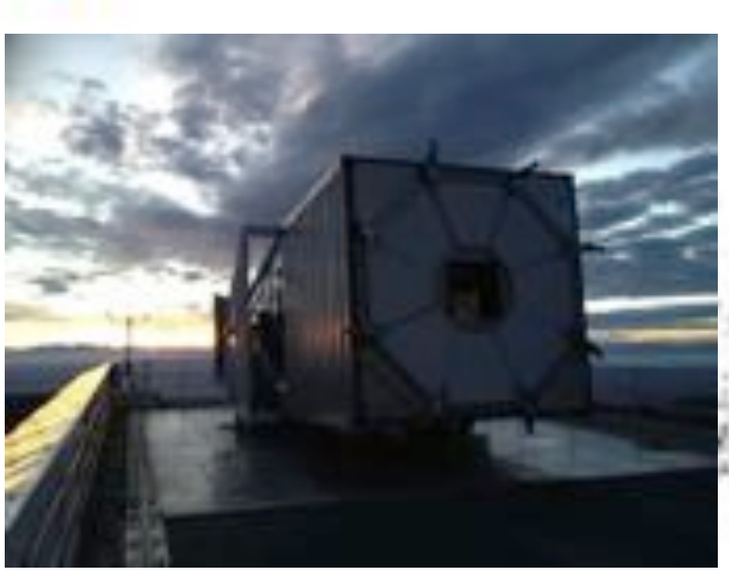
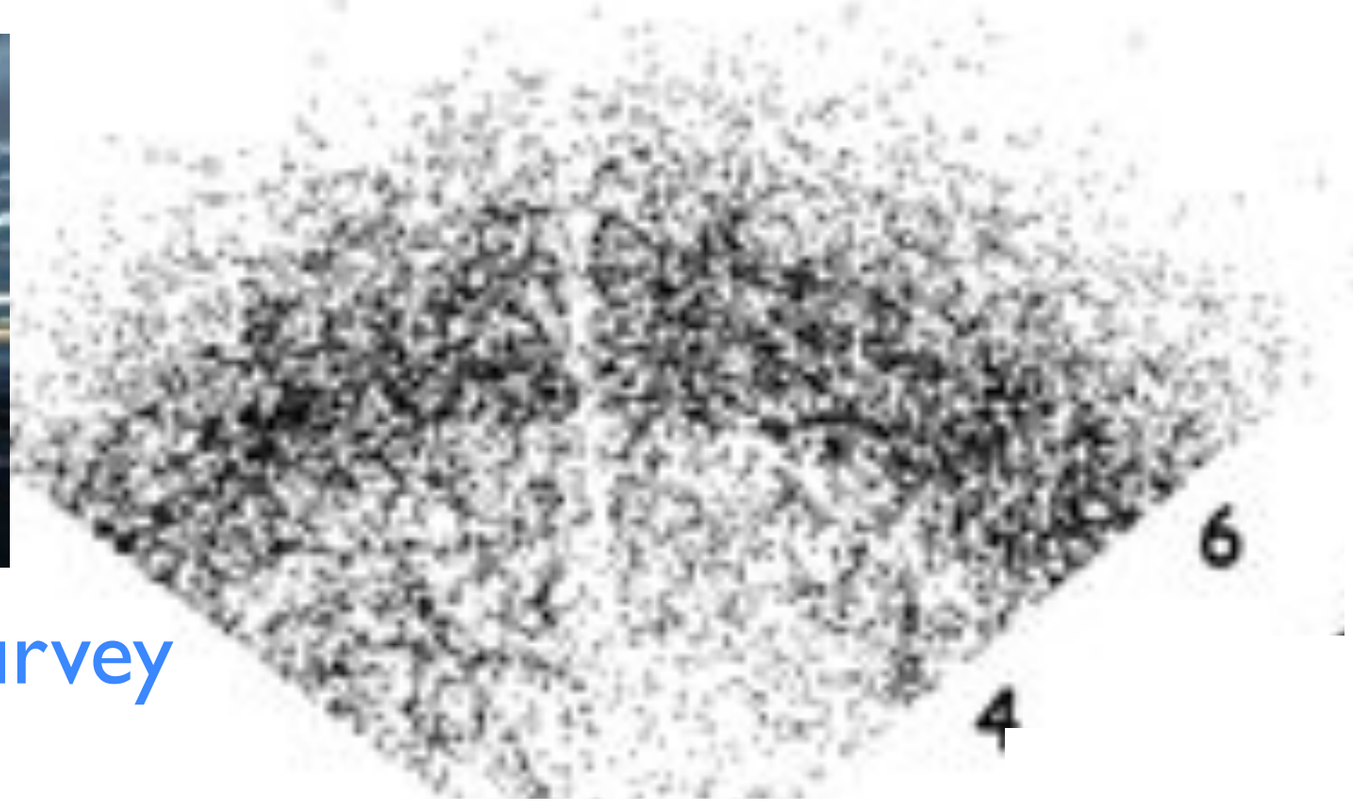
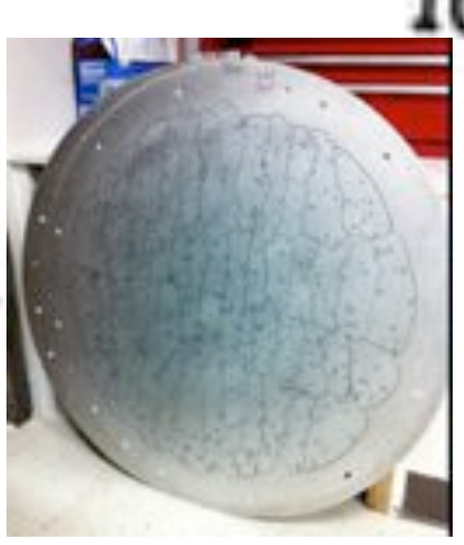
Cosmology
at the % level or better
with redshift surveys







twitter: @eBOSSurvey

Jean-Paul Kneib, *Kyle Dawson, Will Percival, David Schlegel*
and the eBOSS & DESI team

Graphic: Anze Slozar

Outline

- A bit of History & Motivation
- Recent BOSS results
- eBOSS
- the future: DESI (but also PFS, 4MOST, Euclid)
- Conclusion

Edwin Hubble (1929):
first measurement of the expansion of the Universe

Annie Hall (1977):

- He's been depressed

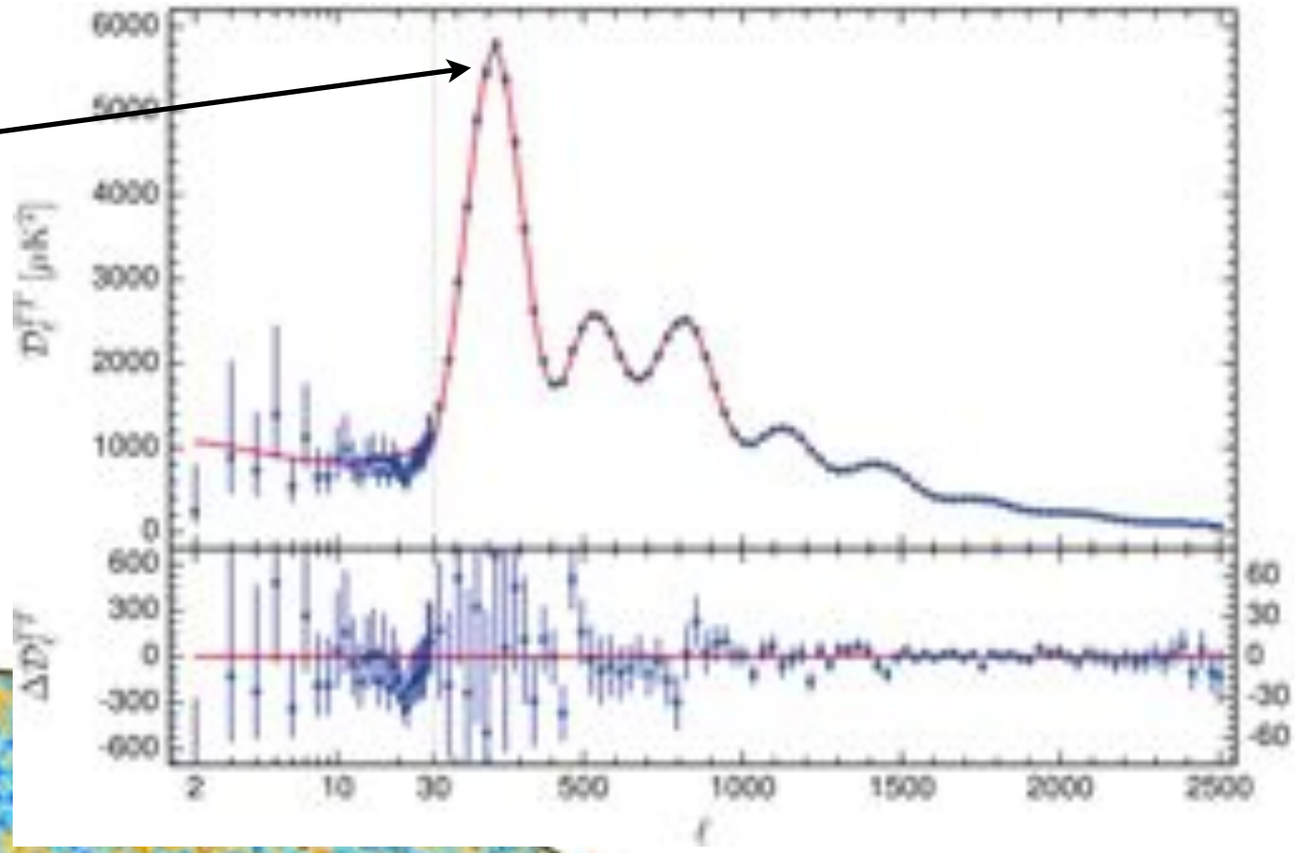
- The Universe is expanding, the Universe is everything. What is the point?

- You here in Brooklyn, Brooklyn is not expanding!

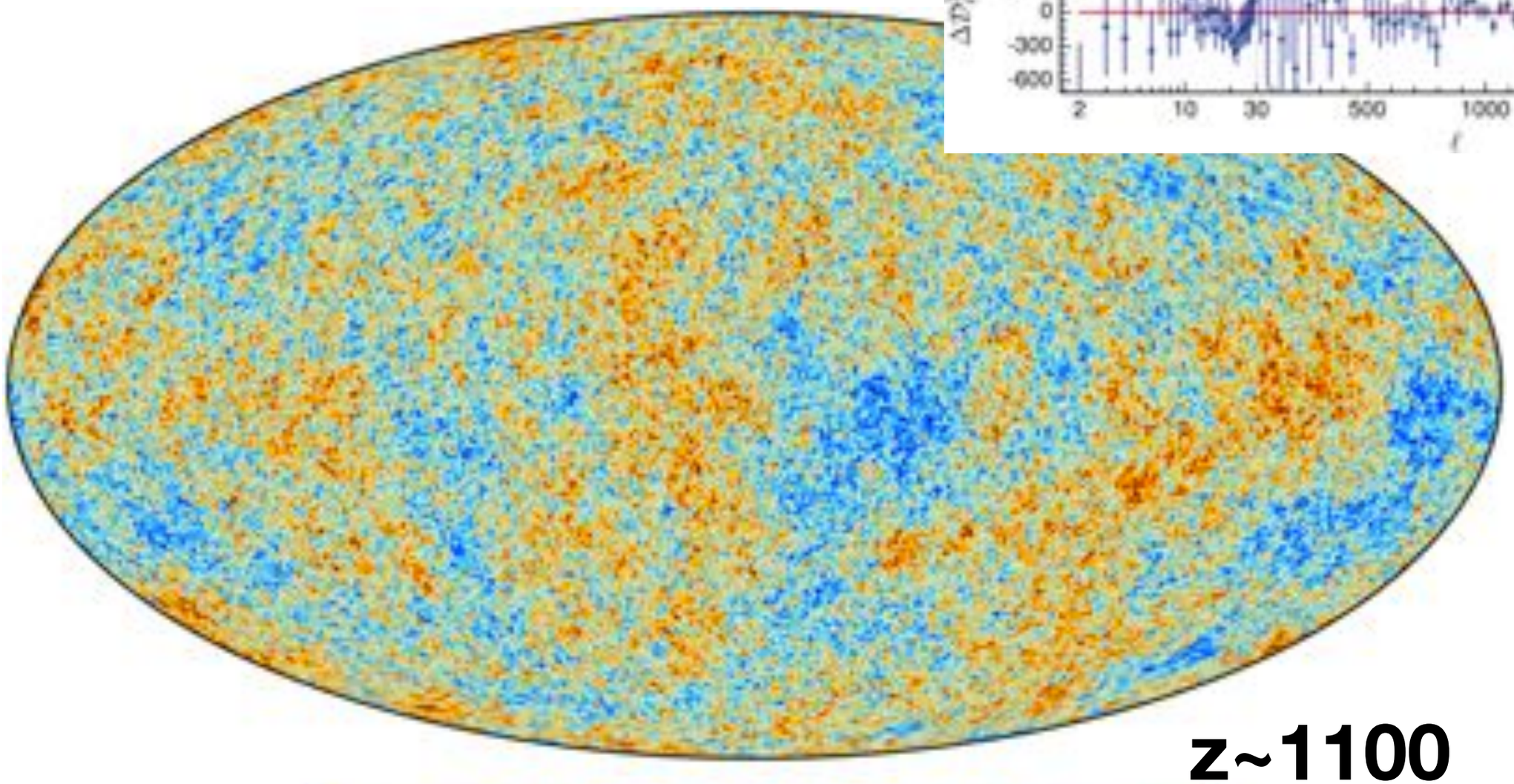
Nobel Prize of Physics (2011):

The **expansion** of the Universe **is accelerating** confirmed by the study of distant type Ia SuperNovae

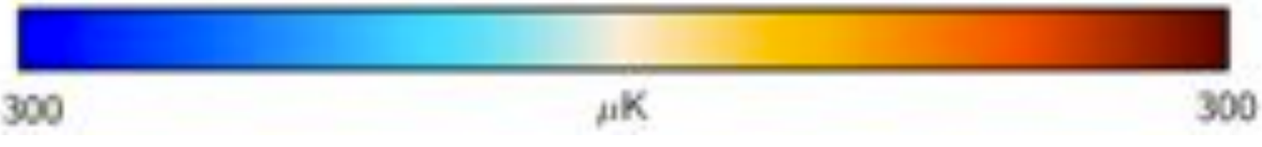
Planck results (latest Feb 5, 2015)
Baryonic Acoustic Oscillation
scale measured to 0.1% at z=1000



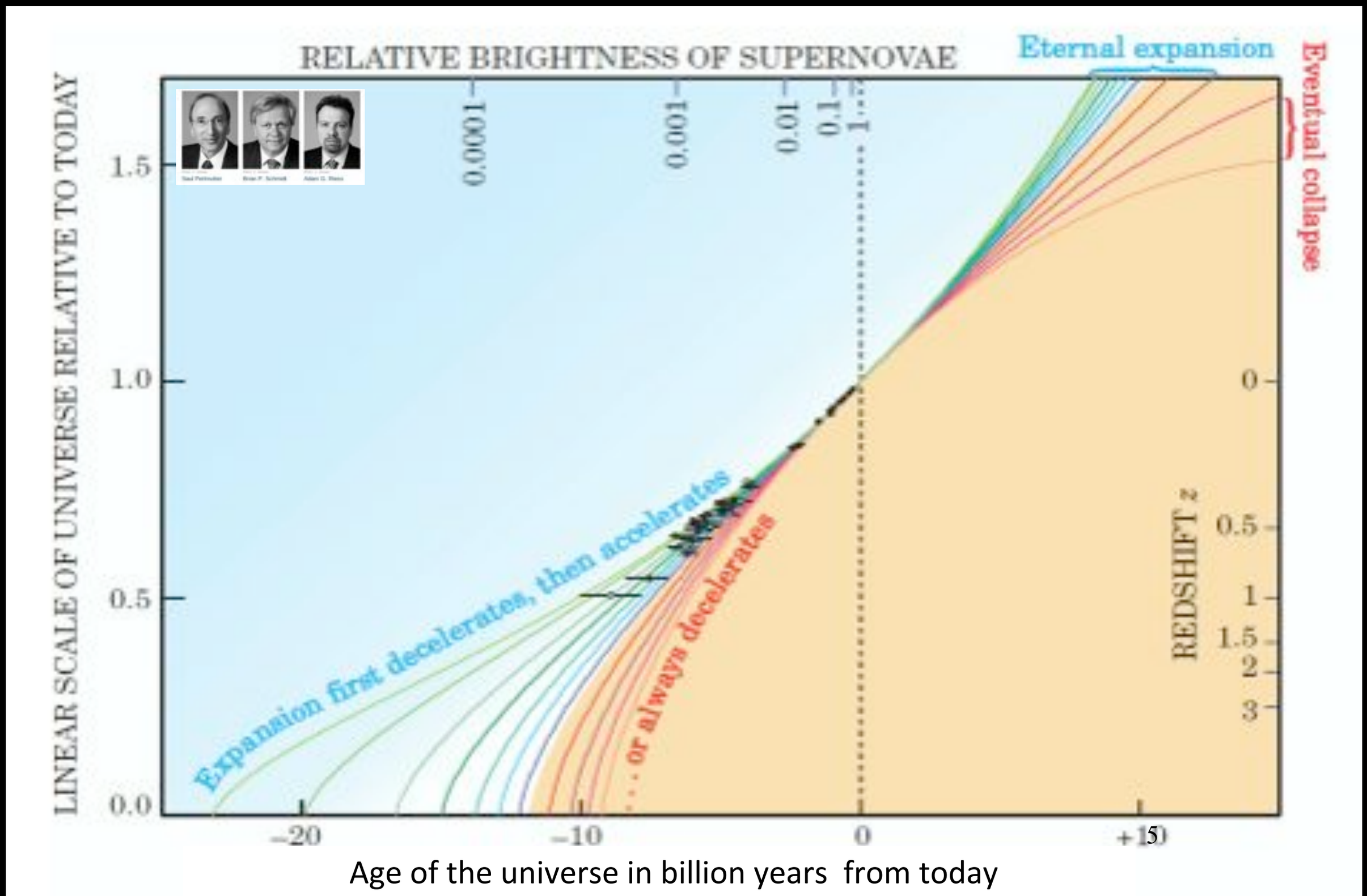
Planck CMB map



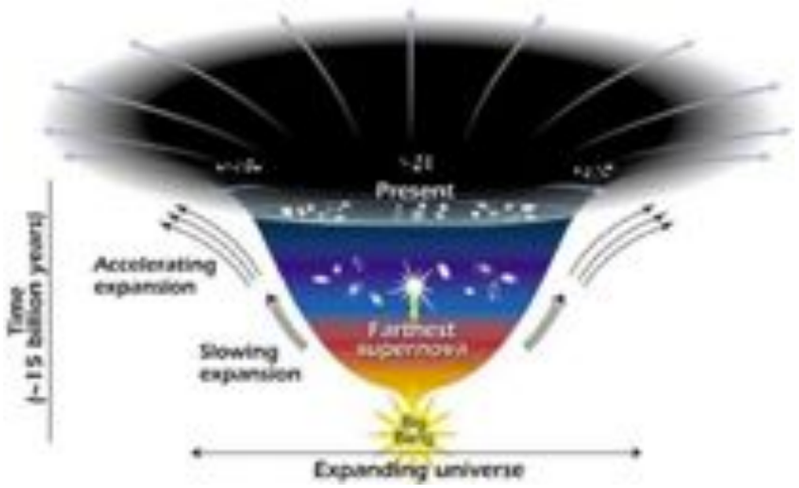
z~1100

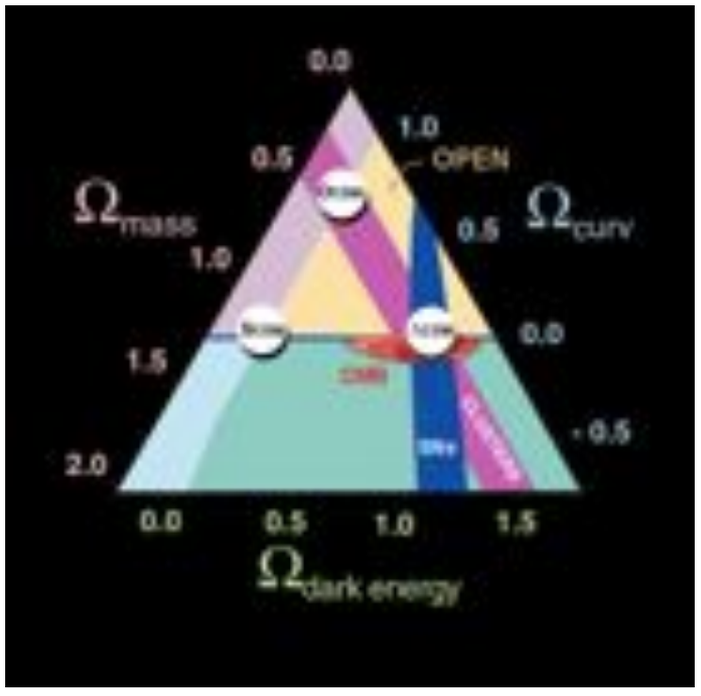


Universe expansion is **accelerating**!



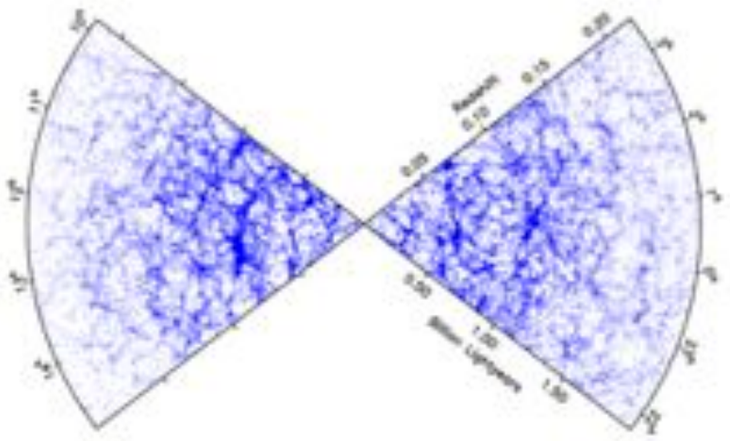
Understanding the accelerated expansion of the Universe

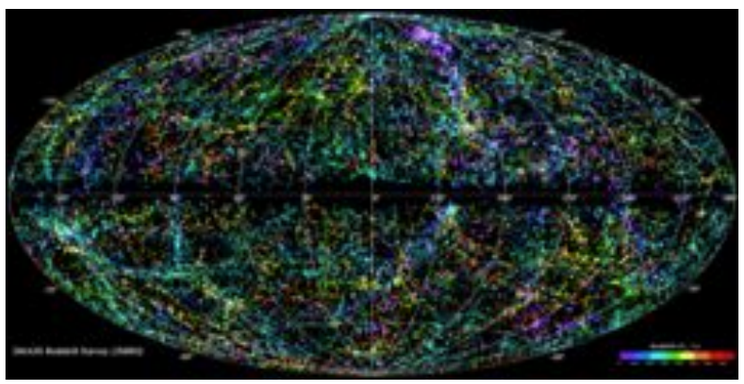


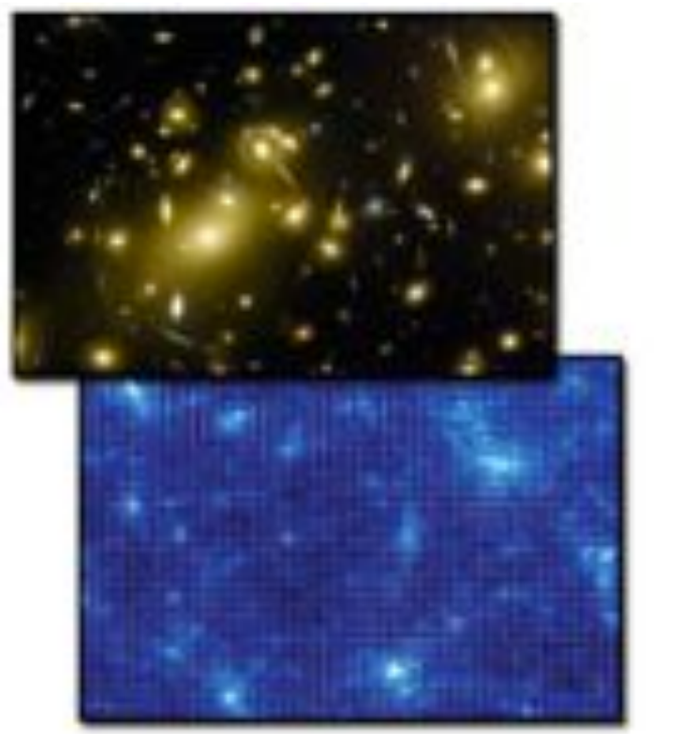


- **Origin of the accelerated expansion?** (many theories)
  - **Dark Energy** ? a new unknown component (probe its nature: eq. of state)
  - **Modified Gravity** ? correction of General Relativity on large scales
  - **Fractal Geometry/Scale Relativity??**
- **No good/simple/unique theory:** solve this with new observations => **precision cosmology: % level or better**

Understanding the accelerated expansion of the Universe



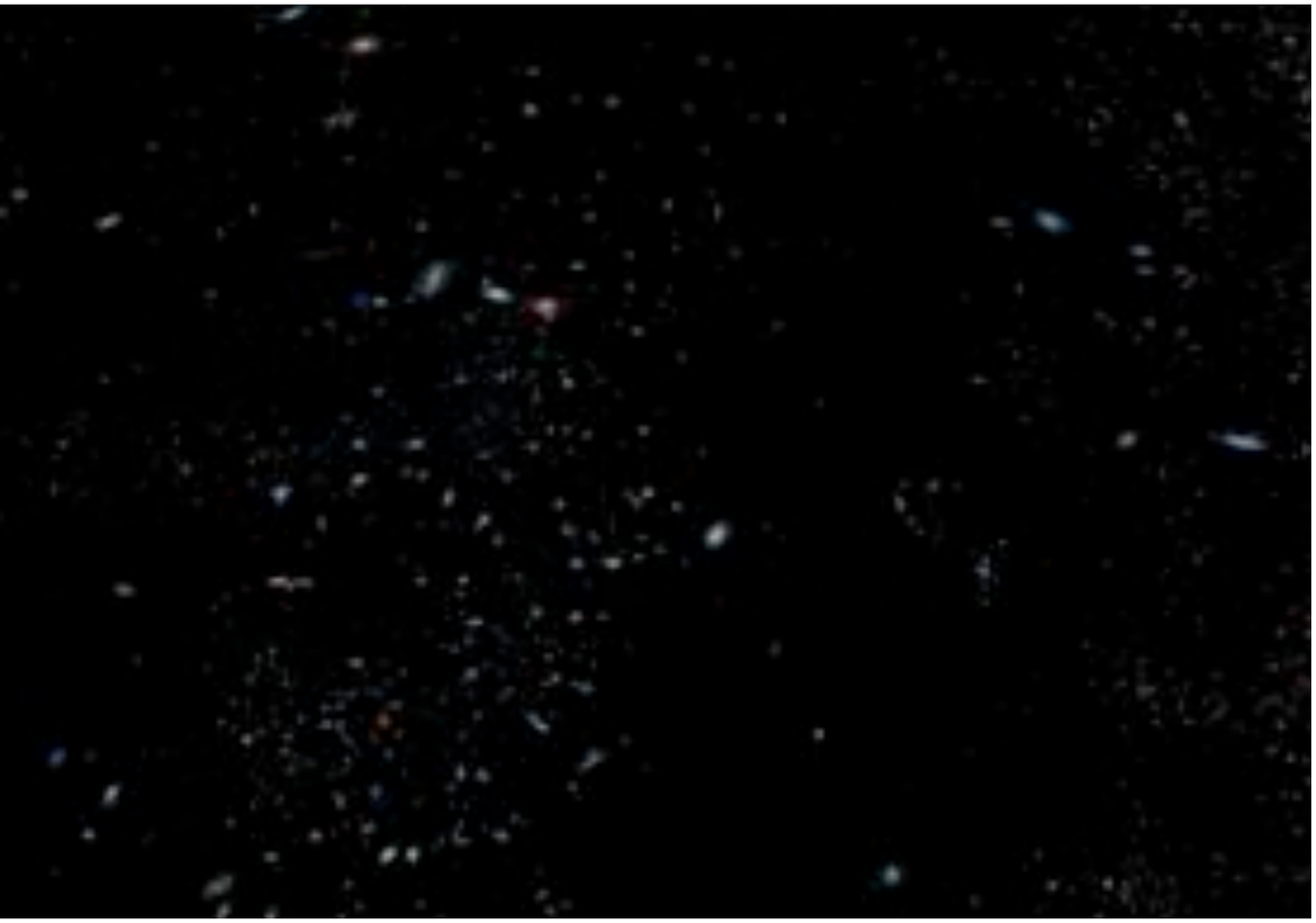




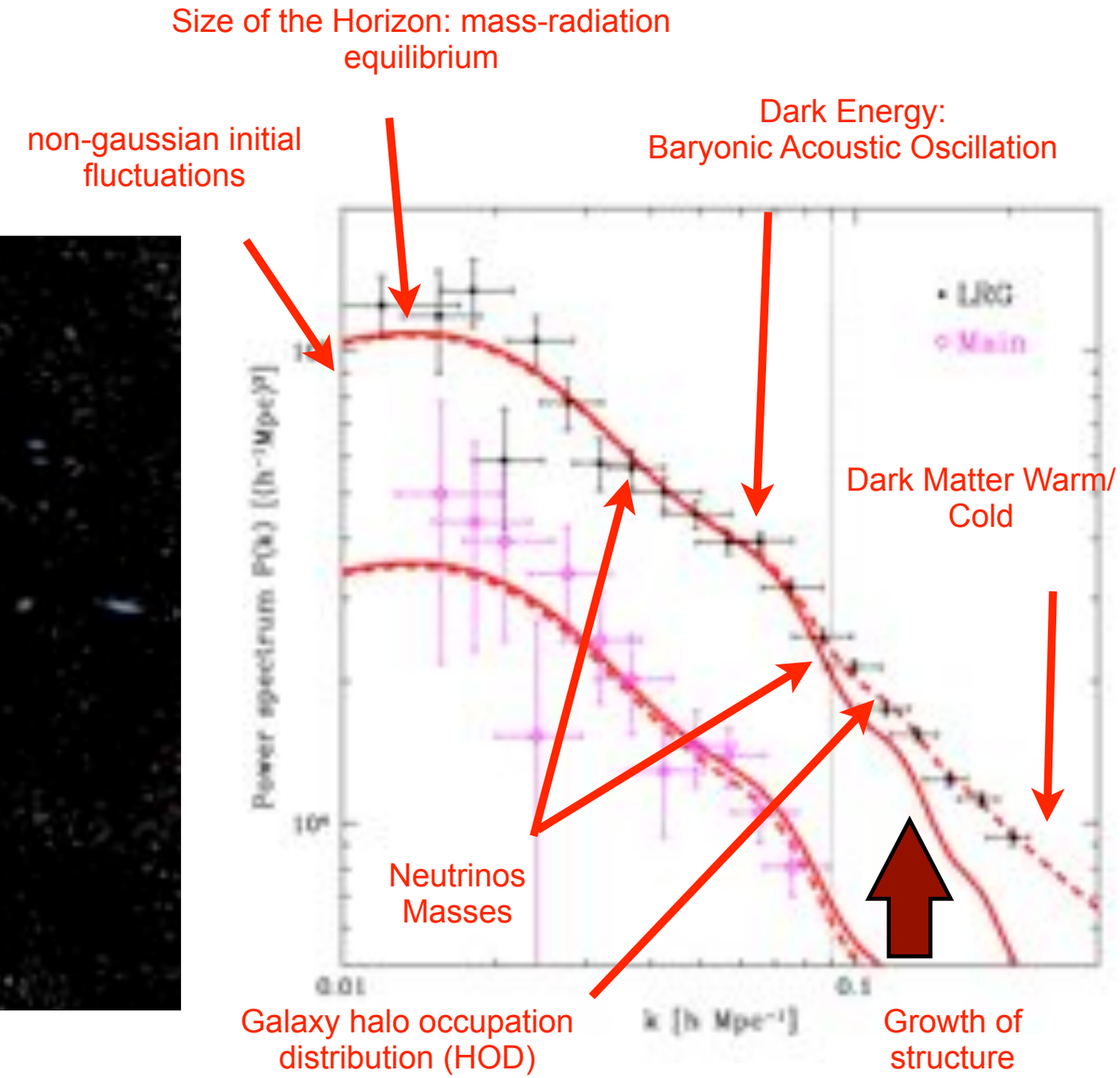
- **New powerful probes of the Cosmic Web Universe**
  - Massive *galaxy redshift surveys* using: **Baryonic Acoustic Oscillations** (BAO) & **Redshift Space Distorsion** => 3D Galaxy map
  - **Gravitational weak lensing** surveys (WL) => DM map

