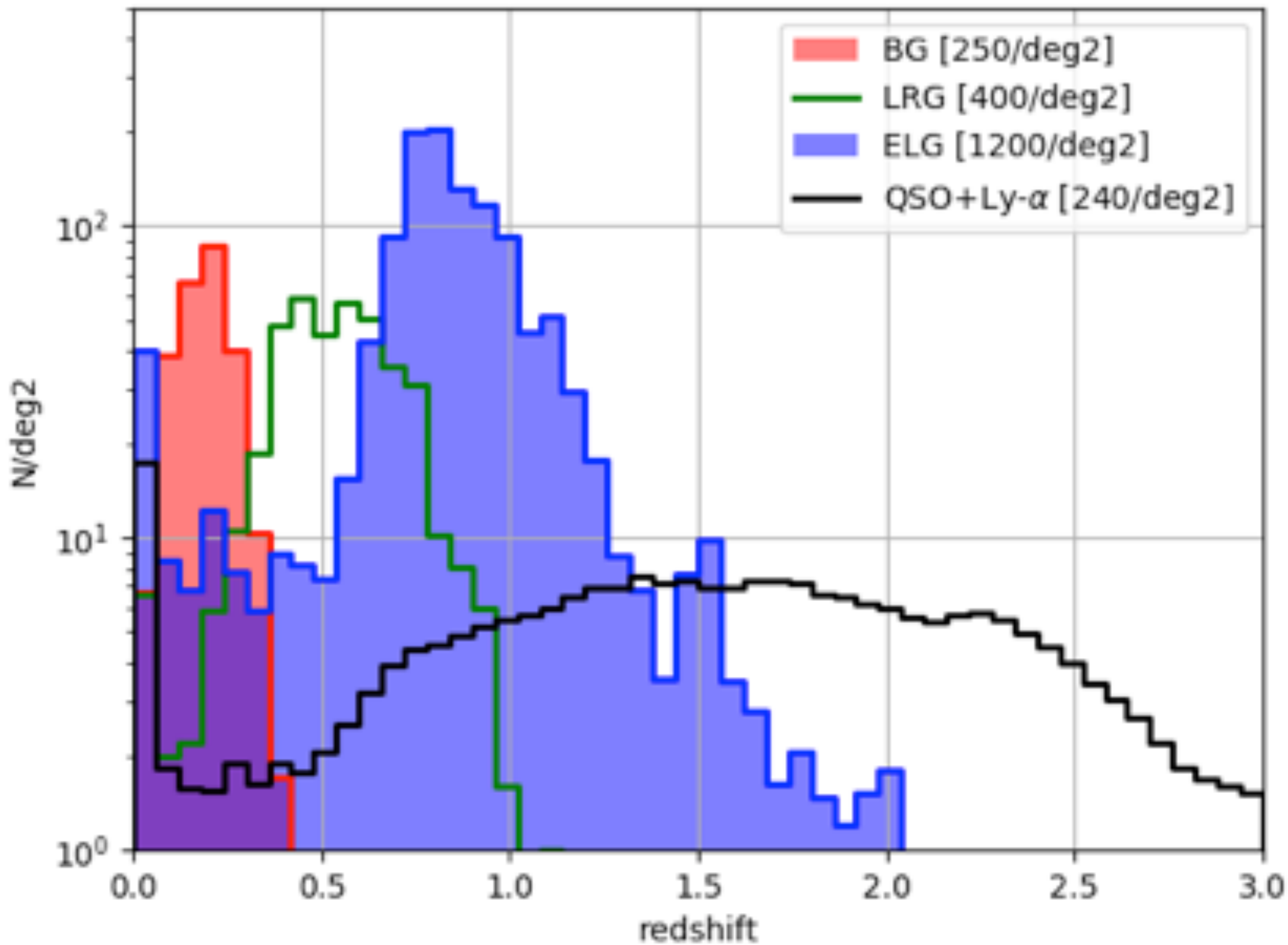
4MOST (2022-2027)

- Complementary to *DESI* in the North
- Complementary to *Euclid in redshift+ WL cross-correlation*
- *Cross-Correlation with HI radio-map+CMB*
- Cosmology survey will gather ~8 million of spectra of galaxy and AGNs
- Messenger White paper: Richard et al. 2019 [astro-ph/1903.02474](https://arxiv.org/abs/1903.02474)



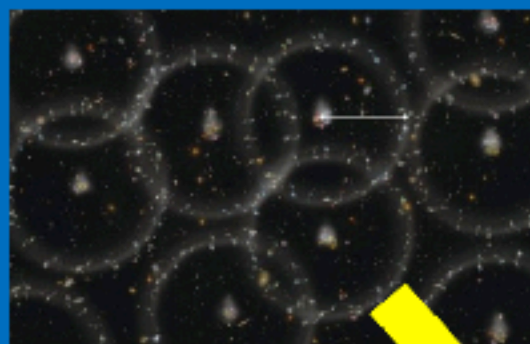


4MOST Redshift distributions



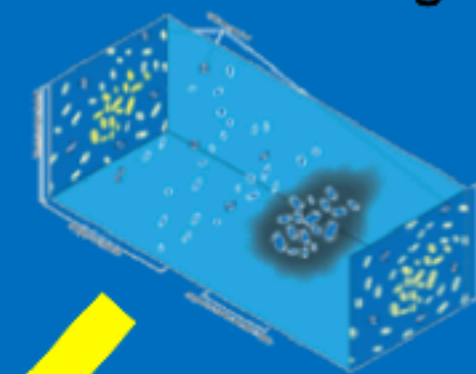
Euclid: a survey machine driven by cosmology

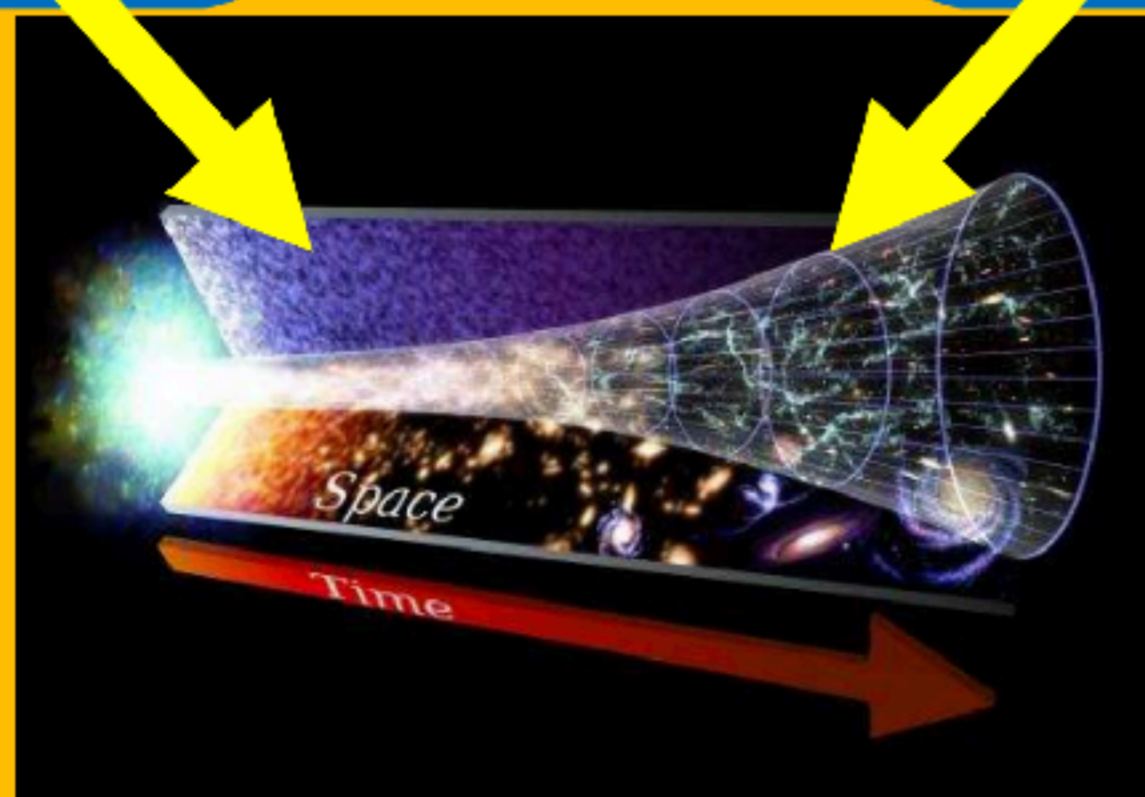
Galaxy clustering

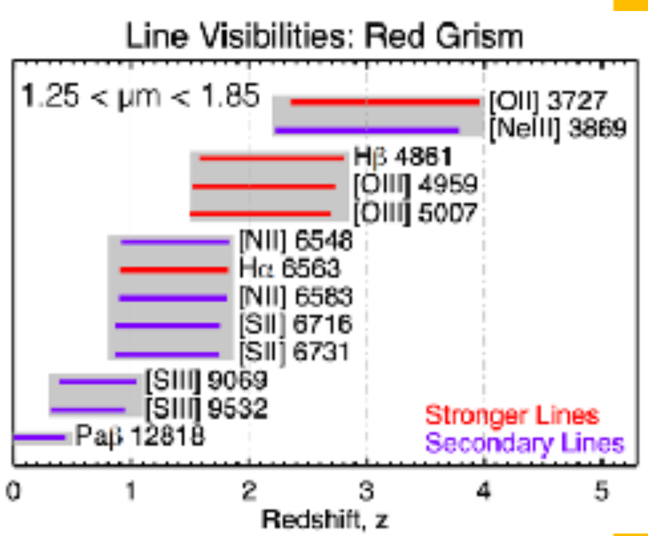


BOSS

Weak lensing

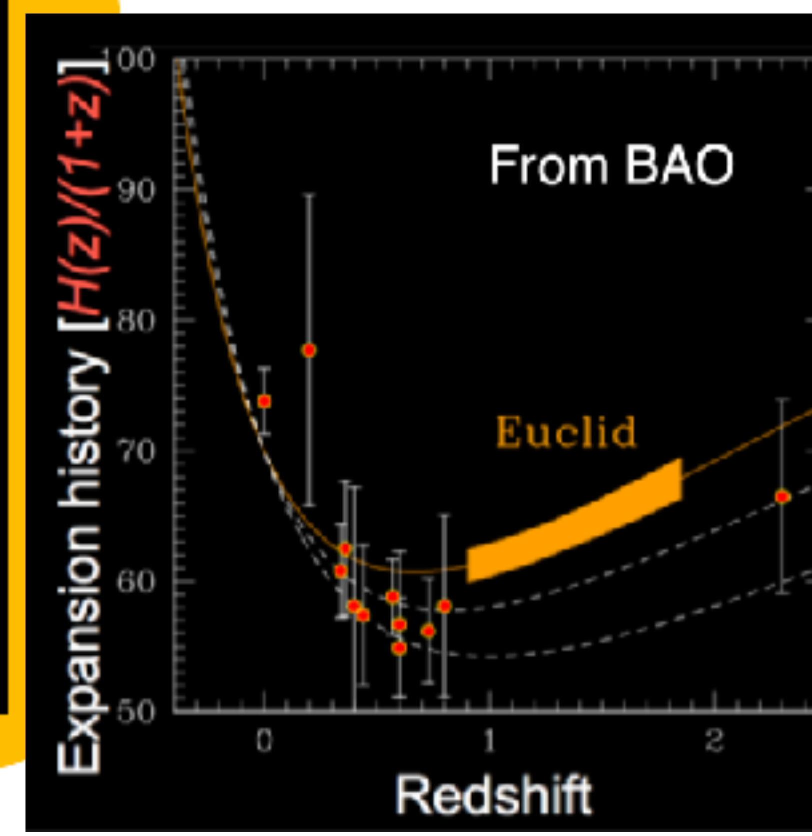






Addison et al.