Galaxy Power Spectrum

3D mapping of the position of galaxies

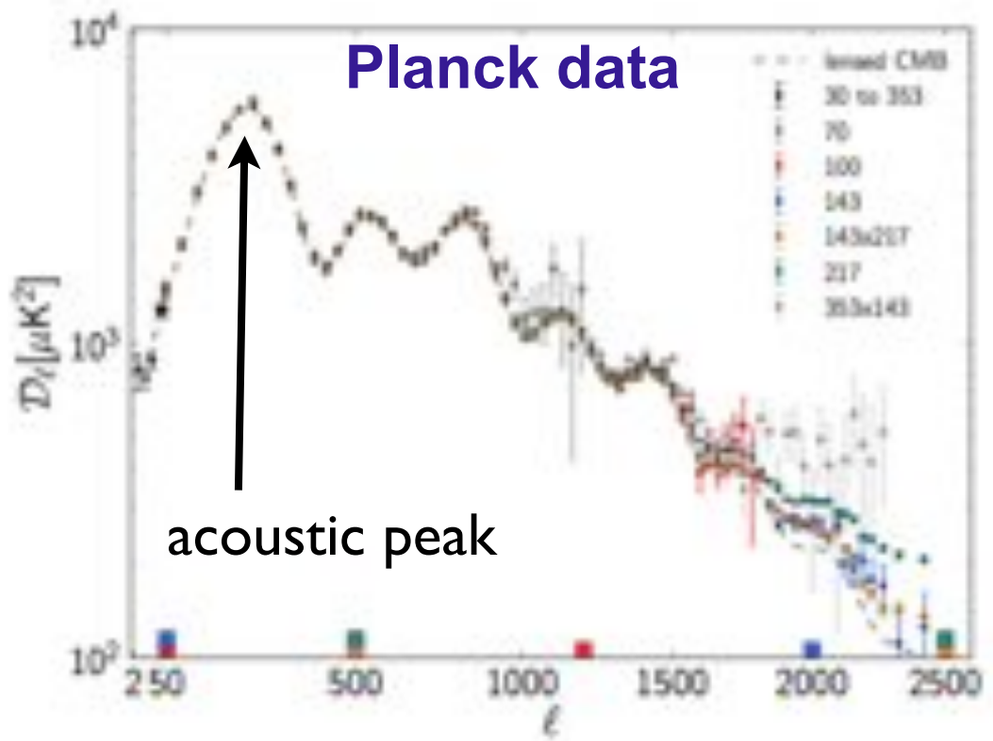


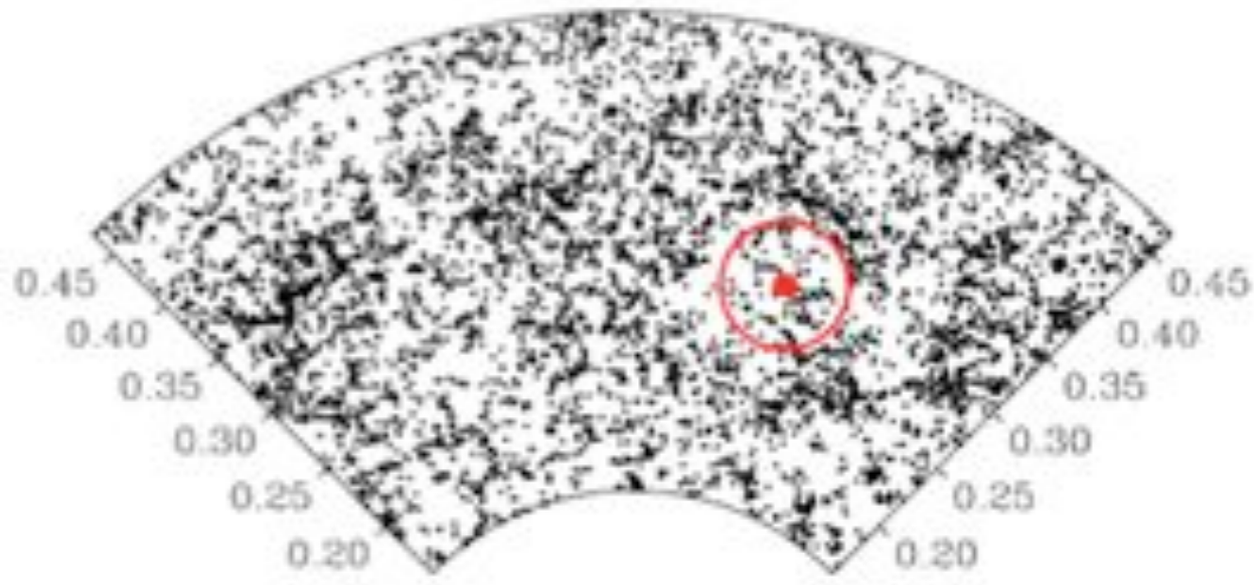
Distribution of galaxies (SDSS)

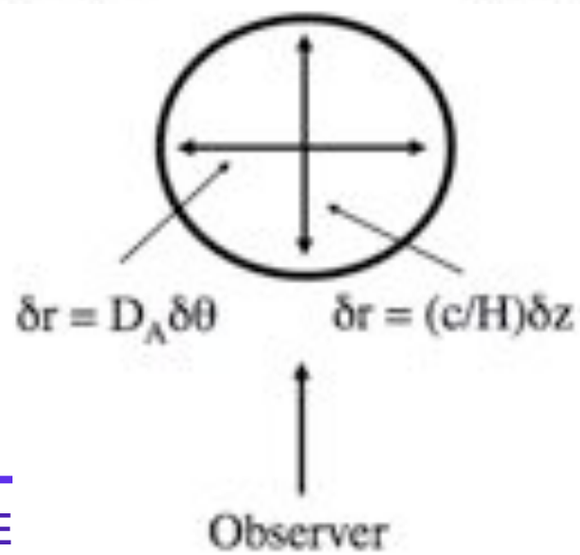


Baryonic Acoustic Oscillation

- Early Universe: each overdensity is an overpressure that launches a spherical sound wave
- Seen in the CMB (z~1100)
- Sound waves freezed at ~150 Mpc at recombination
- Seed galaxy formation with a preferred separation at BAO scale (local overdensity)
- **BAO measurement yields H(z) and $D_A(z)$ relation**

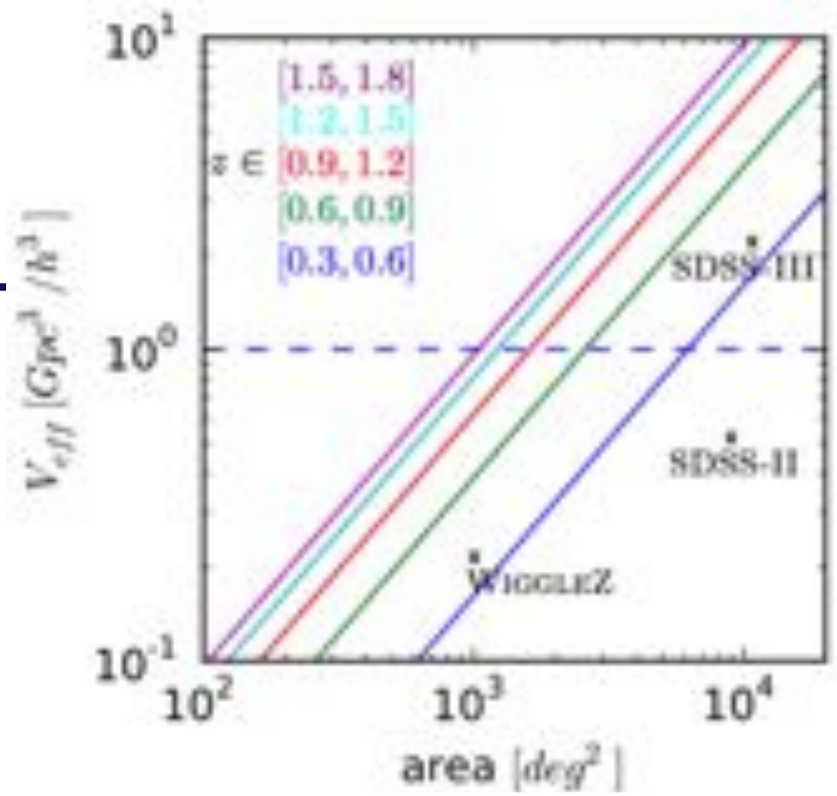






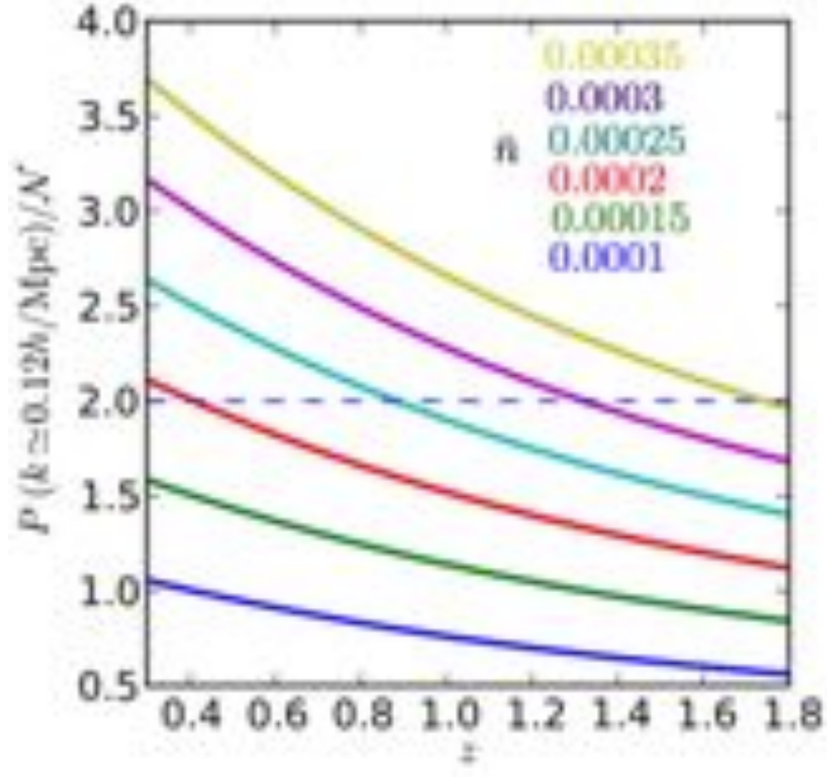
BAO survey strategy

- BAO scale is big! <u>degrees scale</u> => **very wide field survey** (ultimately as much sky as possible)
- Number density of tracers should increase with redshift to keep shot noise small (also helps for reconstruction)
- High bias tracers are more valuable (red galaxies)
- **Aim to measure BAO [distance-redshift] for various redshift bins - to probe Universe expansion**



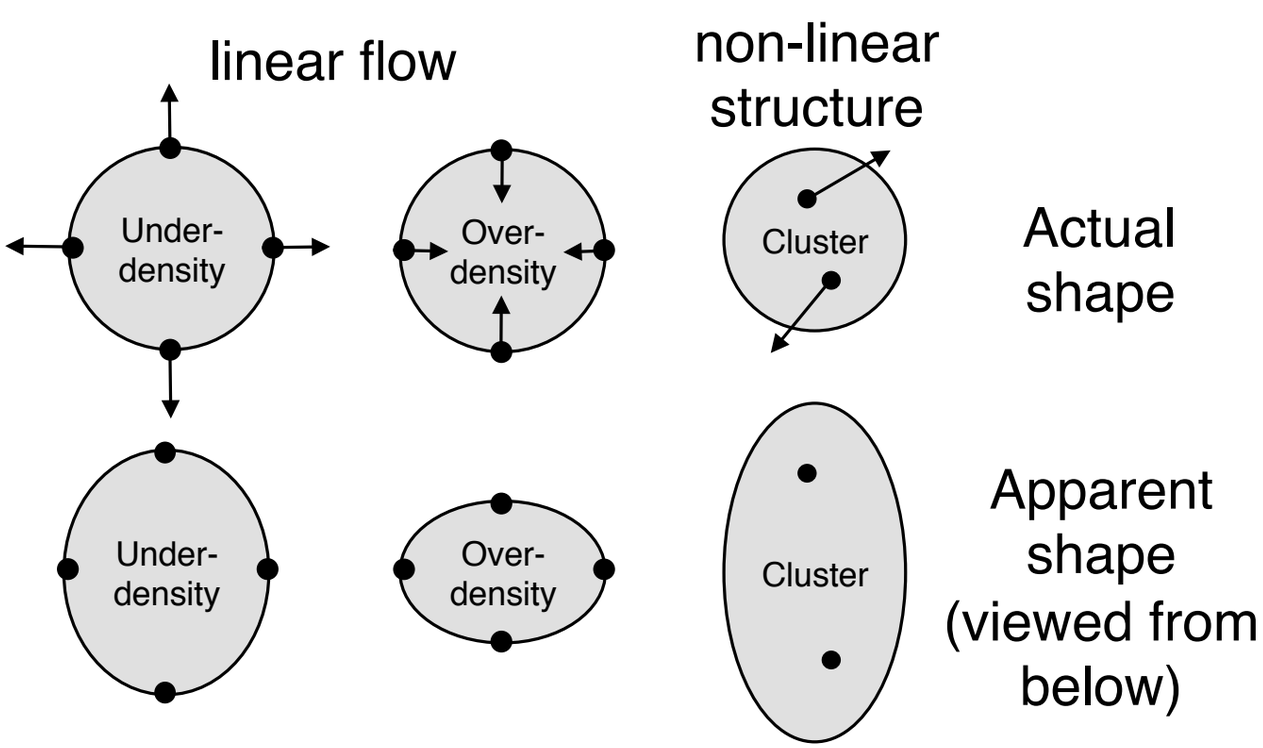
~5% BAO

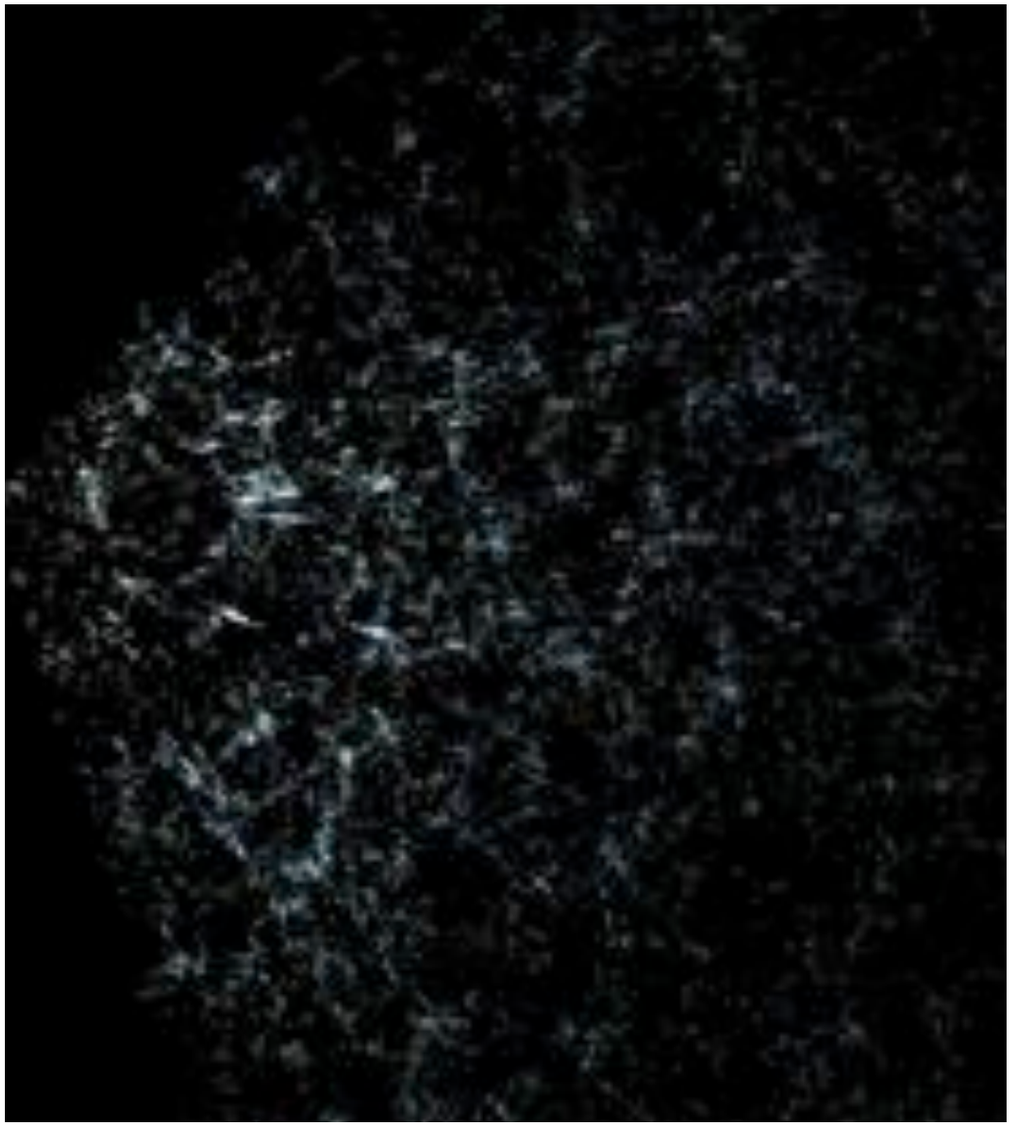
Large survey area to beat cosmic variance, and lead to accurate measurement



A high number density of sources is required to beat shot noise statistics

Redshift-Space Distortions





- Observed redshift depends on both Hubble expansion and additional "peculiar velocity"
- Galaxies move with structure growth
- extra clustering depends on amplitude of peculiar velocities

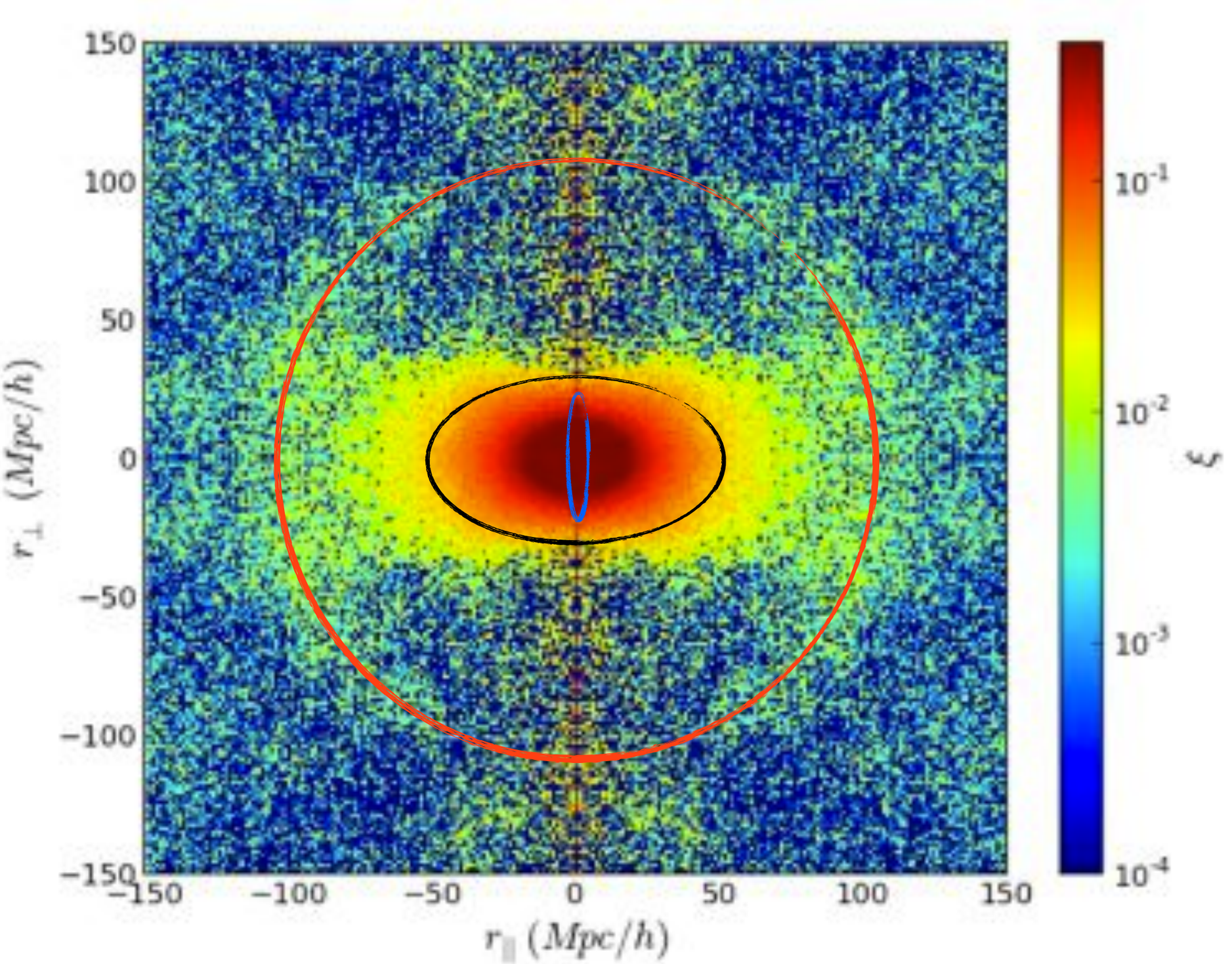
$$f(z)\sigma_8(z) \propto \frac{dG}{d\log a}$$

- where G is the linear growth rate

RSD measurements

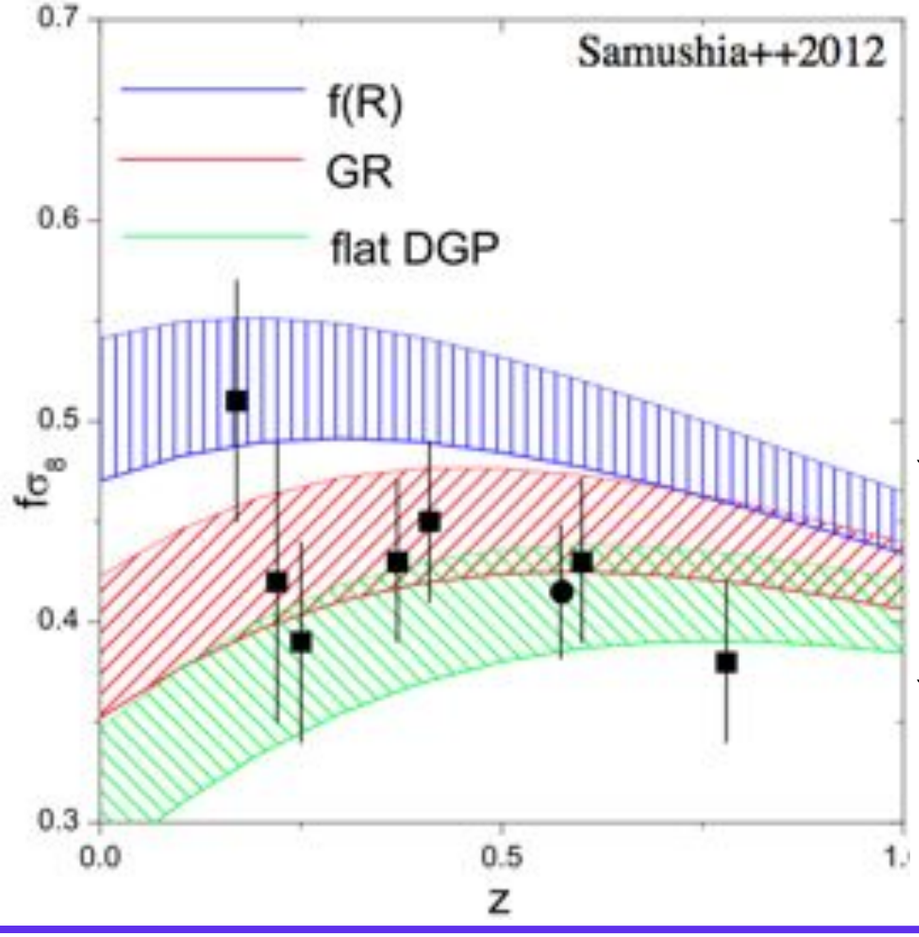
2D correlation function: parallel & perpendicular to the plane of the sky.

How much the 2D correlation is squeezed is a measure of RSD at a given z.

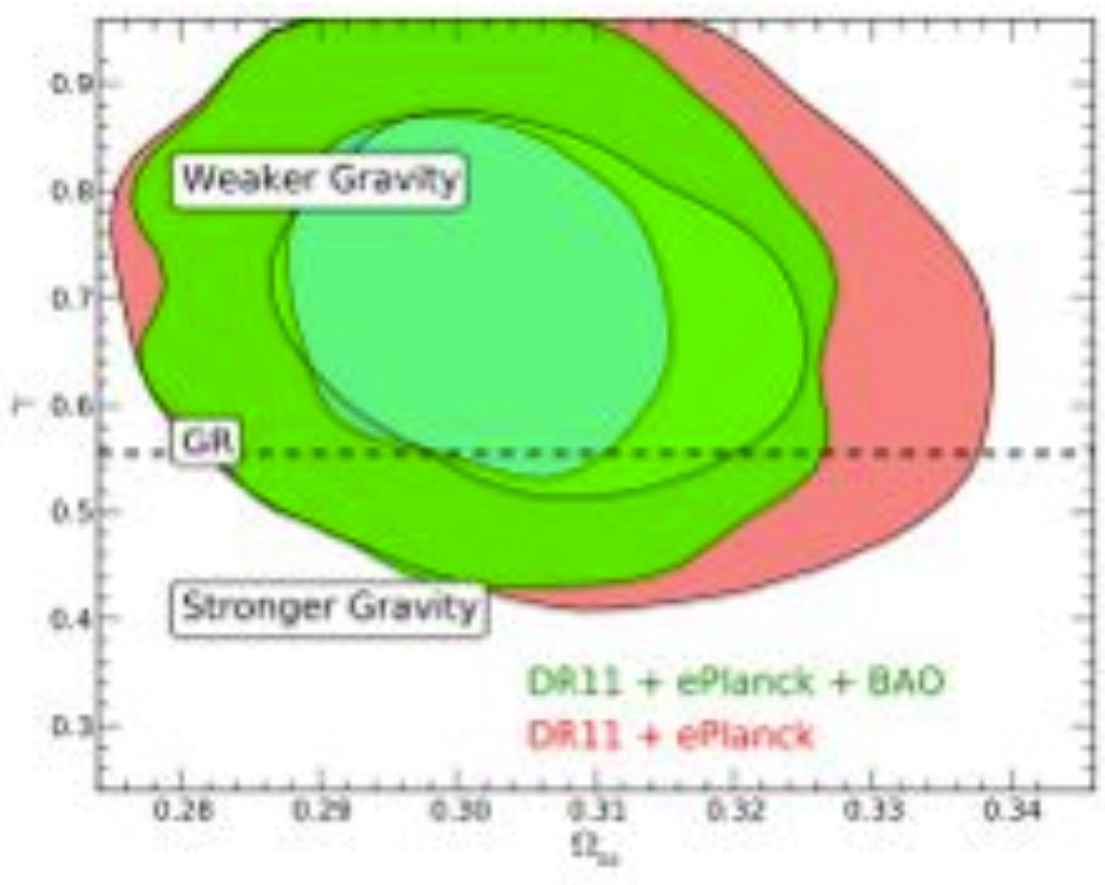


RSD constraints

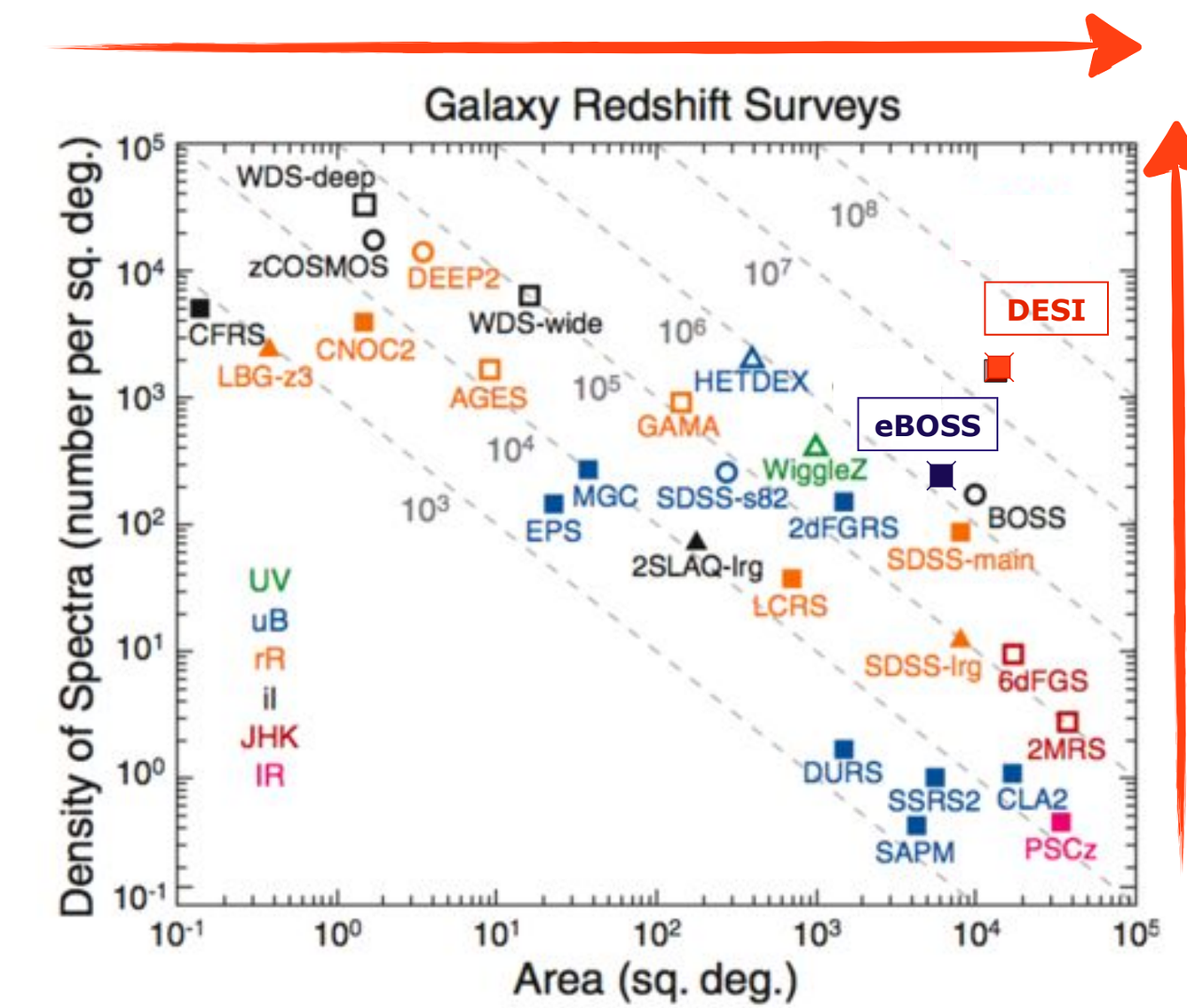
- Now measured with 6% precission simultaneously with geometry (assuming Planck, Samushia et al. 2014)
- Anisotropic clustering allows huge improvement on w!
- Provides a number of GR tests (BOSS consistent with GR).



Samushia et al. 2013; MNRAS 429, 1514

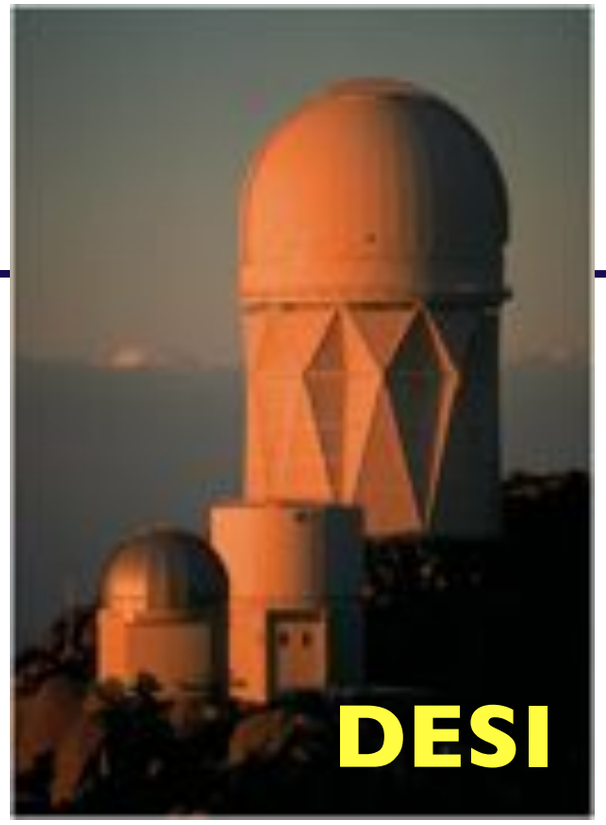


Massive galaxy redshift surveys



- **Hubble (1930):** expanding Universe
- **CfA Redshift Survey (1985):** first large scale structures (wall, filaments)
- **2dF (~2000):** 1500 sqdeg
- **SDSS (~2002):** 5700 sqdeg
- **VVDS/DEEP2 (~2004):** deep Universe ~1 sqdeg
- **WiggleZ (2011)**: 800 sqdeg (BAO)
- **SDSS-III/BOSS (2014)**: 10,000 sqdeg BAO/LSS (BAO)
- **e-BOSS (2014-2020):** BAO/LSS: 7,500 sqdeg w/ LRG+QSO & 1,500 sqdeg of ELGs (BAO)
- **DESI** (2019) Optical Telescope
- **Euclid** (2020) Space mission
- **SKA** (2025) Radio Telescope

Understanding the accelerated expansion of the Universe



- **Main future projects: Precision cosmology measurements** (below 1% level) => require **Big-Data**
  - **DESI** experiment (**2019**): 35 millions galaxy redshifts (z<1.5)
  - **Euclid** space mission (**2020**): gravitational lensing from space using 1 billion galaxy shapes & ~50 millions galaxy redshift (z>1)
  - **SKA** radio interferometer (**2025**): gravitational lensing & redshift survey

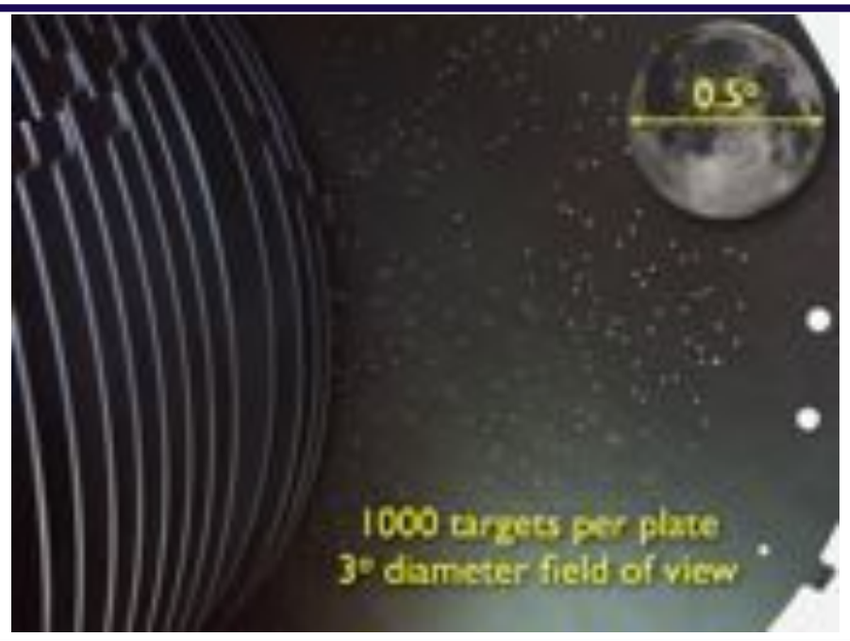
SDSS-III/BOSS
Baryon Oscillation Spectroscopic Survey

Key Project uses most capable BAO instrument in the world

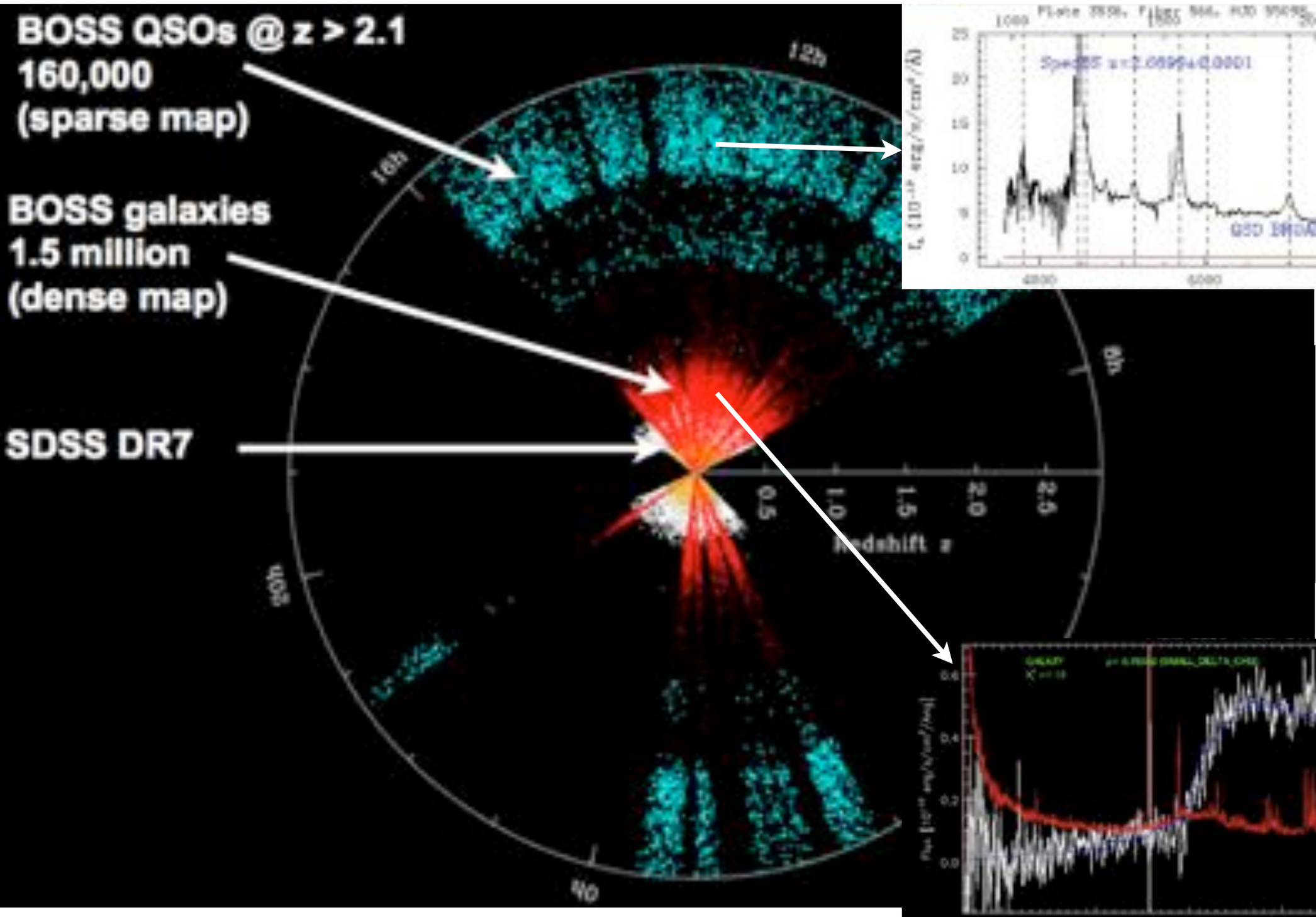
2.5-meter Sloan Telescope
3 degree field-of-view

The Sloan Telescope & BOSS spectrograph

- 90 cm aluminium plate with 1000 holes for fibers,
- 45 min to plug for typical 1 hour observation on sky
- up to 9 plates observed per (good) night
- 1.5 millions redshifts in ~4 years
- The best multiplexing spectroscopic facility still

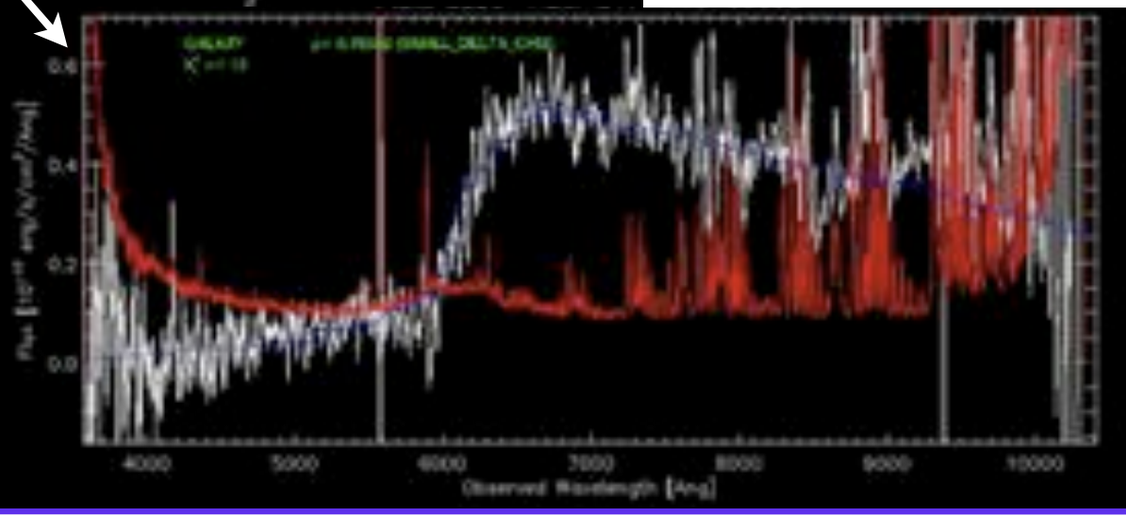


BOSS Main Surveys (2009-2014)

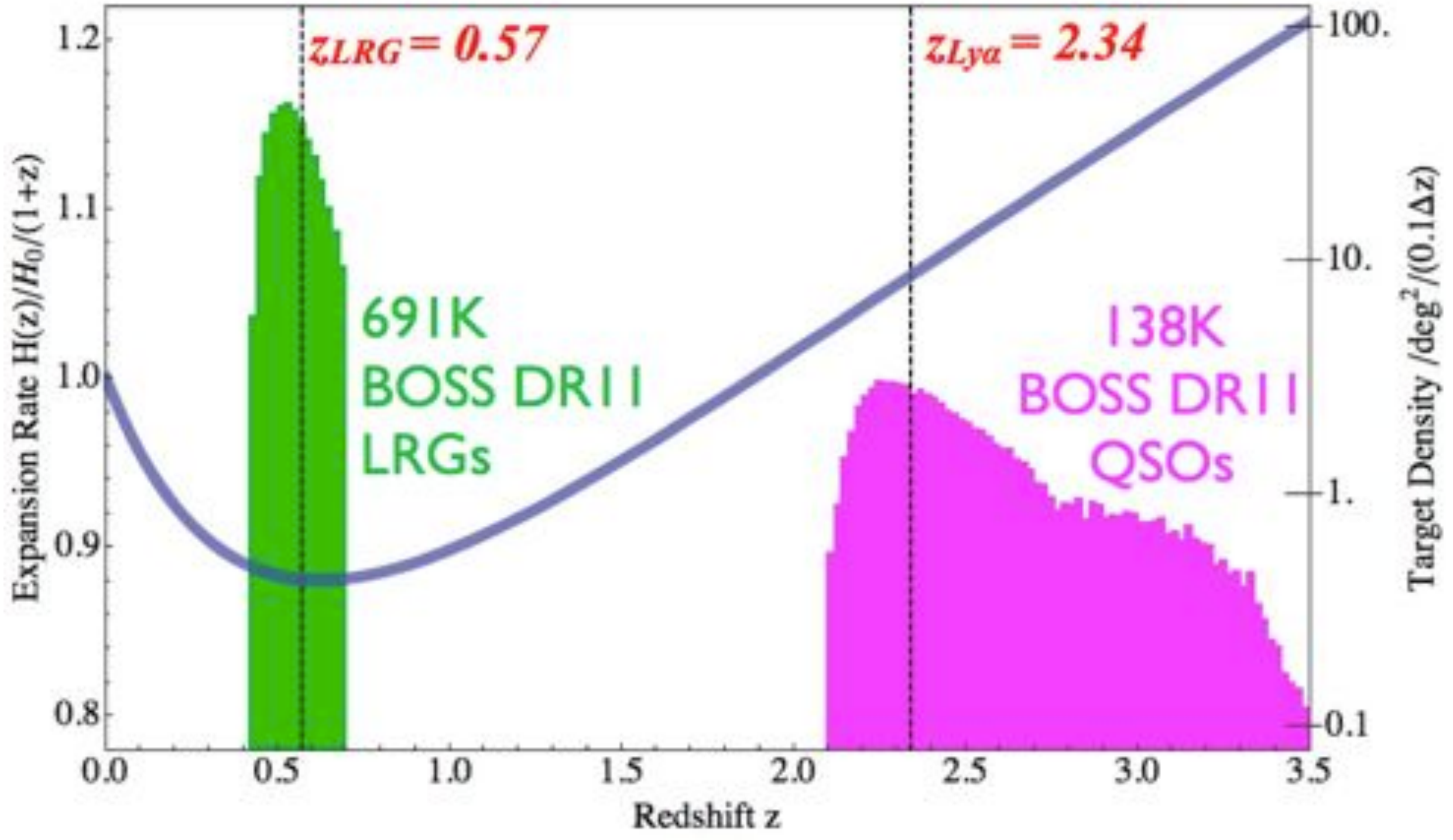


Quasar at z=2.67

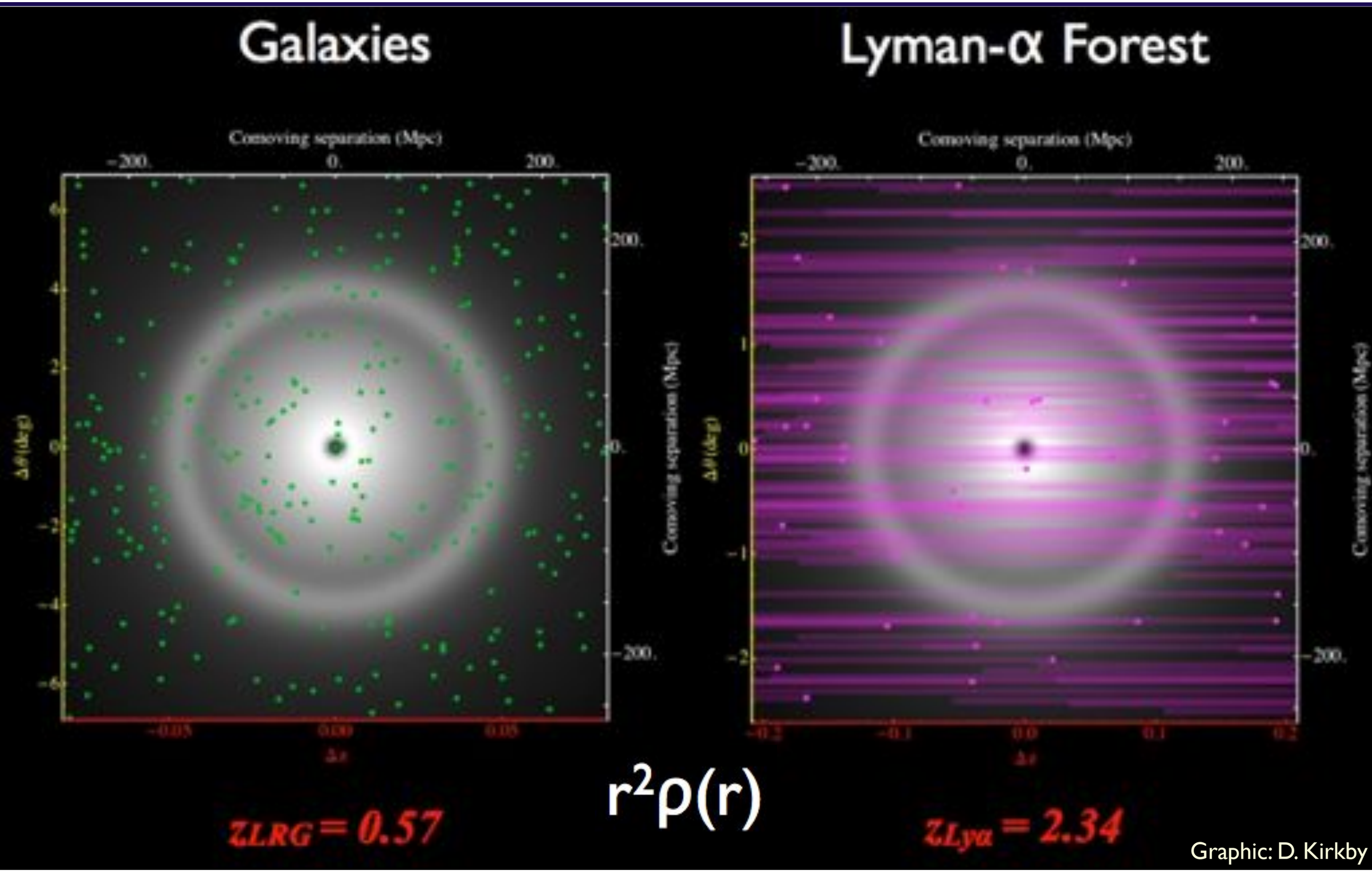
Galaxy at z=0.78



BOSS Main Surveys (2009-2014)



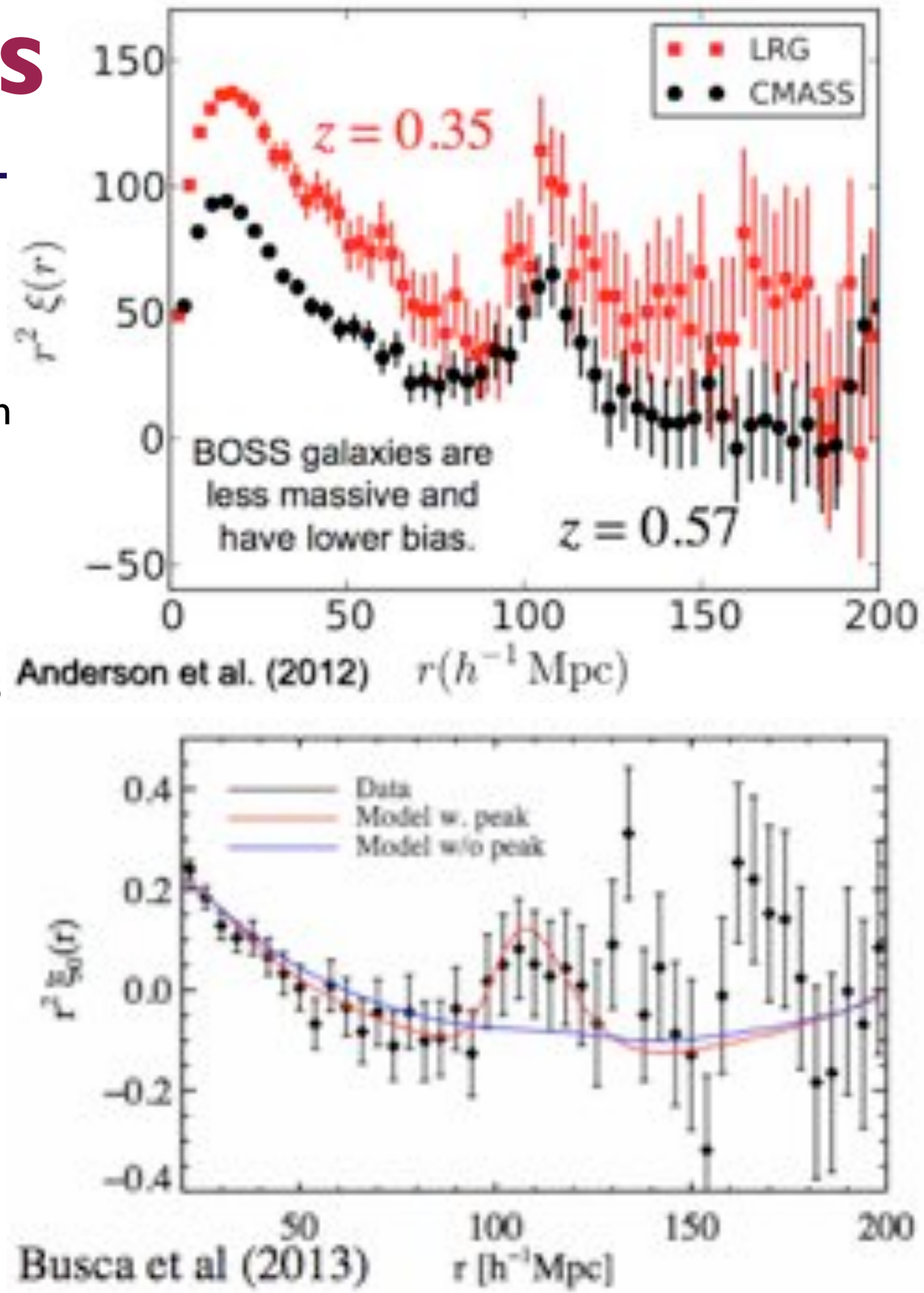
BAO measurements



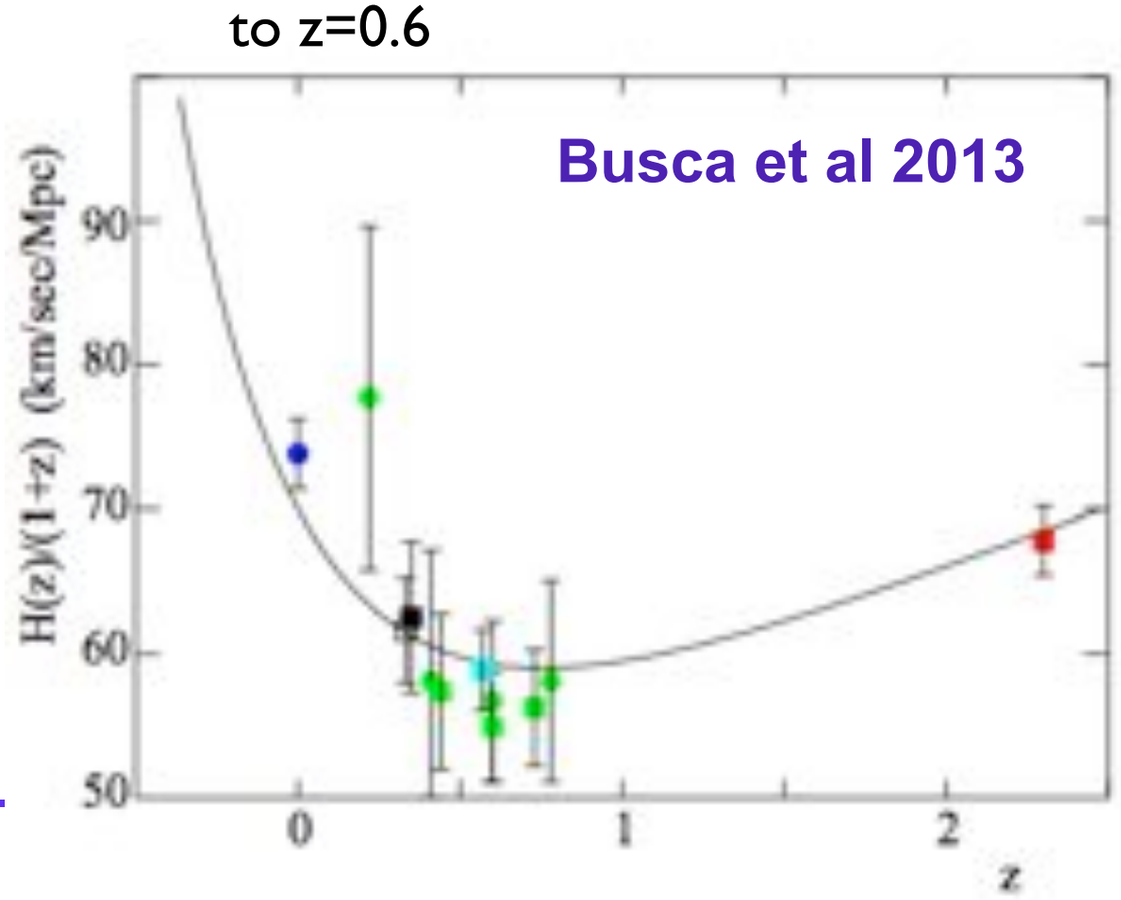
Graphic: D. Kirkby

BAO Results with BOSS

- BOSS is targeting 1.5 million galaxies over 0.2<z<0.6 over 10k sqdeg, & 150k z>2 quasars
- Distance measured to z=0.57 to 1% precision (Anderson et al 2014)
- H(z) measured at z=2.3 to better than 4% precision (Busca et al 2013)
- Detection of cosmic deceleration from z=2.3 to z=0.6