1<z<2



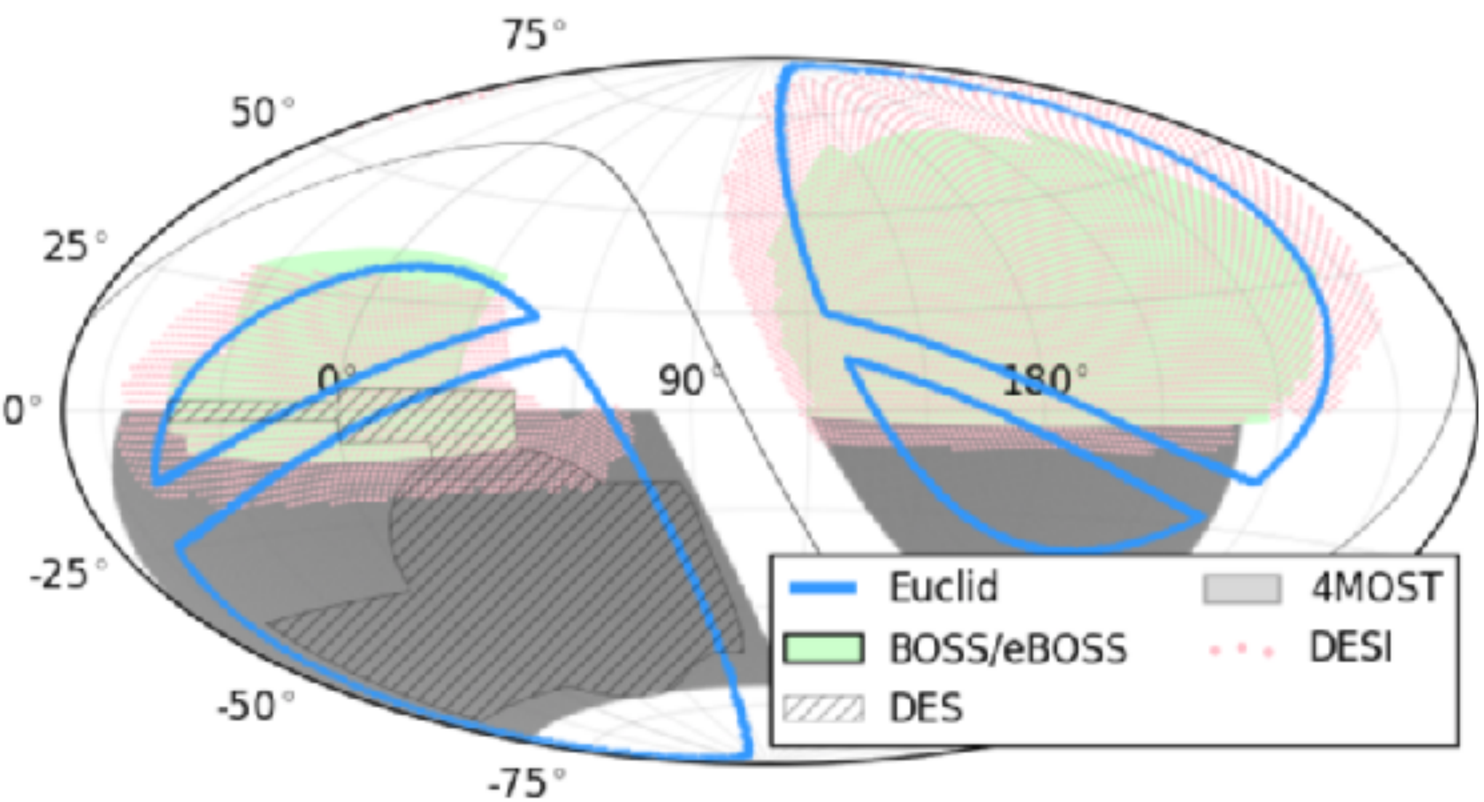
Type 1a supernovae

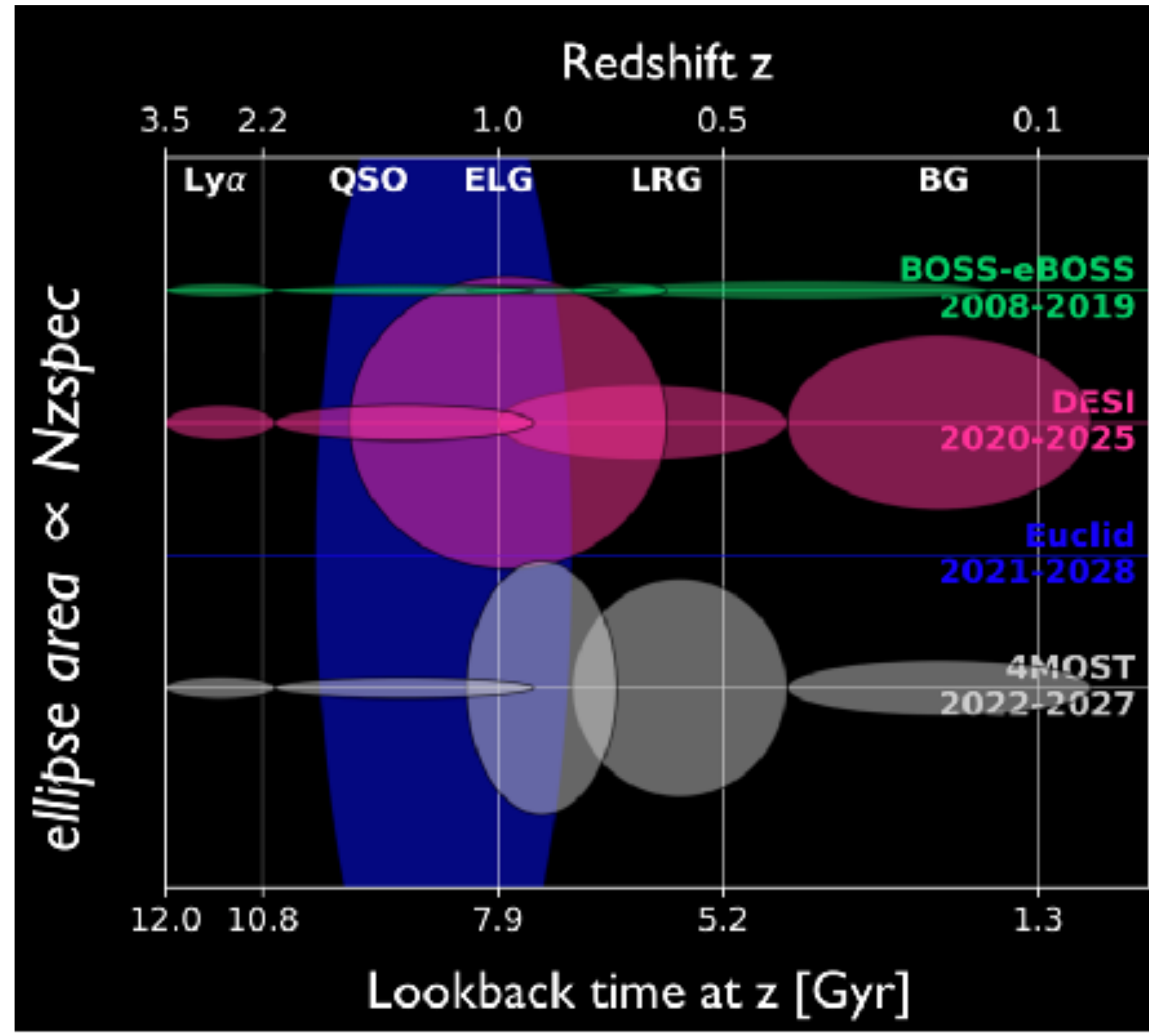
Cluster counts

CMB cross correlations

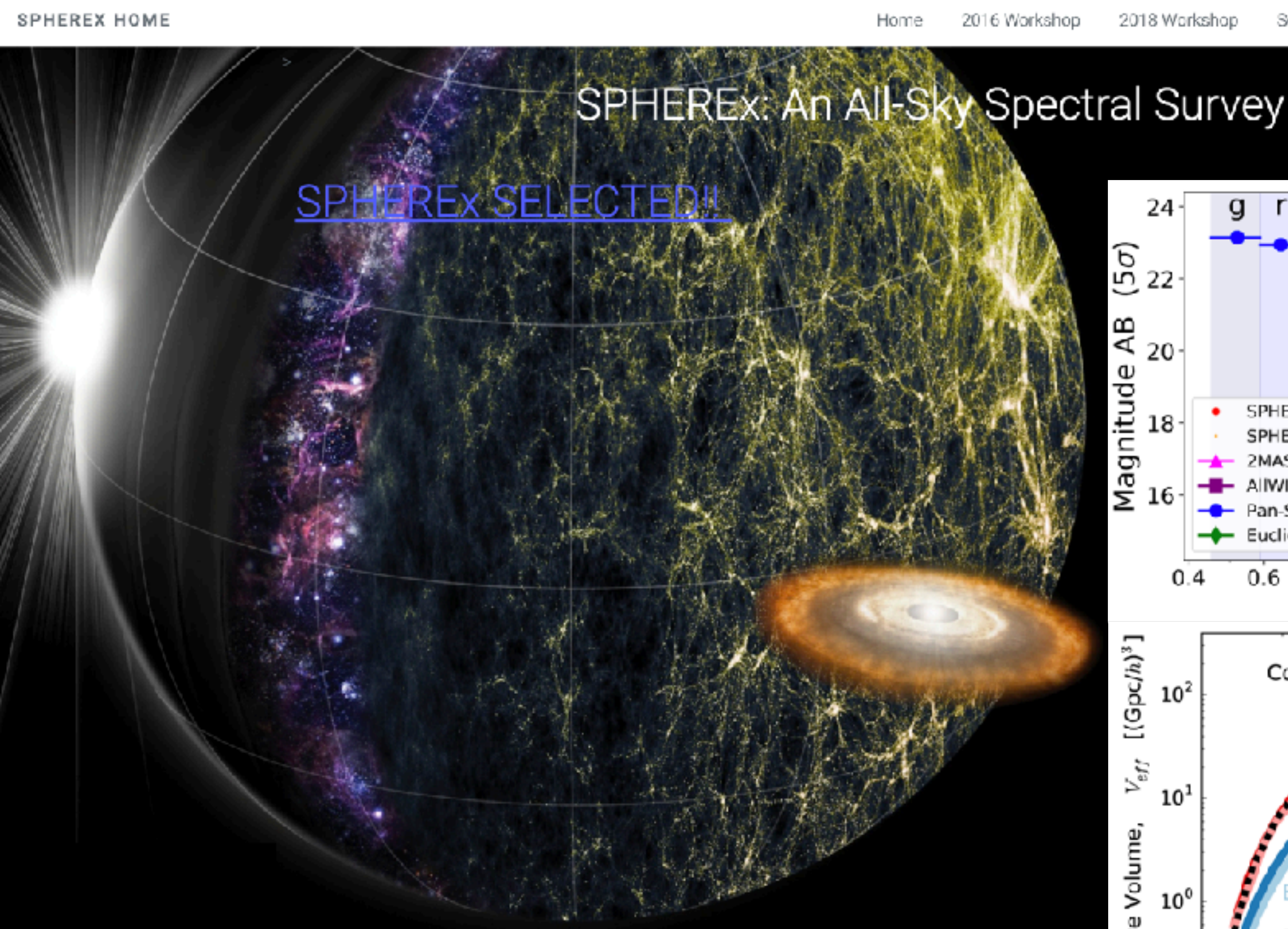