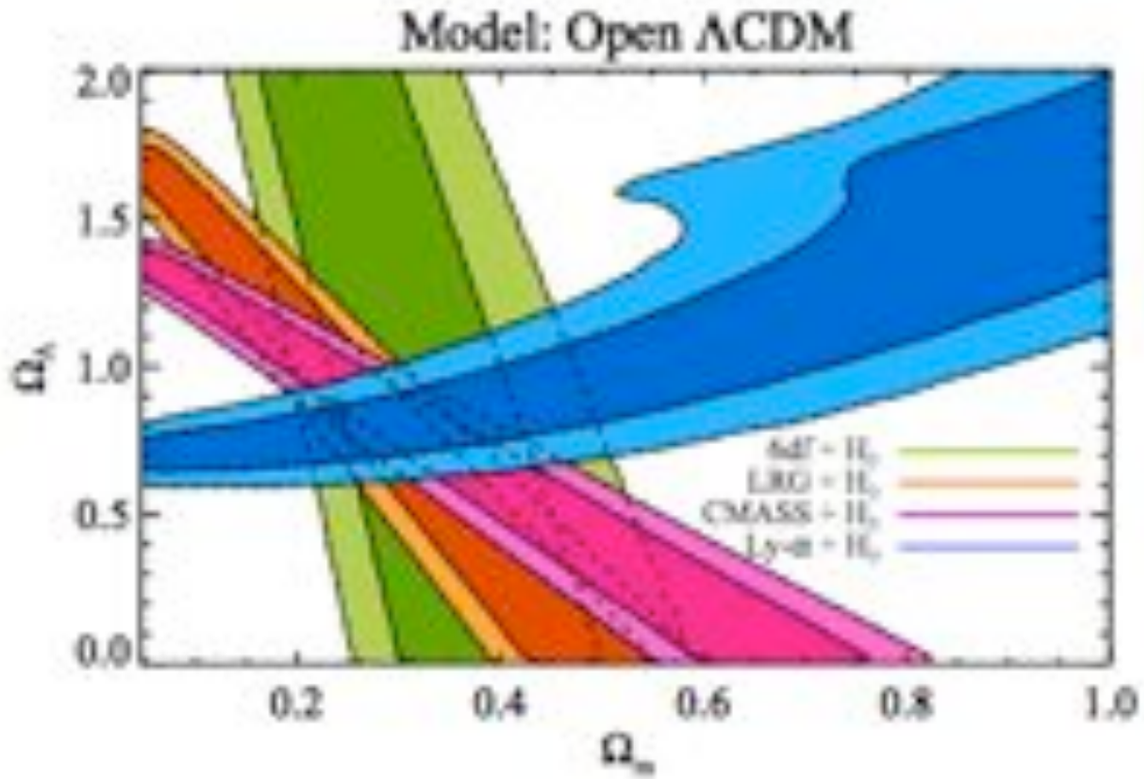
Anderson et al. (2012)

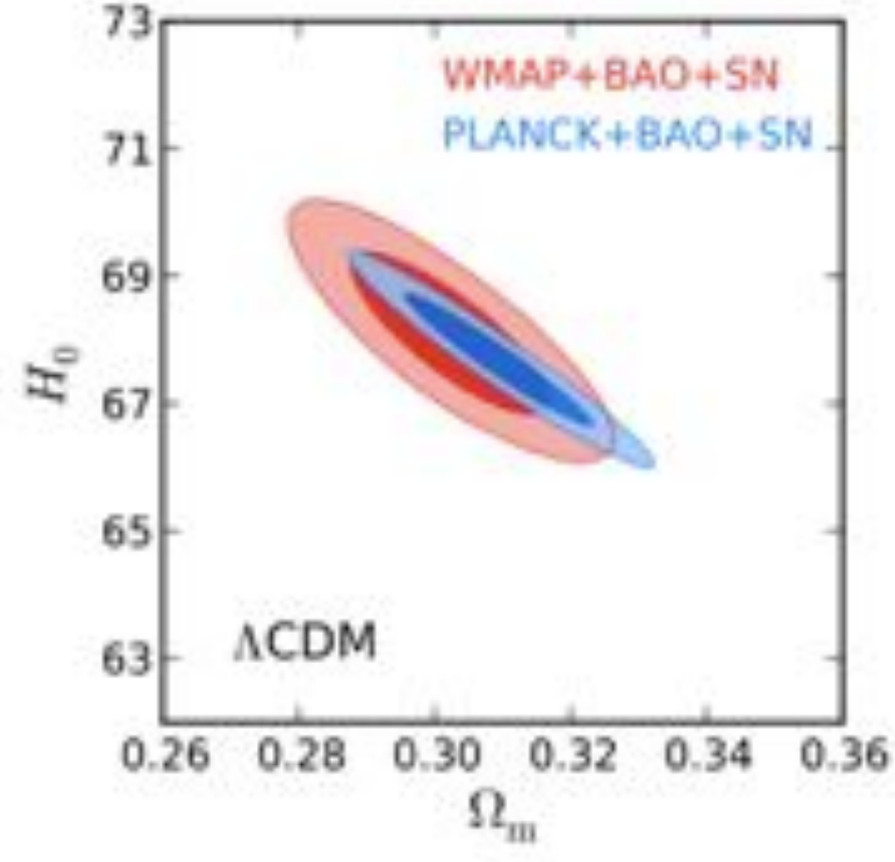


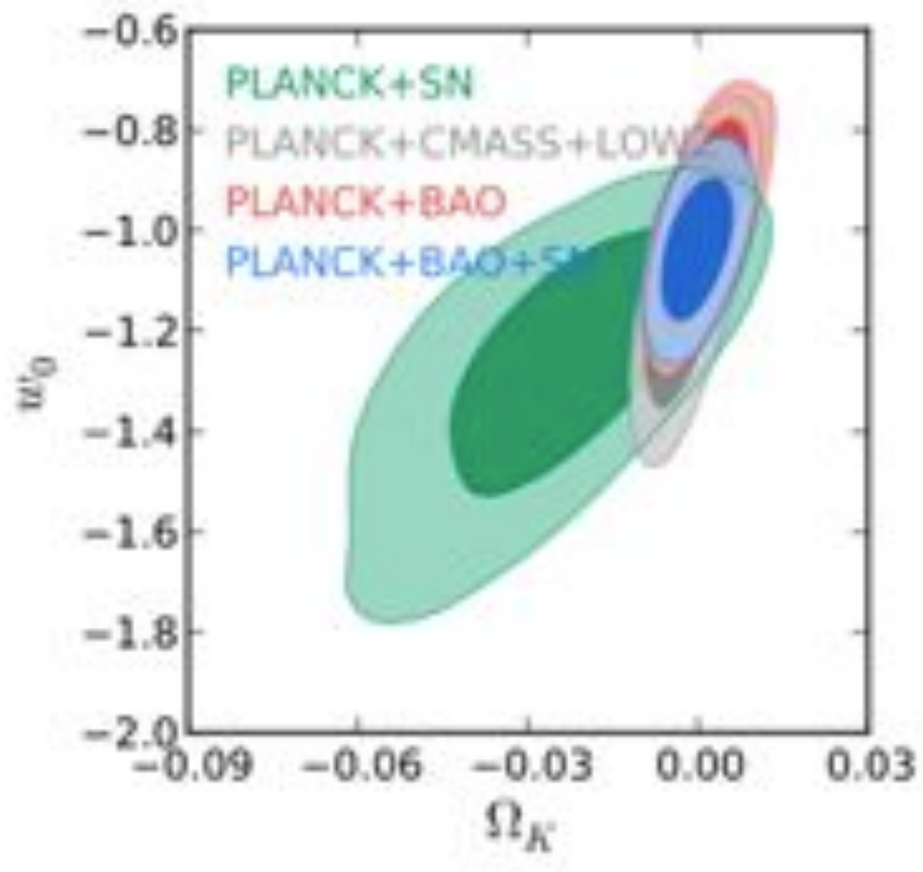
Busca et al (2013)

Cosmological constraints

- Combination of BAO measurements at different redshift is very constraining
- Combination with CMB (+SNe) is providing stringent constraint on the cosmological model



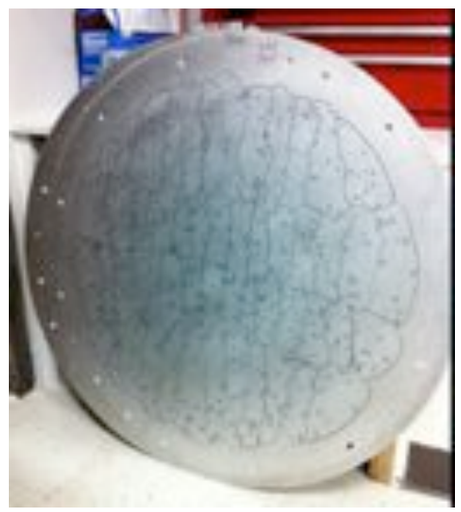




eBOSS: the new Cosmology SDSS project

- Part of SDSS-IV
  - Fully funded for 5 years (likely 6)
  - Half of dark time (split MaNGA)

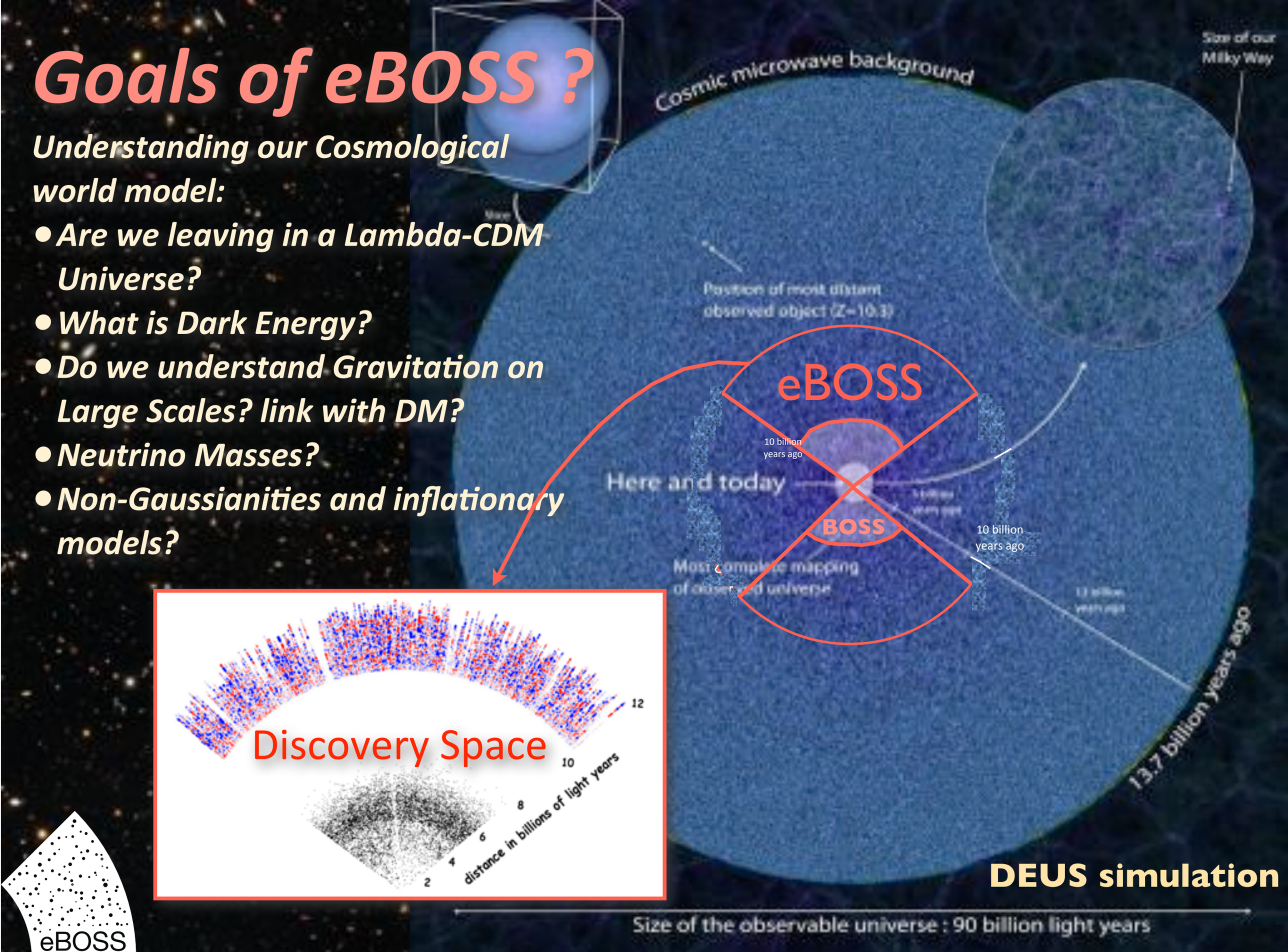
- Uses BOSS spectrograph, targets from SDSS+WISE+(DEcam?) imaging
- extend BOSS to higher redshift
- include ancillary projects: TDSS, SPIDERS



Goals of eBOSS ?

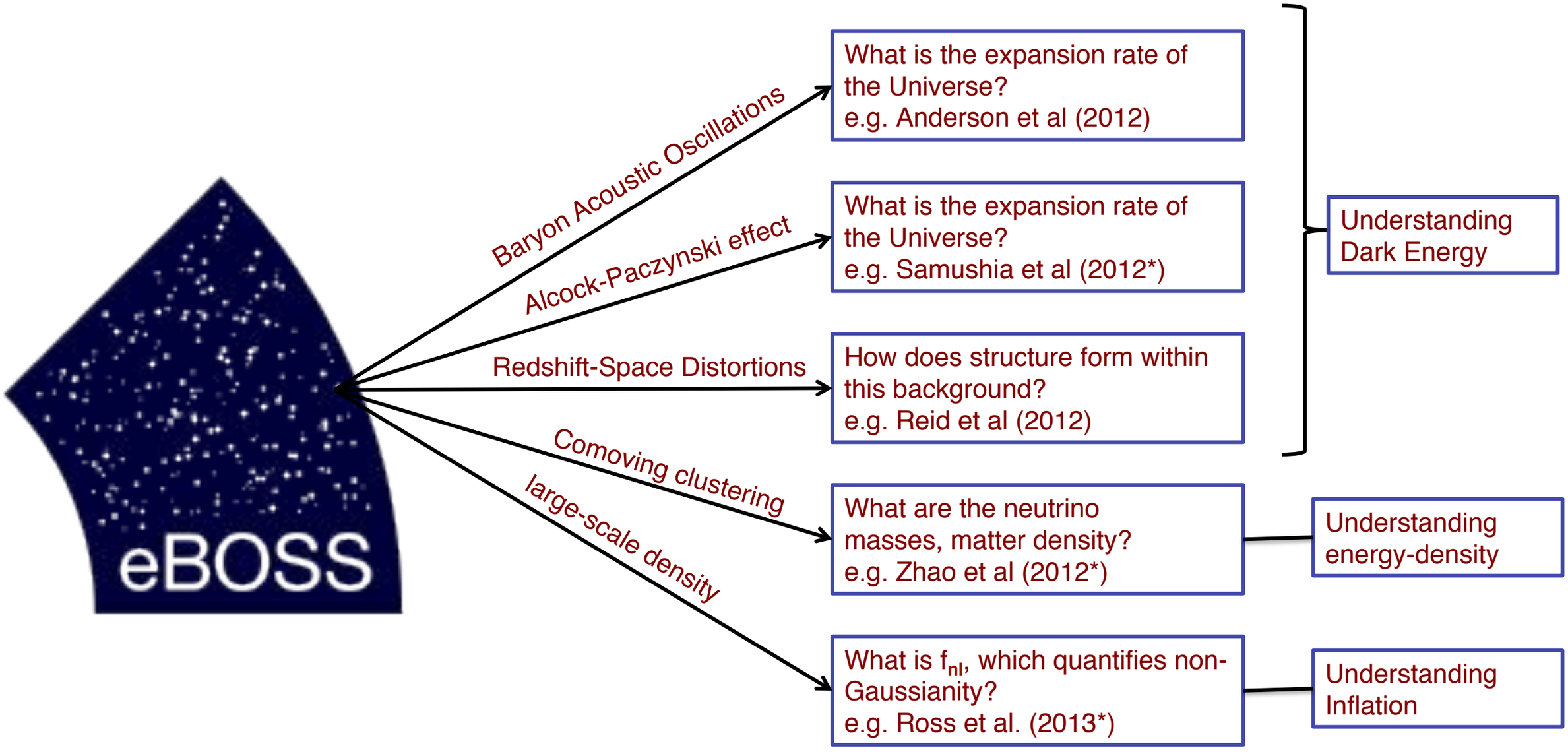
Understanding our Cosmological world model:

- ***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?***

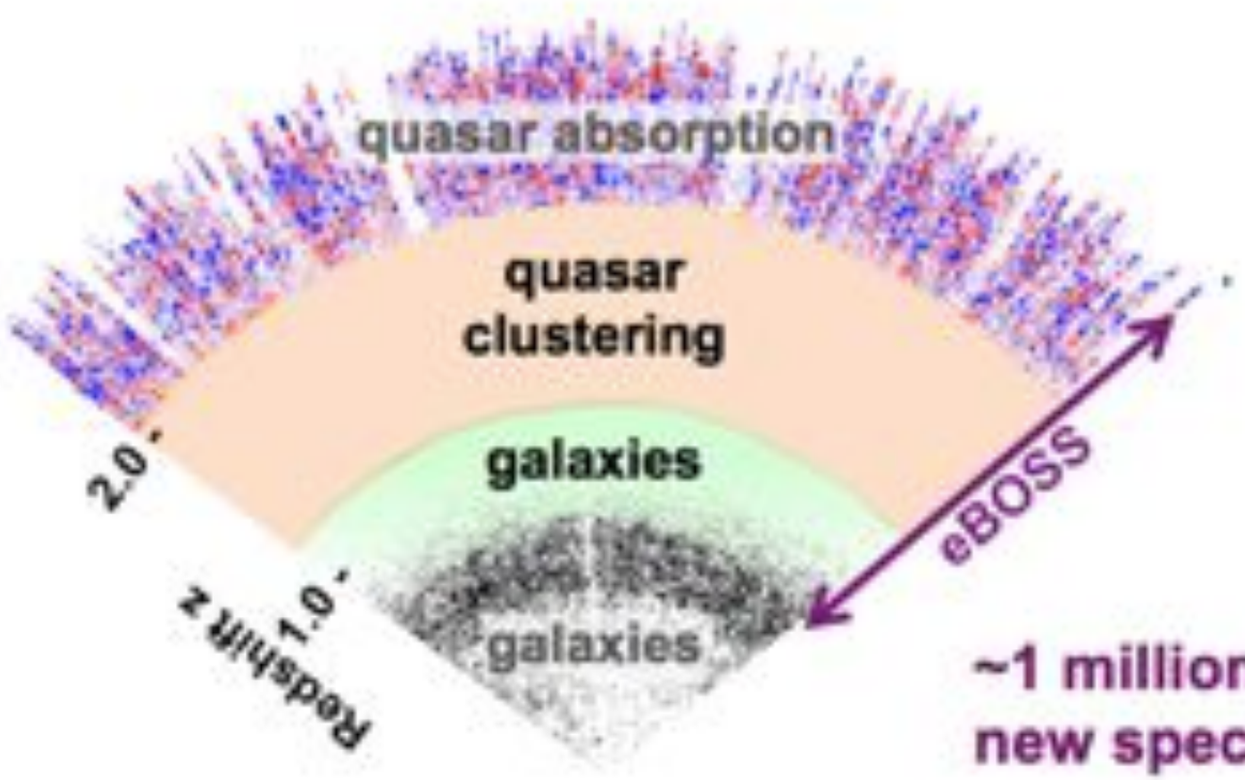


eBOSS

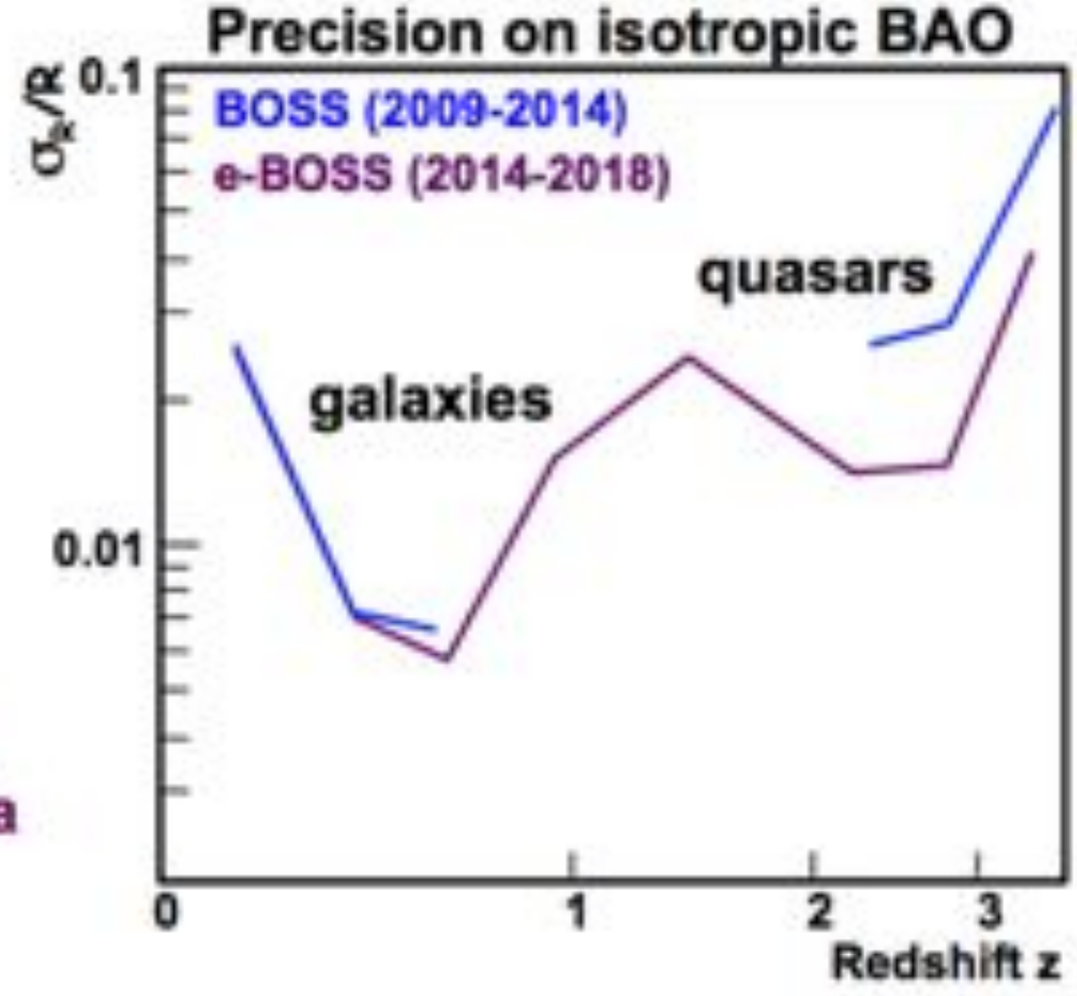
Science Driver = Cosmology



eBOSS BAO forecast



~1 million new spectra



0.6<z<1.2 galaxies

- Star-forming galaxies
- Extend z-range

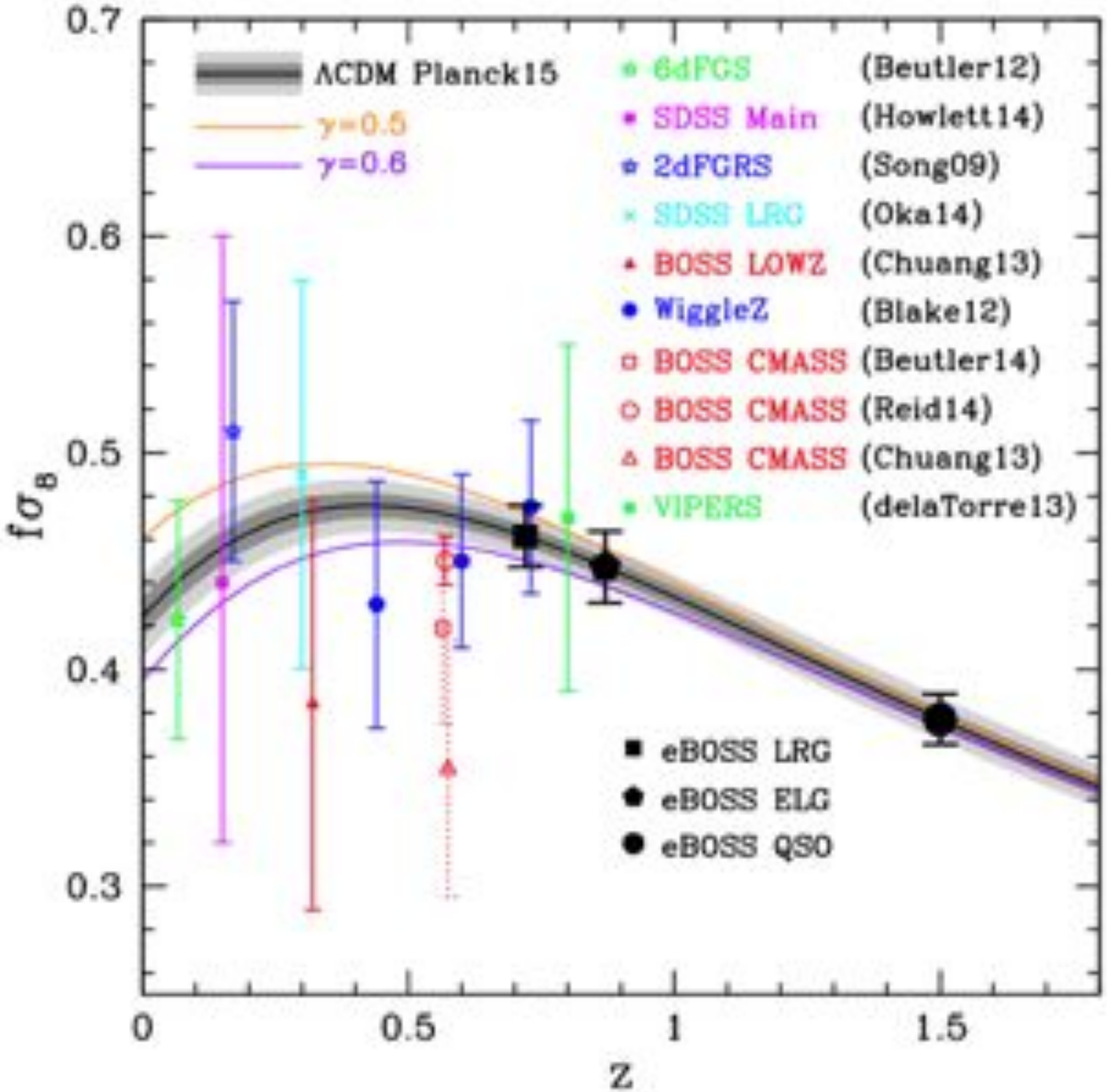
1.0<z<2.2 quasars

- Point-sources as tracers of matter
- Unchartered region

2.2<z<4.0 quasars

- Ly-α absorption as tracer of matter
- Density x2 over BOSS

eBOSS RSD forecast



2nd Science Driver = Quasars

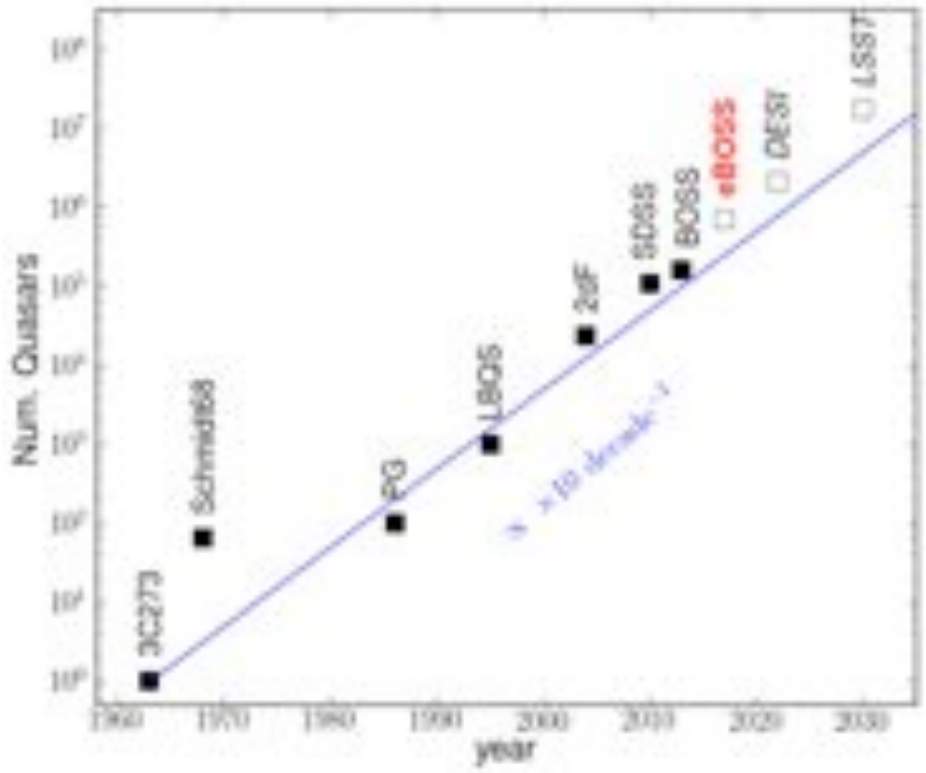
★eBOSS will soon be the largest quasar survey

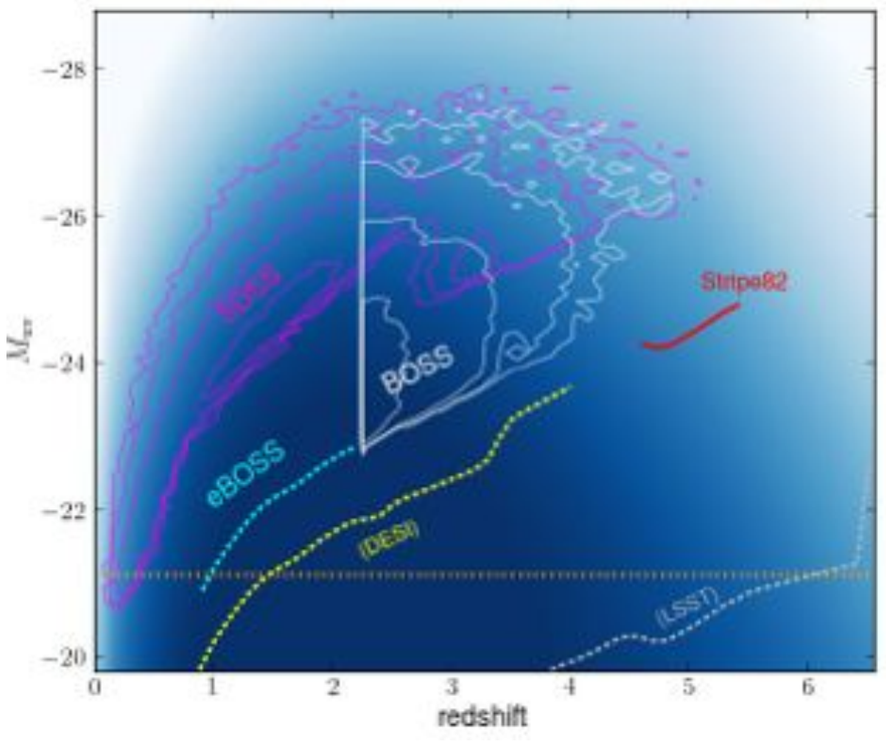
★3 surveys: CORE, TDSS, SPIDERS

- optical/mid-IR, variability, and X-ray selections

★ Many science topics

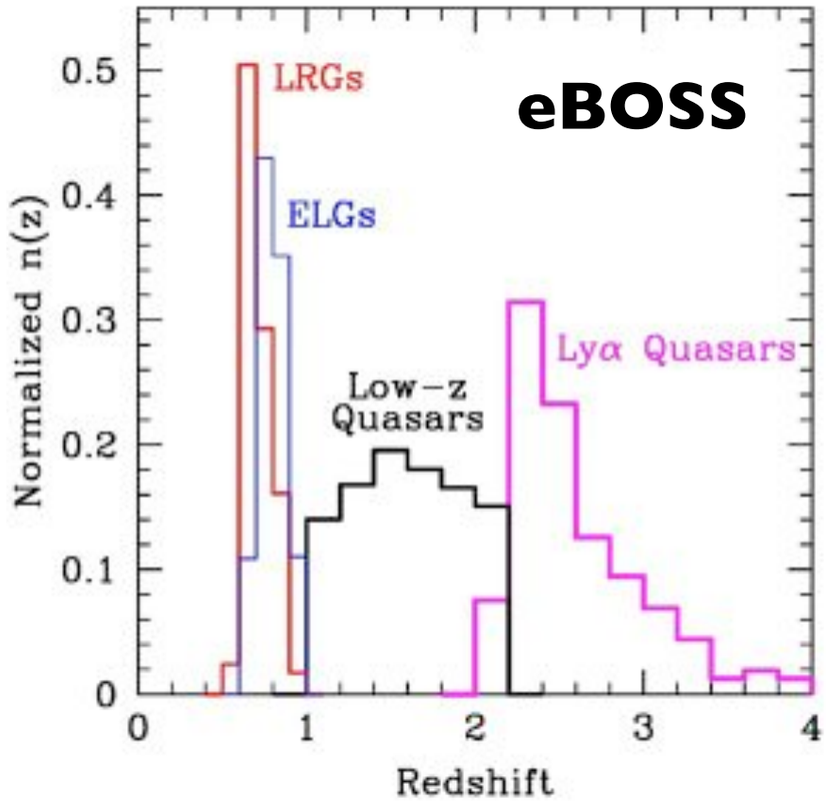
- **Clustering**: how do BHs occupy halos? do faint AGN have different clustering strengths? largest sample of *spectroscopic* quasar binaries/multiples
- **Luminosity function**: how does the faint end evolve to z~2?
- **BH mass** estimates for a large quasar sample
- **Variability**: hypervariables, TDSS Few-Epoch Spectroscopy, Reverberation Mapping
- **Quasar physics**: detailed, high-S/N composites in narrow bins of quasar properties

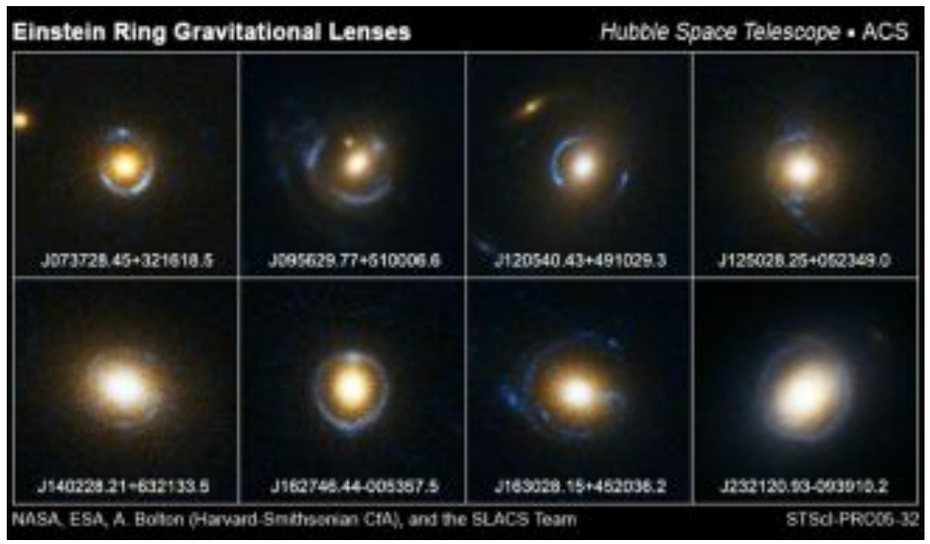




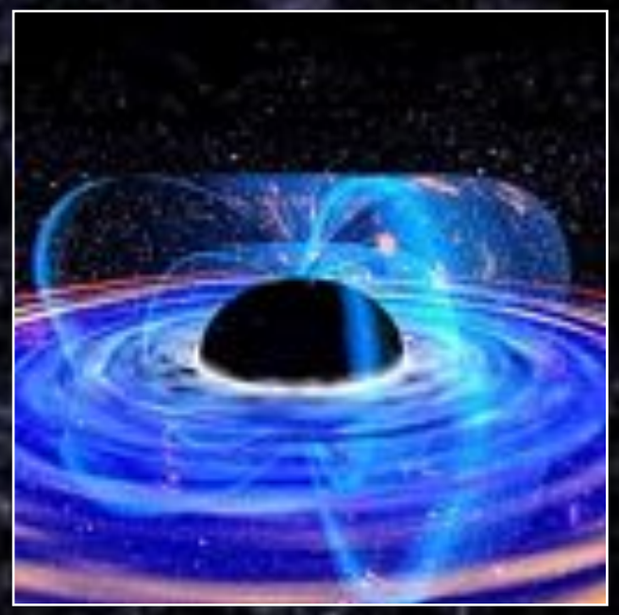
3rd Science Driver = Galaxies

- Photo-z calibration by cross-correlation (Important for DES, LSST)
- Small-scale galaxy clustering: Halo positions and densities of galaxies as a function of properties
- Cross-correlation with Ly-α forest: probe Gas & metal distribution around ELGs and LRGs
- Discovery of strong lens systems from spectra
- Physics from high S/N stacked spectra
- *Galaxy Clusters discovery and science (Synergy with SPIDERS)*





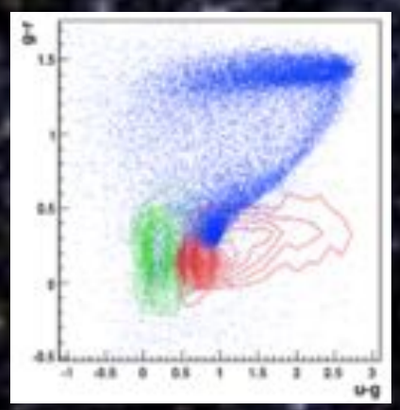
Gas that falls into a black hole settles into a so-called accretion disk. Friction and magnetic fields in the disk cause the gas to heat and emit UV and X-ray light.



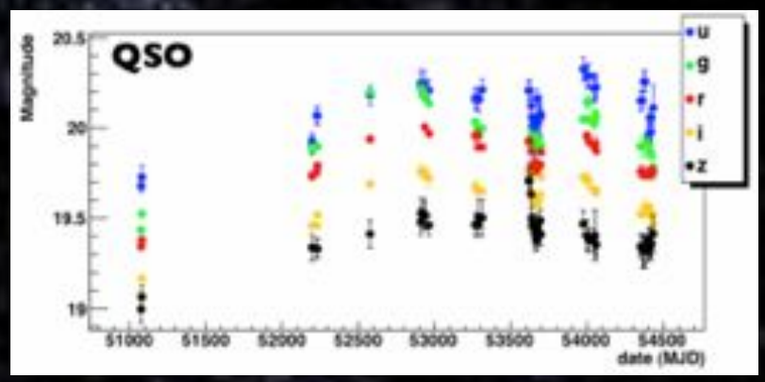
Targeting QSOs

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

eBOSS / **TDSS** **SPIDERS**



SDSS+WISE



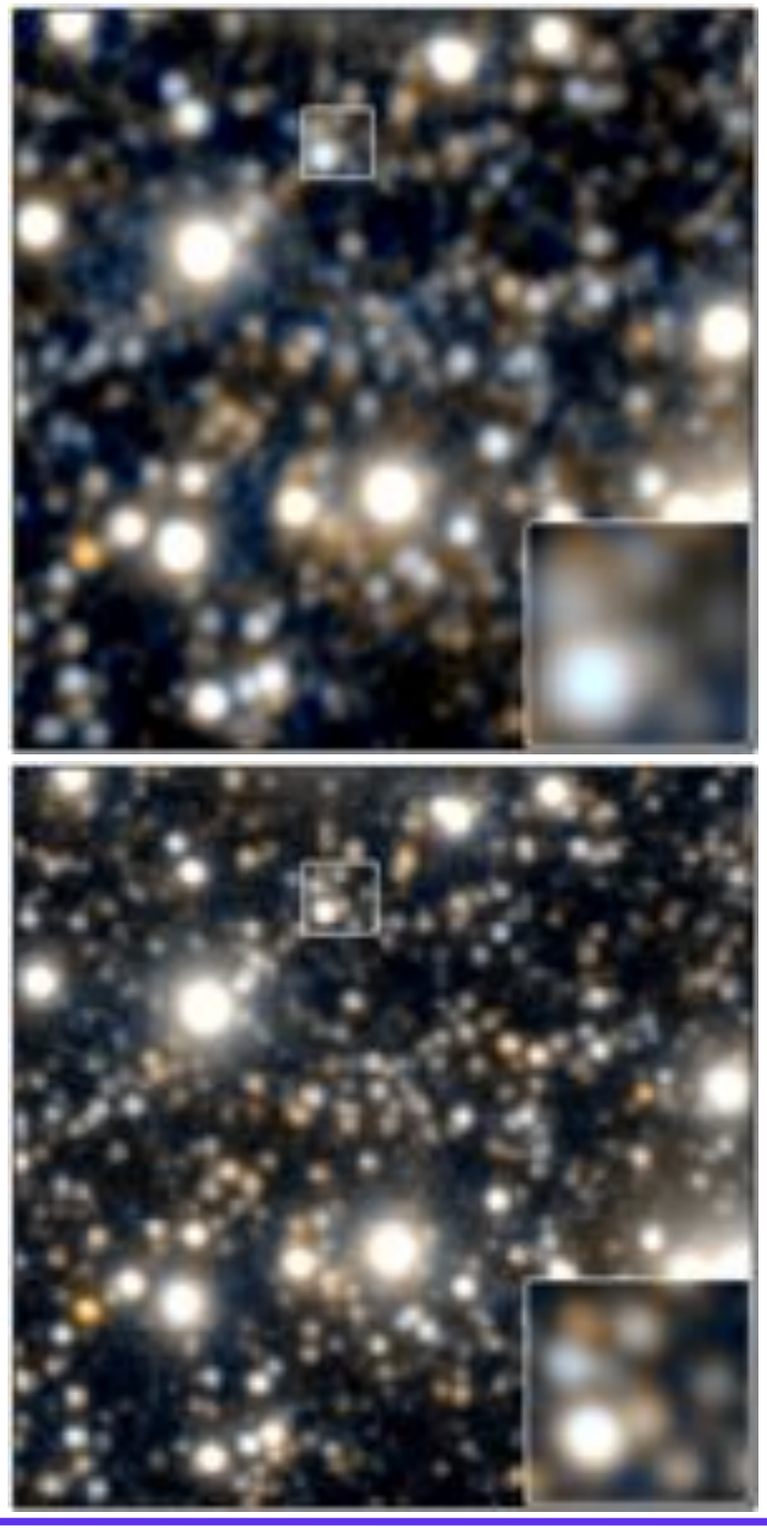
PTF PanSTARRs

eROSITA

eBOSS

WISE data

- "unWise" co-adds of the WISE data (**Lang**, Schlegel, Hogg et al 2014, arXiv:1410.7397)
- Forced photometry based on the SDSS photometric catalogue
- Key information used for the QSO and LRG target selection
- Use WISE for ELGs ?



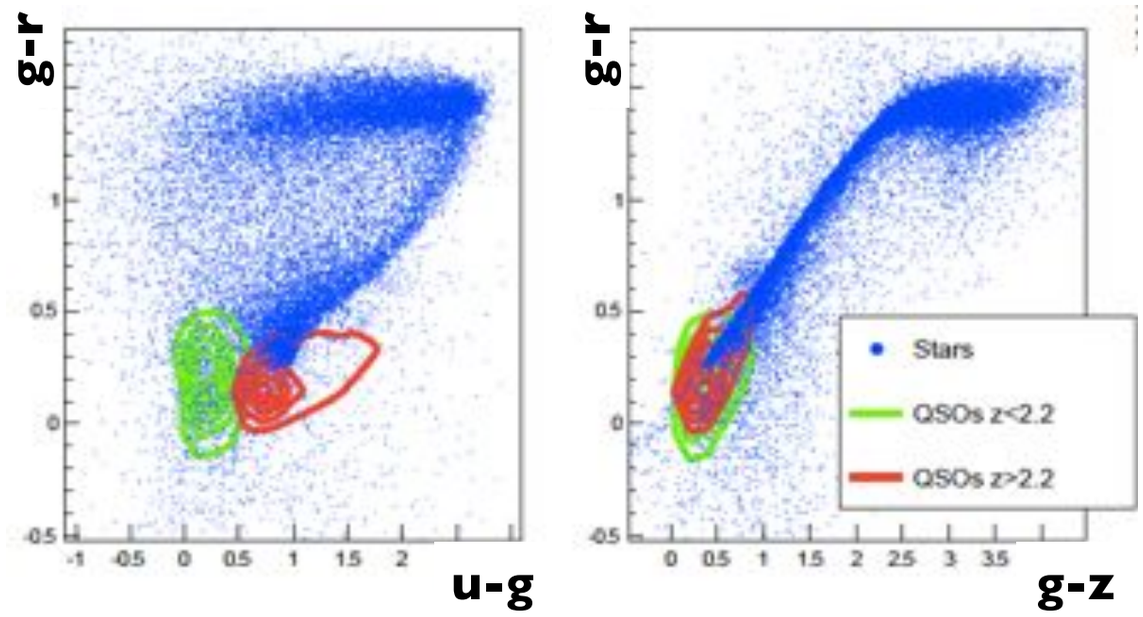
Targeting "Core" Quasars (XDQSO+WISE)

CORE selection – density & uniformity for tracer QSOs

- **XDQSOz (extreme deconvolution)**

  Bovy et al. (2011, 2012)

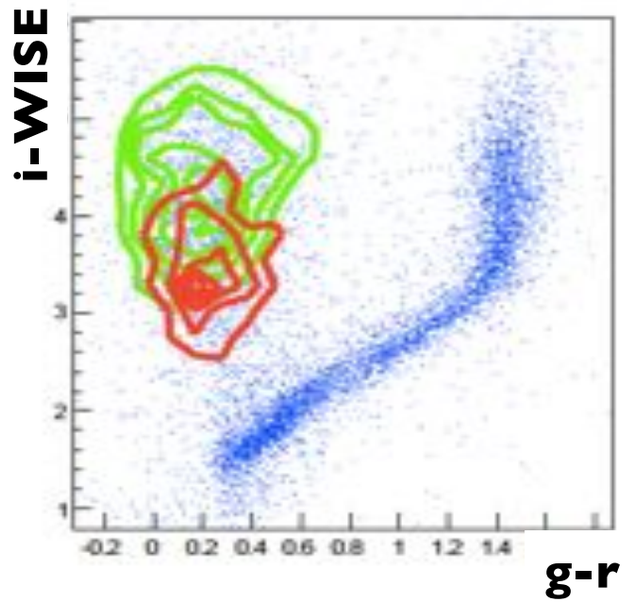
  - **Require P(QSO, z>0.9) > 0.2**
  - **Very efficient at z<2.2**



- **WISE (color cut)**

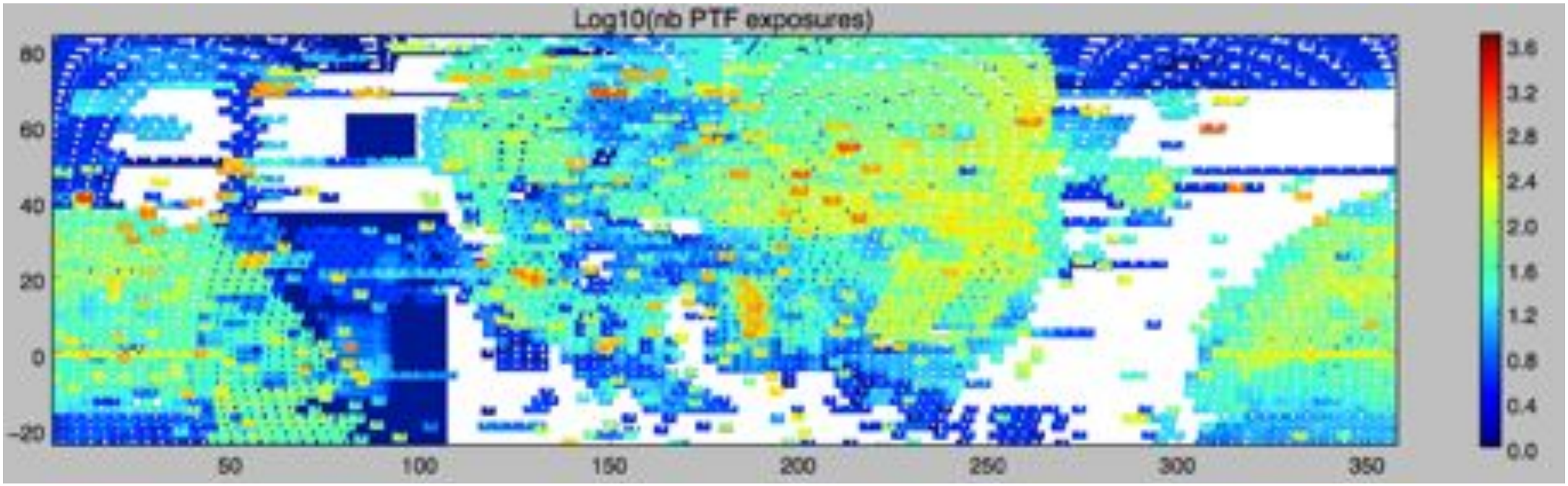
  - **Forced aperture-photometry (*D. Lang & D. Schlegel*)**
  - **Require SDSS – WISE > (g – i) + 3**

    where WISE = stack of 3.4μm & 5.6 μm bands



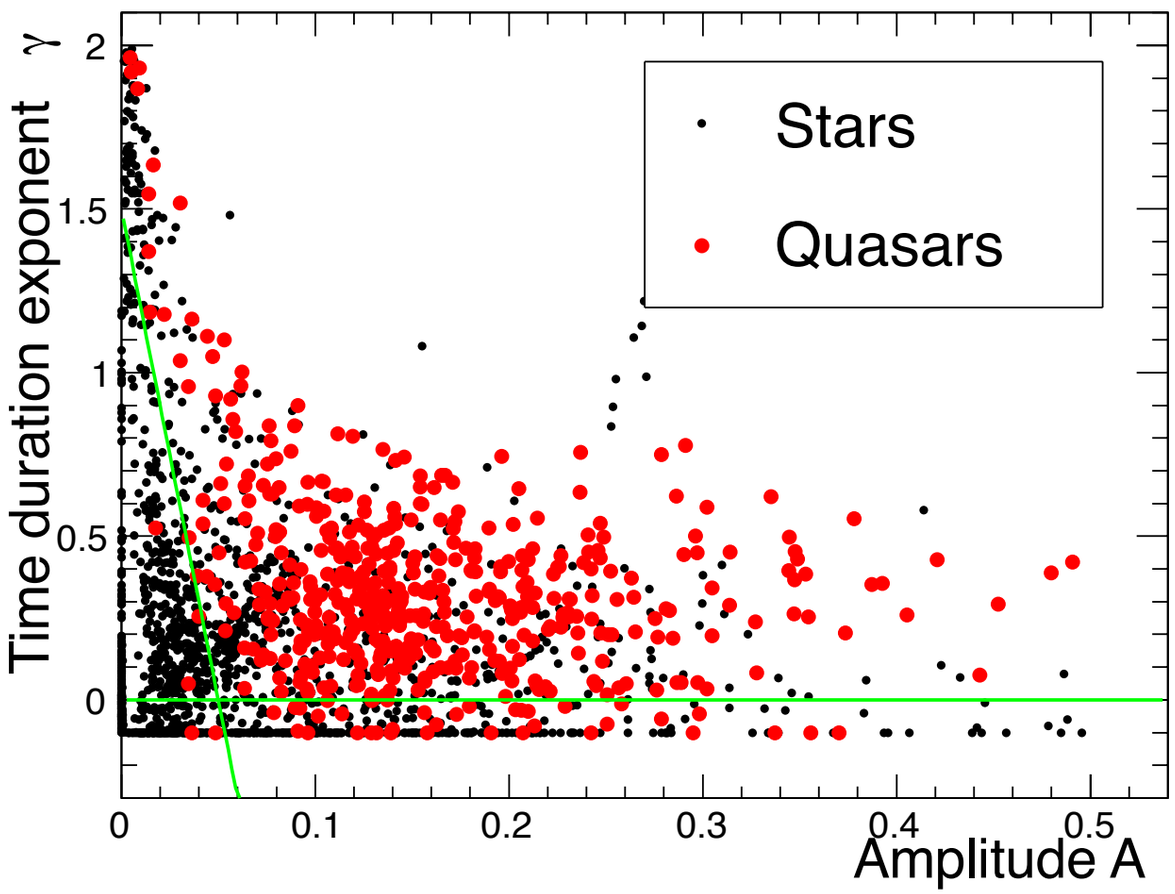
Palomar Transient Factory

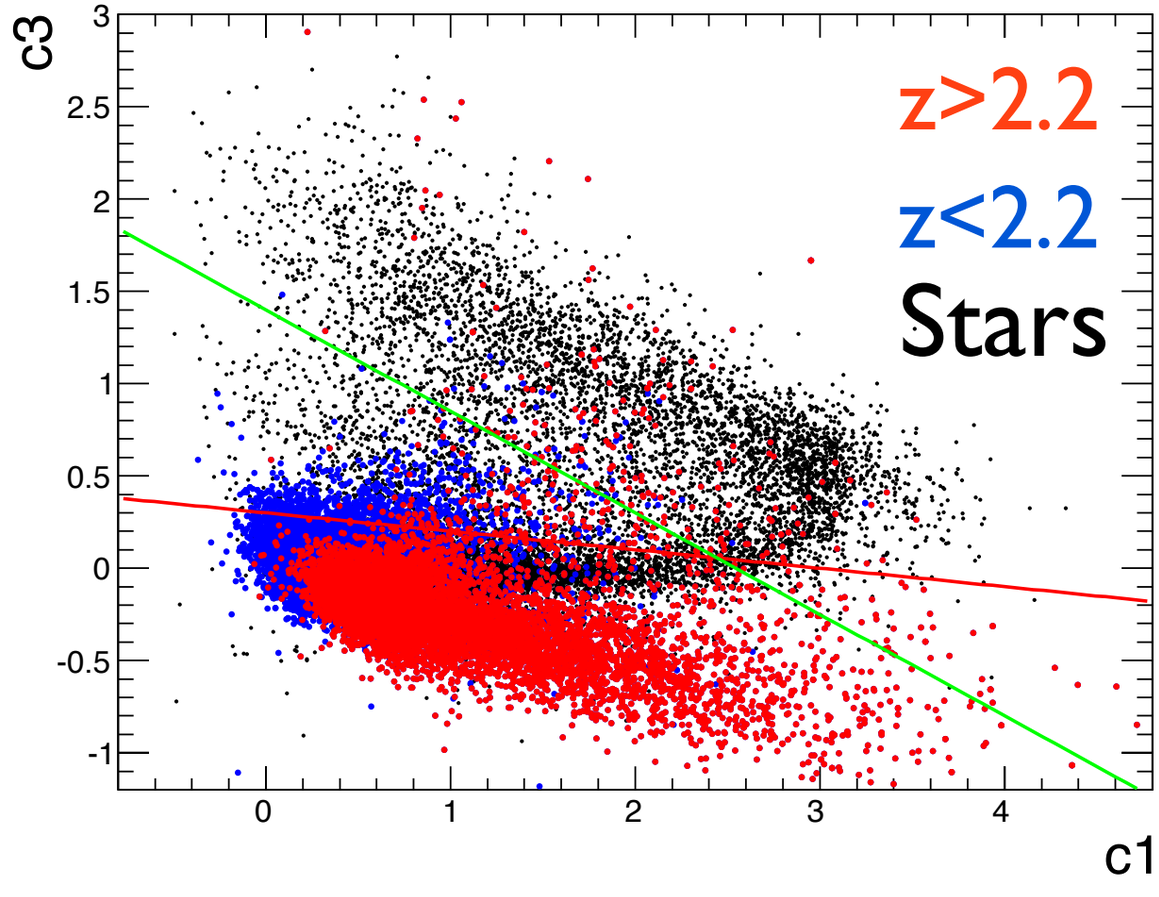
- **Palomar Transient Factory (PTF 2009-2012, iPTF 2013+)**
  - Wide-field survey, ~ 1 measurement / 5 nights for each region of the sky (SN search)
  - 8 deg2 fields with 12 CCDs of 8kpix (11 working), R/g bands (we use only R)
  - Depth ~ 21 mag / exposure



Targeting PTF QSOs - for Ly-alpha

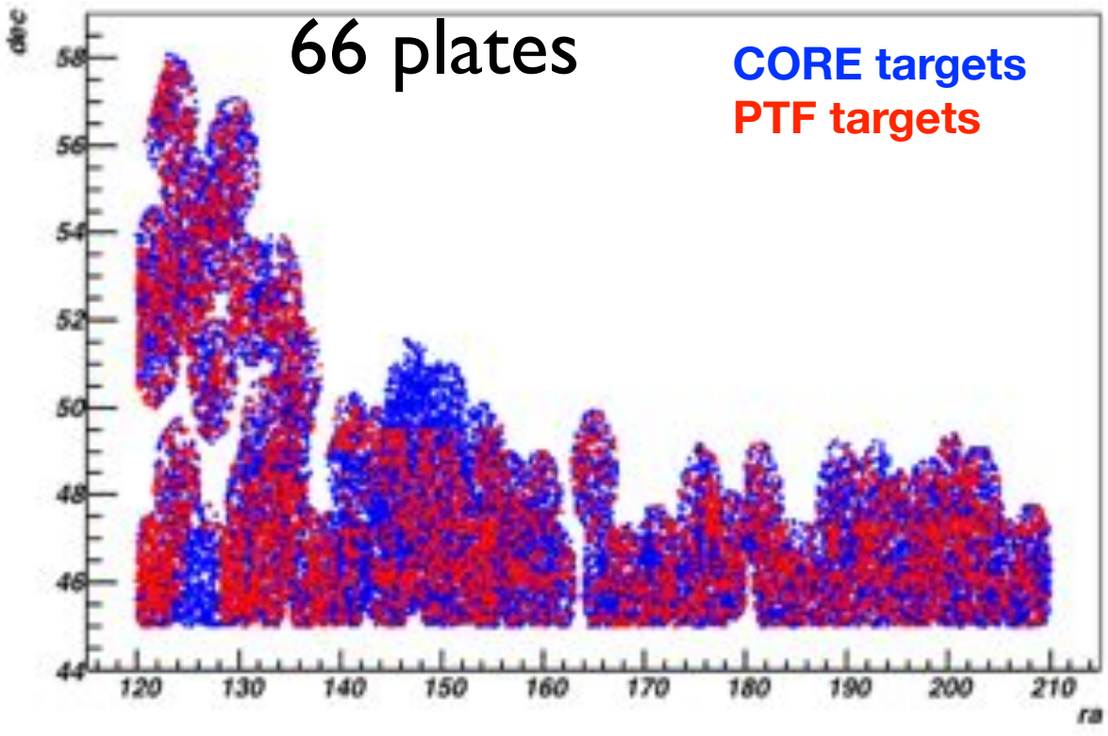
- **Use quasar variability for TS using PTF data**
  - QSO intrinsic variability structure fct ~ A x Δt^{γ} , signal on long timescales ~ years
  - Complemented by color-cuts to remove variable stars