DESI/4MOST/Euclid

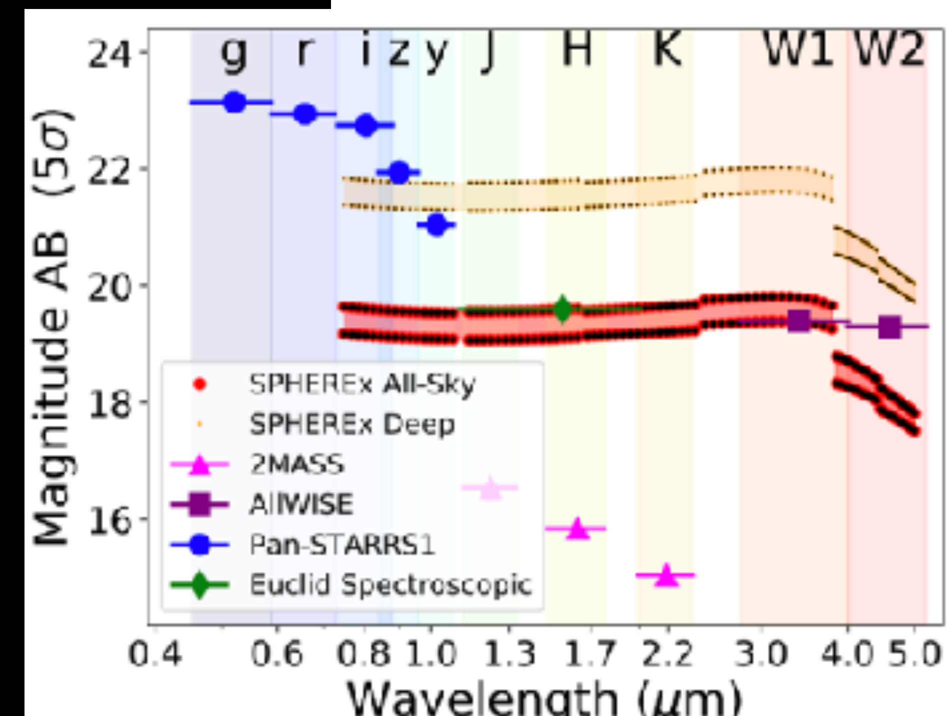
2026: ~100 million redshifts 0<z<3 over ~20'000 sqdeg.

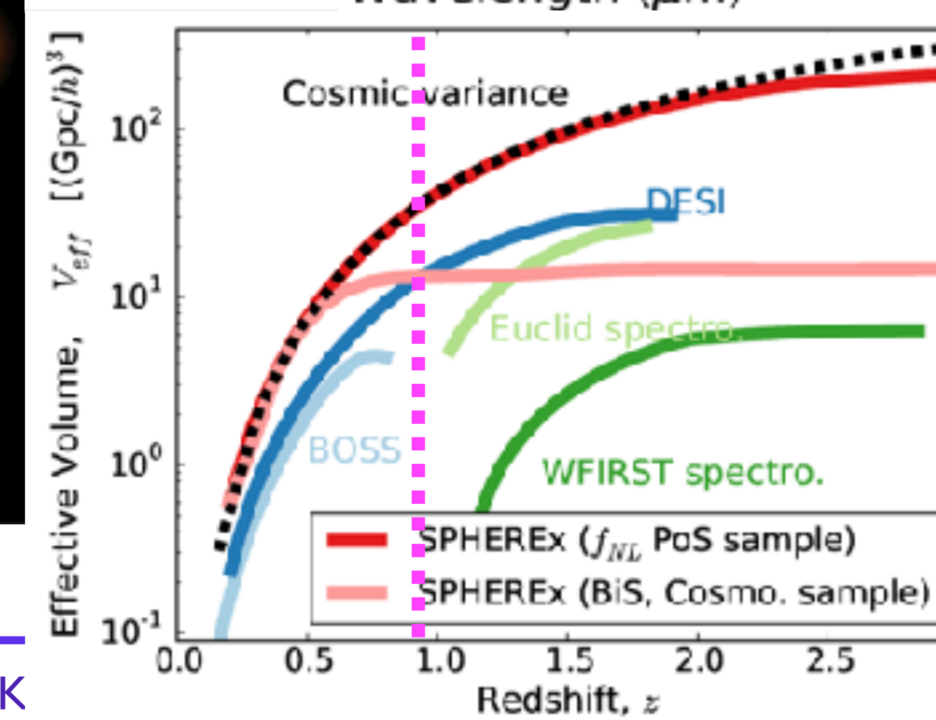




SPHEREx (2023-24)