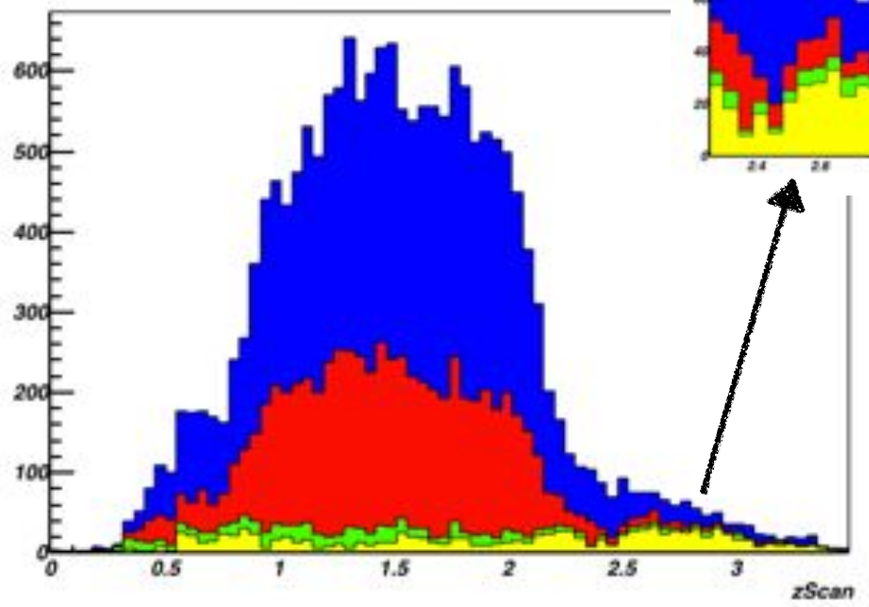
Myers et al QSO selection

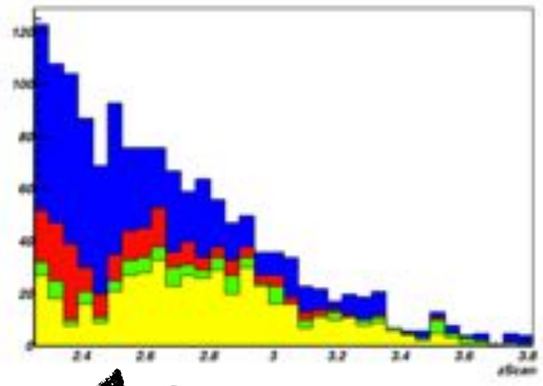
TS Quasars - Validation with SEQUELS



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

Visually confirmed QSO

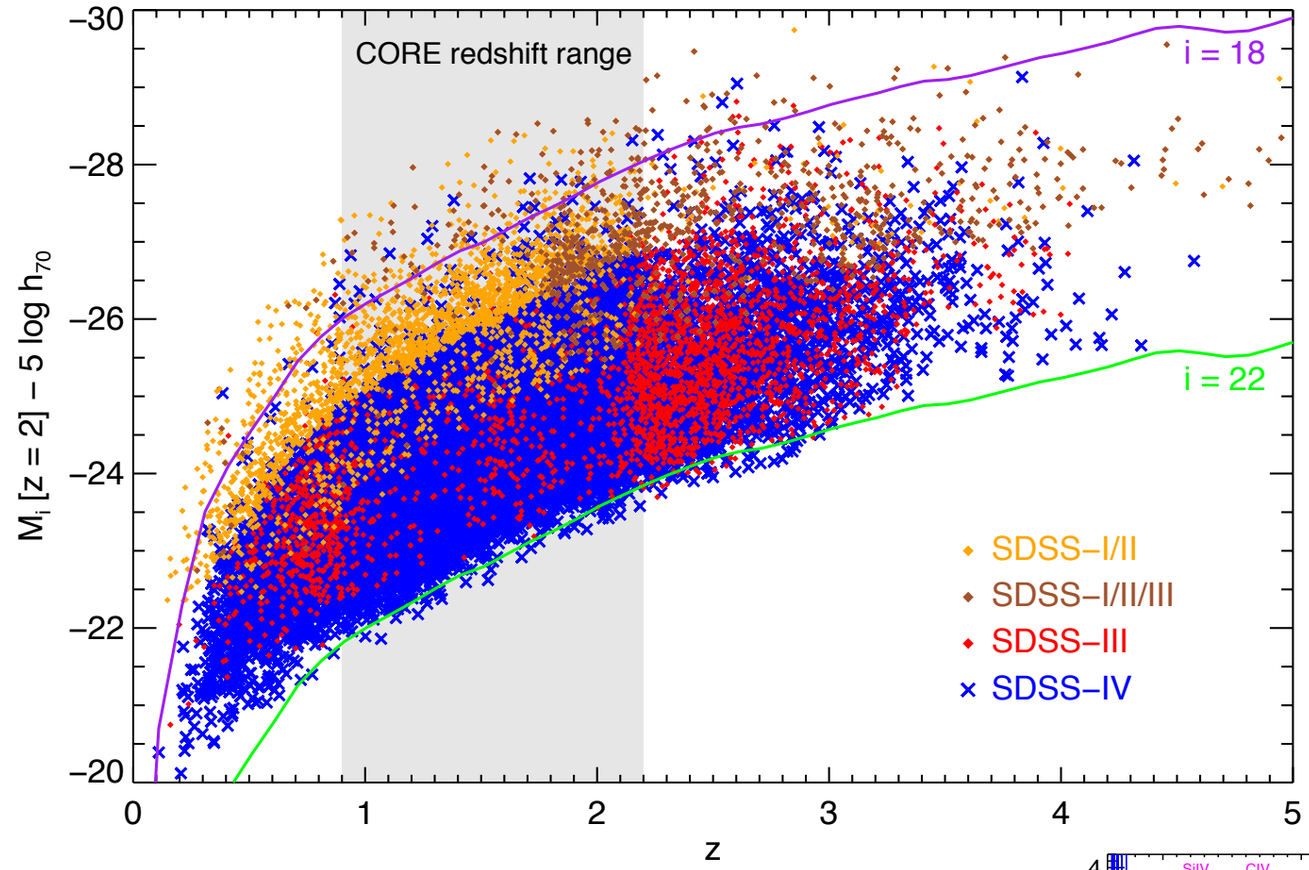




CORE only
PTF + CORE
PTF only
PTF only - additional selection cuts

- **SEQUELS targeting show that QSO target selection complies with SRD**
  - 86 deg^{-2} QSO core target => **60 deg^{-2} with 0.9<z<2.15 and 5.4 deg^{-2} with z>2.15**
  - 20 deg^{-2} QSO Ly-a target => **at least 6.5 deg^{-2} with z>2.15**
- **Homogeneity of QSO core targets:** (less than 15% variation)
  - NGC: 97% of the area SGC: 77% of the area

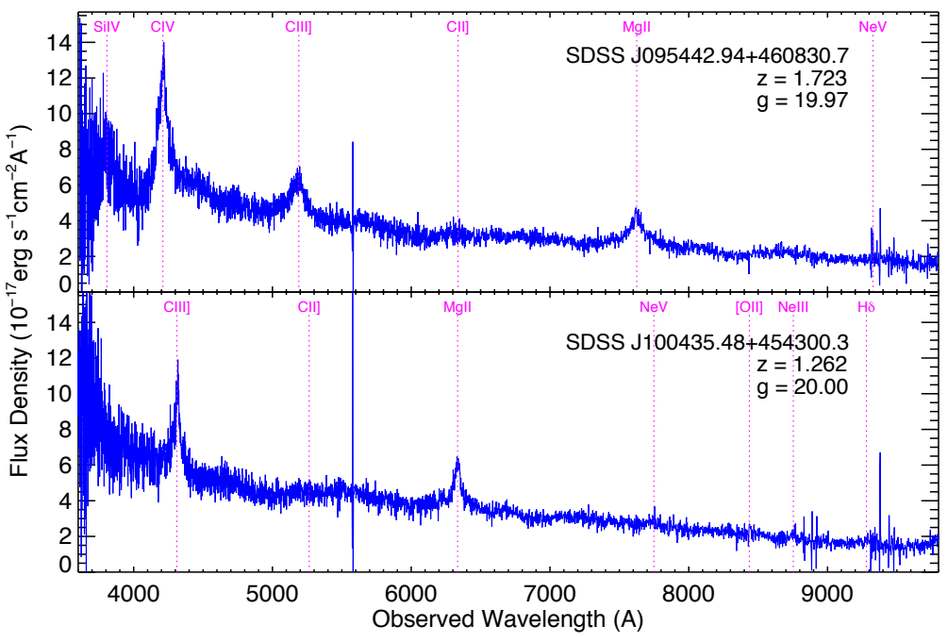
eBOSS QSOs

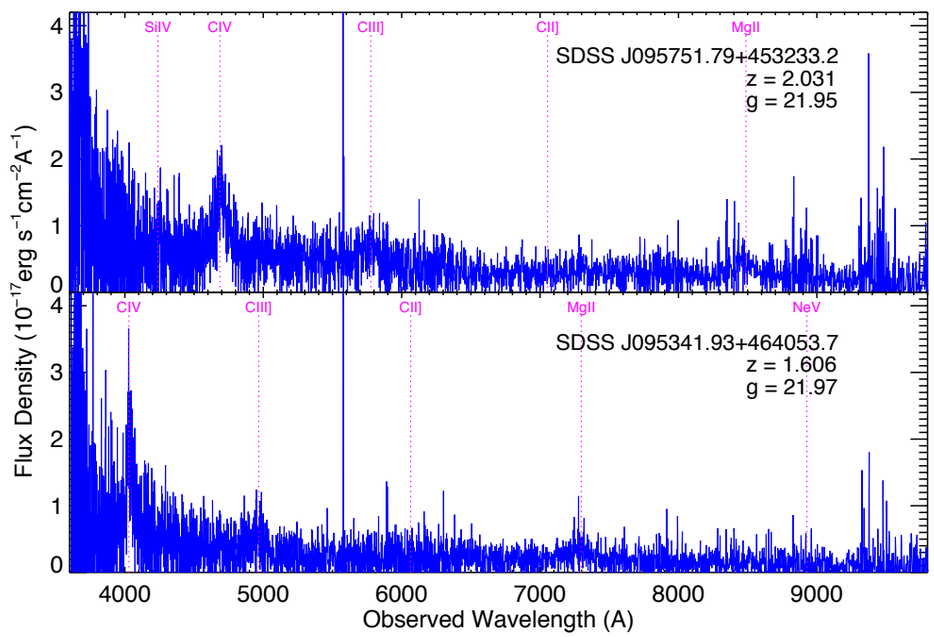


Huge QSO Science Legacy

g~20

g~22





Targeting Galaxies

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

- WISE for LRGs

- SCUSS or DES for ELGs

SDSS imaging

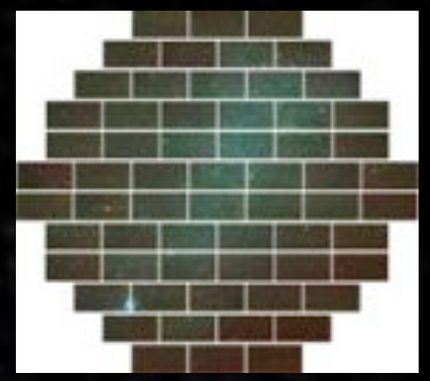
LRG

SDSS+WISE

ELG

SCUSS U-band
+ SDSS gir
+WISE

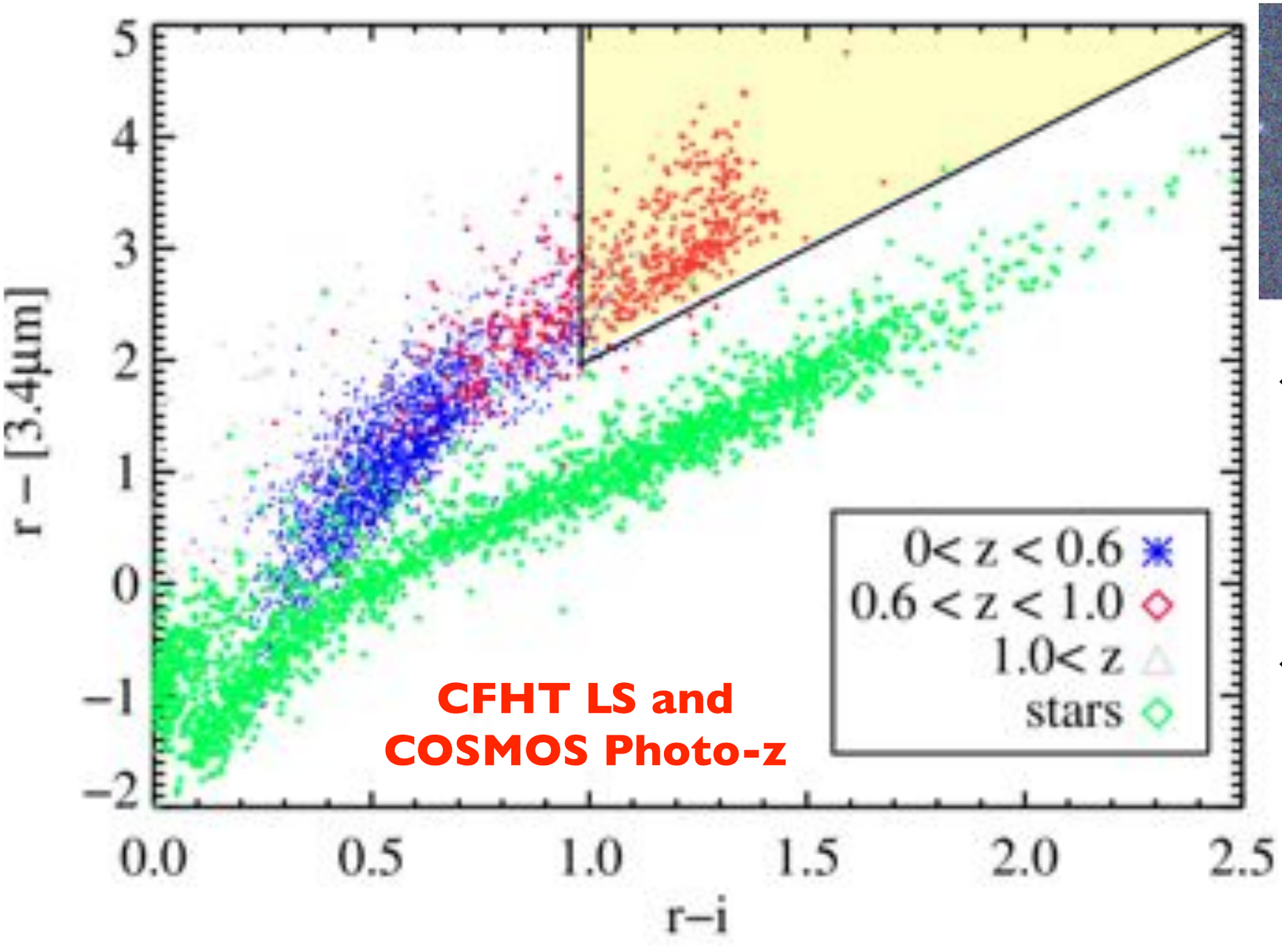
?

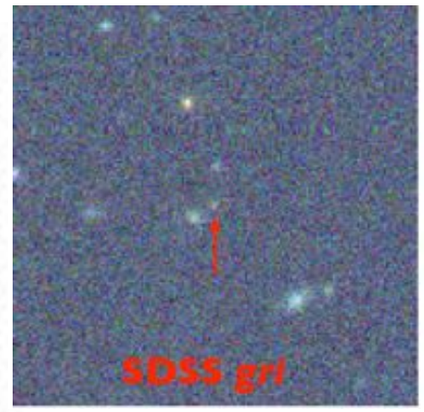


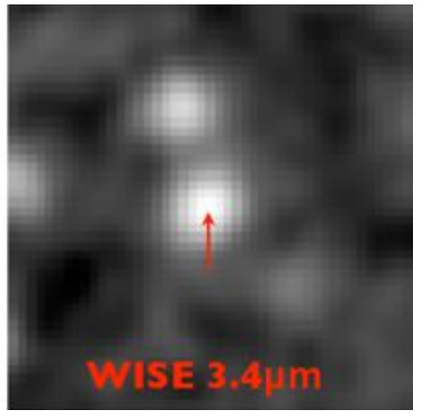
DEcam
grz selection

eBOSS

LRG selection algorithm



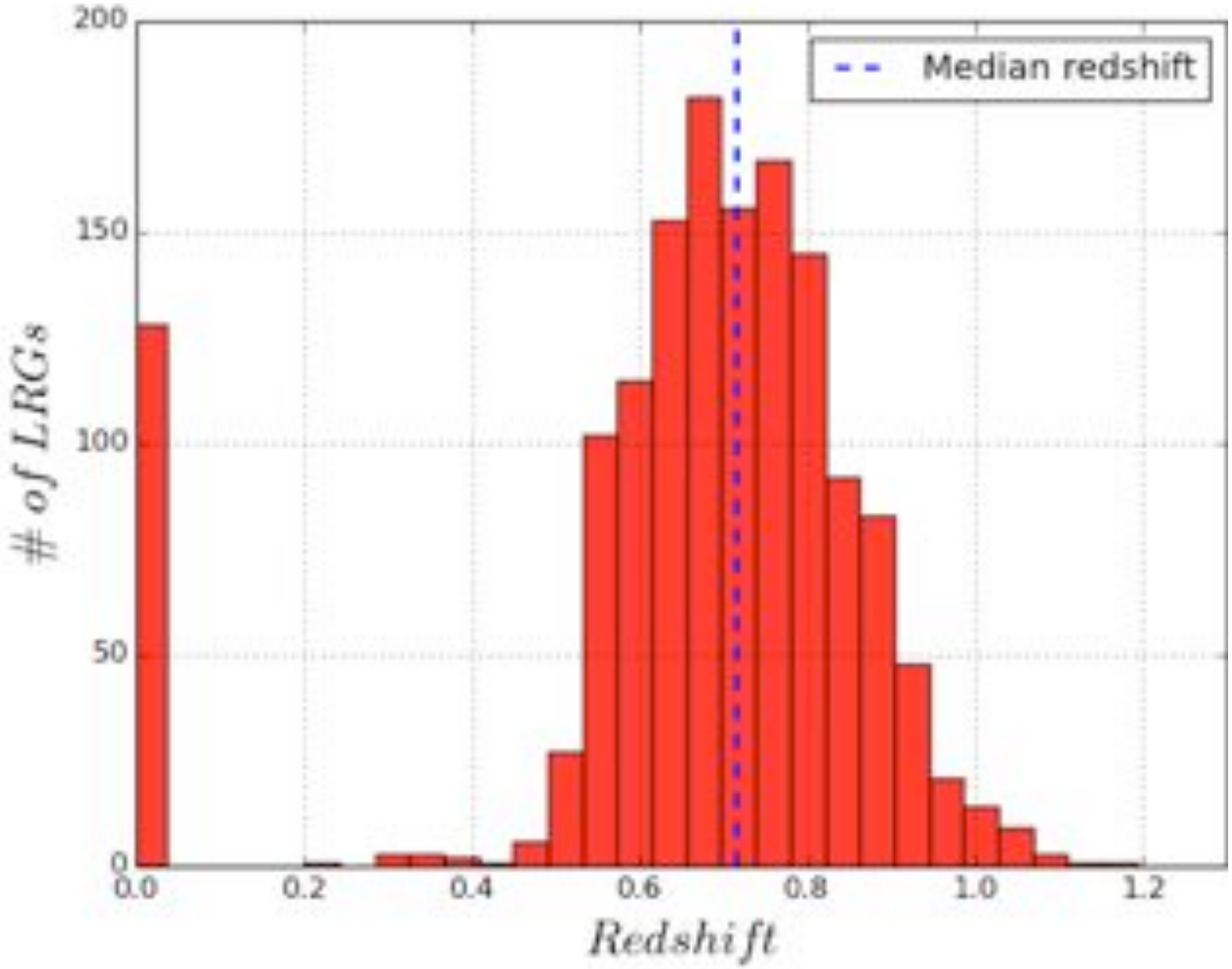




- New method combines optical and WISE (infrared) photometry to select z > 0.6 LRGs.
- All objects with *r-i* > 0.98 & *r-[3.4 μm]* > 2.0**(r-i)* (shaded region) and *i-z* > 0.6 are selected.

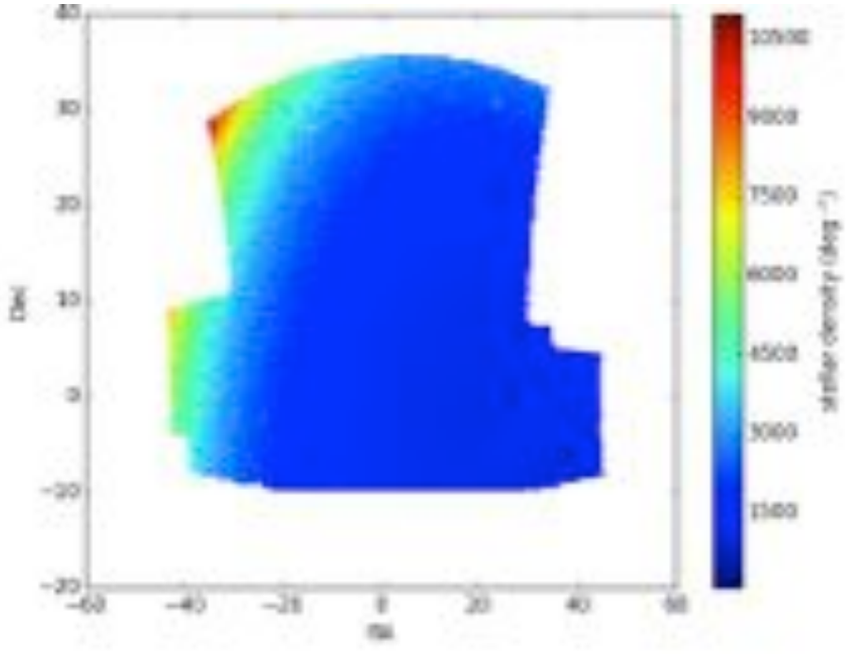
Similar selection can be done in other optical-infrared color spaces, e.g. *i-w1* & *i-z* or *r-W1* & *r-z*.

Successful targeting by BOSS ancillary surveys

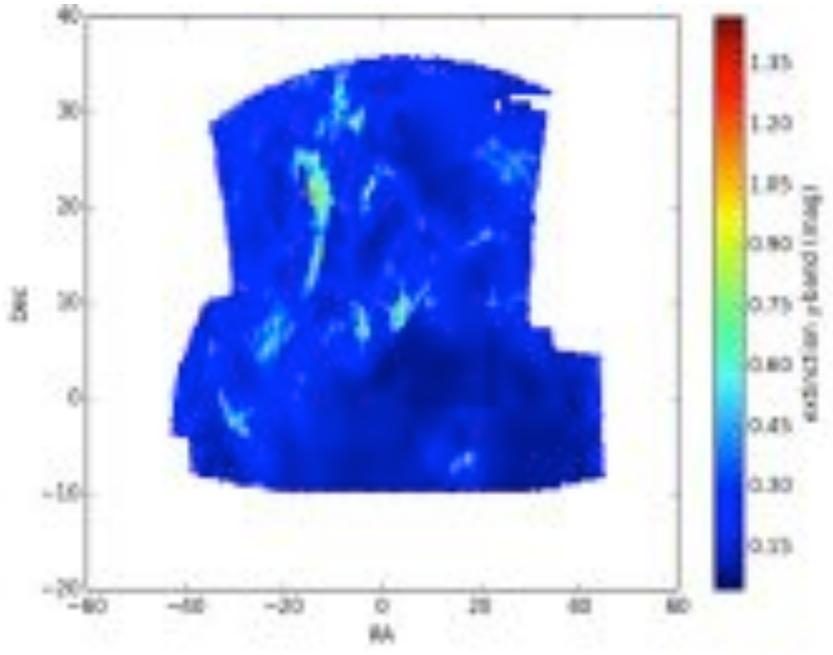


- ~10,000 $z<20$ mag LRGs targeted via BOSS ancillary survey.
- 98% of spectra yield secure redshift measurements.
- BOSS Ancillary Program SEQUELS targeted ~70,000 LRGs with median redshift, **z~0.71**
- Completeness 81% of LRGs with $0.6<z<1$
- **~60 deg^{-2} reaching the targeted 375,000 LRGs**

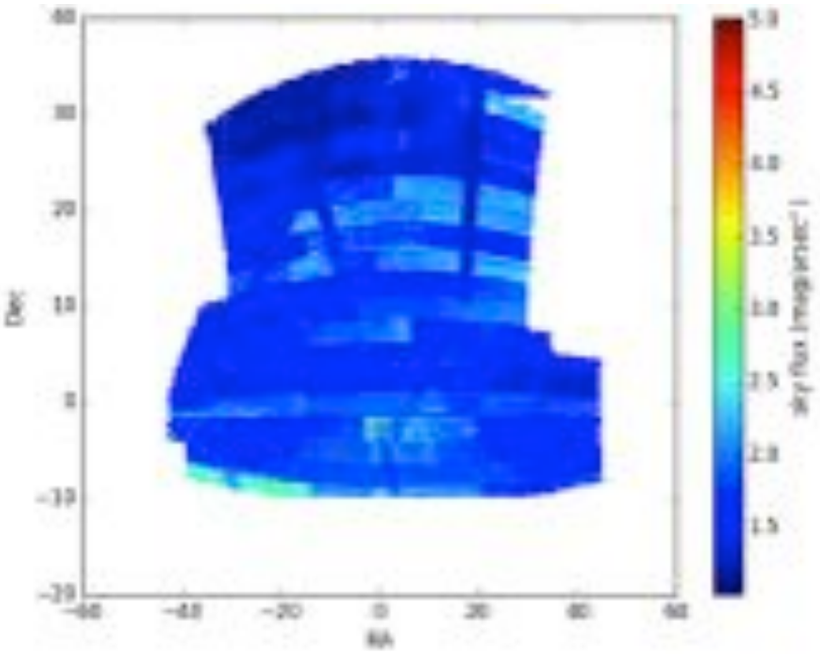
Additional color cut, *i-z >0.6*, pushes the sample to higher redshifts.