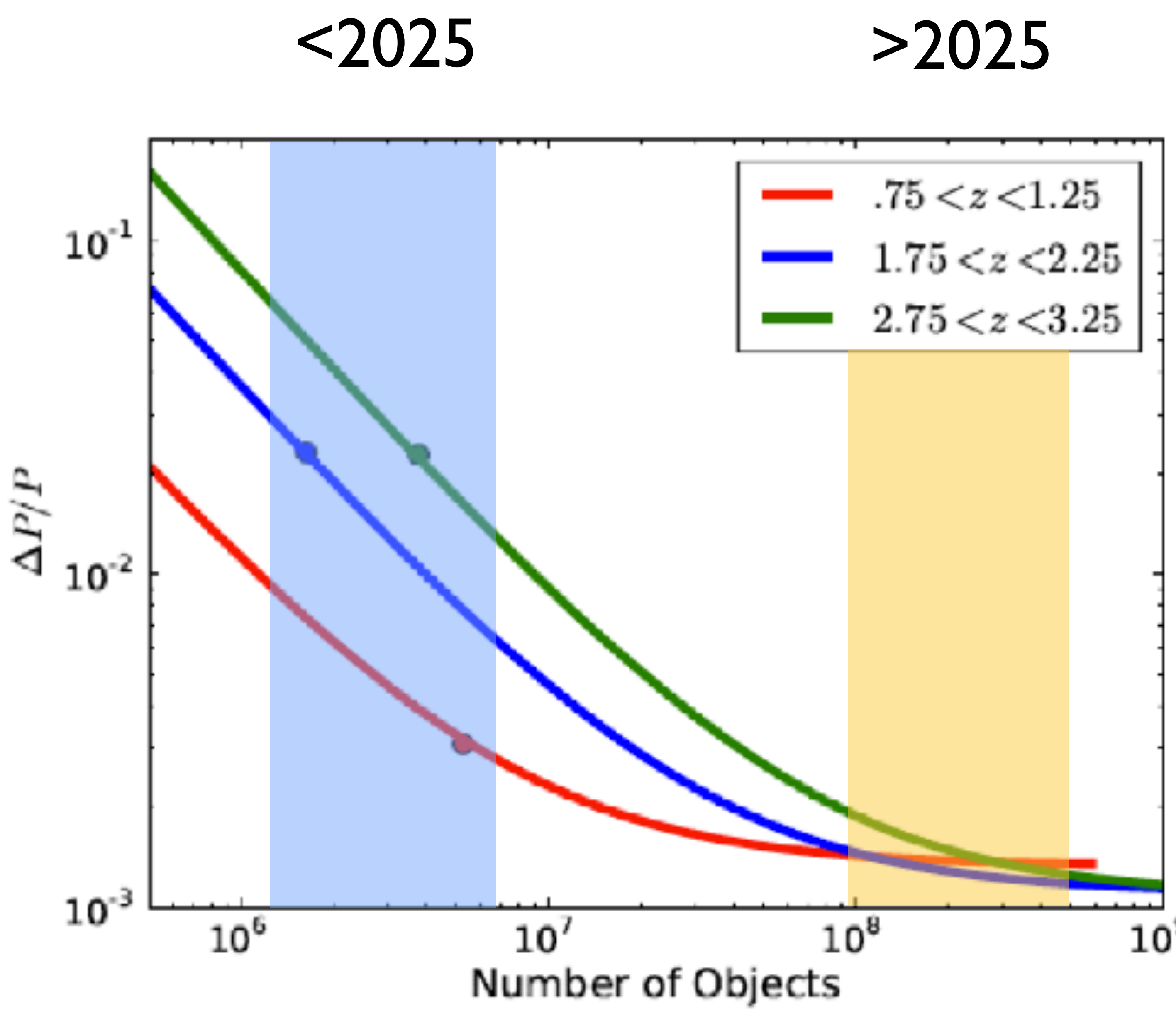






Future massive spectroscopic surveys

- Most of the cosmological information can be found in the Power Spectrum.
- How many redshift measurements to reach the maximum of information?
- Use of many tracers (galaxies/quasars)
- **Can we measure ~billion of redshifts?**



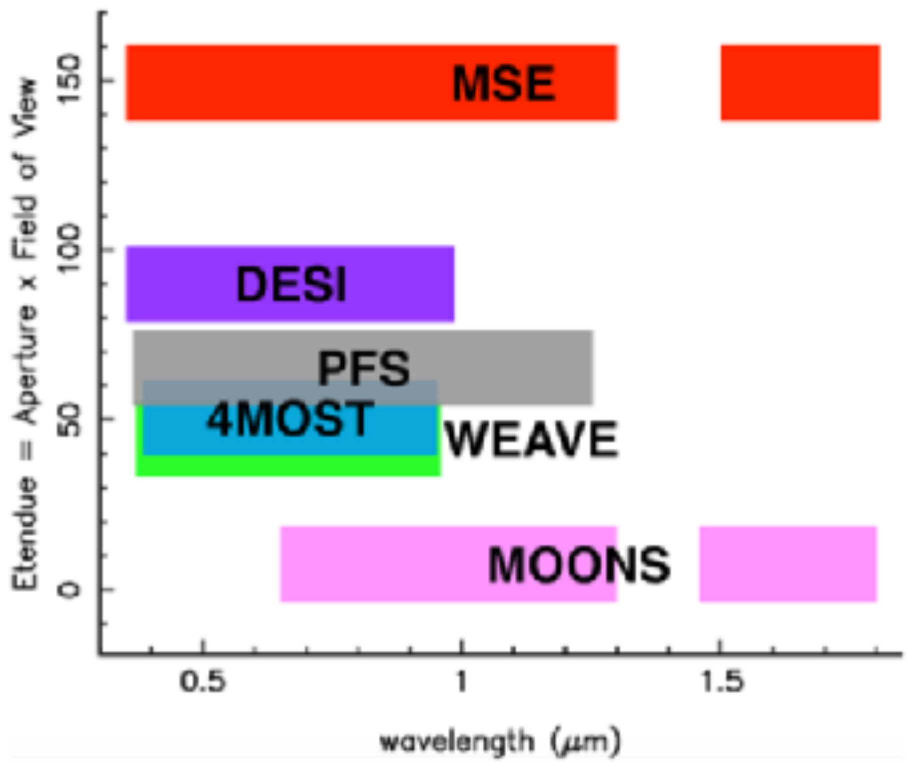
Dodelson et al 2016

New Project(s) ?

- **What project after? MSE, DESI-2, SpecTel, LOT?**
- *Larger telescope!! 10-12m telescope (**yet to be build**)*
- *Likely larger multiplexing: >=5'000, possibly ~15'000 (if ~7mm diameter fibre positioned robots)*
- Science interest goes beyond just cosmology ... also mapping the Milky Way, counterpart of GW/GRB events
  - Affordable telescope, spectrograph, detectors?
  - Smaller fiber positionner robots?

New Project(s) ?

- MaunaKea Spectroscopic Explorer (**MSE**) http://mse.cfht.hawaii.edu/ (2028?)
  - Replace the 3.6m CFHT telescope in Hawaii, by a ~11m diameter telescope; >3200 fibers
- **US/NSF+DOE plans** - follow-up of LSST
  - check e.g.: https://kicp-workshops.uchicago.edu/FutureSurveys/ - **Dodelson et al 2016**
- **LOT,** 12m Chinese telescope, but more an observatory
- **ESO Plans**: Brainstorm led by Richard Ellis
  - New telescope designs suitable for massively–multiplexed spectroscopy: **Pasquini et al 2016, Ellis et al 2017**
- **MEGAMAPPER ?**



MegaMapper

Astro2020 APC White Paper

The MegaMapper: a $z > 2$ spectroscopic instrument for the study of Inflation and Dark Energy

Thematic Areas: Ground Based Project, Cosmology and Fundamental Physics

Principal Authors:

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Institution: Lawrence Berkeley National Laboratory
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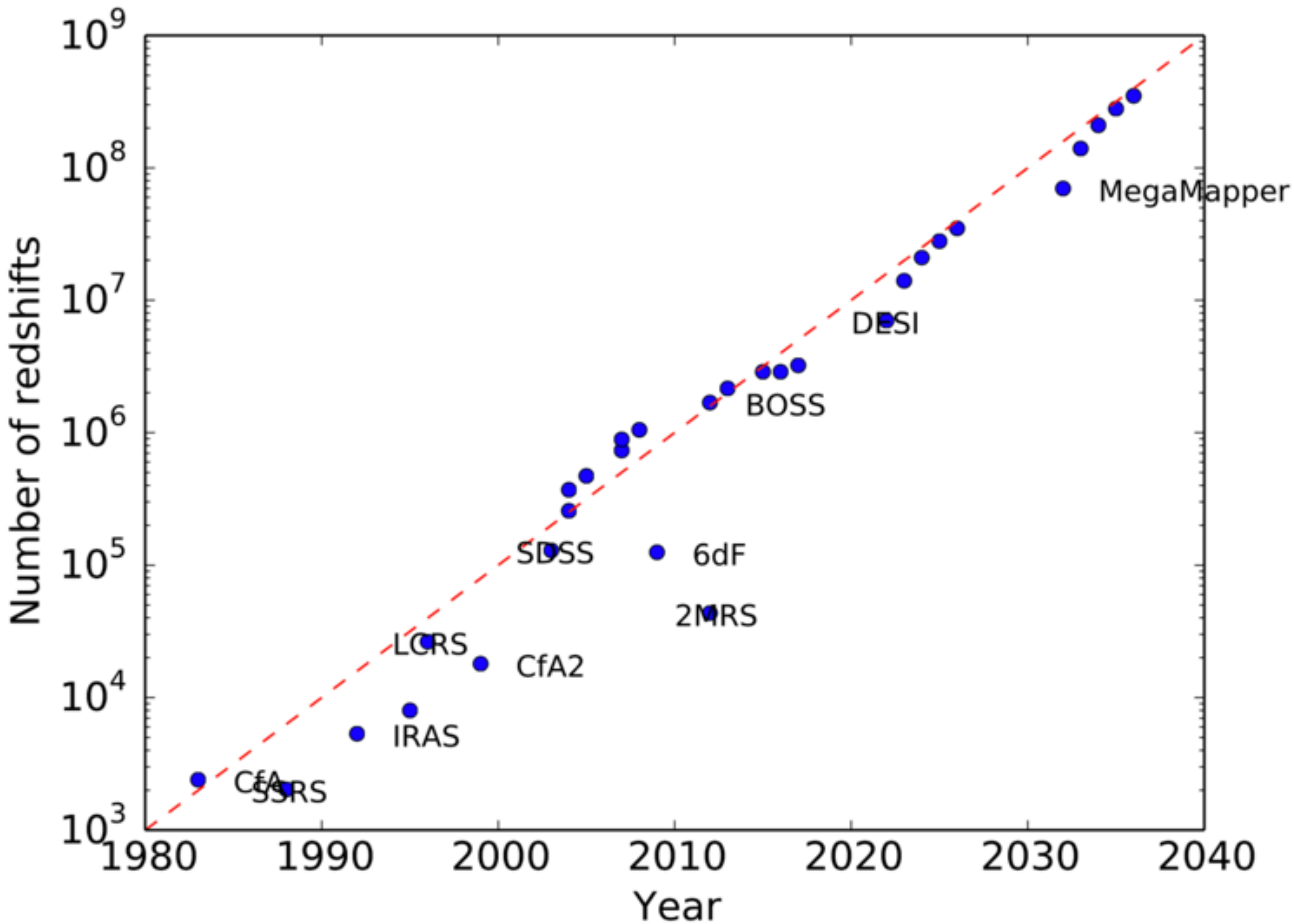
Institution: Observatories of the Carnegie Institution of Washington
Email: jak@carnegiescience.edu

Proposing team:

Greg Aldering[1], Stephen Bailey[1], Charles Baltay[31], Christopher Bebek[1], Segev BenZvi[30], Robert Besuner[3], Guillermo Blanc[2], Adam S. Bolton[20], Mohamed Bouri[4], David Brooks[24], Elizabeth Buckley-Geer[29], Zheng Cai[5], Jeffrey Crane[2], Arjun Dey[20], Peter Doel[24], Xiaohui Fan[6], Simone Ferraro[1], Andreu Font-Ribera[24], Gaston Gutierrez[29], Julien Guy[1], Henry Heetderks[3], Dragan Huterer[11], Leopoldo Infante[2], Patrick Jelinsky[3], Matthew Johns[2], Dionysios Karagiannis[7], Stephen M. Kent[29], Alex G. Kim[1], Jean-Paul Kneib[8], Luzius Kronig[8], Nick Konidaris[2], Ofer