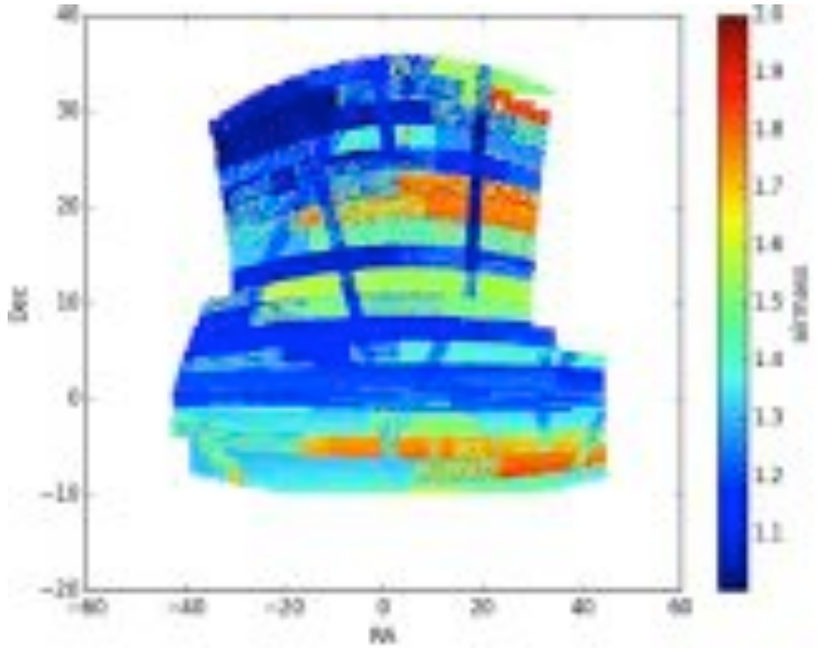
Stellar Density



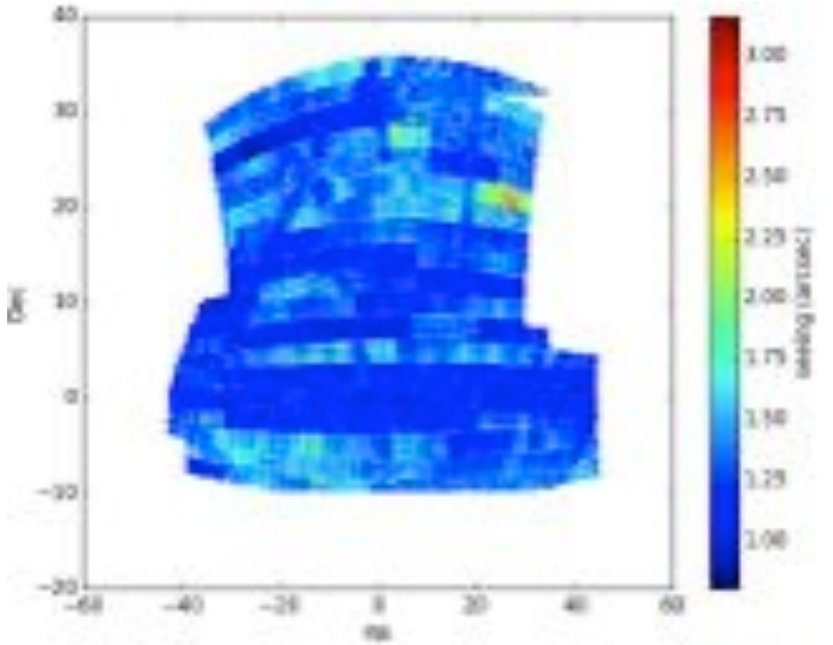
MW Galaxy Dust



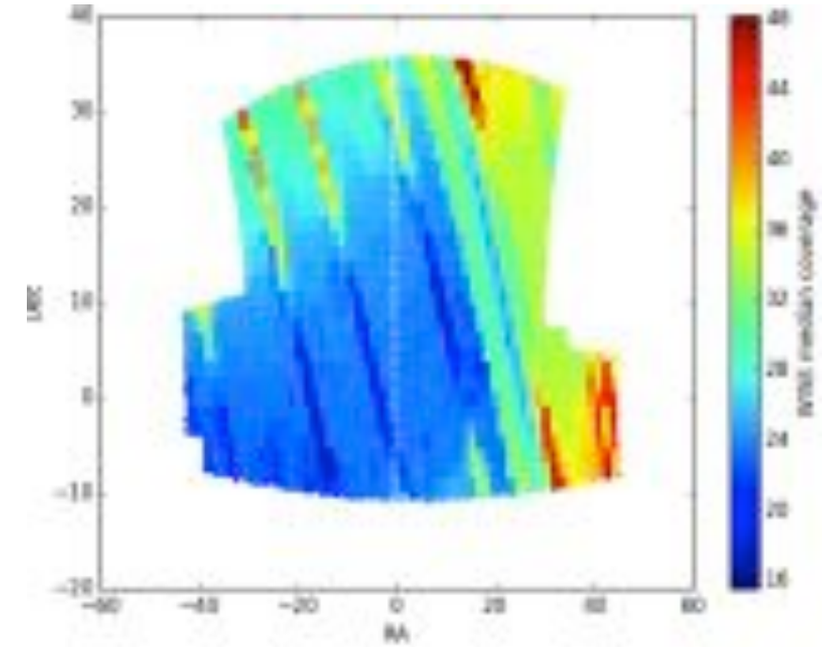
Sky Flux



Airmass

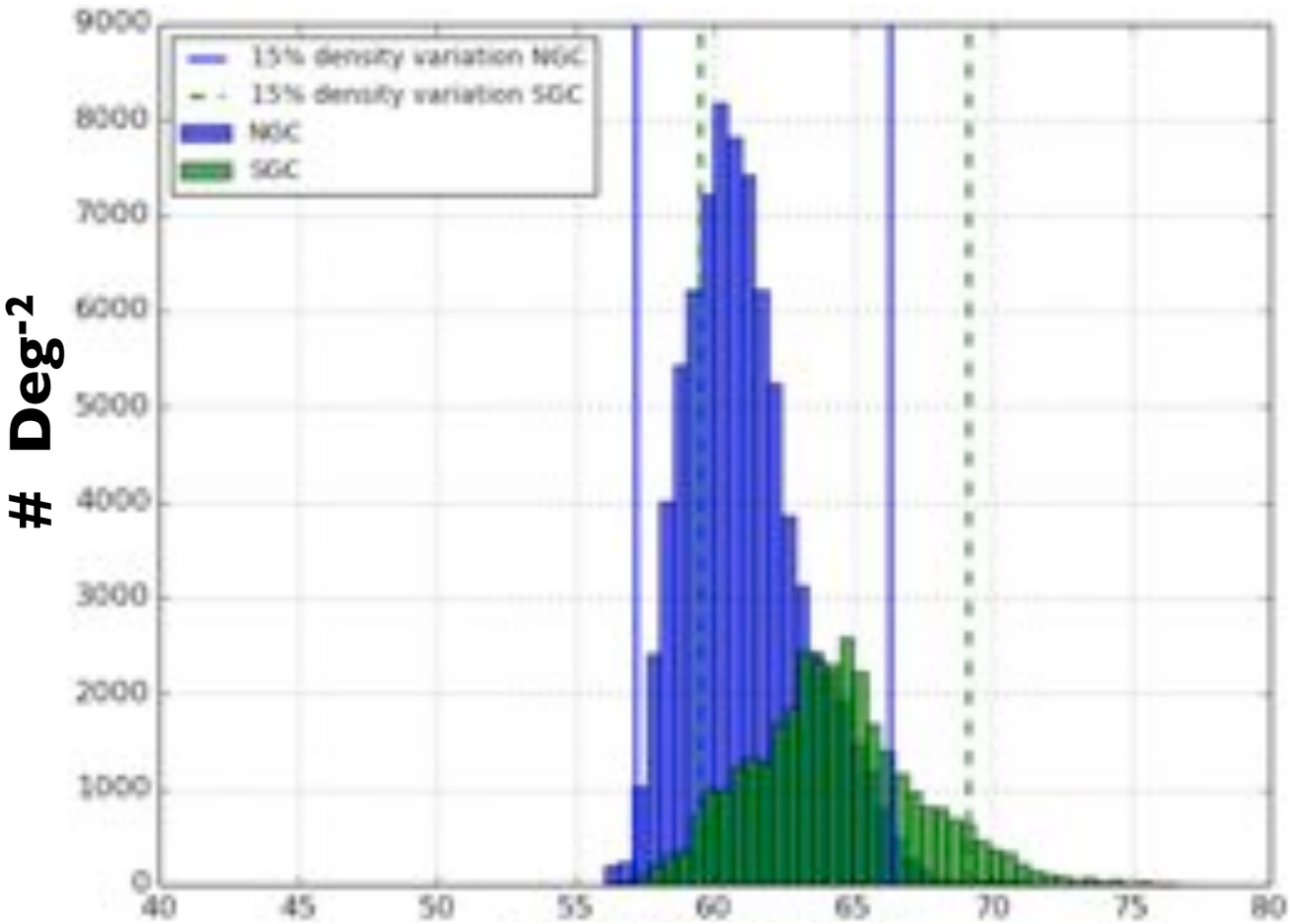


Seeing



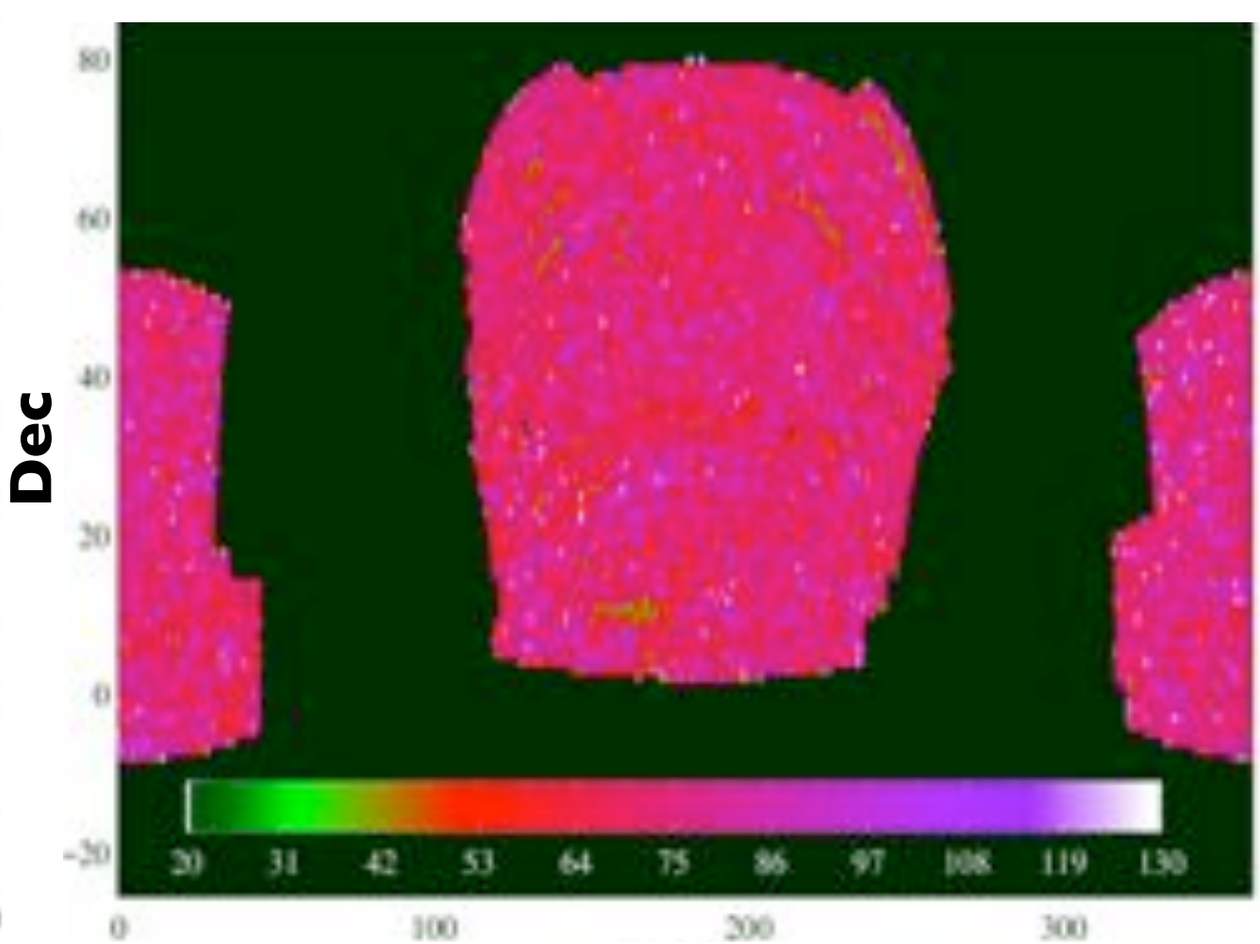
WISE depth

eBOSS LRGs predicted & observed density



Predicted mean density

Already 40,000 LRGs observed (SEQUELS+eBOSS)

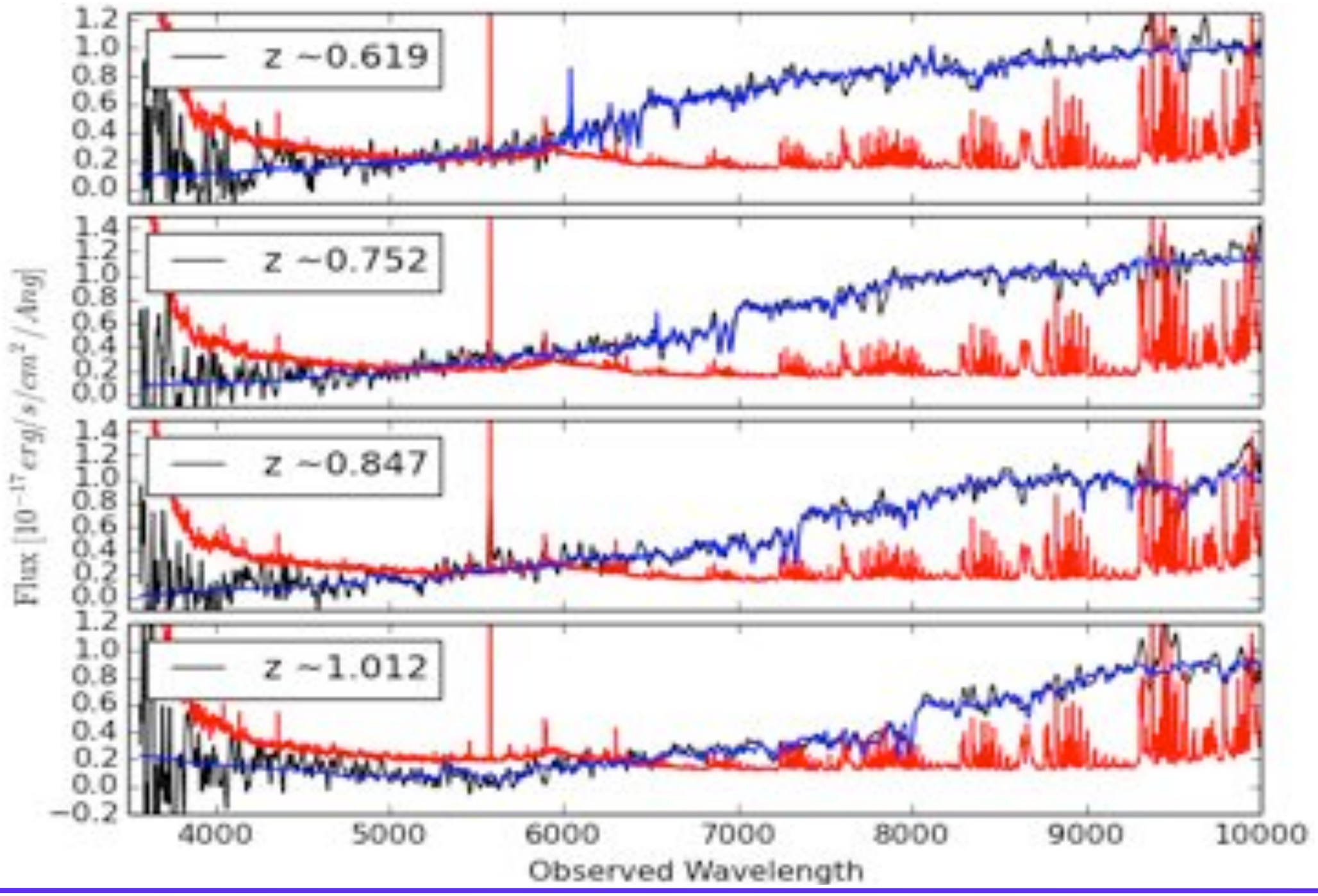


RA

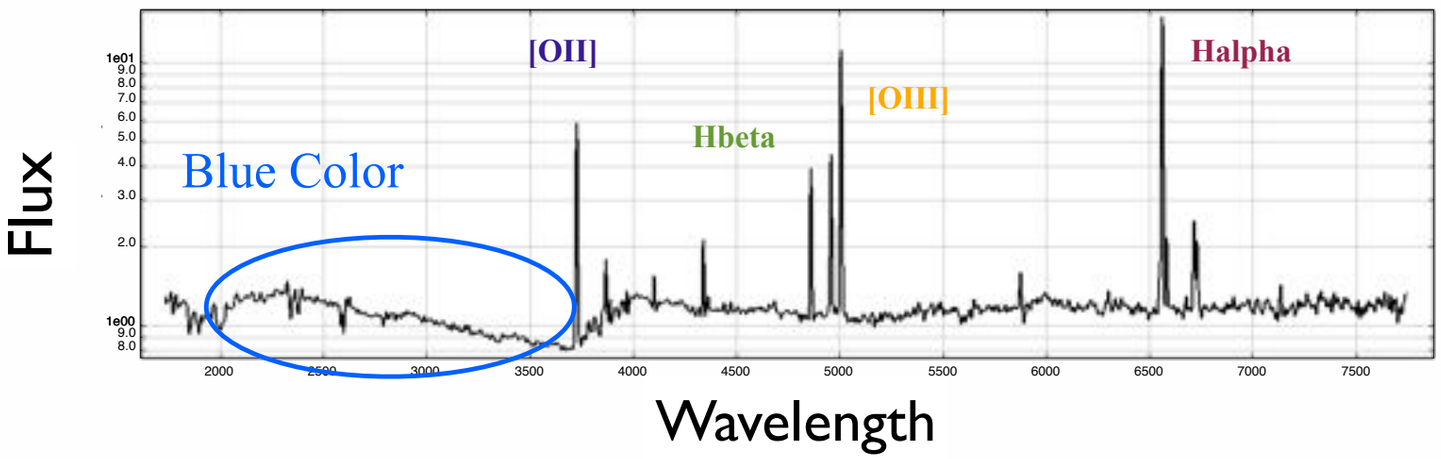
- Homogeneity: less than 15% variation
  - NGC: 96% of the area
  - SGC: 80% of the area

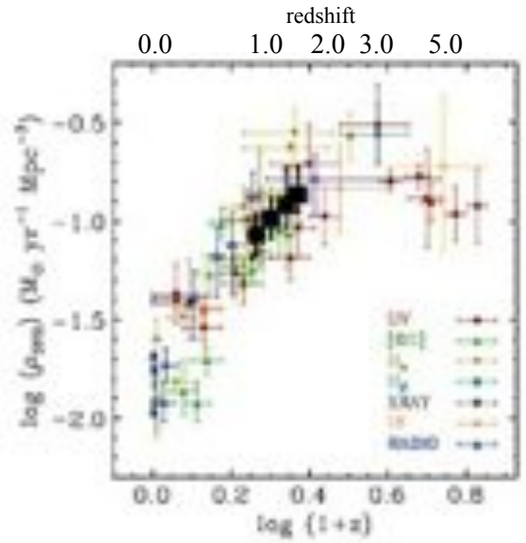
Secure redshift measurements across the redshift range of interest 0.6<z<1

A template spectrum based upon observations of the nearby elliptical galaxy NGC 4552,



ELG Survey Motivation





- **First 2% BAO measurements with ELG** - preparing future survey
- **Add a BAO point a z~0.85** (higher-z than LRG, universe is ELG dominated at z>0.7)
- Multi-tracer improve RSD measurement ? (constrain RG)
- Help solve eBOSS scheduling issues over South Cap
- ELG possible because SFR was ~10x higher at z~1; resulting strong emission lines allow secure redshift determination in ~1 hour with SDSS
- **Currently evaluating different TS strategies**

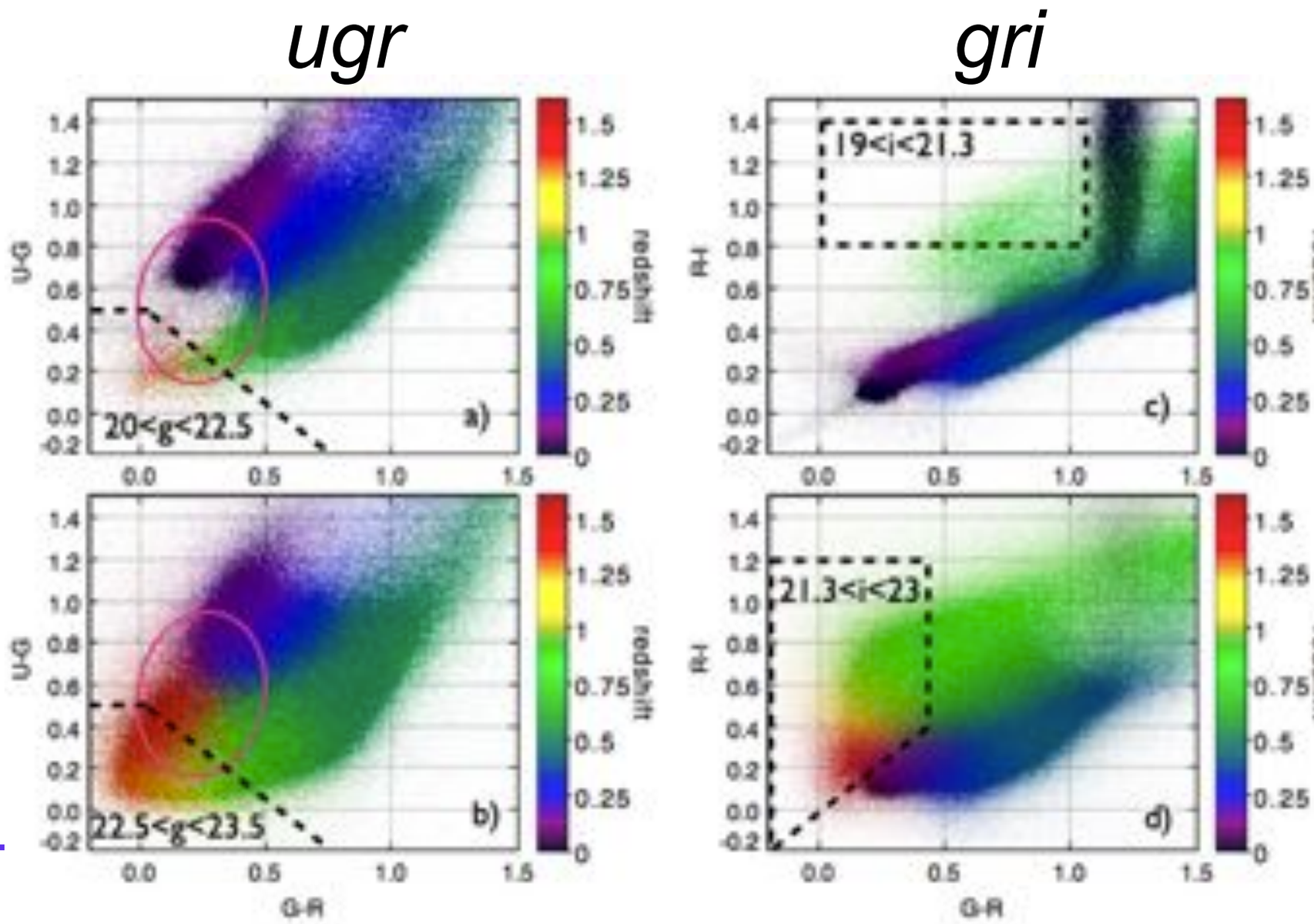
ELG target selection

2011: BOSS Ancillary project looking for high luminosity [OII] emitters

- 880 ELGs with *ugr* selection, [0.6<z<1.7]
- 900 ELGs with *gri* selection, [0.6<z<1.1]
- ~70% z-efficiency in both selections

Bright Selection (eBOSS)

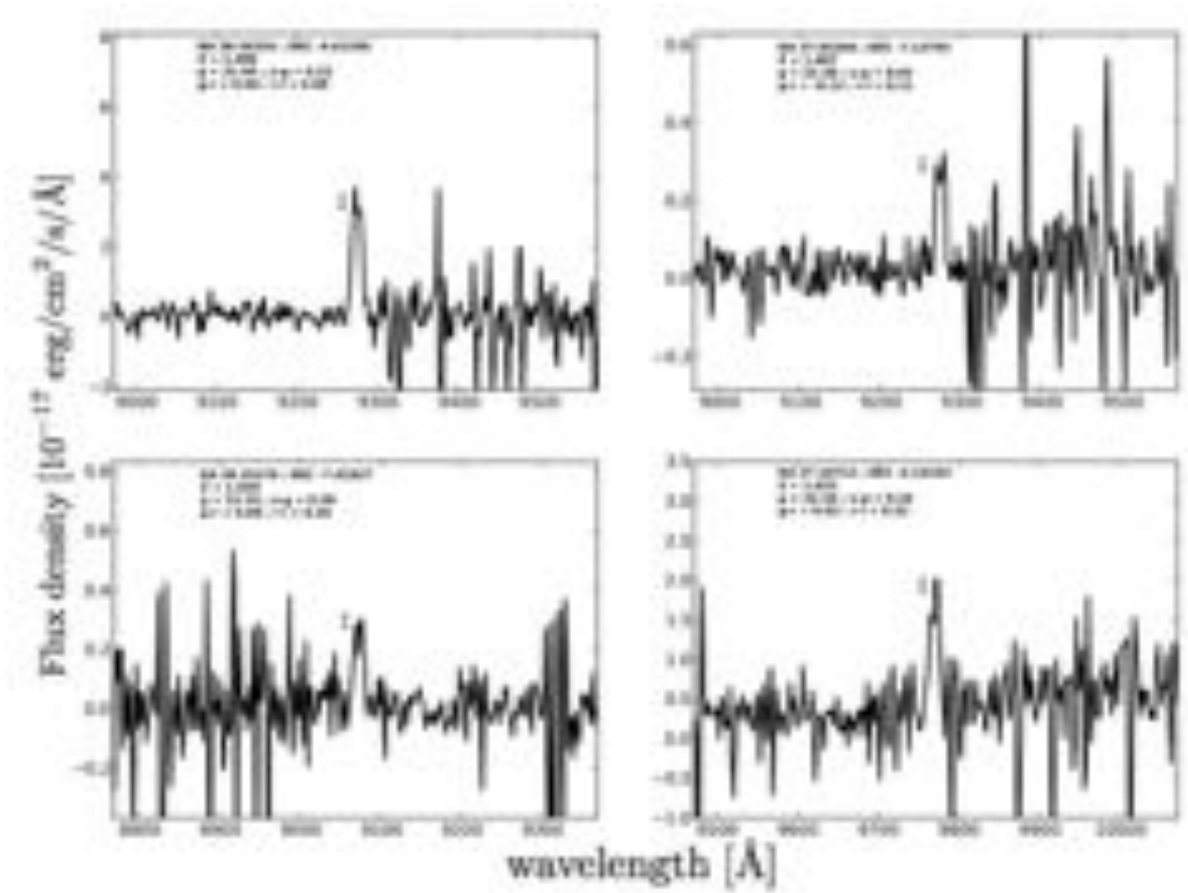
Faint Selection (DESI/PFS)

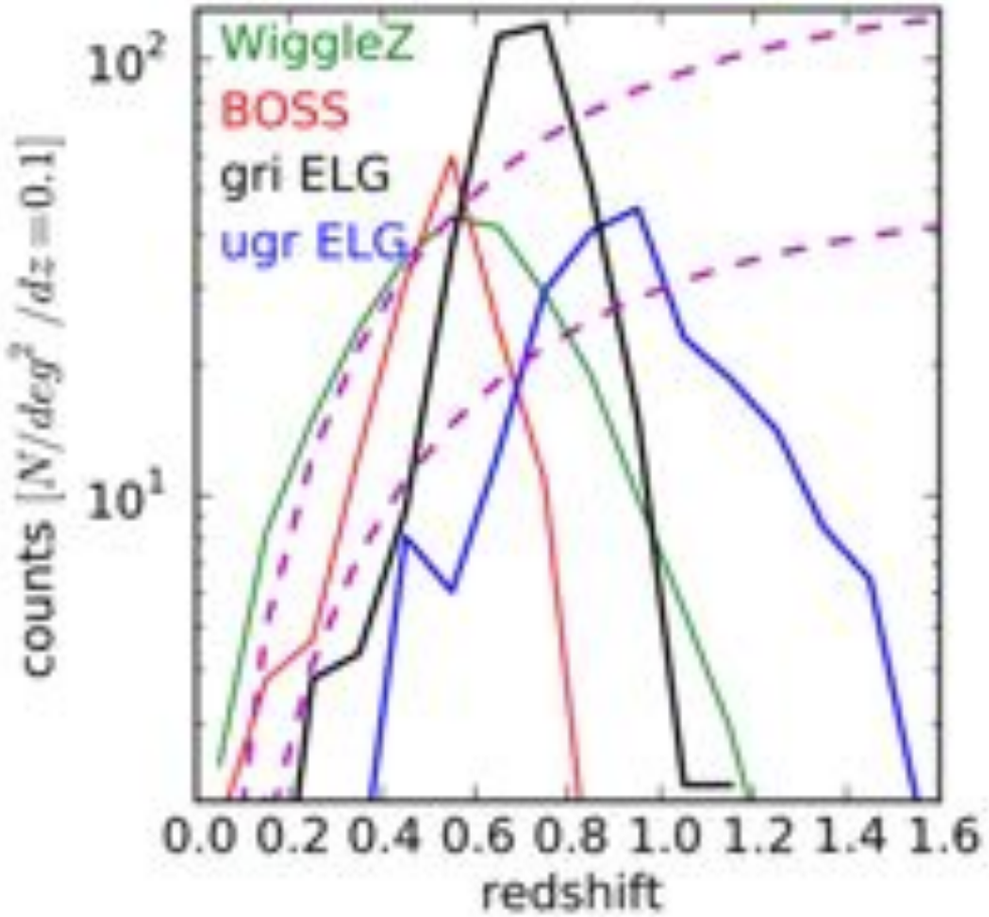


Comparat et al 2013a

ELG target selection

- High-z measurement and N(z)
- Redshift efficiency is linked to photometry quality (e.g. 60% and 75% for SDSS and CFHT)





Comparat et al 2013a

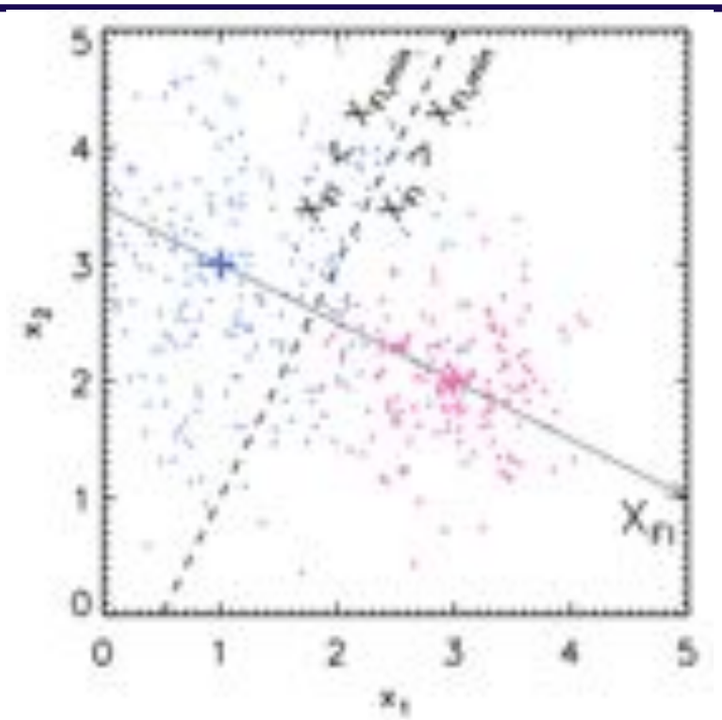
eBOSS Requirements for 2% BAO measurements

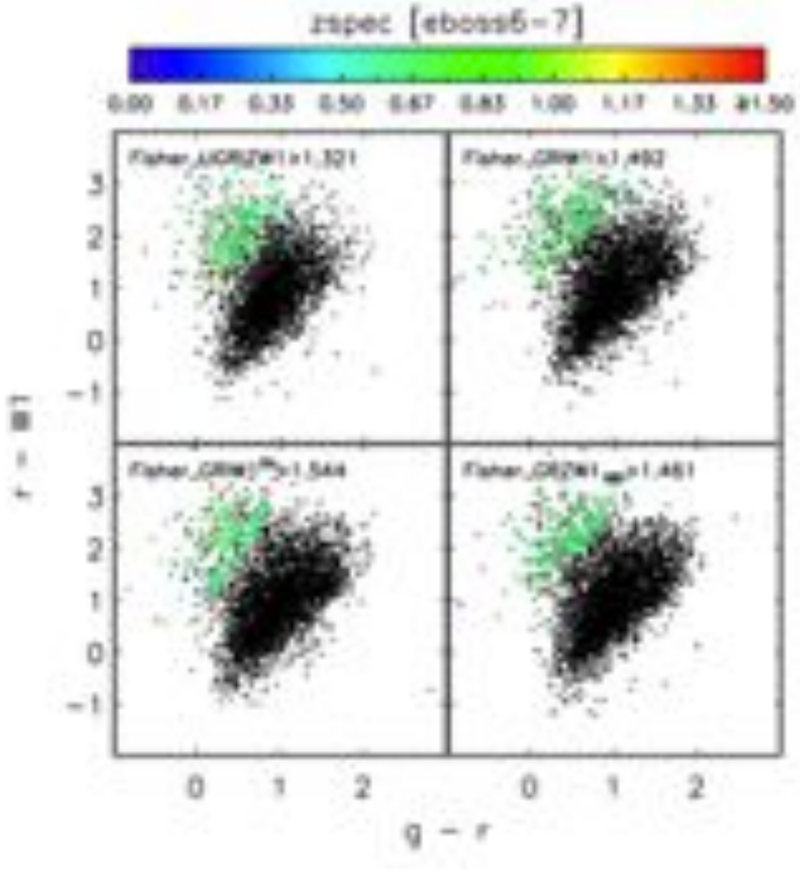
eBOSS SRD require an ELG sample satisfying:

- (Area > 1500 deg^2 or 500 deg^2 at 3 times the density)
- Total number of targets > 270.000.
- Observation completeness > 74%
  ("fraction of targets that result in a usable redshift in the range 0.6<z<1.0").
- Redshift accuracy < 300 $km.s^{-1}$ RMS
- Catastrophic redshift < 1%.
- Fluctuation in galaxy density < 15% (total) within the survey footprint (critically depend on photometry used)

ELG targeting algorithm

- Started with simple color cuts using SDSS+SCUSS
- Moved to Fisher discriminant techniques when including WISE data: linear combination of color terms, using training samples (Raichoor et al 2015)
- Currently exploring the DECaLS survey for ELG TS : http://legacysurvey.org/dr1/

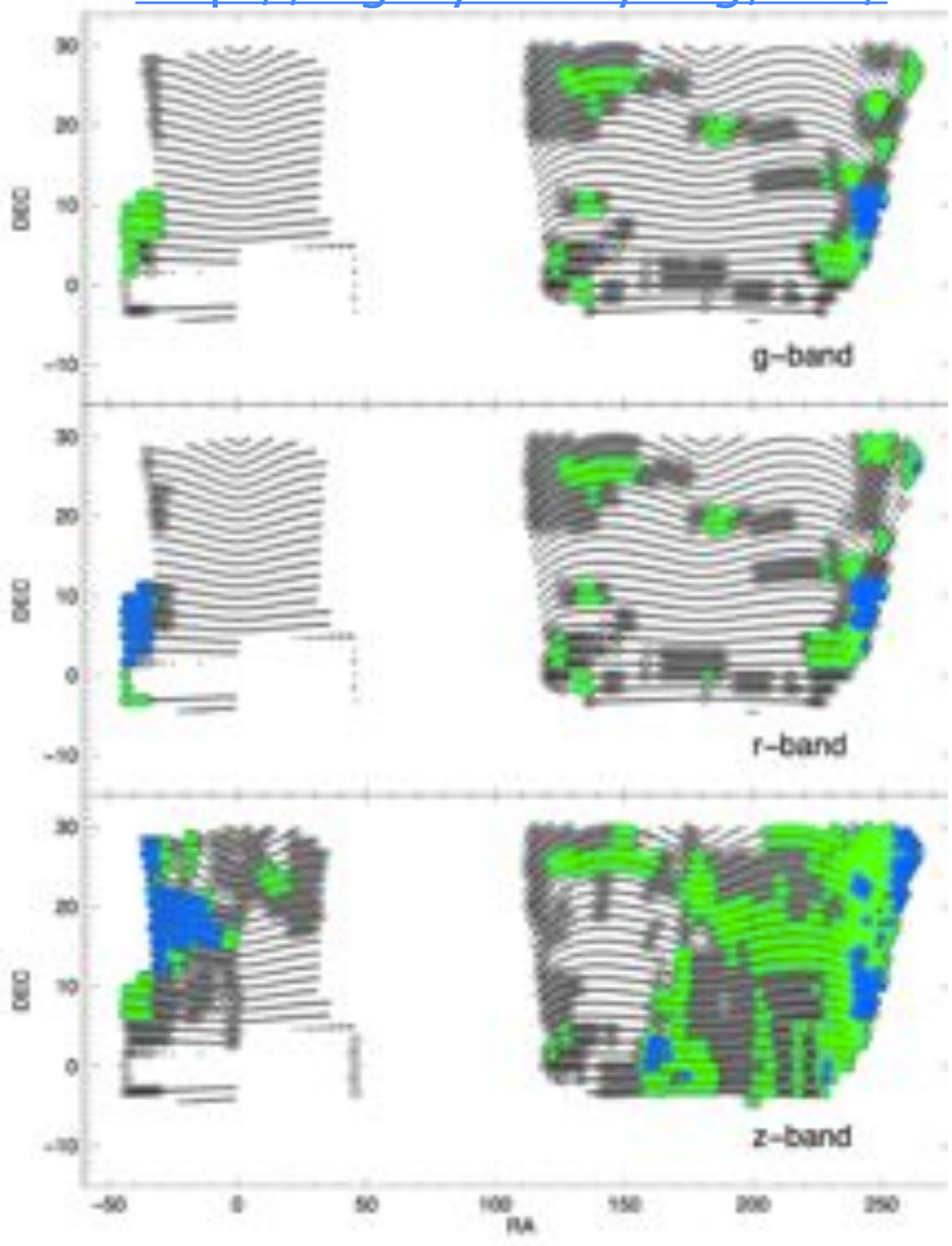




DECam Legacy Survey

- Designed for DESI target selection, will cover 6700 deg^2
- Use DEcam data, own data reduction. Use Tractor do conduct photometry. Match the data with the WISE data.
- Public data release every 6 months, quick turnaround between acquisition and release.
- Data can be used openly. Future release will likely include DES imaging too.