MegaMapper



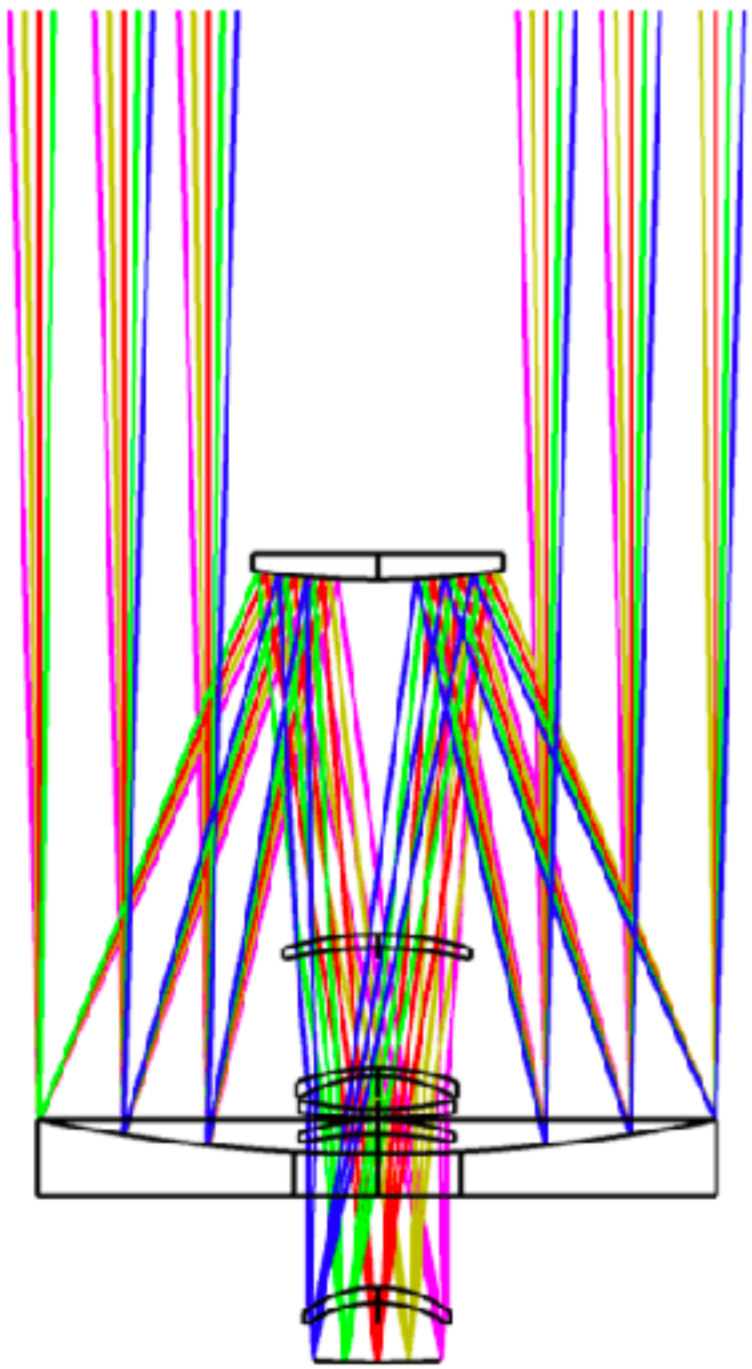
Number of redshifts
Year
10^3
10^4
10^5
10^6
10^7
10^8
10^9
1980
1990
2000
2010
2020
2030
2040
CfA
SSRS
IRAS
LCRS
CfA2
SDSS
6dF
2MRS
BOSS
DESI
MegaMapper

MegaMapper

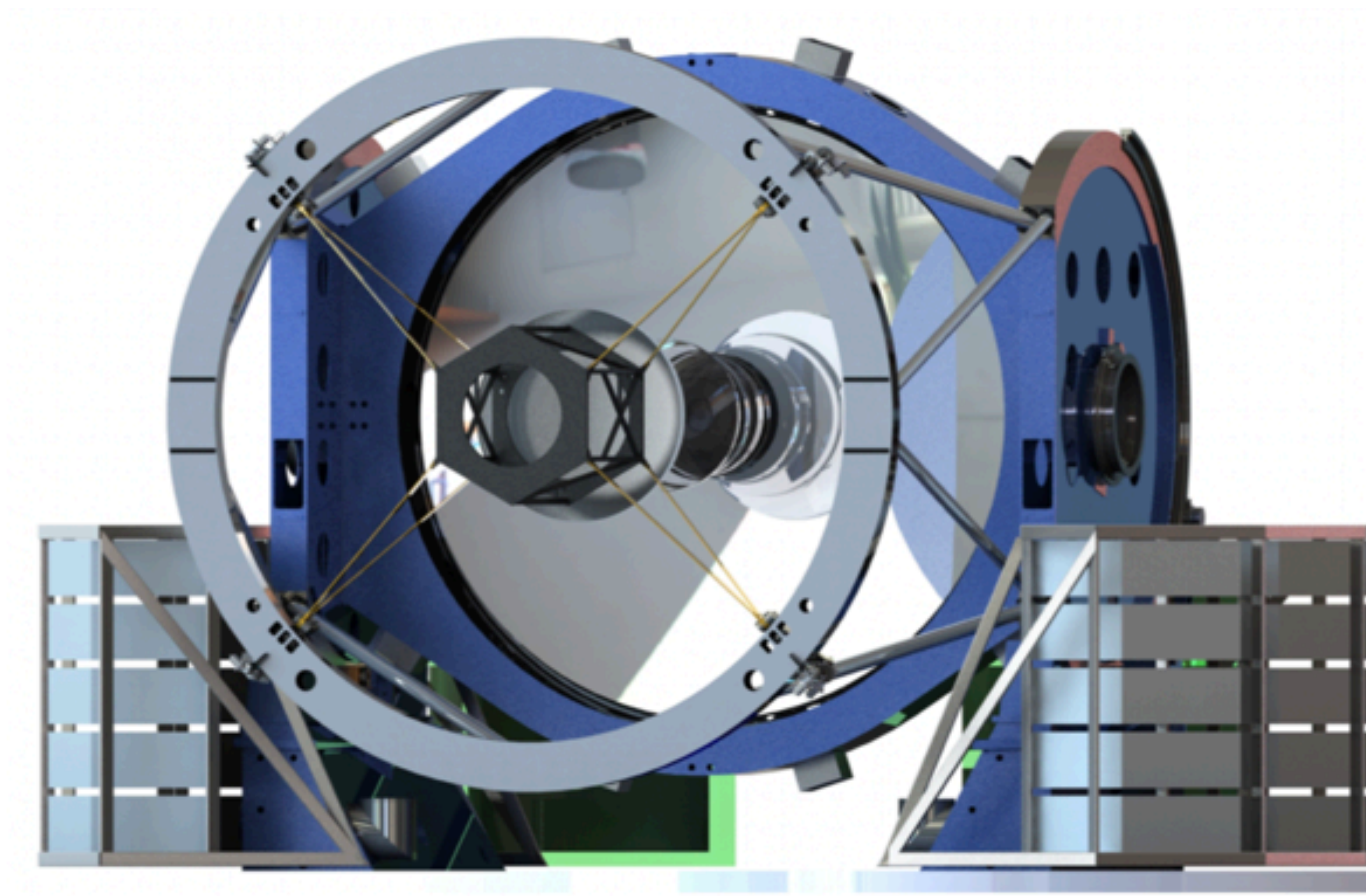
- 6.5m telescope (2 Magellan blank mirror unused)
- Wide field corrector
- 20'000 fiber robots
- ~32 spectrographs if reusing DESI concept (16 exist)

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**	$\mathbf{0.9^2}$	**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



Component	Cost ($M)	Basis of estimate
Telescope facility	70	Magellan 1 & 2
Secondary	10	Vendor ROM
Corrector	20	DESI
Focal plane	10	DESI
Fibers	5	DESI
Spectrographs	24	DESI and SDSS-V
Total	139	



Hollow Shaft Motor R&D

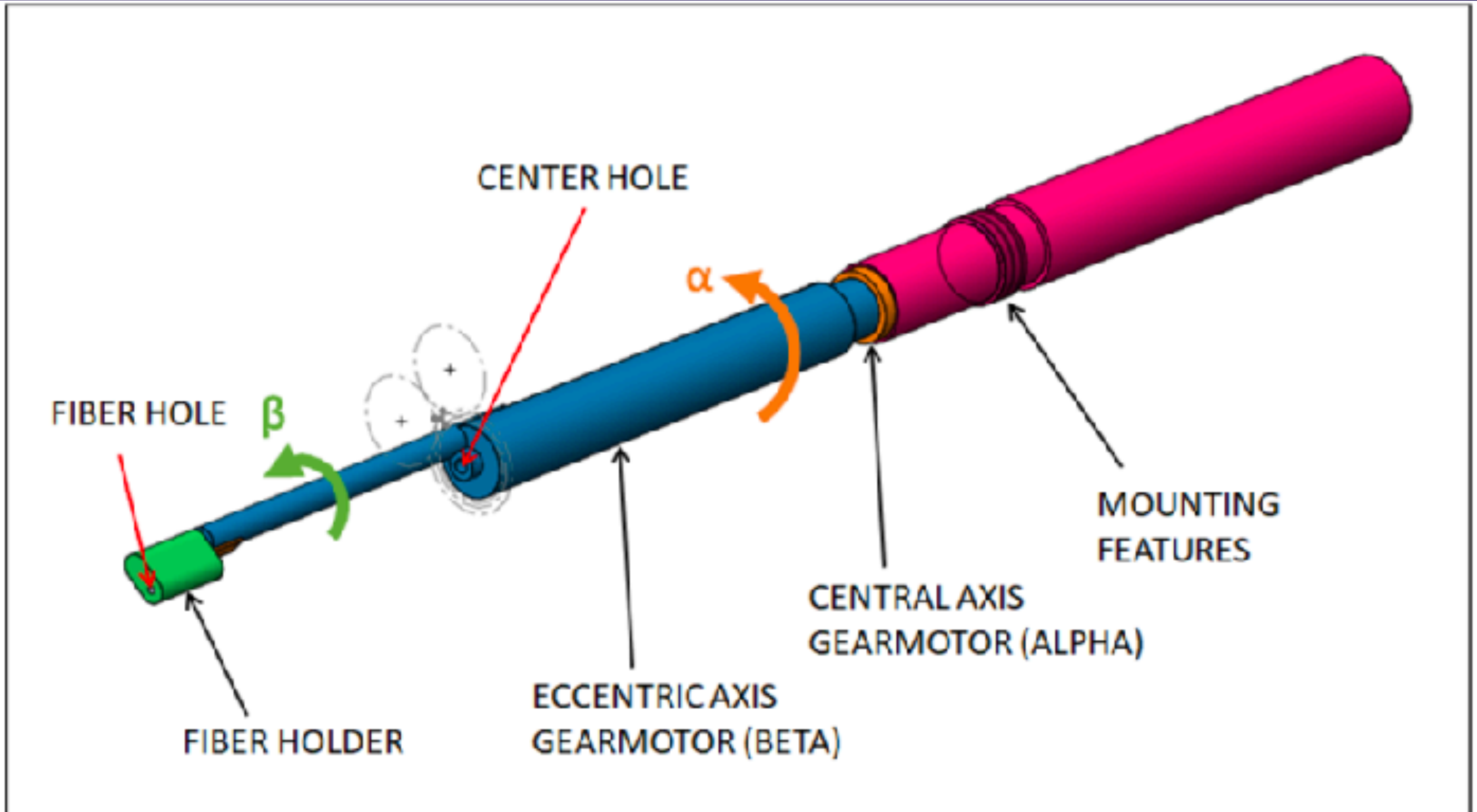
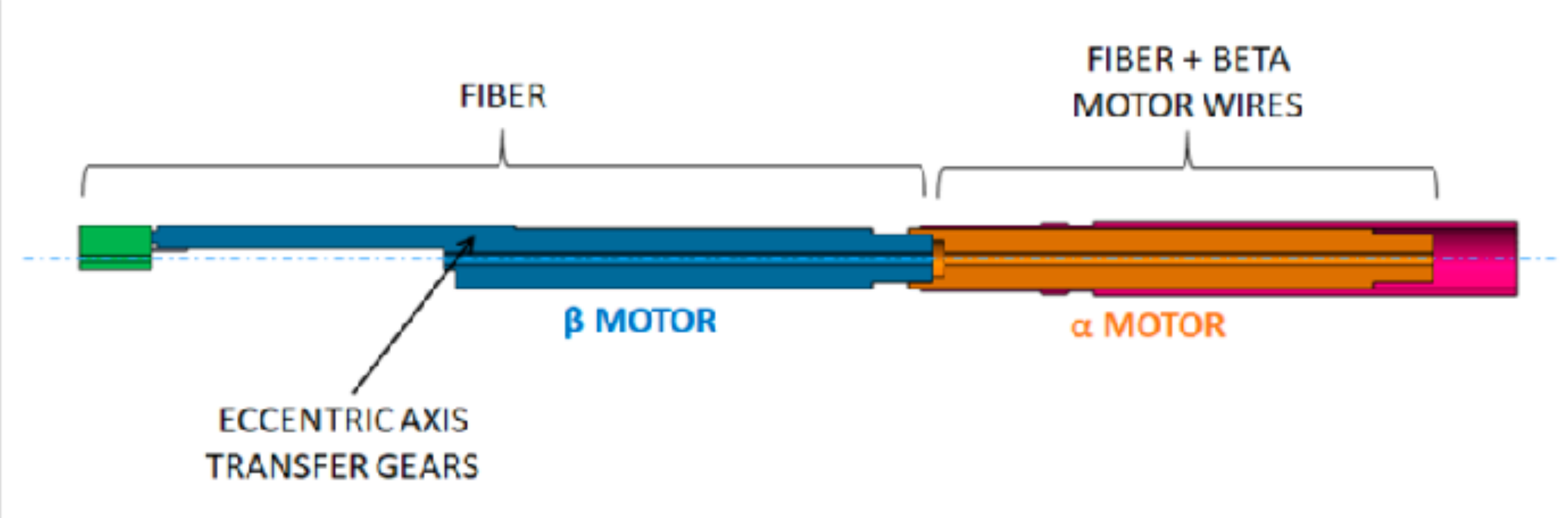


Fig 1. Cartoon of our concept for the overall robot, showing ALPHA and BETA motors.

- Goal 6mm diameter
- 20’000 robots for megamapper



Massive Spectroscopy Sum-up

- *Current massive optical/near-infrared spectroscopy projects charting up to z~3.5 to be completed in 2026-28 !*
- Other projects in discussion, but should we have to wait beyond 2032 (e.g. LOT, MSE, LSSTspec, SpecTel) ?
- *SKA-1 wide field radio survey will bring a new avenue in massive spectroscopic surveys: HI galaxies with interest in particular at higher redshift $1.5<z<4$*
- *Other route - MEGAMAPPER ?*

THANKS !