- http://legacysurvey.org/dr1/



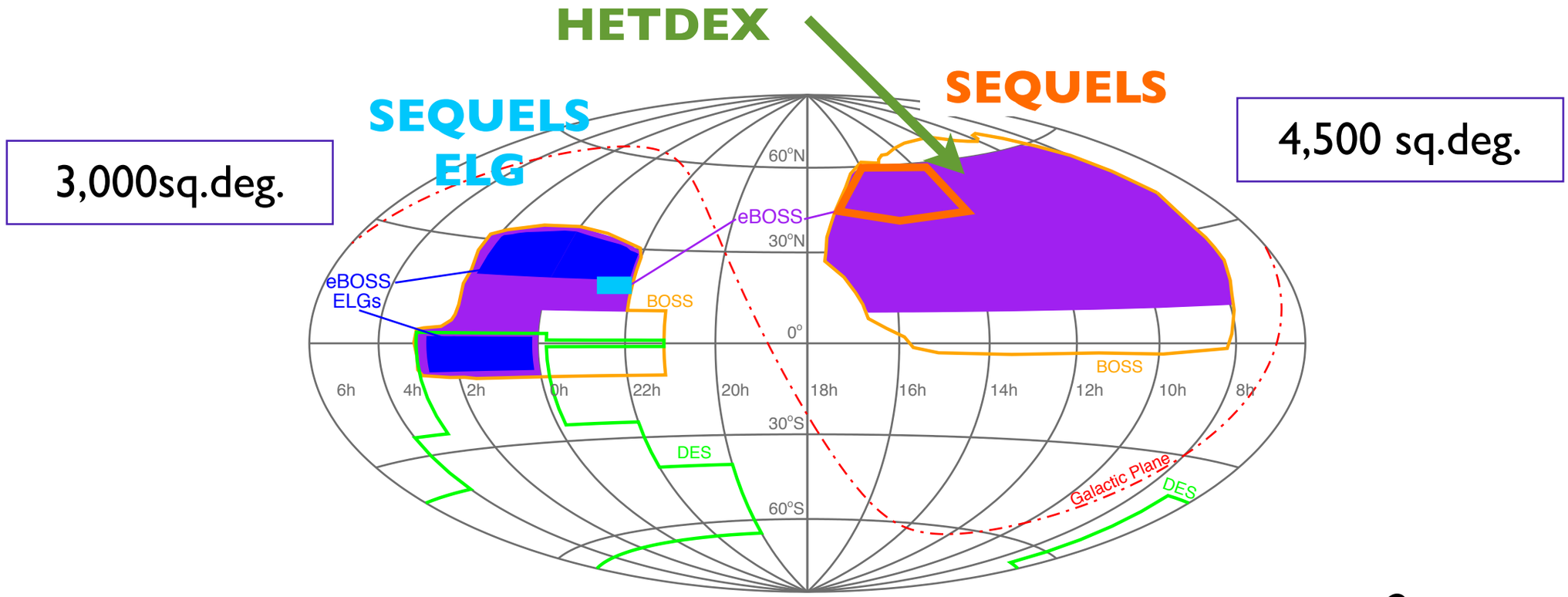
ELG TS evaluation vs. requirements

	DEcam 1500 deg2	DES 500 deg2	(SCUSS)+SDSS +WISE
Data Availability over Area	**LIKELY - DECaLS**	**YES - but scheduling issue**	**YES**
Efficiency 70%	**76% [0.7-1.1]**	**72% [0.7-1.1]**	**~68% [0.6-1.0]**
Catastrophic (<1%)	**<0.5%**	**<0.5%**	**<0.8%**
Homogeneity	**LIKELY: DECaLS**	**YES**	**YES: ~80% of SGC**
Mean z	**0.87**	**0.85**	**0.78**

Ambitious TS

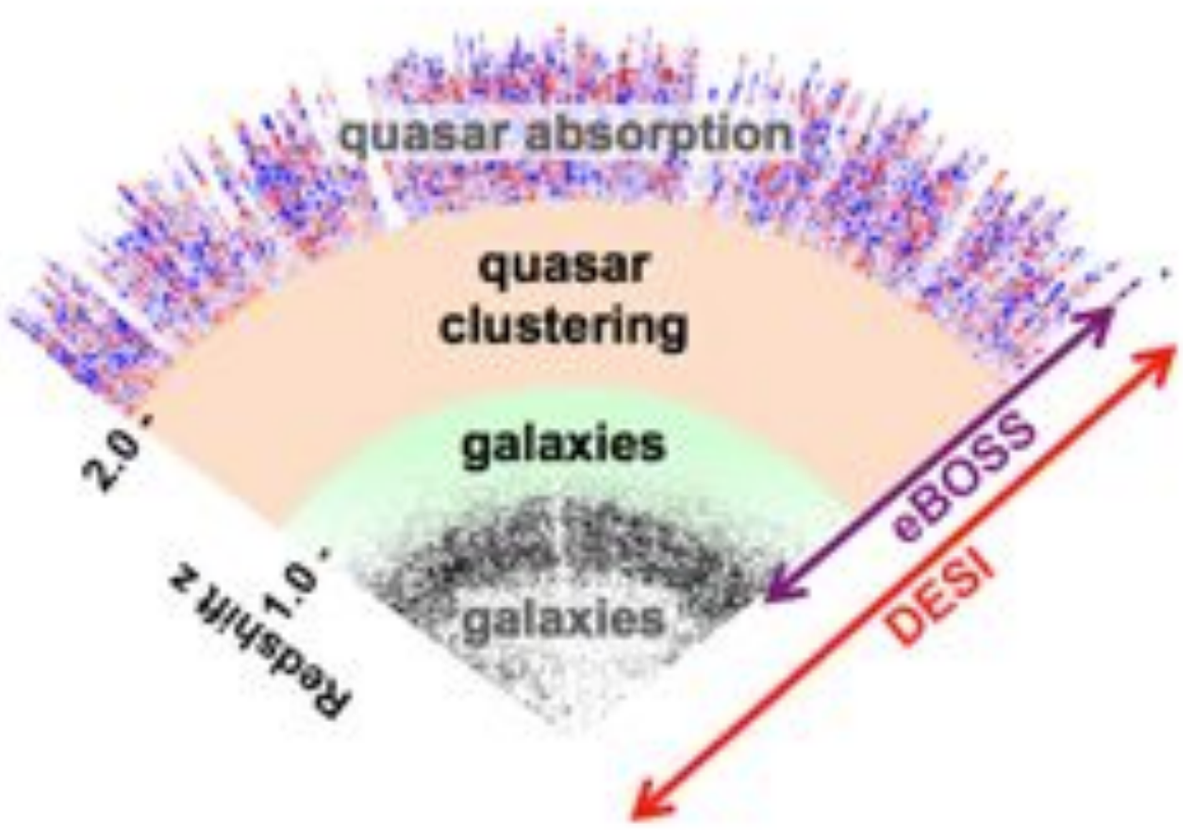
Safe TS

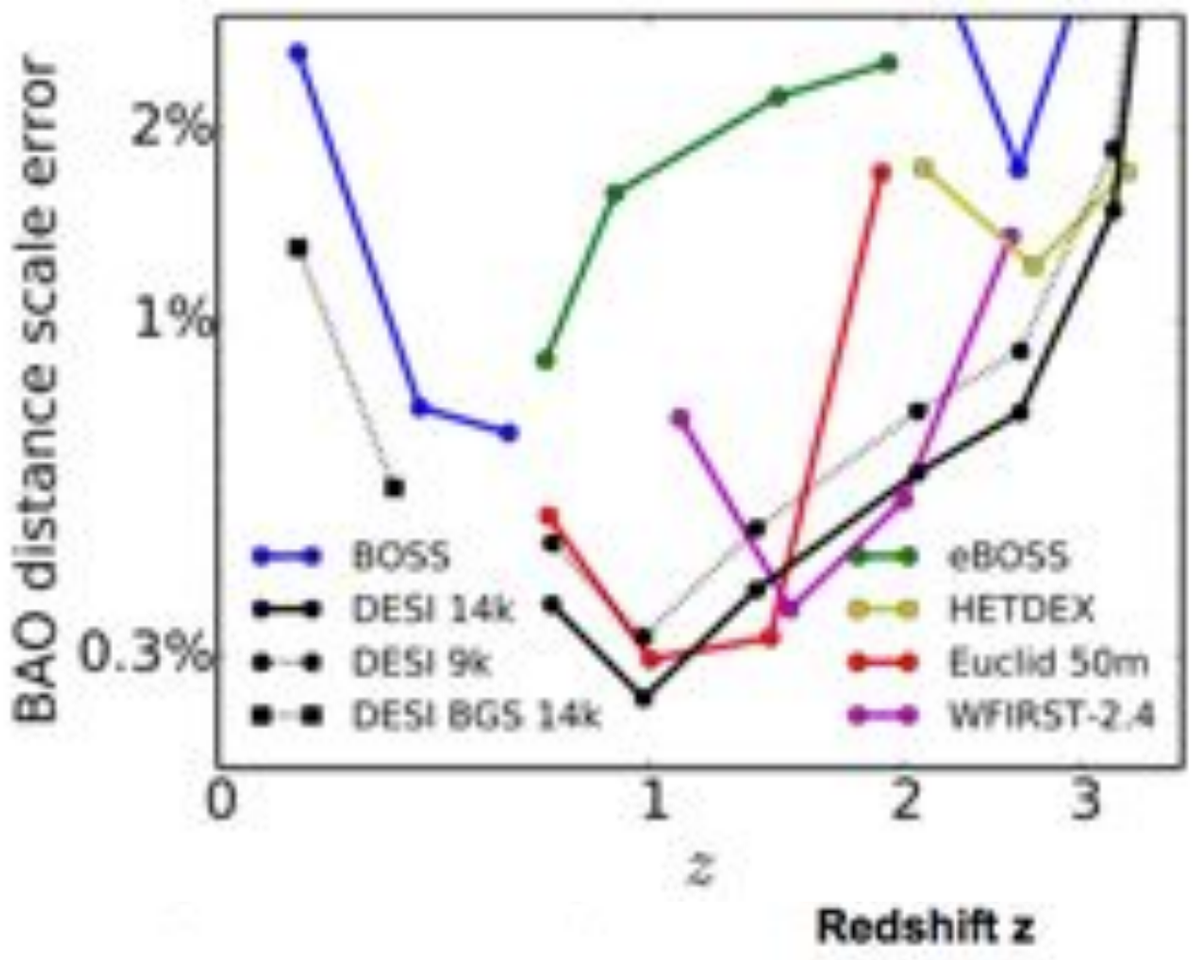
eBOSS Survey Planing



- *'Commissioning'*: SDSS-III/SEQUELS ~250 deg^2 of LRG and Quasars (Jan-Jul 2014)
- 7500 deg^2 of LRGs and Quasars (Sept 2014- July 2020)
- 1500 deg^2 of ELGs (Sept 2016- Jan 2018)
- including TDSS and SPIDERS sub-project.

Future BAO measurement





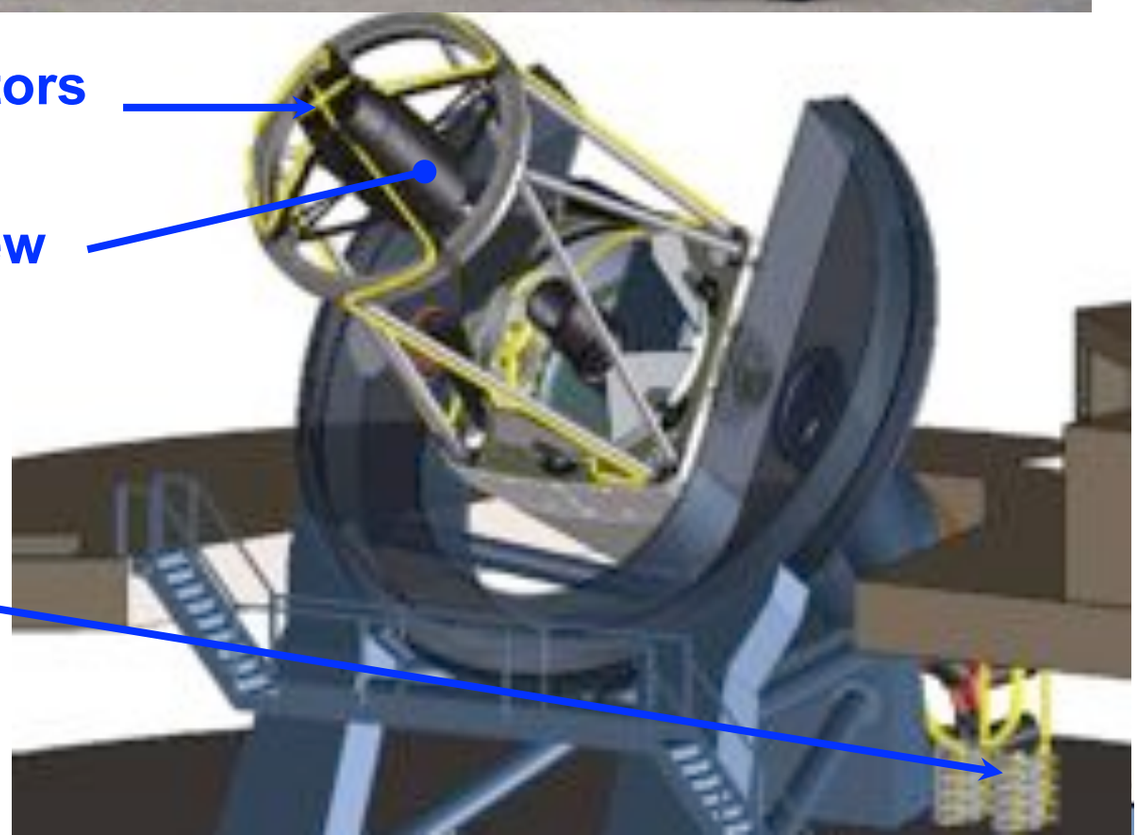
Ultimate ground-based survey

- **14,000 deg2: *all* Northern extragalactic hemisphere**
- **Cosmic-variance limited to z ~ 1 (galaxies)**
- **20 million galaxy and quasar spectra**

Much below 1% measurement, impact of systematics?

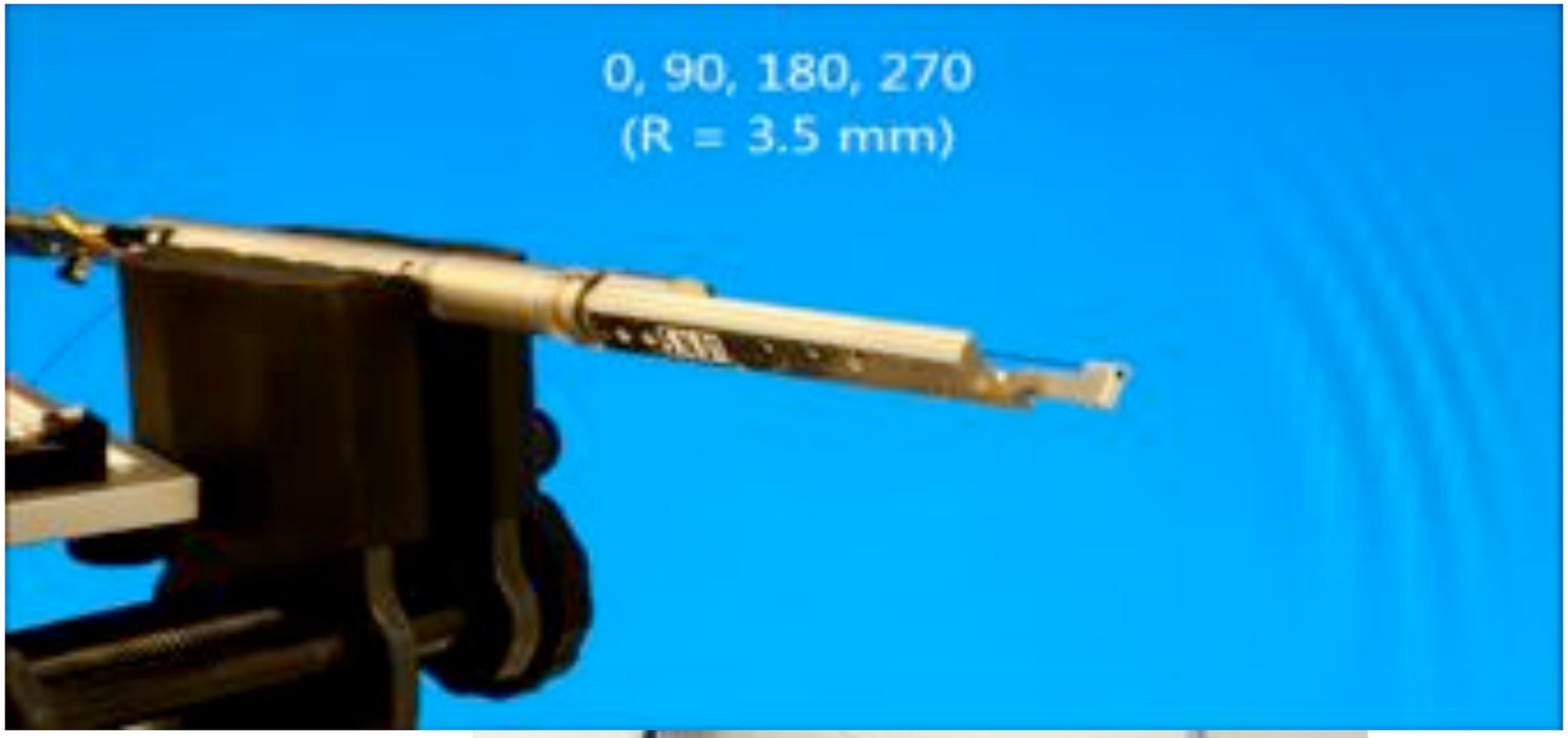
Dark Energy Spectroscopic Instrument

- **Map 35 million galaxies**
- Experiment to be installed on the 4m Mayall telescope at Kitt Peak in Arizona
- **International project** selected by the Department of Energy in the USA with many European countries involved (35+ institutions) **~200 participants**
- **EPFL involved in developing the fiber-positioner robotic system.**



Fiber Positioners (Actuators)

- **Based on 4mm diameter gear-motors.**
- **Positioning of the optical fiber to a few micron accuracy**



Spanish-Swiss
10mm diameter design

Electronics for actuator control developed at EPFL

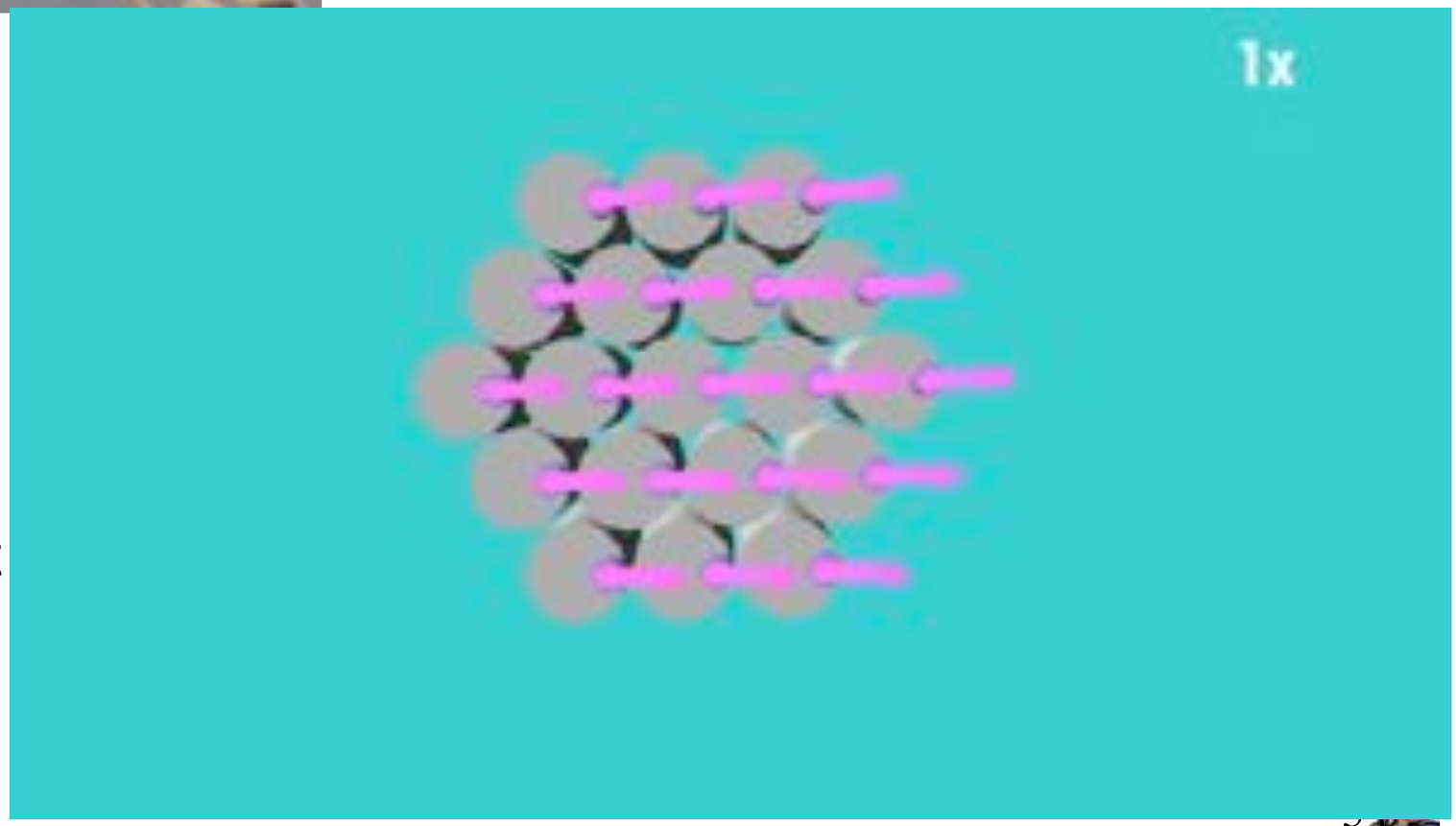
Coordination of the many fiber positioners

React

- Multi-robot system
- Crowded work space
- Mechanical constraints

- Avoid Collision

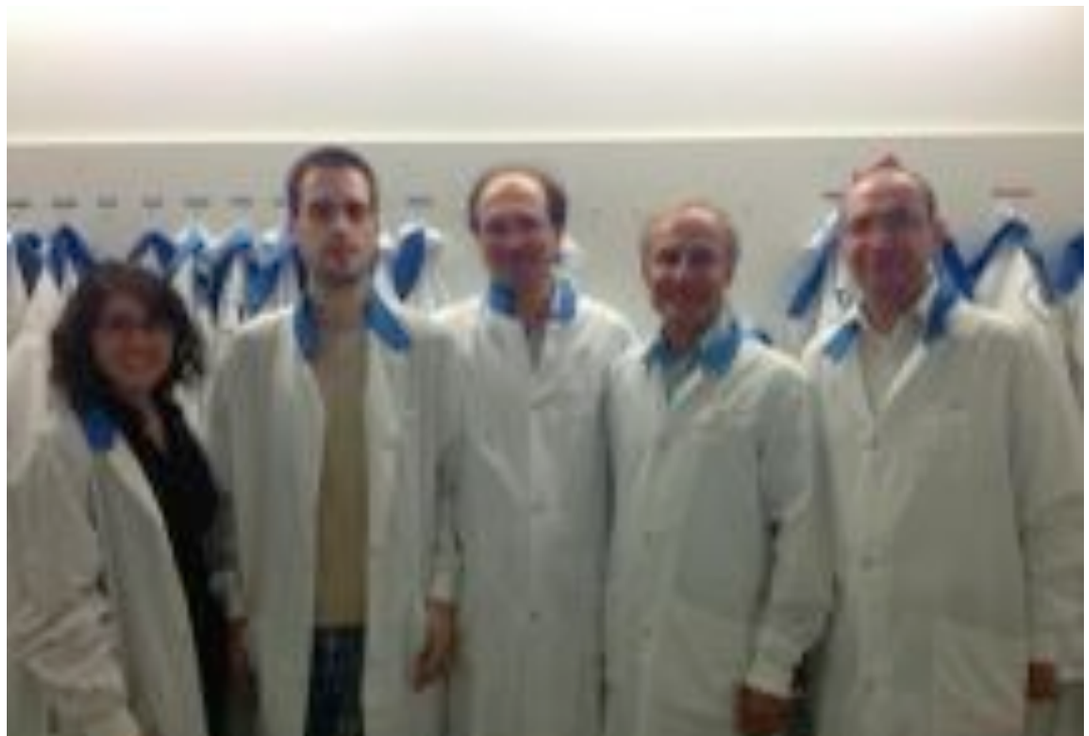
* Use of decentralised navigation function to find collision free trajectories, in order to place the thousands fiber positioners at their target location.
* Each robot is independent.
* One can optimise for speed and/or energy consumption to minimize heat production.



Makarem 2014 PhD work

Astrobots group at EPFL

- Interdisciplinary group at EPFL to focus on robotic fiber posizionino system, started in February 2013.
- New 10mm prototype constructed at MPS a Swiss company, April 2014
- **Prototype presented at the DESI collaboration meeting, May 2014 but not selected. Berkeley design was selected.**
- **Massive production (5000 units) starting end of 2015**
- **Instrument ready on telescope in 2018**
- Now, involved in a new similar project: MOONS a project with 1000 actuators for the ESO VLT telescope.



EPFL interdisciplinary team:

- Laleh Makarem (REACT)
- *Jean-Paul Kneib* (LASTRO)
- *Hannes Bleuler* (LSRO)
- Mohamed Bouri (LSRO)
- Philipp Horler (LASTRO/LSRO)
- Denis Gillet (REACT)

http://astrobots.epfl.ch/

Conclusion

★ eBOSS is collecting data !

★ **170 plates observed, at 1/9 of the LRG+QSO survey**

★ ELG targeting is converging

★ Preliminary clustering analysis; Mock simulations underway, in particular QSOs and ELGs

★ Technical papers in preparation - out this summer 2015

★ First Cosmology results of eBOSS in mid-2016

★ DESI is on tracks, production of fiber positioners starting in 2016, with first light end 2018. Survey start nominally in 2019.

★ 4MOST, Euclid, SKA should follow ...